The Changing Faces of the Earth's Magnetic Field

Mioara Mandea
Erwan Thébault

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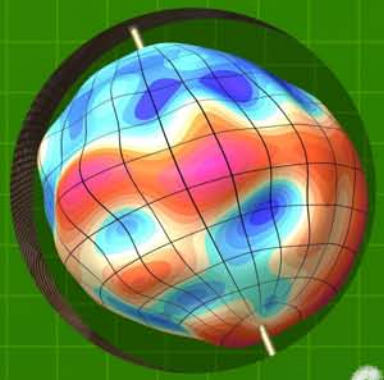

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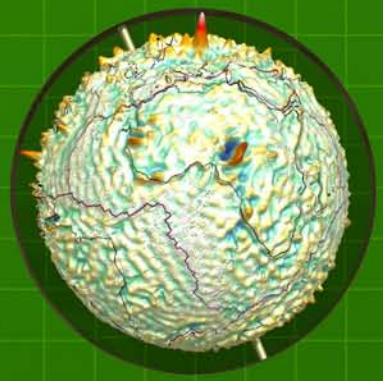

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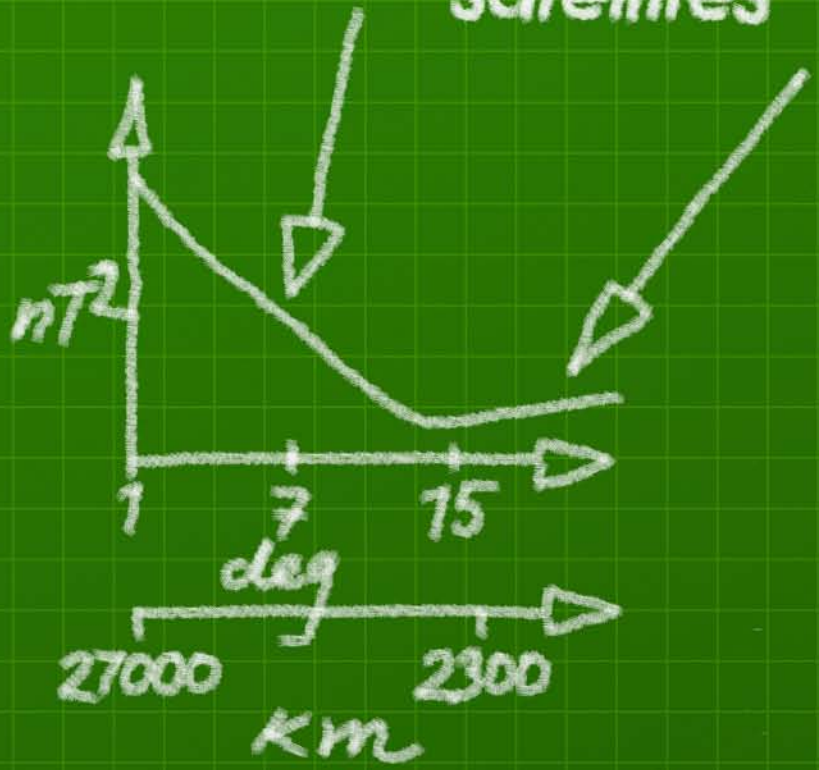

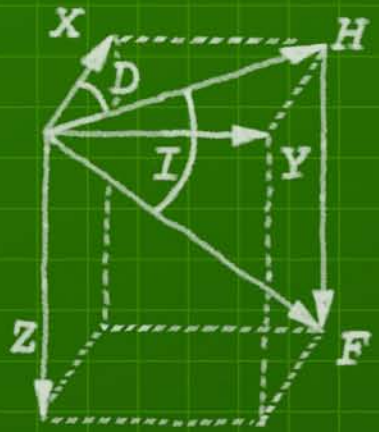

The Changing Faces of the Earth's Magnetic Field

A glance at the magnetic lithospheric field, from local and regional scales to a planetary view

Mioara Mandea[1] and Erwan Thébault[2]

1. GeoForschungsZentrum Potsdam, Telegrafenberg, Potsdam, Germany
2. Institut de Physique du Globe de Paris, 4, Place Jussieu, Paris, France

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Foreword

The aim of this publication is to provide an easily understood description of the Earth's magnetic field for a broad public audience, which may in turn be used as a guide for high school and undergraduate teachers in Europe and beyond. While we have endeavoured to provide information consistent with the current status of scientific research, many aspects of the geomagnetic field are still being actively explored and will undoubtedly change in the coming years. Moreover, we recognise the inherent difficulty of describing such complex phenomena in a highly simplified form that still remains satisfying to both familiar and unfamiliar readers. Geophysicists will probably find the writing simplistic, and we therefore apologise to our colleagues for oversimplifications and potential mistakes. Nevertheless, we hope that presenting the Earth's magnetic field in a more educational and simplified fashion will be useful for them and/or their students. We have included carefully selected illustrations to clarify concepts for the reader. A glossary of specific terms pertaining to Earth's magnetism, noted in text by stars, is included at the end of this book, however it is limited to only those terms we consider to be of particular importance.

Further readings

For more details the reader is referred to two recent publications 1) Encyclopedia of Geomagnetism and Paleomagnetism edited by David Gubbins and Emilio Herrero-Bervera, Springer, 1000 pp, 2007 and 2) Treatise of Geophysics, Elsevier, 10 vol. 2007. A short list of references is also included at the end of this book.

Responsibility

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Introduction

When we observe the Earth at geological time scales, we discover that it is largely composed of fluids, and not just because over two-thirds of the entire surface area of the globe is covered by water. Below the mostly solid crust* is the mantle, which is a sort of very viscous fluid. Lying underneath the mantle is even more fluid in the liquid outer core* convecting between the mantle and the solid inner core.

The ability to determine the structure of our planet's interior has always been challenging, because even the deepest boreholes do not penetrate to depths more than 10 km, barely a scratch compared with the Earth's radius (6371.2 km). Indirect observations are thus necessary, and geomagnetism is one of the oldest and most important geophysical techniques used to remotely explore the mysteries of the Earth's deep interior.

The story begins centuries ago when the first ideas surfaced suggesting that the Earth's magnetic field, itself, resembles a giant magnet. Like a conventional magnet, the Earth has two magnetic poles, however, they do not coincide with the geographic poles. At the magnetic poles, a compass needle stands vertically pointing either directly towards or away from the magnetic centre of the Earth. A bar magnet loses its magnetic properties over time, but the Earth's magnetic field has been around for billions of years, so something is sustaining it. In reality the Earth differs from a solid magnet, and its magnetic poles are in constant motion as a result of continual geological fluid convections in the outer core. A century ago, Einstein stressed that the origin of the Earth's magnetic field was one of the greatest mysteries of physics. While our comprehension of the Earth's magnetic field has remarkably improved, the self-sustaining, and somehow chaotic, nature of the Earth's magnetic field remains poorly understood.

Direct measurements of the magnetic field supply high spatial and temporal resolutions, albeit restricted to the last few hundred years or less than a decade when considering satellite measurements. Since the temporal variations of the geomagnetic field* occur on timescales ranging from seconds to millions of years, our view is thus restricted to a very short time span. In order to capture the essence of the past magnetic field activity, indirect measurements based on the paleomagnetism* of rocks provide valuable but low-resolution information on the field over timescales of thousands to millions of years. The combination of these direct and indirect observations is useful in reconstructing the history of the Earth's core field. Because the past magnetic field has been imprinted in the Earth's crust, paleomagnetism and geomagnetism also give the essential tools needed to piece together the geological units broken apart through geological times. The lithospheric field can be measured at a variety of scales, ranging from the weak magnetic sediment signals at local scale to the strong magnetic basement at regional and continental scales. It largely arises from the magnetic properties of the underlying rocks and tells us about the past and the present status of the Earth's dynamics and thermal history. Most of the information leading to our present understanding of the Earth's crust dynamics is a result of lessons from magnetics.

In this work, we mainly focus on the geophysical interpretation of the Earth's magnetic field recorded in the crust. This choice is justified by the recent release of the first version of the World Digital Magnetic Anomaly* Map (WDMAM), an international effort towards the mapping at 5 km altitude of the magnetic anomalies originating for the Earth's crust. At the same time, a brief summary of the outstanding achievements brought by recent satellite missions give an overview of the science expected from the unprecedented combination of the WDMAM and the forthcoming European satellite mission, Swarm. Moreover, as the magnetic rocks are arranged in such an intricate way, with superimposing layers of various rocks from the top of the crust to the bottom,

only the integration of magnetic data acquired at various altitudes with gravity, seismic, geochemical, remote sensing, and geologic data allows us enhanced interpretation and reduces their inherent ambiguities. The examples discussed in the following pages were selected for their originality and their interdisciplinary applications.

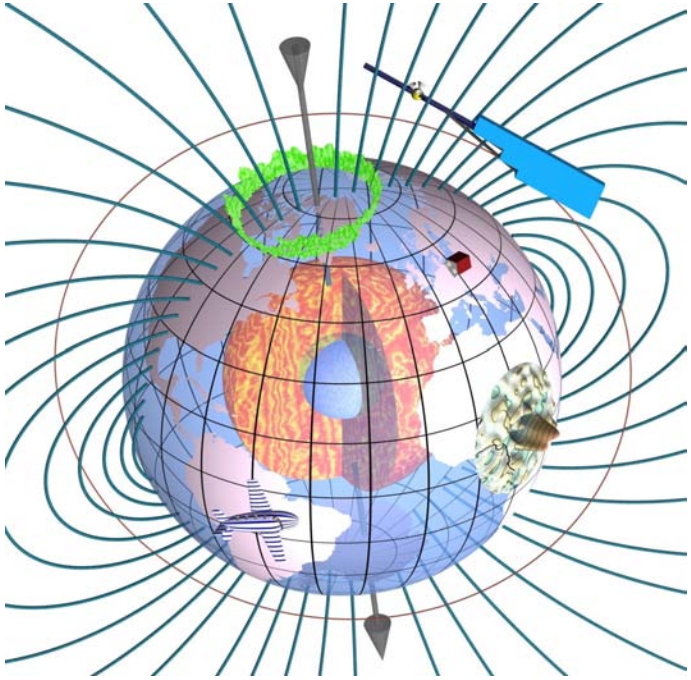


Figure Introduction: The main part of the Earth's magnetic field is due to a geodynamo mechanism in the liquid, metallic, outer core, and is known as the main field or core field (see the outer core shown in red and yellow). To this dominant contribution of the Earth's magnetic field one must consider the lithospheric field that arises from rocks that formed from the molten state and thus contain information about the magnetic field at the time of their solidification (see the Bangui magnetic anomaly signature in the central African region). Another significant contribution is that of external field sources, which originate in the ionosphere (see their signature in the northern high latitude indicated in green) and magnetosphere. Information about geomagnetic field variations, in time and space, are obtained from ground (as magnetic observatories, one being shown in Europe), near-ground (as, for example, the aeromagnetic surveys, indicated by an aeroplane over South America), and space measurements (as CHAMP magnetic satellite).

Even if magnetic fields are better described with the help of mathematics, this book is devoid of equations and concepts are explained using case examples. The reader should, however, keep in mind that our understanding of the Earth's magnetic field is in a state of motion and is strongly contingent upon magnetic field measurements. The measuring devices, assumptions, modelling techniques, and approximations are constantly refined as geophysical problems are elucidated and new data are available. Each magnetic field contribution is itself complex, and an additional layer of complexity is introduced to the overall system by interactions between all magnetic field contributions, from the core, the crust, and the external fields. The interactions are, in general, "non-linear", meaning that the Earth's magnetic field is much more than the sum of its parts. Understanding this is important for interpreting past changes, for monitoring the present state, and for forecasting future magnetic field evolution on the basis of magnetic measurements. Bearing in mind this complexity is also important when "zooming" in and looking closely at lithospheric field patterns, when addressing lithospheric tectonics and hazards, when studying the influence of large impacts on the early tectonic development, or even when considering regional distribution of energy and regional resources. A part of this complexity is simplified here...

... with a prerequisite review of the Earth's magnetic field, and the history of its measurements, provided in the first chapter. This is followed by illustrations of magnetic field applications at local and regional scales for various purposes, ranging from archaeology to plate tectonics. The third part tackles the satellite perspective and the most striking results that have been obtained during the last decades based on satellite data. Even more outstanding results should be expected in the coming years based on the joint analysis of the WDMAM and satellite data. In a fourth part, we illustrate how the expertise gained in the Earth's magnetic field can profit the understanding of Earth-like planetary magnetism.

First part: The Earth's magnetic field and its complex behaviour

Definition and history

When you use a map, you might need a compass to tell you how to locate North, but have you ever wondered what "North" means and where its definition comes from? There is a dual answer to this question and North can be either geographic or magnetic. They usually do not coincide. The geographic North Pole and South Pole are where the Earth's axis of rotation intersects with the surface. The North magnetic pole is the point where the Earth's magnetic field is vertical in the northern hemisphere. The Earth's magnetic field has an invisible area of influence that we may experimentally sense by using iron filings sprinkled on a piece of paper with a dipole magnet underneath. At the Earth's surface, a compass needle swings until it aligns along this magnetic North-South direction. In reality, the Earth's magnetic field has a more complicated geometry than a pure North-South axial dipole*. Traditionally, and for obvious reasons, magnetic observations were made at the Earth's surface. The magnetic field is thus commonly described in a local reference frame, either using the Cartesian X, Y, Z or the angles D, I coordinate system (Figure 1.1).

The magnetic field is a physical vector quantity given in Teslas; in SI units 1 T equals $1\,\mathrm{kg\,s^{-1}C^{-1}}$. Two other units may be found in the literature, the Gauss, which is 10^{-4} Tesla and the gamma (γ), which is not much used nowadays, equals 1 nanoTesla (nT). For the angular reference frame, the magnetic field is expressed in degrees or radians.

Observing the Earth's magnetic field has a long and diverse history, from its infancy in oceanic navigation, during the Earth exploration ages, to the more recent conquest of space. The careful collection of data and indirect observation through history has allowed us to understand the large varieties of space and time variations of the Earth's magnetic field. It is so complex that nowadays many geomagnetic disciplines evolve in parallel, while constantly interacting with each other. Geomagnetism and paleomagnetism unveil the mysteries of the magnetic field of the Earth's lithosphere*. Geomagnetism focuses on the recent past and the present geomagnetic field*. Paleomagnetism endeavours to reconstruct the history of the magnetic field.

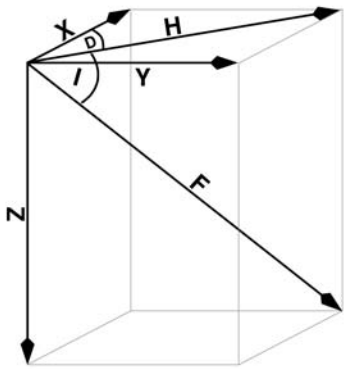


Figure 1.1: The X and Y components are both aligned parallel to the Earth's surface but are directed either geographically Northward (X) or Eastward (Y). H is the horizontal component vector parallel to the Earth's surface and directed towards magnetic North and Z is the vertical analogue pointing downward towards the surface, in the Northern Hemisphere. As can be seen, the strength F of the magnetic field is independent of the reference frame. The inclination (I) is the angle between H and F, and represents the downward vertical dip seen in the compass needle, while the declination (D) is the angle between magnetic North (H) and geographic North (X).

In order to comprehend how the science of the Earth's magnetic field emerged it is instructive to go back in time, as early as the first century AD. The earliest form of a magnetic compass was invented by the Chinese, but it seems to have been employed more for geomancy and divining purposes than for navigation. This first compass consisted of a lodestone spoon rotating on a board carved with symbols. During the following centuries the frictional drag between the spoon and the board was overcome by compasses based on floating or suspended needles.

The compass was probably introduced in Europe by the Arabs during the XIIth century; its first quotation for navigation is by Alexander Neckman around 1190. One century later, the first discussion about the concept of magnetic poles was written by Petrus Peregrinus. He de-

scribed in his *Epistola de magnete* (1269) how he determined the magnetic pole positions of a spherical piece of lodestone and showed that the magnetic force is stronger and more vertical at the poles. Petrus Peregrinus' experiment was resumed and extended 300 years later by William Gilbert who extrapolated the conclusions to the Earth. Only from the XVIth century, and this first attempt to set up a theoretical formalism, can geomagnetism be regarded as a science. A series of long term geomagnetic field measurements evidenced changes of the geomagnetic field direction, the so called "secular variation". It was recognised in 1634 by Henry Gellibrand who compared declination observations made in London at different epochs.

Despite the already long history of compass utilisation for navigation purposes, we must wait till the beginning of the XVIIIth century to see the first magnetic map over a large terrestrial area. Edmund Halley, who discovered the comet that bears his name, commanded the *Paramore*, a small sailing ship, and carried out magnetic surveys in the North and South Atlantic Ocean, and its bordering lands, between 1698 and 1701. The first map showing lines of equal declinations of the magnetic field in the Atlantic Ocean was compiled and published in 1700. It is worth noting that the origin of the magnetic field, in the Earth's deep interior or in the crust was still in debate at the time.

The theory of magnetism follows the scientific revolution initiated by Isaac Newton. The first basis for the magnetic field concept in physics was established by Michael Faraday in 1821. This was closely followed by the important event in geomagnetism history, when Carl Friedrich Gauss and Wilhelm Weber began investigating the theory of terrestrial magnetism in 1832. By 1840 Gauss had written three important papers on the subject, all dealing with the current theories on terrestrial magnetism. The potential theory equations, like the Laplace and Poisson equations, the harmonic theorems and the spherical harmonic representation of the magnetic field, all are derived from Gauss' work on geomagnetism. We also owe to Gauss, in his *Allgemeine Theorie des Erdmagnetismus* (1839), the first geomagnetic field model demonstrating the mainly dipolar nature of the Earth's magnetic field. Nowadays, a Global Positioning System (GPS) receiver is carried on most of aircraft, but a magnetic field model is always used as a backup in case of system failure and it is worth noting that the modelling approach of Gauss is still widely used today.

The discovery of electromagnetism by the Danish scientist Hans Christian Ørsted and the French physicist André-Marie Ampère led Michael Faraday to the notion of fluid dynamos. Later on, the observation of sunspot magnetism by the astronomer George Hale led Sir Joseph Larmor to suggest in 1919 the idea that dynamos could naturally sustain themselves in convecting conducting fluids. This modern dynamo theory is applied to our planet and explains the geomagnetic field originating from the Earth's deep interior. This major breakthrough was the springboard for various modern research in geomagnetism, so fruitful, that only a few of achievements can be reported here (for more exhaustive details, the reader is referred to *References*).

The Earth's magnetic field sources

The study of the Earth's magnetism requires multidisciplinary approaches, which are themselves constantly evolving. Locating the magnetic field produced in the Earth's core would have been hopeless without progress in the understanding the nature of the Earth's interior. In the same vein, the lithospheric field* could not have been explained if the basis of rock magnetism were not concurrently founded.

The Earth's total magnetic field is approximately dipolar and was inclined by about 10.3° from the planet's axis of rotation in 2005. The geomagnetic field geometry is however more complicated, due to variations in space and time. We noted that Joseph Larmor was able to explain the principal source of the magnetic field by convecting viscous iron fluids in the Earth's core. Nowadays, we know that the internal magnetic field is a superposition of the changing core magnetic field, the

dominant internal source, and the static near-surface lithospheric field of secondary magnitude. These internal fields interact with the solar wind plasma and the interplanetary magnetic field. This produces external fields with respect to the Earth's surface located in the ionosphere* and the magnetosphere*. Our main purpose is to show the magnetic face of the lithosphere, but since all sources constantly interact with each other, it is necessary to make a brief review of the magnetic sources origin.

The internal field

The core field Seismic wave velocity contrast brought our first view of the Earth's internal structure. From 6371 km to about 2900 km depth, the Earth is mainly composed of iron. This Earth's core is made up of two distinct parts, a ∼1250 km-thick solid inner core and a ∼2200 km-thick liquid outer core (Figure 1.2). At such temperatures and pressures, the orientations of spins within iron become randomised and iron does not carry magnetism by itself. The common idea picturing the magnetic field as a gigantic axial magnet is thus completely flawed. To the contrary, as the Earth rotates and cools, the liquid outer core spins and convects, creating the Earth's magnetic field. At ∼2900 km depth, there is a transition named the core-mantle boundary, a limit at which the patches of the convection can be studied.

The core field, referred to as the main field, represents more than 90 % of the geomagnetic field measured at the Earth's surface. It ranges in magnitude from some 30 000 nT at the equator up to more than 60 000 nT in polar regions. For studying the core flow producing this part of the geomagnetic field, the radial component (sign-changed vertical component) and its temporal variation are used (Figure 1.2).

The core field is not static and undergoes both spatial and temporal variation. For example, the magnetic poles are constantly in a state of motion (Figure 1.3). Much of this change, known as secular variation, is clearly evident in vector field time-series measured at magnetic observatories. For lithospheric studies, the most dramatic and important changes of the core field are the excursions or the reversals* during which the direction of the magnetic field is opposite. During recent epochs the field has been reversing every 0.5 Ma on average, but the polarity scale shows considerable time variability during the geomagnetic field history. These core magnetic field changes are recorded in the lithosphere and inform us about the dynamic past of the Earth.

The lithospheric field The Earth's lithosphere has also an associated magnetic field, commonly referred to as the crustal* or lithospheric field. This field is some 400 times smaller that the core contributions and generally ranges from 0 to ± 1000 nT. It is carried by the crust and the upper part of the Earth's mantle, within a thin layer 10 km - 70 km thick, depending on the location. The physical processes originating the lithospheric field are completely different from those generating the core field. No magnetic sources are observed between 70 km and some 2900 km depth as the thermodynamic conditions do not allow rocks to sustain magnetisation. The reason why these magnetic sources are restricted within a thin layer has something to do with the temperature, the Curie temperature, at which the formation and maintenance of rock magnetic fields is mitigated. The magnetic field of a rock depends on its mineral content and the main magnetic mineral in the crust, the magnetite (Fe_3O_4), loses its magnetic properties at 580°C.

The Earth's crust carries both induced* and remanent magnetisations* that depend non only on the chemical composition and the crystal conformation of subsurface rocks, but also on the Earth's core field history, as it is shown later on. This magnetic property of a rock and its ability to retain remanent magnetism basically depends on grain size, pressure, and temperature. A coarse-grain structure is a poor carrier of remanent magnetisation in comparison to a fine-grained rock. Continents formed in the early ages of the Earth's history, at a time when the thermal gradient was so high that a scum eventually formed atop the convecting mantle.

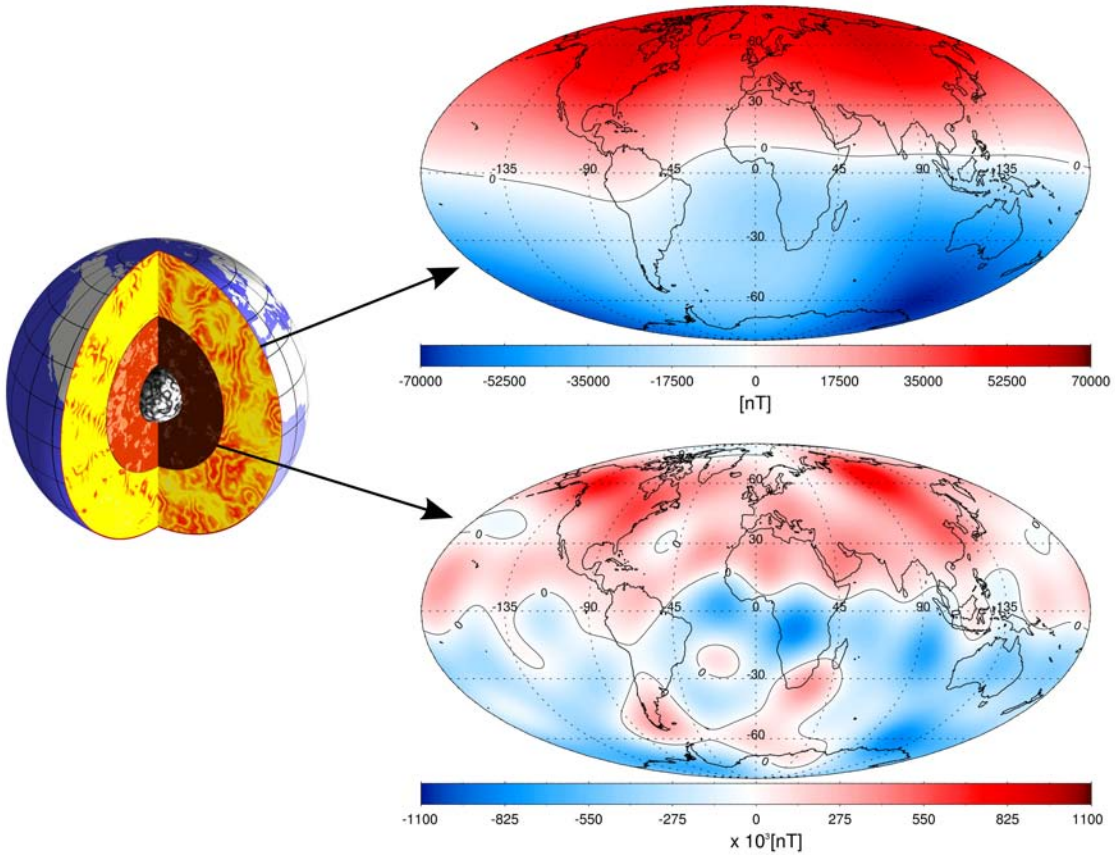
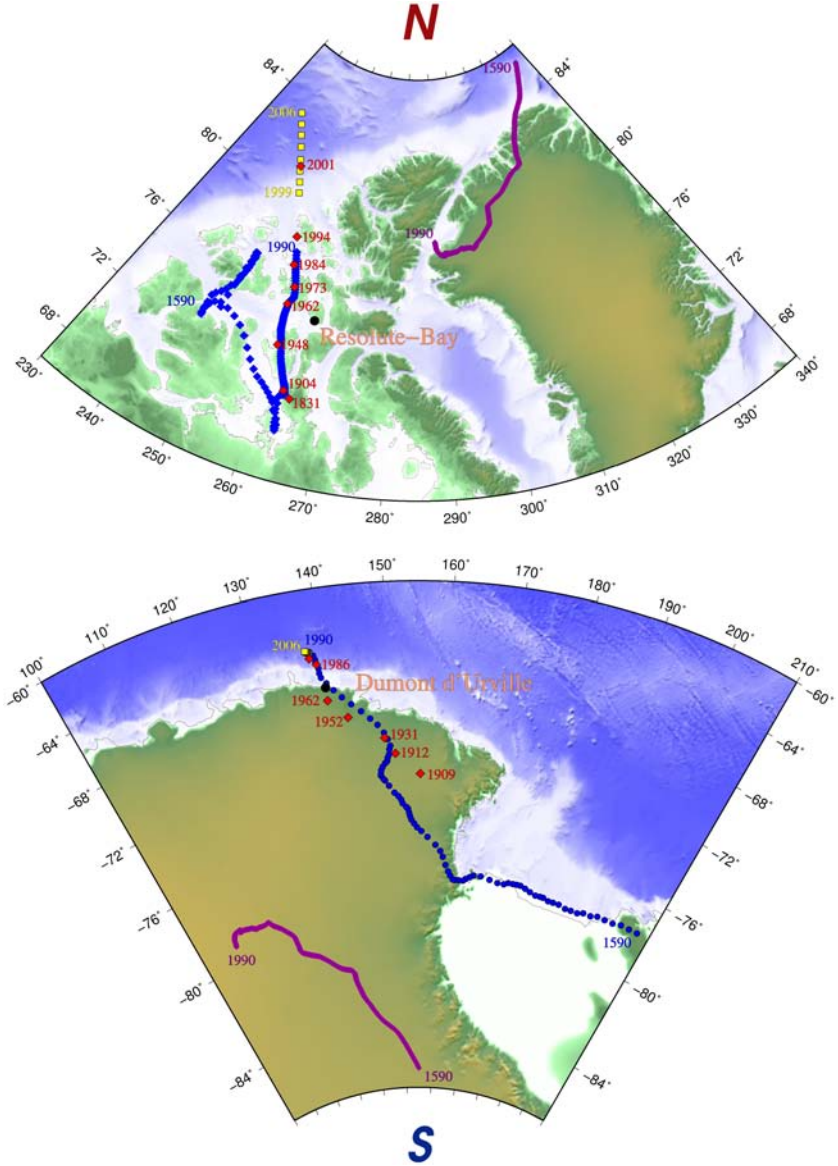


Figure 1.2: The internal structure of the Earth (left side) and the vertical component of the geomagnetic field represented at the surface (top right side) and at the core-mantle boundary (bottom right side), for the epoch 2005.0 (based on the *Olsen et al. (2006)* model). The core magnetic field is mainly dipolar but the field is modulated by smaller scales. The structure of the vertical component depends on the depth at which the magnetic field is represented, the smaller scales being more apparent at the core-mantle boundary than at the Earth's surface. For dynamo modelling, the magnetic field is represented at the core-mantle boundary.

Figure 1.3: The North and South Magnetic Poles locations, defined by areas where the field lines penetrate the Earth vertically, from direct measurements (red diamonds); from the *Jackson et al. (2000)* model, over the period 1590-1990 (blue circles); from the *Olsen at al. (2006)* model, over the period 1999-2006 (yellow squares). The magnetic poles change more quickly and show a strikingly different behaviour in Northern and Southerm Hemisphere. The geomagnetic poles, defined as poles of the approximated dipole field, are also shown (purple diamonds).



This low density "floating" layer was mainly composed of granite, a rock having a medium to coarse-grain. Continental magnetism is thus dominated by induced magnetisation. To the contrary, by virtue of its constitutive finegrained structured basaltic rocks, the oceanic crust is an efficient carrier of remanent magnetisation. It is thus more convenient to separately study the oceanic and continental lithospheric field.

Things are more complicated in detail as new continental rocks are constantly forming through continental magmatism. We may reasonably assert that over continents remanence cannot be neglected at short scales but, since remanence is unstable with increasing temperatures, induced magnetisation dominates the large scale crustal field. Distinguishing between remanent and induced fields is a long-standing problem in geomagnetism. However, this basic bimodal view helps us to infer information about the subsurface rocks.

The crust is defined as the outermost layer of rocks and can be distinguished from the underlying mantle rocks by its composition. In seismic maps, an abrupt increase in the velocity of earthquake waves is observed between the crust and the upper mantle. This so-called Mohorovičić discontinuity (Moho*) reveals a change in rock composition at 60 km depth over continents, on average. This transition depth does not always coincide with the depth at which the rocks lose their magnetisation. The lithosphere magnetic field is thus carried by the magnetic lithosphere and is therefore different from definitions used in geochemistry, seismology or geology, even if in average they all converge to each other. It is difficult in practice to isolate precisely the lithospheric field contributions because the core field partly masks the large lithospheric magnetic structures. The lithospheric field is thus approximated by what is called "the anomaly field", which is the difference between the measured data, containing all magnetic sources, and estimates of the core and external fields. In the following, we refer to lithospheric, crustal or anomaly field to approximate the magnetic field created by the geological sources lying in the magnetic lithosphere. It is important to keep in mind that only features shorter than 2500 km are currently resolvable.

The external field

The Sun's magnetic field dominates interplanetary space within the solar system. The Sun's magnetic activity has a periodicity of 11 years, known as the solar cycle. Streaming from the Sun at a speed of about 350-500 $\mathrm{km\,s^{-1}}$ is a plasma of neutral hydrogen atoms, protons, and electrons. These particles compose the solar wind, governed by the equations of plasma physics. Immediately surrounding the Earth, at about 10-20 Earth's radii, exists a region called the magnetosphere, where the solar wind particles do not normally penetrate. A complicated system of currents exists in this region. The equatorial circulation of the system constitutes an electric current, the ring current, which generates a part of the magnetic field observed at the Earth's surface.

In the outer part of the Earth's atmosphere, a region called the ionosphere lies between about 50 km and 600 km above the Earth's surface. Because ultraviolet light from the Sun ionises the atoms in the upper atmosphere, the sunlit hemisphere is much more conducting than the nighttime one. Strong electric currents circulate in the sunlit hemisphere, generating their own magnetic fields, with intensities up to 80 nT. Solar activity is irregular and the daily variation can be obscured by much more energetic processes, known as magnetic storms*. The effects of solar storms are nicely seen through the polar auroras* (Figure 1.4 - left side). However, their effects can be damaging for electrical devices both on the ground (Figure 1.4 - right side) and at satellite altitudes. At the terrestrial surface, magnetic storms can change the Earth's magnetic field producing surges in power lines and long oil or gas pipelines. A spectacular manifestation of a large space storm occurred in 1989 when currents on the ground caused a failure in the Hydro-Quebec electric power system. It left 6 million people in Canada and the US deprived of electricity for over 9 hours. Solar flares can also blind satellites, provoke radio blackouts and considerably reduce satellite lifetimes.

Figure 1.4: Effects of magnetic storms: one of the most spectacular phenomena, the "Aurora Borealis" or "aurora" for short, produces flickering curtains of dancing light against the dark sky (left side, courtesy of *C. Heinselman*) and damage to a power transformer produced during the March 1989 magnetic storm (right side).

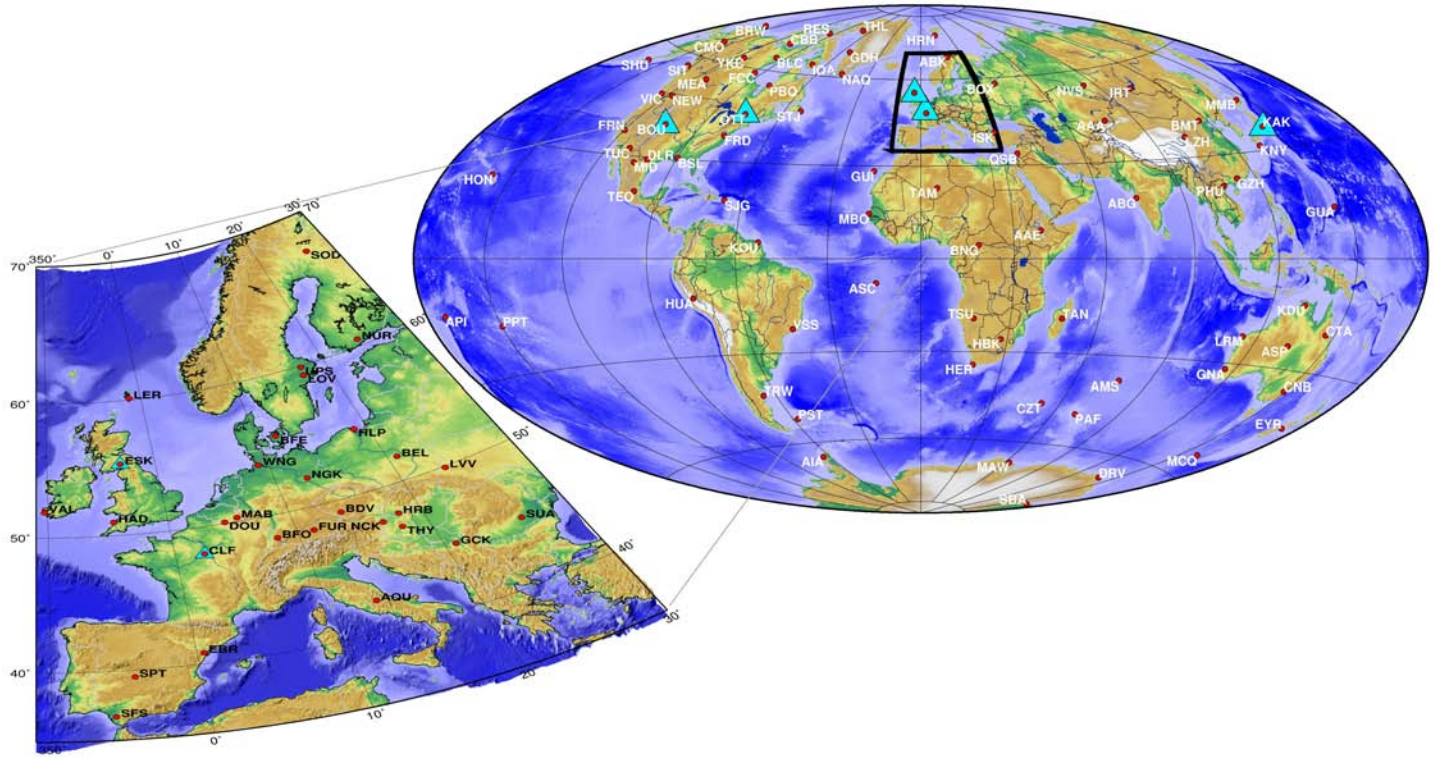


Figure 1.5: Distribution of geomagnetic observatories, part of the INTERMAGNET program, (red dots) in 2006. An INTERMAGNET Magnetic Observatory (IMO) has full absolute controls and provides one-minute magnetic field values. All these observatories, indicated by their IAGA code, send their data to Geomagnetic Information Nodes (GINs, blue triangles) at Edinburgh, Golden Colorado, Hiraiso, Kyoto, Ottawa and Paris. Installed mainly on continents the observatories are very unevenly distributed over the Earth's surface, so the magnetic variations at short spatial scales can hardly be detected.

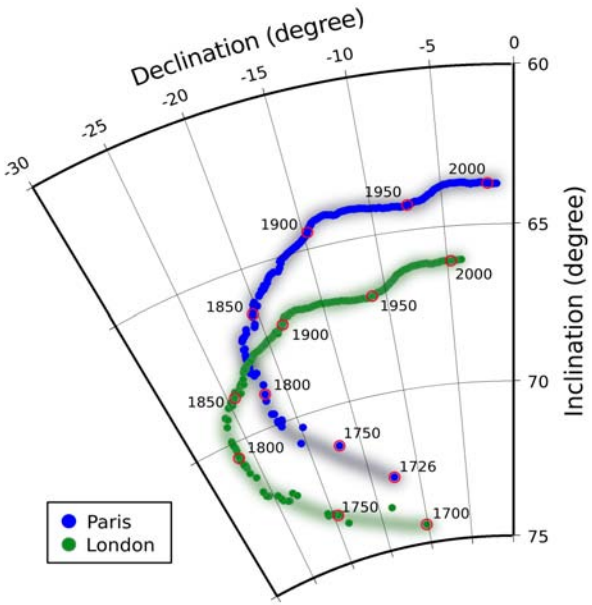


Figure 1.6: The direction of the Earth's magnetic field for two declination series, Paris (measurements adjusted to the French observatory of Chambon la Forêt) and London (measurements adjusted to the British observatory of Hartland). Points, plotted on a zenithal equidistant projection (Bauer diagram), correspond to available declination and inclination measurements.

In addition to these very important societal issues, the external field hampers the correct identification of lithosperic sources. The external activity being dominant in the daylight, in the polar regions and near the magnetic equator, anomaly maps are often contaminated by external sources in these regions, and only night time data are suitable at satellite altitudes. Any contamination from the external field may lead to erroneous geological interpretation.

Measuring the Earth's magnetic field

Major achievements have been obtained in the past thanks to the tenacity of keen observers and ingenious instrumentalists. Magnetic field measurements are the keystone of geomagnetic advances. In principle, the core, lithospheric and external field sources could be accurately identified, and thus corrected for, with a permanent dense network of ground stations and a swarm of satellites. This is obviously unrealistic and our recent comprehension of the magnetic field is built on a time and space limited sampling of the magnetic field.

The permanent magnetic observatories Measuring the magnetic field is a long European tradition. In some places, like Paris and London, the declination measurements start as early as the XVIth century. However, the installation of permanent magnetic observatories dates back to the XIXth century, only. The long average time series recorded at observatories allowed for the discovery of the secular changes of the core magnetic field. Figure 1.6 shows the variations in declination and inclination over the last few centuries for Paris and London series. The more rapid variations measured at observatories account for the external field activity at the observatory location. The main purpose of a magnetic observatory is thus to study the core and large external fields, but not the lithospheric field. The uneven distribution of magnetic observatories over the continents does not allow the detection of magnetic variations at short spatial scales (Figure 1.5). For this reason, correcting the data measurements for the secular variations or the external field is less accurate in some regions than in others. In oceanic areas, for example, the uncertainty in the secular variation is large and magnetic anomaly maps in oceans are usually less accurate than maps over continents. This data uncertainty has been shown to be problematic in all geophysical disciplines and large international efforts have been made to build autonomous magnetic observatory at ocean bottoms (Figure 1.7). For lithospheric field analyses, observatory data are thus employed mainly for correcting other platform data for the core field, the secular variation and the rapidly varying external field.

The network of repeat stations In order to circumvent the problem of observatory distribution, repeat station networks exist on national levels. The three components of the magnetic field are measured regularly, usually every five years, in order to determine the "national" secular variation and to update magnetic charts. When available, repeat station data are interesting for lithospheric field representation because they provide a unique set of vector measurements over a large regional area on the ground surface. The repeat stations are devoted to monitoring the temporal changes of the internal magnetic field. The detailed features of the lithospheric magnetic field are so complicated that the spatial distribution of observatory or repeat station measurements is by no means adequate. Moreover, dense ground measurements, when existing, are generally inappropriate because of the irregular surface topography and the anthropogenic activity that creates artificial magnetic sources in many different places. Therefore, measurements from aircraft along regular profiles are more convenient.

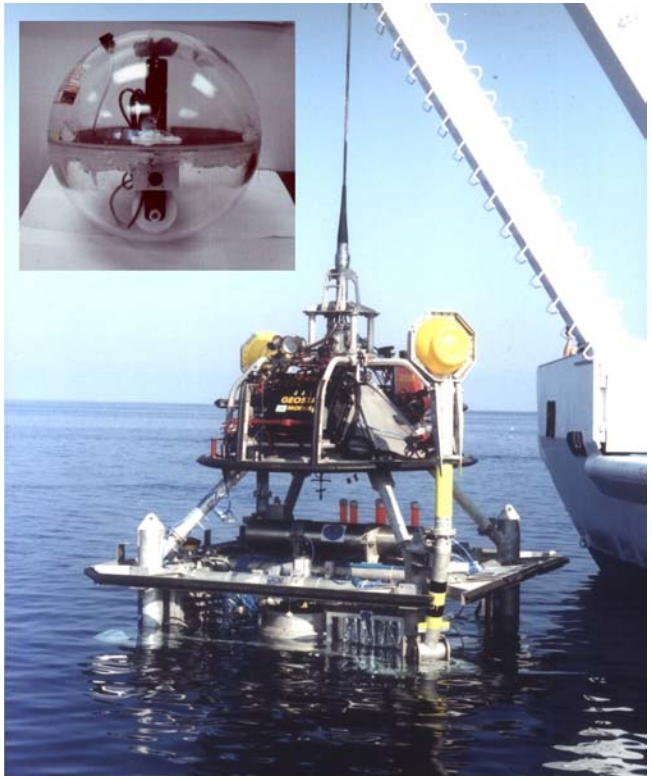


Figure 1.7: Mobile docker and seafloor station used in the framework of GEOSTAR (Geophysical and Oceanographic STation for Abyssal Research) European Project. The GEOSTAR sea bottom observatory contains several sensors, among them a scalar Overhauser magnetometer and a three-component suspended flux-gate magnetometer, both placed in the yellow boxes at the end of the two booms, which are extended at the seafloor (Courtesy of *A. De Santis*).

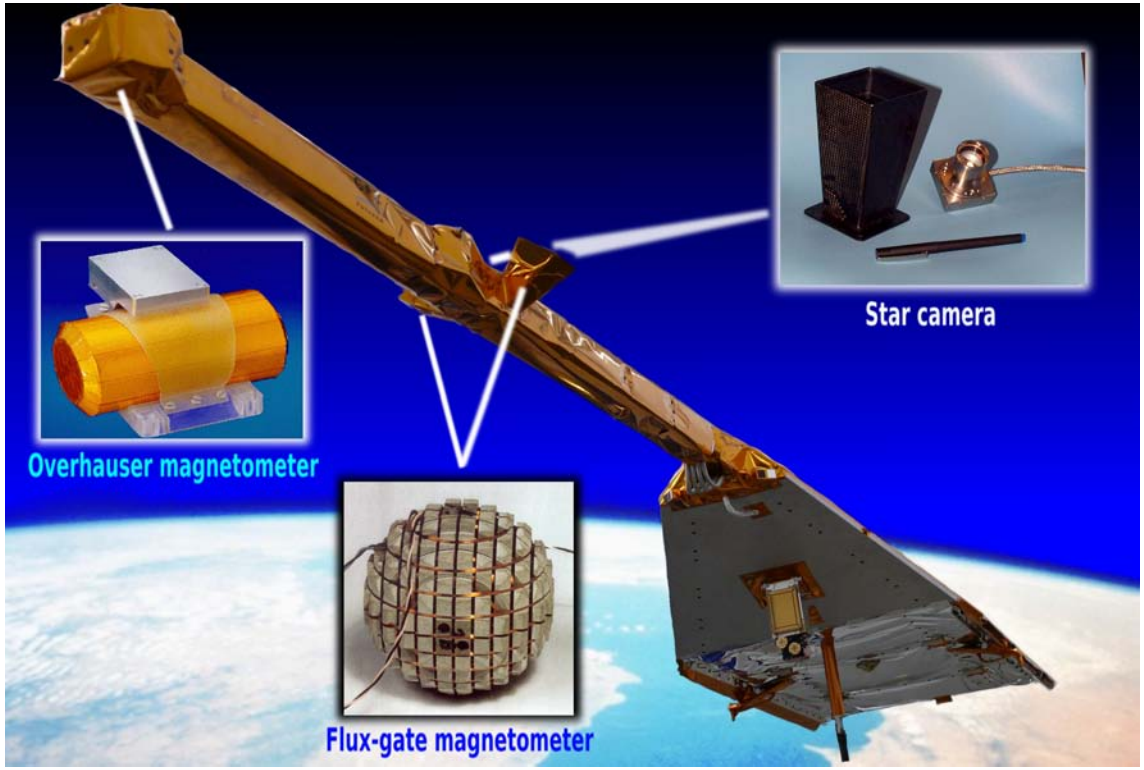


Figure 1.8: CHAMP (CHAllenging Minisatellite Payload) satellite – photo of the real-size model in GeoForschungsZentrum Potsdam, Haus H. CHAMP, launched in July 2000 is still fully operational (2007). This small satellite is carrying on its 4 m boom highly precise, complementary instruments for measuring the Earth's magnetic field (two flux-gate sensors mounted together with the star cameras about halfway between the satellite body and the Overhauser magnetometer at the tip). CHAMP, in a low-Earth, near-polar orbit, provides an ideal platform for obtaining the required high resolution magnetic field measurements. With its high inclination orbit (87°), CHAMP covers all local times, and its long active life-time allows the study of core field changes. The low circular orbit, starting at 454 km altitude and decaying over the life-time to below 300 km, together with the greatly advanced instrumentation flown on CHAMP have improved the accuracy of describing the lithospheric field.

Aeromagnetic surveys* Since it is extremely difficult to point a fixed direction in space, aeromagnetic surveys record the strength of the magnetic field; i. e they take scalar measurements. Aeromagnetic surveys usually cover areas of a few kilometers to hundreds of kilometers in dimension. They are carried out for a variety of purposes. Fields of research include, for instance, investigation of crystalline basement and mineral explorations, faults, fracture zones, and volcanic structure imaging. Large aeromagnetic surveys with wider profile spacing are devoted to both regional and detailed geological investigations over landmass and continental shelves. They can provide information about the distribution of rocks occurring under thin layers of sedimentary rocks, useful when trying to understand geological and tectonic structures.

Aeromagnetic surveys are fast, which reduces the secular variation contribution for a given survey. The external field variations are taken into account using the nearest observatory or a fixed base station set up especially for the survey. Once the aeromagnetic data have been collected, they are corrected for the estimated Earth's core magnetic field and any field changes. Aeromagnetic data are thus exclusively devoted to magnetisation detection in the lithosphere at various scales and take an image of the lithospheric field that is assumed to be static. As it is shown in Part 3, the main difficulty arises when we try to merge individual surveys into a large consistent compilation. Since an aeromagnetic survey is realised only once at a given epoch, the secular change of the magnetic core field, if not properly corrected for, may create a level error between adjacent surveys.

Satellite measurements Since the 1960's, with the American OGO series of satellites, the Earth's magnetic field intensity has been measured intermittently by satellites at altitudes varying from less than 400 km to 800 km altitude. The main advantages of a satellite mission over airplane surveys are its capability to measure the magnetic field over a rather short period and at a relatively constant altitude, to ensure a homogeneous data distribution and finally to provide data measured with the same instrument characteristics. These properties are extremely valuable for magnetic field monitoring in general and, more precisely, for describing the lithospheric field.

The first satellite mission that provided vector data for geomagnetic field modelling was initiated by the National Aeronautics and Space Administration (NASA). The MAGSAT satellite operated over six months between 1979 and 1980, a short period that provided the first consistent, but low resolution, maps of the lithospheric field. The following 20 years lacked high-quality spatial magnetic field missions, but the Danish Ørsted satellite, launched in 1999, improved that situation. As the primary goals of that mission have been to study the variations of the geomagnetic field and its interaction with the Sun particles stream, its high altitude does not provide a high resolution view of the lithospheric field sources.

The most successful mission for lithospheric field study is the German CHAMP (Challenging Minisatellite Payload) satellite (Figure 1.8) launched in July 2000 and still fully operating (in 2007). Its low-Earth quasi-circular orbit is particularly suitable for lithospheric field mapping. The initial average satellite altitude was 454 km, but the satellite is slowly descending and is at about 350 km altitude in 2007. The recent lithospheric maps obtained from CHAMP data are more robust compared with the previous ones and have an unprecedented resolution.

Second Part: The use of magnetic anomalies at regional scales

Magnetic surveys were traditionally acquired for resource exploration in order to increase the resolution of the edges of magnetic bodies and to estimate their depth and delimit their dimensions. Among these applications, we may mention the detection of ore bodies, which have a strong magnetic signature, and also some oil and natural gases, which are trapped in sedimentary basins. Other applications are more or less indirect. Diamonds, for instance, have no magnetisation, but are found in kimberlite, an igneous rock having very deep mantle sources and a distinctive circular signature. The magnetic prospecting technique is also useful to track anthropogenic buried materials, like unexploded bombs or hidden weapons. Magnetic mapping can also be used to reduce the environmental impact of resource exploration. For example, abandoned oil wells have depths varying from several tens to hundreds of meters. They may act as conduits for the contamination of groundwater by oil field pollutants. Remains of the prospecting such as tanks or metal-building can easily be detected and once located, the wells can be sealed to prevent the transmission of contaminants into aquifers.

A complete and exhaustive review of magnetic mapping is not possible here and we decided to focus on the geophysical applications that bring a scientific understanding of our planet's history. However, as we could not completely refrain ourselves, we start this part with an example showing an original result using magnetic prospecting at a local scale. The following examples have been selected to give a flavor of magnetic anomaly applications and interpretations at various spatial scales.

Archaeological support, the Mesopotamian city of Mari

Since historical times, topography, climate and vegetations have greatly changed and exact contours and locations of buried cities mentioned in ancient writings are often unknown. Visualisation and mapping of hidden structures are possible and helpful for delineating the boundaries and the main structures of an archeological site.

In 2001 - 2002, a magnetic survey was carried out over a large part of Mari (Tell Hariri, Syria), an important Mesopotamian city. This city was destroyed by Hammurabi, the King of Babylon in the third part of the second millennia BC. The magnetic anomaly map reveals a picture with possible walls and streets. In particular, a large band was associated with a main street going from the Palace (Figure 2.1) to a gate in the city wall. It supports the idea that the major city axes, around the palace and the sanctuaries, were conserved throughout the city life. This extended survey was also fruitful for inferring hypotheses about antique urbanisation.

The magnetic signal appears blurred and erratic in some places. This is because the city is made of consecutive layers of adobe bricks, which do not carry a very strong magnetisation. Adobe bricks seem to acquire a weak magnetisation during the casting process that induces the alignment of individual magnetic grains along the Earth's magnetic field. Beyond the archeological interest, we thus encounter an interesting but poorly understood process of magnetic acquisition of rocks.

The identification of impact craters

The recognition of impact cratering as an important planet-building and planet-modifying process on Earth has been rather slow. However, geologists are now realising that giant impacts have had a determining influence on the geological and biological evolution of our planet.

An impact crater is produced by the collision between an asteroid and the Earth's surface. Until now, only 174 impact craters have been clearly identified on Earth, not because our planet has been less bombarded than the Moon or Mars, but because erosion and plate tectonics have slowly erased these terrestrial scars. For this reason, the temporal

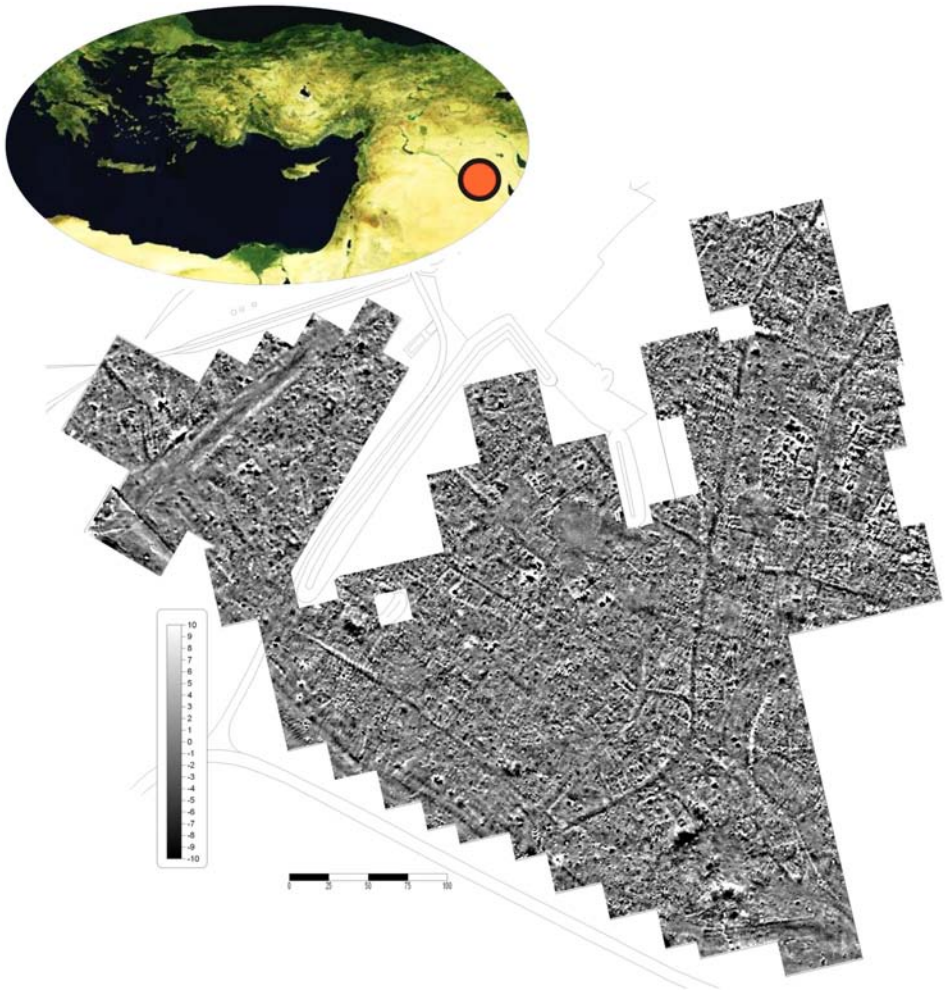


Figure 2.1: Magnetic anomalies over the buried city of Mari reveal the urban plan of the city. The interpretation is nevertheless rather difficult as the building materials are adobe bricks, which are weakly magnetised. Moreover, the general urban plan has been rearranged during the long city history although large axes remained essentially the same. From this, we may conclude that stable urban areas of the city were probably religious, sacred and/or royal. To the contrary, other areas were places of regular city life (Courtesy of *A. Galdeano, IPGP*).

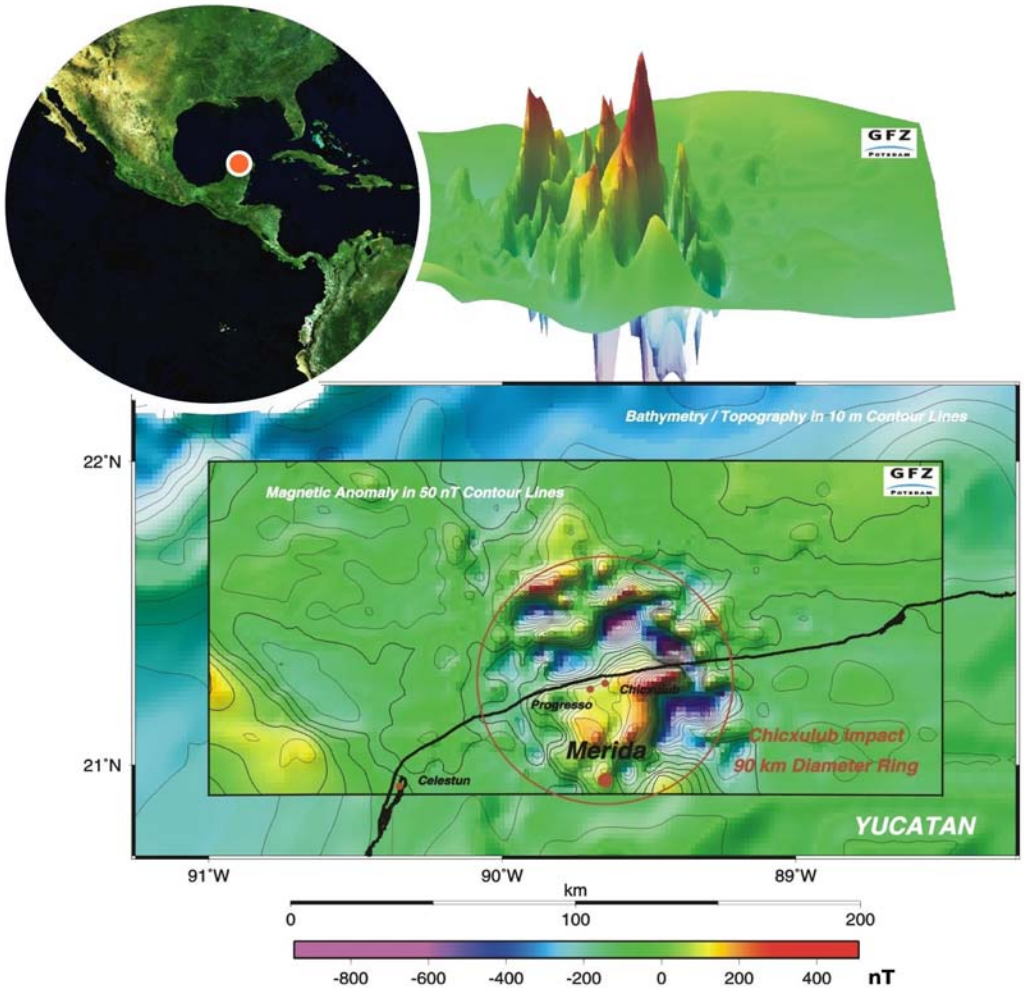


Figure 2.2: The impact crater at Chicxulub, Mexico, is partly covered by water and sediments but can be detected by aeromagnetic surveys. A meteorite brings magnetic iron materials and the heat released by the impact modifies the more homogeneous magnetic field of the crust (Courtesy of *GFZ Potsdam*, graphics: *U. Meyer*).

distribution of impact craters seems highly irregular and more than half are less than 200 Ma old. No craters have been confirmed on oceanic floors probably due to the recycling of ocean floors.

The Chicxulub crater During the Cretaceous-Tertiary (K-T, 65 Ma) transition, the time of the famous dinosaur extinction, about 70% of life diversity disappeared. Although there are competing theories, the most accepted explanation for the extinction is the occurrence of harsh climatic conditions created by an asteroid or a comet impact. The Chicxulub crater is one of the best preserved impact structures, but has no significant topographic signature. It is buried under about one km of sediment and is mostly undersea. Indirect investigation methods, such as airborne magnetic measurements, show the circular anomaly shape of this hidden structure (Figure 2.2). On-site dating was consistent with the estimated geological time of the extinction and the impact was tied to shock quartz grain, iridium anomaly, and isotopic composition of the K-T layer. The magnetic signature consists of two concentric zones with radii of 20 and 45 km but extends to 210 km. The innermost zone has a positive magnetic anomaly, suggesting the presence of a single source, while the second-ring zone anomaly, is less structured, and suggests evidences of numerous smaller dipolar anomalies. Generally, in craters, a low magnetic anomaly is usually observed due to a reduction of magnetic susceptibility* caused by the thermal impact shock.

Are all circular structures an impact crater? Several possible impact structures are still awaiting confirmation, but extreme climatic conditions, remoteness or vegetation and sedimentary covers have hampered further investigation. They have been found using remote sensing techniques (satellite imagery, aerial photography and airborne geophysics) but only ground analysis will be conclusive for recognising shock geological features. For instance, the large anomaly in Central Africa, the Bangui Anomaly (Figure 2.3), has been subjected to different interpretations from very different models. The magnetic anomaly (see also Figure 3.2) can be explained by a pure geological source involving emplacement of basalts in the lower crust as a result of Pan-African orogeny. The second hypothesis involves iron meteoric materials that impacted the Earth more than 1 Ga ago during the Precambrian period. The Bangui anomaly was investigated using gravity, topography and forward modelling of an idealised circular source. Such studies suggested an 800 km diameter impact structure; it would be the largest impact feature found on Earth. Nevertheless, the evidence is tenuous as collateral surface and subsurface data are too scarce to completely assess the validity of the impact hypothesis. It is also difficult to understand how the apparent topographic ring has survived the processes of erosion and crustal deformations since the Precambrian time. Note that the estimated age of the Bangui crater cannot be correlated with fossils or a mass extinction as the fossil records do not become significant until the Cambrian age, an age of major life diversification, almost 500 Ma later!

We must be careful with our interpretation of visual data as not every circular structure is an impact crater. The spectacular feature of Richat, in the Sahara Desert of Mauritania (Africa), was initially interpreted as a meteorite impact structure because of its circularity and its annular rings of 50 km diameter (Figure 2.4). Despite thorough investigations, no traces of shock or meteoric signatures were found and the structure was probably formed by uplift and subsequent erosion of different sedimentary rocks, although its almost perfect circular shape remains intriguing. In Thromsberg, South Africa, a magnetic anomaly has a circular ring-shape and lies beneath a thick sediment layer. The magnetic anomaly seems to correlate well with the topography. Nevertheless, the gravity map (Figure 2.5) shows higher values when low values are generally expected, due to the lower density of sedimentary infill of the depression (for simple craters). Moreover, no shocked minerals are found on site and an intrusive origin of the anomaly is more likely.

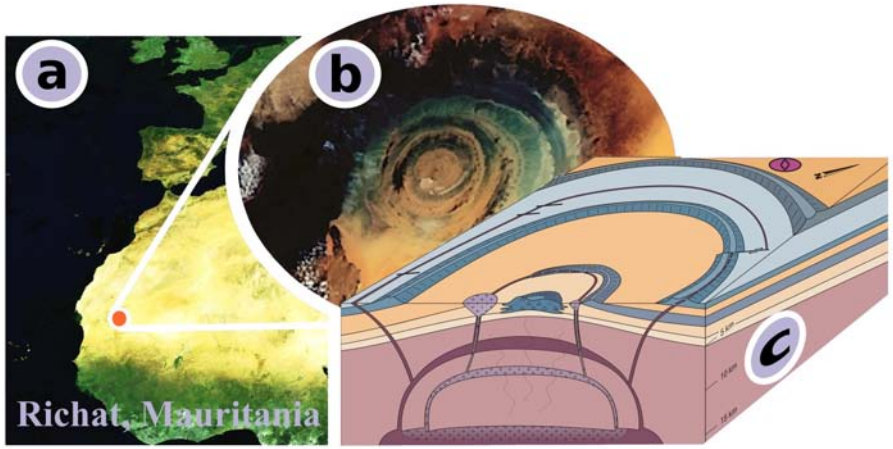


Figure 2.4: The Richat structure lies in the desert of Mauritania (a). Initially interpreted as an impact structure because of its circularity (b: satellite view, Credits *ESA*), it comes from a magmatic doming, a body of magma that solidified beneath the Earth's surface. The doming provoked a permeable fractured zone that favours fluid infiltration. This hydrothermal event induced a chemical mineral dissolution that hastened the collapse of the dome. More resistant rocks, like quartzites, outline the circular structure (c: Courtesy of *G. Matton,UQAM, Canada*, after *Matton et al., 2005*).

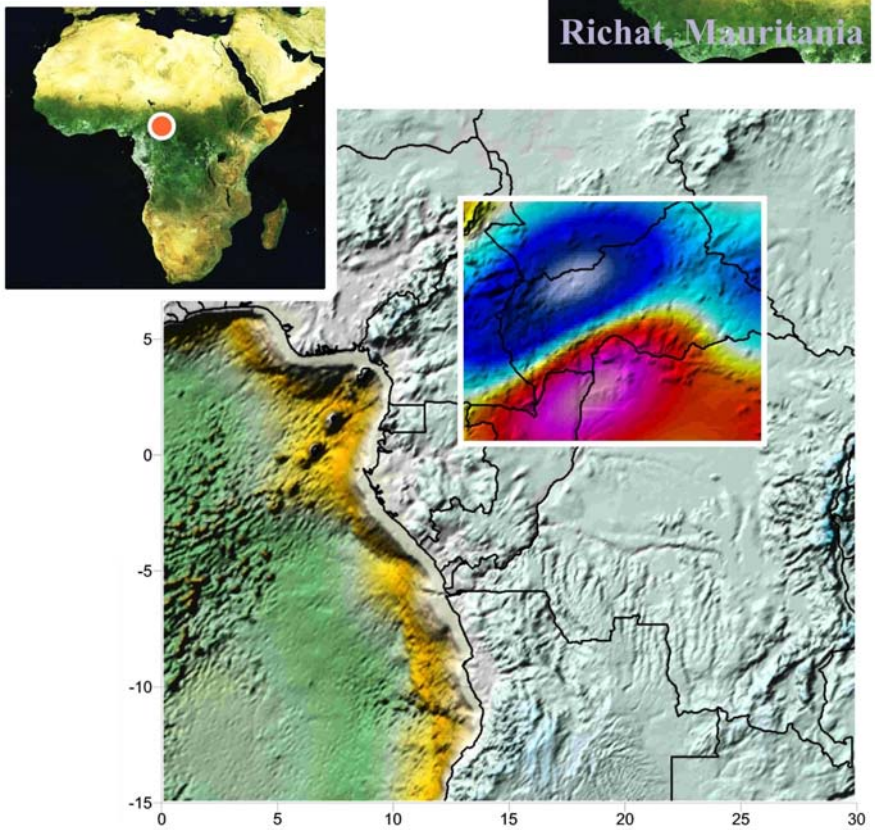


Figure 2.3: The Bangui anomaly is the strongest and the most intriguing magnetic anomaly visible at satellite altitude. Its large extension suggests a source lying deep in the lower crust but its exact characteristics and origin remain under debate. Does the Bangui anomaly originate from a meteoric impact event or is it the relic of a huge tectonic or thermal process?

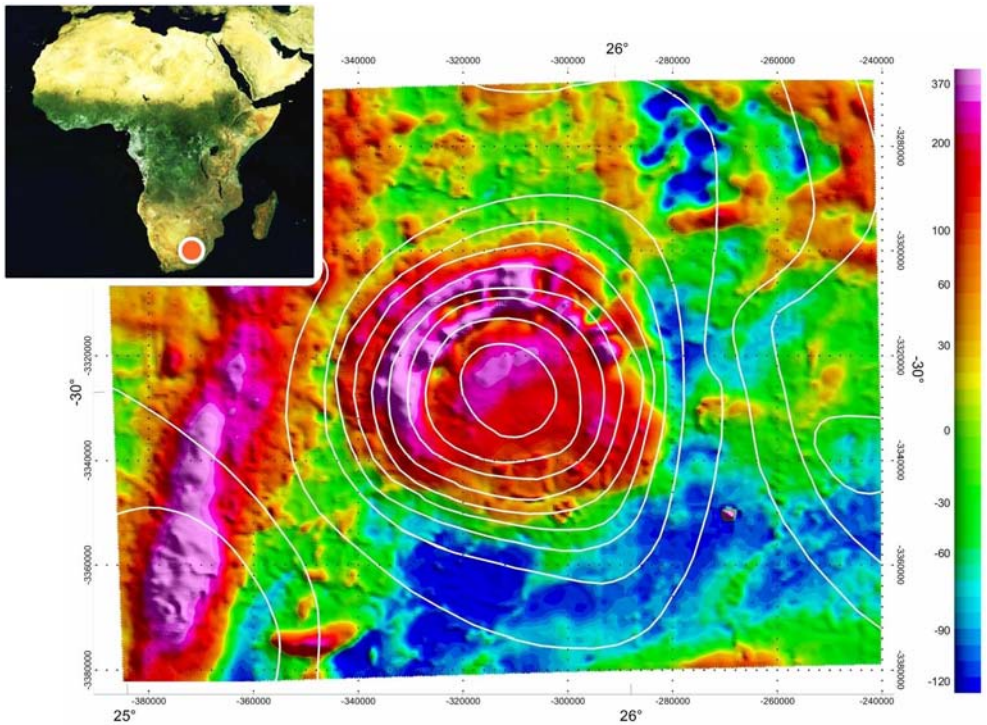


Figure 2.5: The Thromsberg magnetic anomaly, in South Africa, has apparently all the characteristics of an anomaly induced by an old impact event: a positive anomaly with two concentric rims. However, the gravity map (white solid lines), suggests a regular mass concentration not compatible with a shock event. The Thromsberg anomaly illustrates a case where remote analysis may not be fully conclusive without surface data (Courtesy of *L. Gaya-Piqué, IPGP*).

All of these examples demonstrate that morphological and geophysical observations are important in providing supplementary evidence but they are not fully conclusive in the case of complex or old altered systems.

The changing Earth

Plate tectonics has profoundly changed our view of the Earth's dynamics. The tantalising questions surrounding of the origin and evolution of the Earth's crust remain open, but the parental theory of plate tectonics, seafloor spreading, provides valuable insight into mechanisms for the last 200 Ma. One of the most successful contributions of crustal magnetism at global scale was to demonstrate the seafloor spreading theory. Before the general acceptance of plate tectonics in the early 60's paleomagnetism measurements confirmed the relative motion of continents.

Paleomagnetism It mainly focuses on measuring samples taken from rock outcrops and estimating their magnetisation in a laboratory. For crustal anomaly field analysis, these measurements are used to constrain geomagnetic remote detection in order to resolve possible ambiguities.

Paleomagnetism was historically used to establish a geological absolute temporal scale. A magnetostratigraphic scale is a vertical sedimentary succession of layers that is described and interpreted in terms of remanent magnetisation. The reversals in the geomagnetic field recorded in vertical drillings are dated either by isotopic dating or correlation with palynology and paleontology. These latter correlations compare the succession of magnetic reversals with the type of fossils present in the different geological layers in order to approximately determine the layer age.

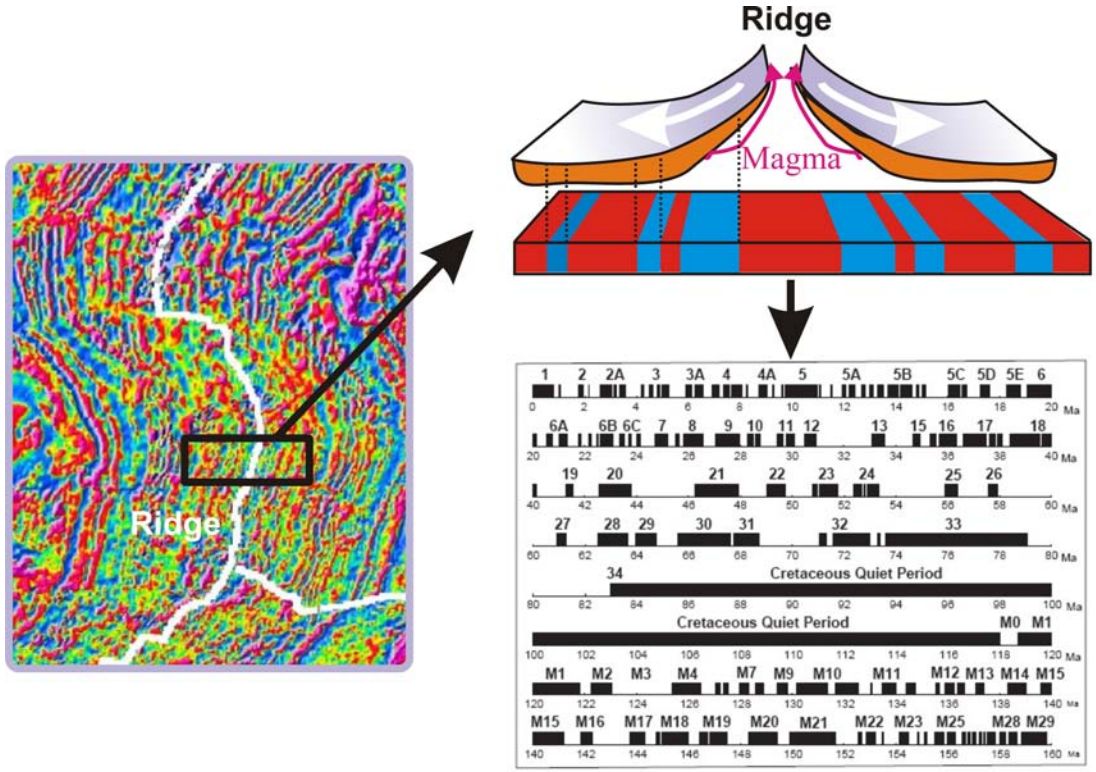
Finding the direction of ancient magnetic fields is not a trivial task as not all rocks can retain their magnetic memory throughout geological history. Moreover, magnetisation degrades with time, erosion alters its properties and tectonic movements change its apparent direction. For this reason, a relatively large number of rock samples are necessary to ensure statistical significance. The knowledge of the local geology is important as apparently erratic magnetic directions usually lead to more consistent results after bedding and tectonic corrections are completed. When two different samples belong to two different tectonic plates, these site corrections are not sufficient as continents are globally moving with respect to each other. Within each plate, rock samples of identical age indicate the same magnetic pole direction that is referred to as "virtual".

A virtual magnetic pole can be estimated for different geological layers and, with the assumption that the Earth's magnetic field has always been axially dipolar, any change in the virtual magnetic pole direction can be attributable to the continent's displacement with time. This "apparent polar wander" is different for each continent.

Figure 2.6 shows the curves of the magnetic polar wander during the last 200 Ma for the western European and northern American continents. These two curves have similar shapes with a spacing equivalent to the Atlantic Ocean width. The only way to reconcile both curves is to adjust the continents such that all rock magnetic laboratory measurements indicate the same direction. We can see that the virtual magnetic poles depend on the relative positions between the different plates. One of the major issues of paleomagnetism is to determine the "true" polar wander and to reconstruct the "true" path of the magnetic field along geological times.

Seafloor spreading Oceans cover 70% of the Earth and half of them are deeper than 3000 m. They are thus mostly unknown and remote sensing plays a key role in the understanding of their dynamics. Oceanic magnetic anomalies are to a first approximation rectilinear. The frequent polarity inversions between two magnetic anomalies was recognised since the 1950's but were lacking a satisfactory explanation (Figure 2.7). In 1963, Vine and Matthew noticed the pattern similarity

Figure 2.6: Paleomagnetic field directions measured from sample rocks show similar directions for Europe (yellow line) and America (pink line) for the last 200 Ma. The only way to reconcile both curves is to rotate the continents with respect to each other. In this example, the lack of absolute reference frame does not allow us to determine the true polar locations (Data: *Besse et Courtillot, 2002*).



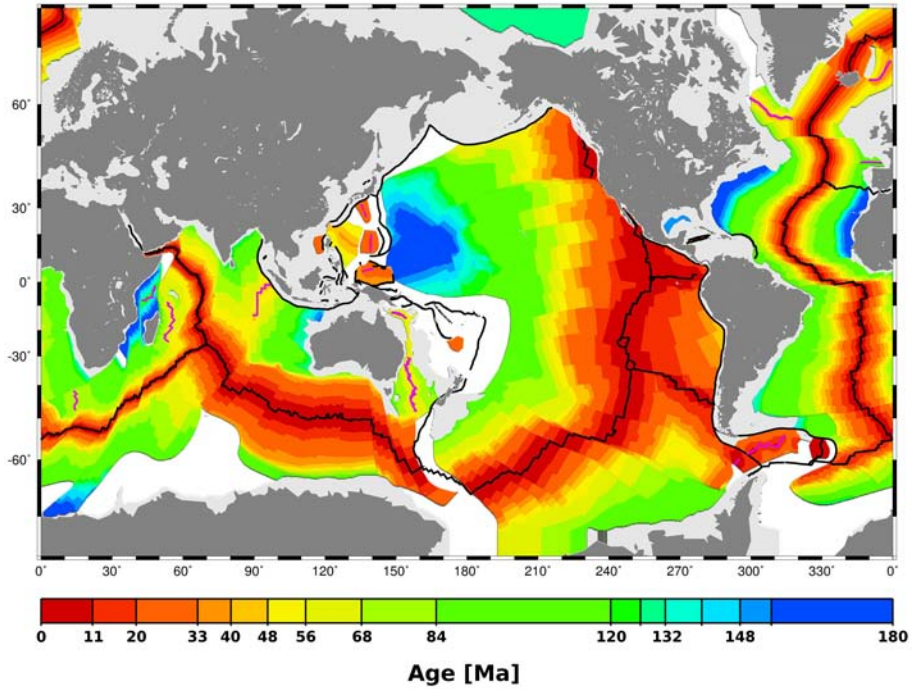


Figure 2.8: The age of the ocean floor is interpolated on a global scale using a database of isochrons and plate reconstruction. Dark grey indicates land and light gray sediment covered continental shelf materials. In some regions (white areas), the age map is incomplete as a result of incomplete geophysical data coverage (After *Müller et al., 1997*).

Figure 2.7: The magnetic anomaly map in oceanic regions displays quasi linear features of alternate signs. The magma ascending along the ridge (white line) solidifies and acquires a magnetisation along the direction of the ambient core field. As new magma ascends, a new crust is formed and is added to the ocean floor that gradually extends. From time to time, the main field polarity changes and oceanic floors record the time and the duration of Earth's magnetic field reversals. During the Cretaceous, the magnetic field kept the same normal polarity for about 35 Ma (Table of isochons: Courtesy of J. Dyment).

between continental vertical magnetostratigraphy and horizontal oceanic lineaments. They proposed that seafloor linear anomalies were formed at different geological times, thus recording the reversals in the Earth's magnetic field. The seafloor spreading theory was born.

As magma ascends along the ridges, it cools and solidifies. The rocks acquire a thermo-remanent magnetisation aligned along the ambient magnetic field. As seafloor spreading continues, the magnetic field is recorded in the rocks symmetrically about the mid-ocean ridge, creating these remarkably continuous lines that are occasionally shifted and curved. These changes of orientation reveal either a setting of the anomaly in a complex system or deformation as a result of seafloor spreading variations and tectonic movements (Figure 2.7).

These lines, the magnetic chrons, are observed all around the world. Even if the data coverage is not very dense on the global scale, it is possible to recognise isochrons, chrons of identical age, and to estimate the age of oceanic floors (Figure 2.8). Based on plate reconstruction using paleomagnetic measurements, global isochrons and gravity data, this oceanic map offers a self consistent global view of the ocean floor.

The magnetic mapping of the oceans is an essential tool for reconstructing the history of the Earth and deciphering the basic oceanic geometry. On a more regional scale, magnetic measurements show more detail and tiny intensity variations inside a given isochron give evidence of more complex kinematics.

Such an example is illustrated by the Carlsberg Ridge that separates the African from the Indian plate. The spreading history of the Carlsberg Ridge is poorly known as a result of a complex system of magnetic anomalies. The "tiny wiggles", which are second-order patterns of the magnetic signal, are recorded by shipborne measurements along profiles (Figure 2.9-a). These small variations are especially informative in complex areas as they allow identifying isochrons (Figure 2.9-b). For instance, according to the location and the deformation of isochrons from 26 to 22 (see Figure 2.8), it is possible to formulate a scenario for the ridge propagation between 65 Ma and 47 Ma. At anomalies 26 and 25, the ridge is made of three compartments and two eastward propagating rifts; at anomalies 24 and 22, the ridge consists of eight compartments and seven westward propagating rifts (Figure 2.9-c). The physical mechanisms inducing a ridge reorientation and a spreading rate modification can be thermal or mechanical. It is unlikely that the Carlsberg Ridge and the "hard collision" between India and Eurasia are connected. A more convincing scenario is that the nearby Deccan-Reunion Hotspot provoked this spreading asymmetry (Figure 2.9-d).

During its northward drifting, India crossed the Reunion Hotspot. The transit of India towards the Eurasian plate caused an asymmetric spreading of the Carlsberg Ridge as a result of the thermal anomaly left by the Reunion hotspot trail. The Carlsberg Ridge opened about 65 Ma ago. With the thermal anomaly lying east of the Carlsberg Ridge (∼56 Ma) more lithosphere was created on the African flank (eastward rift propagation). After India moved northward (∼47 Ma), the hotspot lied south of the Carlsberg Ridge and more lithosphere was created in the Indian flank (westward rift propagation).

In the same vein, finer analyses are also useful for recognising chrons that were shifted during their formation by plate kinematic evolution. The Bay of Biscay is a wonderful example to illustrate both plate reconstruction and oceanic stripes. Magnetic anomaly maps show a fossil triple junction offshore France and Spain (T in Figure 2.10-a). The junction separates oceanic domains that were formed between the European, the North American and the Iberia plates. Precisely identifying the distorted chron gives an estimate of the date that the event took place (80 Ma - 118 Ma ago). Moreover, the transition between oceanic and continental domains is clearly visible offshore of Brittany. Rotation of Iberia is deduced from plate kinematics reconstruction of these chrons and the subsequent opening of the Bay of Biscay induced a compression between the rotated Iberia with Europe that entailed the beginning of the Pyrenean uplift (Figure 2.10-b). Both rotations and dating are further confirmed by independent paleomagnetic declination measurements in the Iberian peninsula.

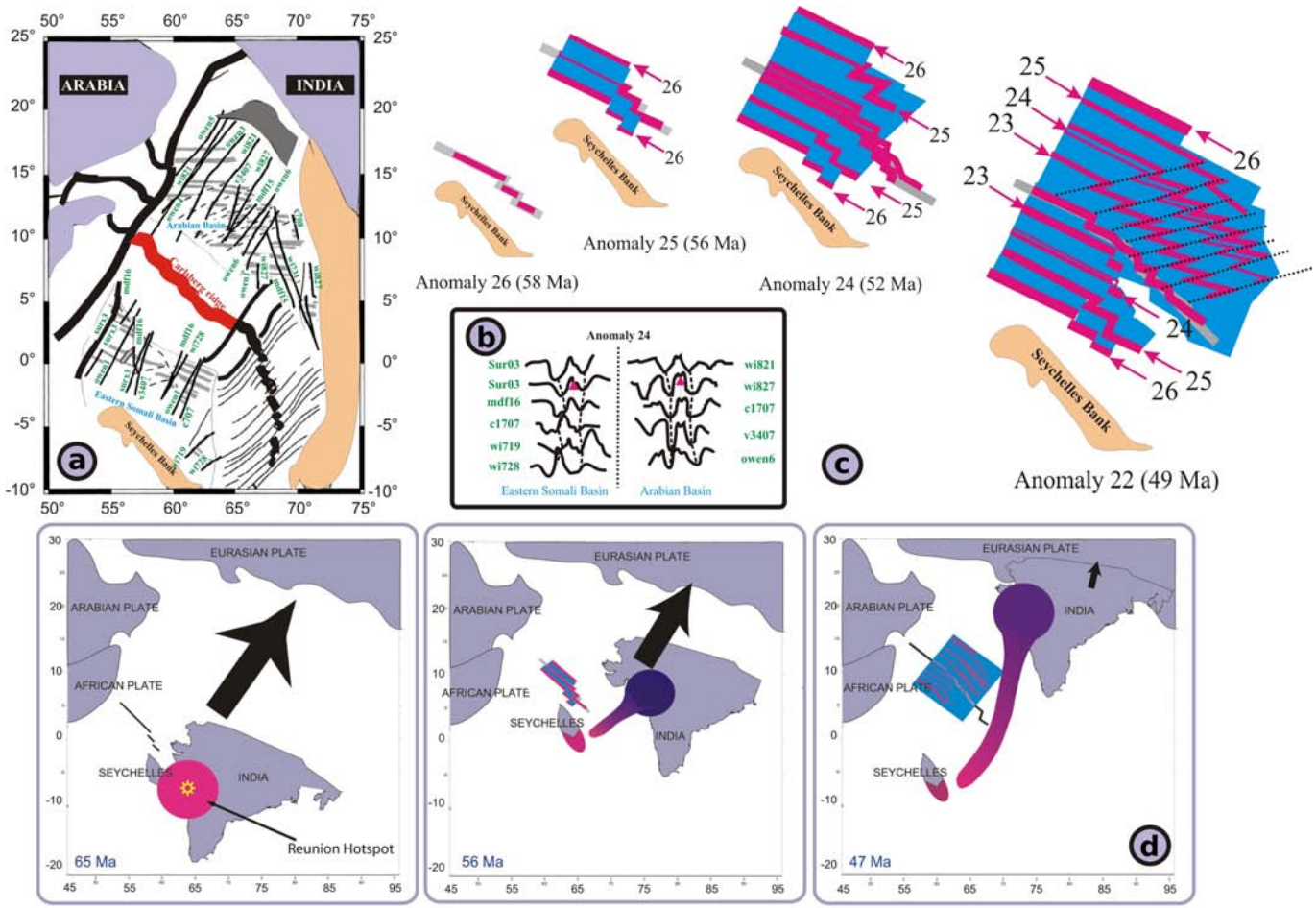


Figure 2.9: The Carlsberg Ridge is a complex, deformed and fractured system. Identification of isochrons along ship cruse profiles (black lines with green labels in a) can be done by studying the tiny variations of the crustal field in magnetic intensity. These so-called "tiny-wiggles" are characteristic for each isochron (b). According to the isochron locations, it is possible to develope a model of the Carlsberg Ridge evolution (in grey) with time. From this model we observe a ridge asymmetry (c). The ridge asymmetry may be caused by the thermal anomaly associated with the Reunion Hotspot (d). At 56 Ma, because the thermal anomaly locates east to the Carlsberg Ridge, more lithosphere is created in the African flank. At 47 Ma, because the thermal anomaly is south, more lithosphere is created in the Indian flank (Adapted from *Dyment, 1998*).

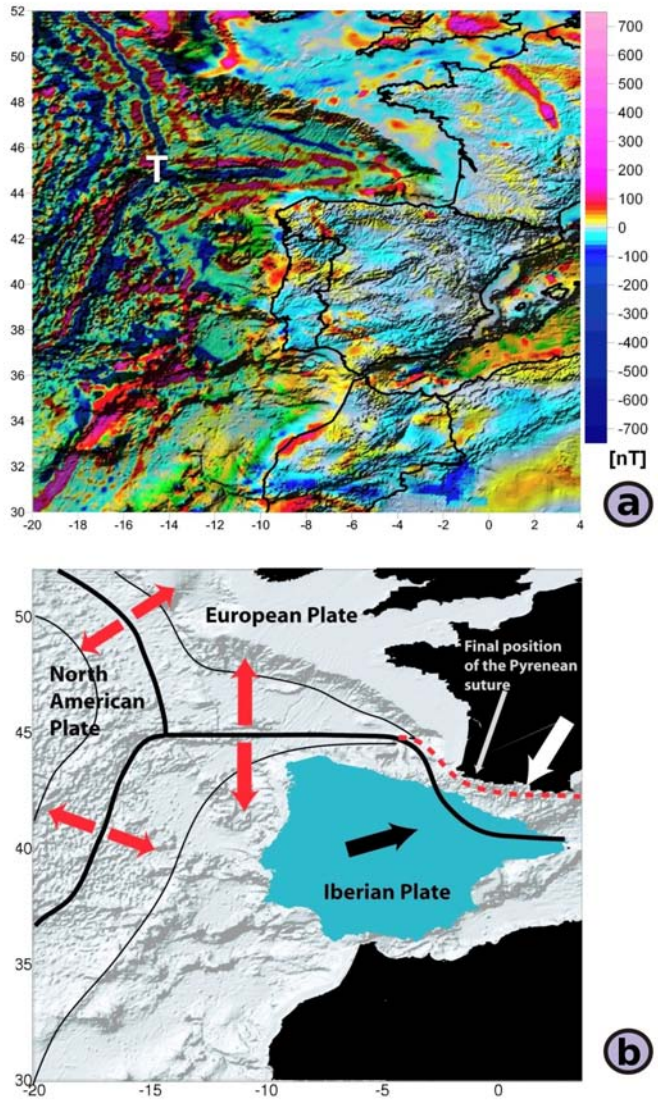


Figure 2.10: (a) The oceanic magnetic anomaly in the Bay of Biscay and the identification of isochrons agrees in favour of ridge spreading starting 118 Ma ago. However, the western part of the anomaly map shows isochrons, closer to the mid-Atlantic ridge and thus younger, not deflecting into the Bay of Biscay. This provides strong evidence that seafloor spreading had stopped in the Bay of Biscay about 80 Ma ago (WDMAM data). b) Analysis of isochron direction changes allows the reconstruction of the ridge spreading directions and thus, the geodynamics between 118 Ma and 80 Ma (Adapted from *Sibuet et al., 2004*).

Paleogeographic reconstruction Conclusions from paleomagnetic measurements and seafloor spreading can be combined into a model of a global paleogeographic reconstruction. As is often the case with terrestrial measurements, the amount of data is too low to systematically and reliably construct the apparent polar wander paths for a single plate without further constraints. Paleogeographic reconstruction thus involves many subjects such as structural geology, sedimentology, petrology, geochemistry, biostratigraphy, radiochronology, paleontology to be combined with magnetic crustal field measurements. As already discussed, a major challenge of paleo-reconstruction using rock magnetism is to remove all the plate movements, tectonic folding and geomagnetic field pole positions, and to find a fixed reference frame. It is reasonable to assume that hotspots form an array of fixed points that provides a mantle reference frame. The relative motions between paleomagnetic poles may thus be combined with the hotspot reference frame in order to derive the "true" polar wander and to picture the continental evolution of Pangea from the Jurassic (200 Ma) until now.

At the beginning of the Mesozoic (250 Ma), all continents formed Pangea, a single supercontinent (Figure 2.11). During the Cretaceous period (95 Ma), the break-up of Pangea was almost complete. The Atlantic Ocean opened allowing the rotation of the Iberian peninsula. The already discussed Chicxulub impact crater occurred during the Maastrichtian (65 Ma) when the North Atlantic was beginning to open. India rapidly moved northward and passed over the Deccan-Reunion Hotspot, leaving a trail of volcanic islands in the Indian Ocean and triggering the Deccan Traps, the largest igneous province on Earth. Paleomagnetic measurements establish that this other extreme event is contemporaneous with the Chicxulub crater. In a relatively short time, it may have released a gigantic amount of CO_2, inducing drastic modifications of atmospheric circulation and composition that may also have played a role in the Cretaceous mass extinction. Later, India came into contact with Eurasia during the Lutetian stage (48.6-40.4 Ma) enabling the uplift of the Tibetan Plateau.

Geologic hazards

Understanding the subsurface of a volcano Volcanic hazard assessment requires integrated geophysical analysis, as the environmental structure of a volcano is generally unique and complex. Thanks to the high magnetic response of volcanic rocks, magnetic data are especially powerful for the investigation of the subsurface structure of volcanic areas.

The island of Vulcano, Italy, is an active volcanic system occurring along a strike-slip fault located in the Aeolian archipelago. The island is composed of four main volcanoes with different vent locations and eruption histories from about 120 Ka to historical times (Figure 2.12-a). This active volcanic region is constantly monitored and complementary geophysical data are available. Paleomagnetic samples show the remanent magnetisation to be roughly aligned along the present ambient field and the island is young enough to assume constant polarity of the remanent magnetisation at depth. The airborne magnetic map shows distinctive structures that roughly correlate with the topography and the geology but major anomalies are interpreted as buried lavas. This offers a unique way to highlight buried volcanic structures that are not evident from the topographic relief. The fact that the cone is not demagnetised suggests that thermal anomalies are restricted to fumarolic conduits and vents.

Using deep drillings and previous knowledge on the volcano structure, it is possible to arrange subsurface blocks and layers with different rock properties in order to predict the measured magnetic anomaly. This so-called "forward modelling", often used in the next sections, is iteratively refined in order to improve the fit of the high resolution magnetic data bearing in mind paleomagnetic and petrological data as guidance to the modelling.

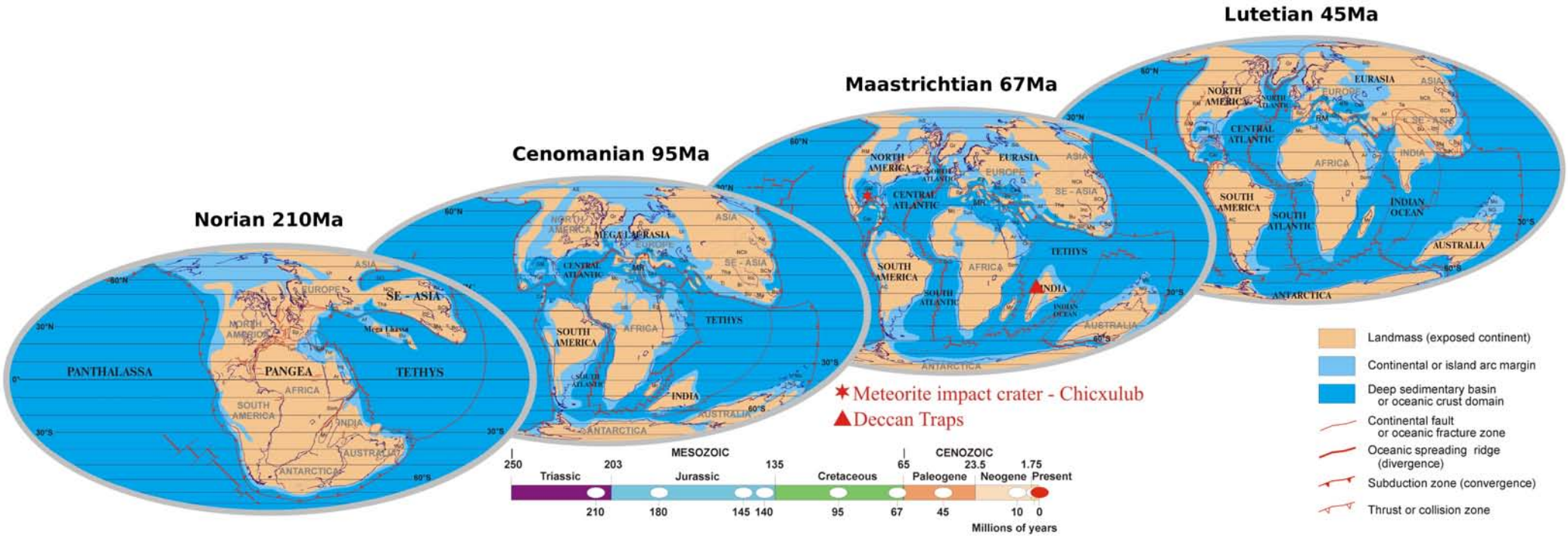


Figure 2.11: Continental drift and continental reconstructions are based on geophysical data, in particular paleomagnetic and oceanic magnetic data (After *Vrielynck and Bouysse, 2003*). A global aeromagnetic map, showing magnetic discontinuities, would be useful to refine the reconstruction, especially for small continental units. Such a global view of the Earth's history is important as it shows the quasi-simultaneous occurrence of the Chicxulub impact and the Deccan traps during the Maastrichtian Period. A combination of both events could have played an important role in the Cretaceous-Tertiary mass extinction.

A cross section of the present volcanic cone (Figure 2.12-b), La Fossa Cone, shows the current vent surrounded by former collapsed volcanic materials (Figure 2.12-c). The lack of magnetism associated with these geological structures can be interpreted as the result of hydrothermal alteration that occurred in the past. This assumption is supported by drilling temperatures that reach about 240°C at 1300 m of depth, a temperature too low to demagnetise rocks. The strongest magnetisation is carried by the outcropping lavas while the overlaying pyroclastics produce almost no magnetic signal in average at airplane altitudes. Such profiles can be sketched in every direction offering a nearly 3D view of the subsurface structure up to 1 km depth. In some places, usually offshore, the model can not be constrained by the geology. Northern Vulcanello, for instance, the model predicts a weakly magnetised material that agrees well with the assumption of unconsolidated sediments affected by a strong fluid circulation given by low velocity seismic measurements but more geophysical data could assess this hypothesis.

This kind of analysis is robust, but represents only the most recent stage in the evolution of the system. In addition, geologists know almost nothing about what lies below the surface. The importance of magnetic studies is that they can provide new evidence about the subsurface structure of a volcanic area, thus contributing to a more thorough knowledge of the evolution of the volcanic system. This has direct implications on the hazard assessment: it is essential to know the behaviour of the volcano in the past to infer how it will behave in the future.

This kind of analysis represents a step towards a self-consistent modelling based on the Geographical Integration System (GIS) that considers all possible geophysical data (Part 3). However, if it accounts well for regional anomalies, the global tectonic and geological contexts are disregarded. As is the case in many situations, it does not address the important question: why does the Aeolian arc, to which Vulcano Island belongs, lie precisely here? A more global view of magnetic anomalies is necessary to answer this question and only a world magnetic anomaly map can help the scientific community to address this fundamental issue.

Mapping a subduction zone: the Java Trench Magnetic methods are a relatively inexpensive way to learn about geologic hazards. As for the examples seen above, geological hazards can be examined at different scales using ground and satellite measurements (Part 3). The magnetic anomaly map realised at sea level (Figure 2.13-c) appears noisy and incomplete at this scale. Thus, the large scale magnetic structures of the Java Trench are hidden or distorted, and complementary magnetic maps derived from satellite data are necessary.

Let us now study an important case with large dimensions to better understand the limits of aeromagnetic maps. In theory, aeromagnetic images of the region surrounding the Great Sumatran earthquake and tsunami of 26 December 2004 could provide us with a current and historical view of the active subduction in the region. The subduction can be seen on the gravity anomaly map by an increase of the gravity field along the subduction zone (Figure 2.13-a). In the same vein, a lithospheric magnetic field satellite image confirms the compression boundary between the Eurasian and Indo-Australian plates (Figure 2.13-b). Even if this conception is oversimplified, a subduction zone near the magnetic equator like the Sumatra Trench has a typical positive magnetic signature above the location where the "cold" magnetic ocean crust penetrates into the relatively non-magnetic mantle.

One reason is that data distribution is not homogeneous and that no data are available inland. The more physical reason is that a magnetic map made using shipborne and airborne data is mostly sensitive to shallow and small dimension magnetic materials. In contrast, the far-field imaging using satellite data has a better sensitivity to the deep and large magnetic anomalies. Both views are complementary and the use of each data depends on the spatial scale at which the study is realised.

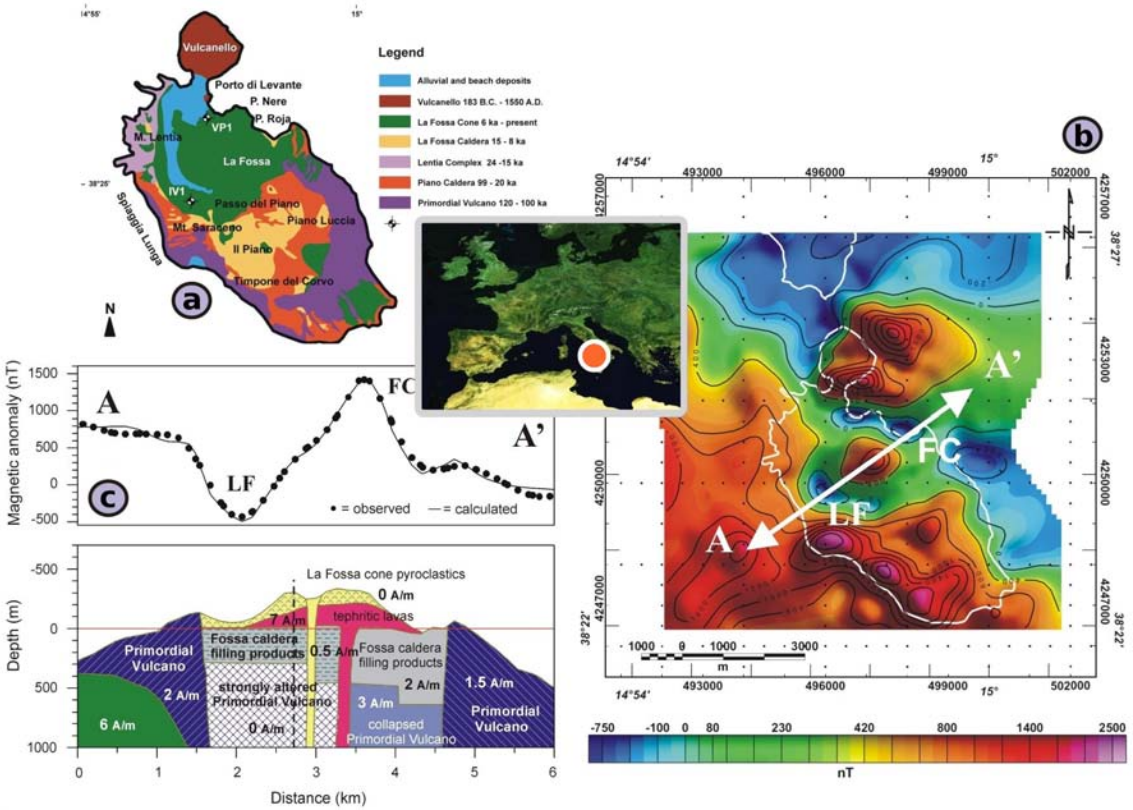


Figure 2.12: The structure of Vulcano Island may be inferred by forward modelling. The technique consists of setting the contour of the geological structures using a geological map (a). Different geological layers are defined with seismic velocity profiles. For each layer, a priori value of the magnetisation is set (b). The priori rock magnetisation values are then iteratively refined by comparing the data and the model prediction (c-top). When the model and the prediction agree well, we have strong evidence that the geological layers and the subsurface rocks were correctly characterised (c-bottom; After *Blanco-Montenegro et al., 2007*).

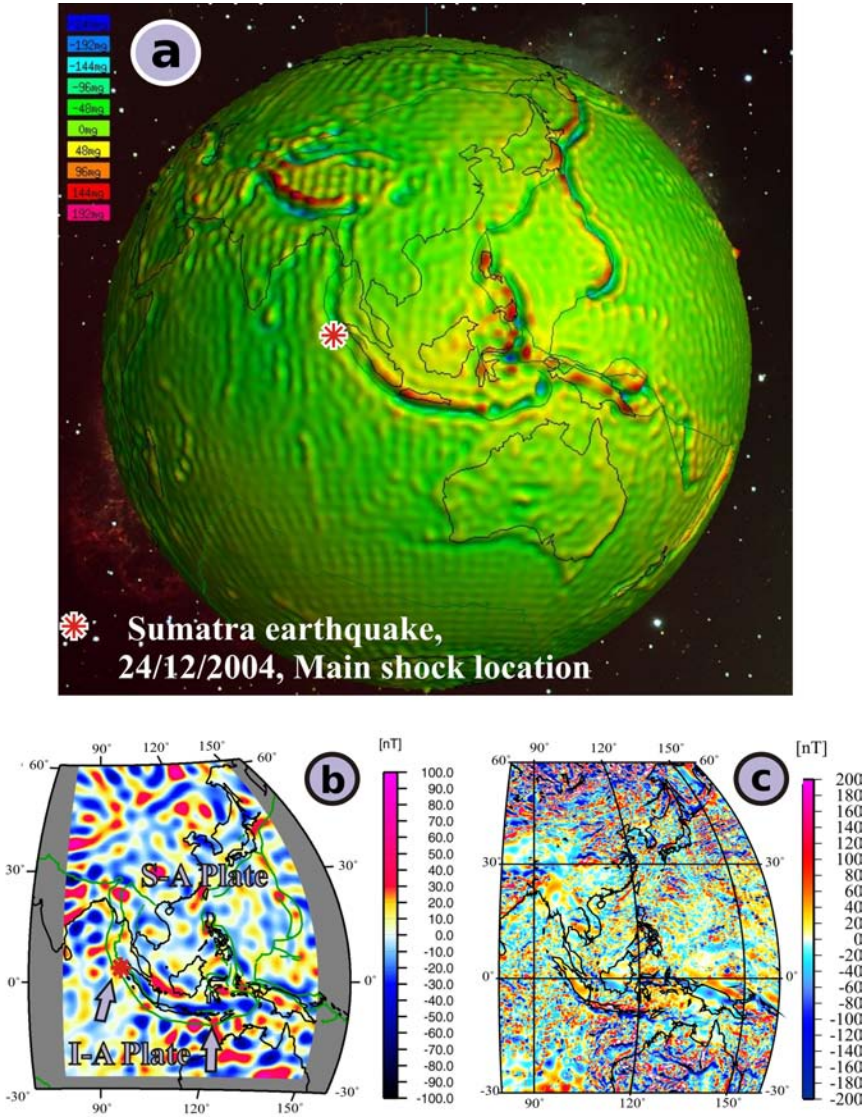


Figure 2.13: The compression boundary along the Sumatra-Java arc is clearly visible in gravity (a) and magnetic (b) anomaly maps using data measured at satellite altitudes. A map using aeromagnetic data only would not give us a clear image of large anomalies and only a combination of near surface and satellite data (c) help to recover the complete signal information. The Indo-Australian Plate subducts under the South-Asian Plate inducing an excess of crustal thickness along and beyond the subduction zone (green line in Figure b). This crustal thickness contrast produces a magnetic signal (figure (a) generated at *http://icgem.gfz-potsdam.de/ICGEM/*).

Third part: Towards a global view of magnetic crustal anomalies

A summary of the importance of aeromagnetic and marine magnetic surveys for the understanding of the geology has been illustrated in the previous pages, but a number of problems remain difficult to solve when only regional or independent compilations are considered. This was illustrated by the example of the large Sumatra region. A worldwide multi-scale view including satellite, airborne, marine and land magnetic data would allow, in principle, an extensive analysis of continental-scale magnetic trends, not available in individual data sets.

A worldwide near-surface aeromagnetic anomaly field

Large spatial variations of magnetic anomalies reflect rock type variations (mainly in the lower crust), while small-scale anomalies reveal local and upper crust variations. Merging all available data into a single map provides a more complete magnetic view of the full extent and depth of the Earth's lithosphere. Such a map can help in linking widely separated areas of outcrop and unifying disparate tectonic and geological units. A given magnetic anomaly could thus be analysed in a global context and we would be able to zoom in and out to understand the local and specific subsurface geological object and its link with the surroundings.

A worldwide magnetic anomaly map can also shed light on at least one important issue. A challenging question is to estimate the ratio of induced versus remanent magnetisation at different depths. Throughout the previous pages, we regularly assumed that remanent magnetisation was dominant at local scales. This approximation is untrue from a global point of view. Addressing the question of when each type of magnetisation takes over from the other at each depth would, in particular, partly unveil the nature of the upper crust. Such studies require consistent data sets over distances of thousands of kilometres, spanning national boundaries. As already discussed, three kinds of data are available, ground stations, aeromagnetic and marine data, and satellite measurements (Part 1). Our comprehensive understanding of the magnetic crust depends on our ability to combine all of these information.

The worldwide compilation

The aim of the World Digital Magnetic Anomaly Map (WDMAM) working group of the International Association of Geomagnetism and Aeronomy (IAGA) has been to provide scientists with a near-surface data compilation containing all possible wavelengths of the lithospheric field. Nowadays, large compilations extending to dimensions of several thousand kilometres are available but, so far, the challenge of handling the number of grids and specifications has greatly hampered the attempt to generate a global view of the magnetic anomaly field.

Producing a compilation is challenging and many difficulties are faced for several reasons. Aeromagnetic measurements were acquired beginning in the early 1960's and 1970's when surveys were conducted by individual countries. Each survey has its own characteristics and was carried out with a specific device at a given epoch and sometimes at varying altitudes. The data reduction protocol is also unique and mostly confidential.

A compilation is made by stitching together the independent regional magnetic surveys after corrections for non lithospheric field contributions. Correction errors cause significant differences in overlapping regions and are noticeable along the edges of adjacent surveys (Figure 3.1). It is thus necessary to adjust each compilation with respect to the others because a simple mapping is uninformative. The merging process is problematic as during this step, medium to large magnetic features are not retained. Since these large features are assumed to mainly depict the deep crust, we are inevitably missing something important for the geodynamic applications of magnetic anomalies.

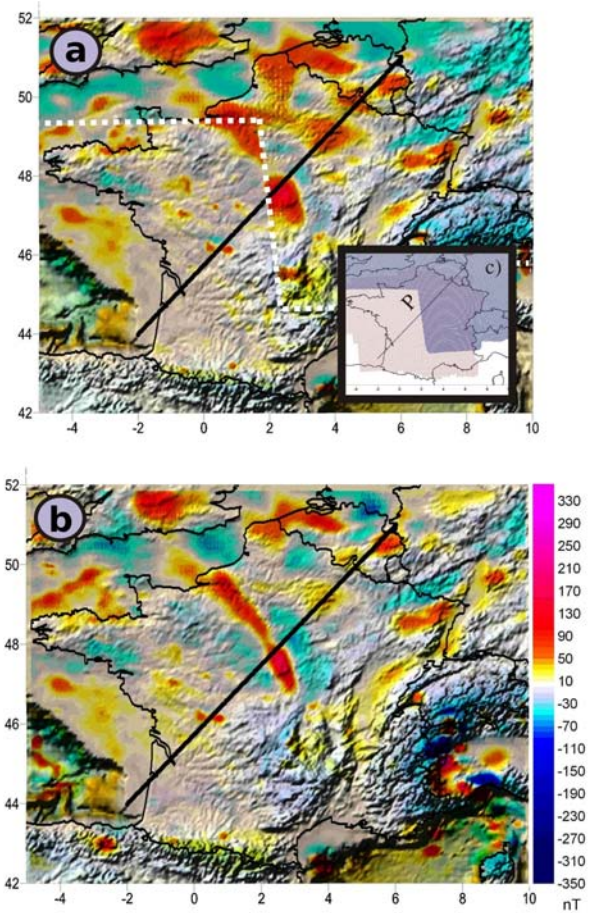


Figure 3.1: The picture shows an example of incompatible aeromagnetic grids (a). In the overlapping regions, the magnetic anomalies neither have the same strength nor exactly the same shape. Further data processing is required to derive a self-consistent compilation over Western Europe by smoothing out these discontinuities. Unfortunately, after processing, large and intermediate wavelengths are inevitably degraded (b).

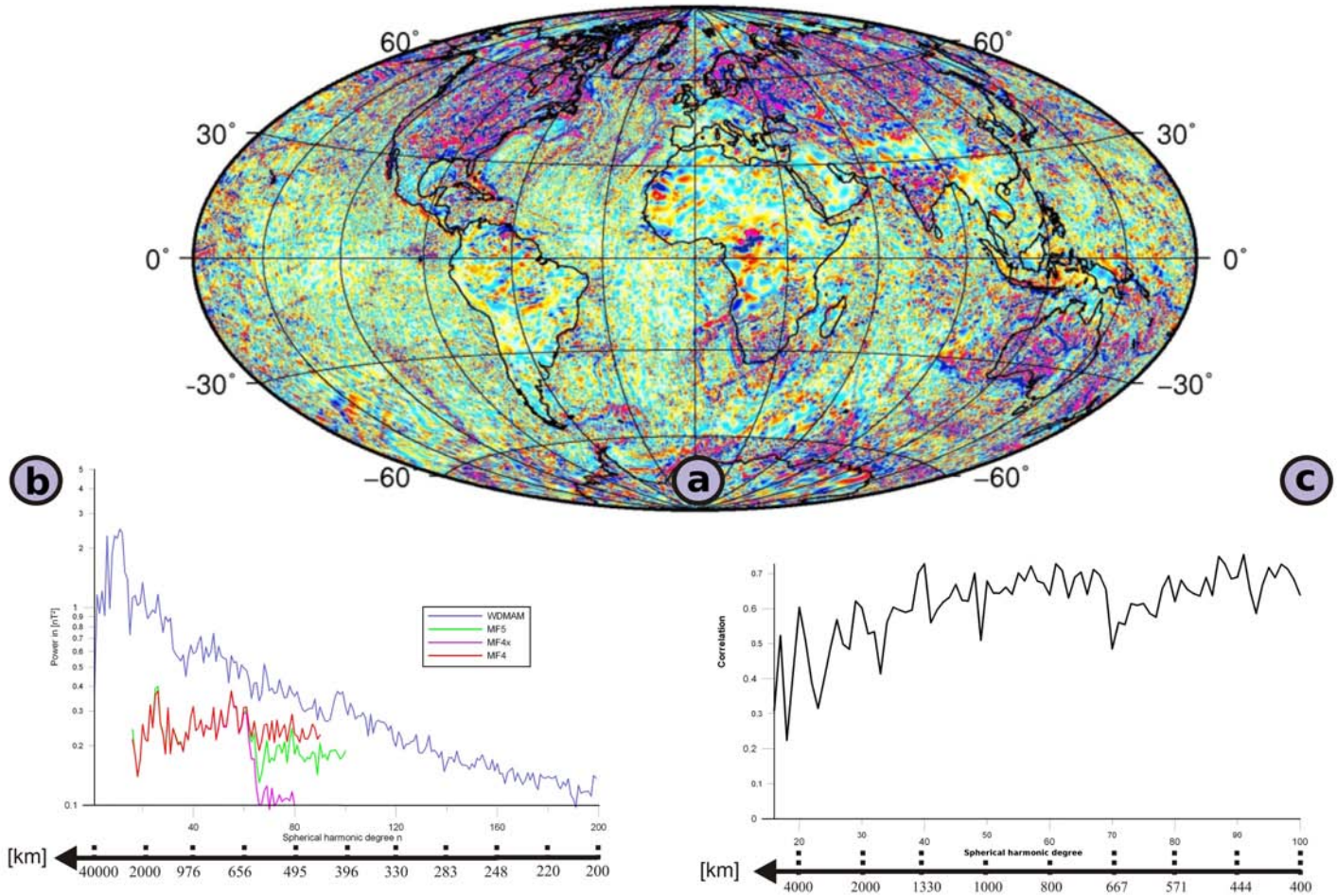


Figure 3.2: A spherical harmonic model to spherical harmonic degree 500 (∼80 km) is estimated and calculated at 5 km altitude from the WDMAM compilation (a). The magnetic spectrum shows that near surface and satellite data are complementary (b). Low degrees, corresponding to wavelengths larger than 2000 km are not correct in aeromagnetic compilations while no signal is detected from satellites for wavelengths smaller than 400 km. The correlation between both datasets for wavelengths in the range 400 km-2000 km is correct even if satellite models have less power than the WDMAM (c: After *Hamoudi et al., 2007*).

The global merged grid may be represented by spherical harmonics* with Gauss coefficients as the key parameters. Such a mathematical representation is useful to filter out the remaining noise and non potential fields, to calculate the magnetic field anywhere in the space where Laplace equation holds, and to perform spectral analysis allowing the comparison to satellite-based models. In theory, the magnetic field calculated from data acquired at satellite altitude should be identical to a magnetic field model based on near-surface data, only. In reality, the nature of noise, instrumentation, measurement platforms, distances to the magnetic sources and data coverage are so different that models do not correlate at all wavelengths (Figure 3.2-c). It is difficult to pinpoint exactly the origin of the disagreement, but the merging procedure used to assemble near-surface data is somewhat cumbersome and medium to large features, which dominate at satellite altitudes, are slightly degraded. For this reason, it is more prudent to remove features larger than 400 km from the WDMAM map and to replace them with a satellite based model in an attempt to recover the lost or inaccurate part of the magnetic signal measured at aeroplane and shipborne altitudes. In oceanic regions lacking data, an oceanic magnetic model based on isochrons and oceanic ages is calculated (see Figure 2.8).

The digital grid is presented at 5 km altitude and is available on a 3' x 3' grid (about a 5 km spacing) on the World Geodetic System 1984 ellipsoid (WGS84). The map (Figure 3.3) and digital data can be obtained from the Commission for the Geological Map of the World.

At the present stage, it is also difficult to exploit the full resolution of the WDMAM grid using spherical harmonic representation because of data gaps. The data density and availability greatly vary between the Northern and the Southern Hemispheres. The arctic region, for instance, is almost fully surveyed while large gaps remain in Antarctica. Another approach, the regional modelling, can be used if we need to focus on a specific region only. In regional modelling, it is possible to take advantage of the WDMAM compilation and to merge near-surface and satellite data in a single self consistent regional model. We are thus able to represent the altitude variation of the lithospheric magnetic field at resolutions of a few kilometres. Altitude variations are important to assess the depth of the magnetic sources (Figure 3.4).

The WDMAM gives the essence of the magnetic anomalies at 5 km altitude. Its release is still too novel to illustrate its scientific outcomes. In Figure 3.3, we may however recognise the remarkable correspondence between the major magnetic anomalies of South America and Africa across the reconstructed rifted continental margins. The WDMAM will thus certainly become an important tool for evaluating competing hypotheses and reconstructions of continental and oceanic assemblies of most regions of the world and understanding their geologic evolution at various spatial scales. In the following, we present a few exemplary accomplishments based on satellite measurements, which have 400 km maximum resolution. These examples offer the reader a relish of what is awaited from the exploitation of the WDMAM compilation.

The satellite perspective of the Earth's lithospheric field

The advent of the satellite era brought a major breakthrough in our understanding of the magnetic field at large scales. The main advantage of the satellite lithospheric magnetic satellite view is that the whole Earth is covered at a relatively constant altitude. Moreover, local complexities of magnetic anomalies are smoothed out when measuring the far field. Only the major structures remain, which provide us with a uniform mapping of the magnetic deep crust and upper mantle.

Qualitative geology

A global magnetic anomaly map is a means for geologists to identify large-scale tectonics, especially in places where no regional geology and tectonic maps are available. A common method of interpretation consists of comparing the anomaly field with geological and tectonic maps.

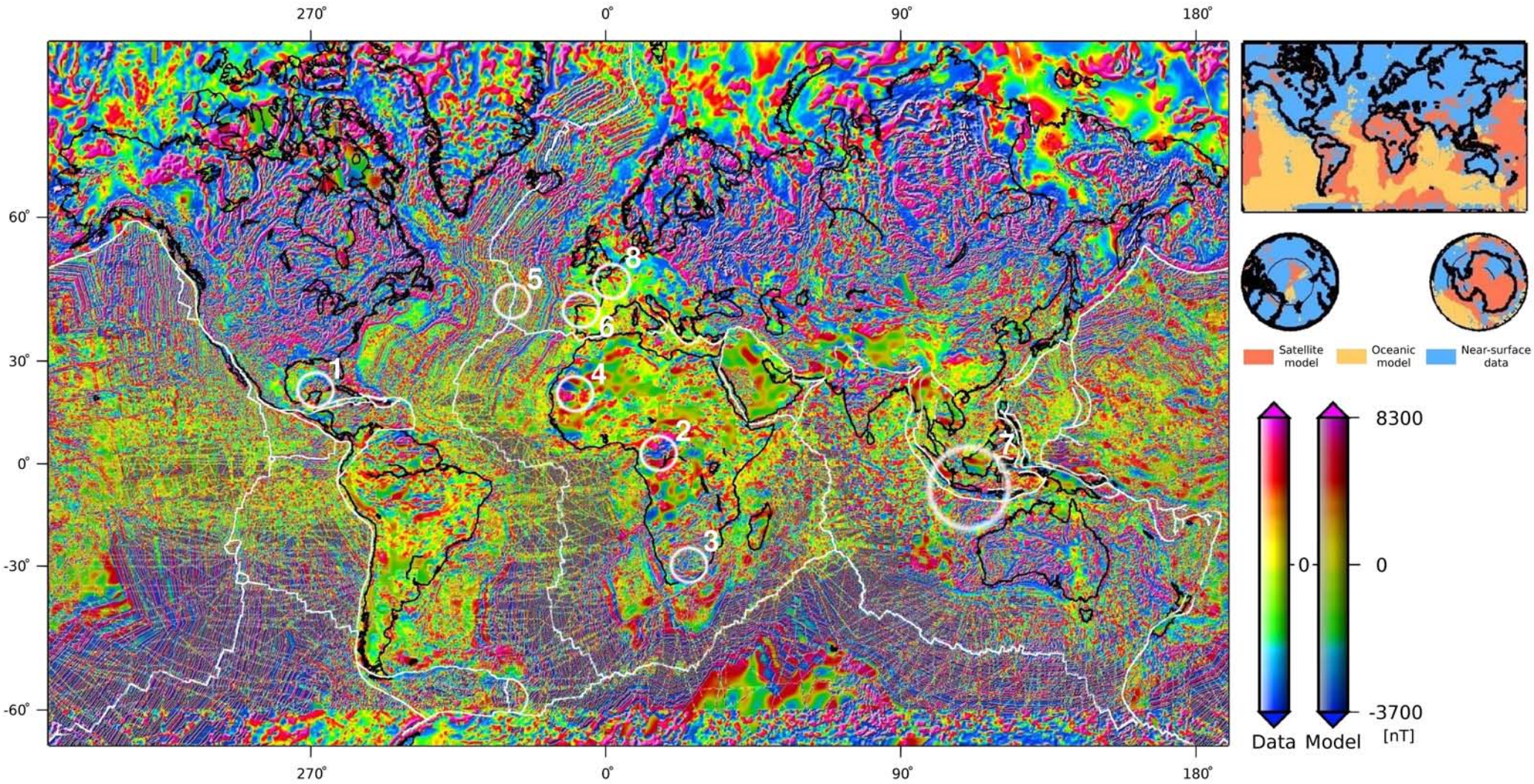


Figure 3.3: The first edition of the World Digital Magnetic Anomaly Map gives the essence of the worldwide magnetic anomalies at 5 km altitude. The thumbnail presents the data distribution and shows that a large part of the Southern hemisphere remains poorly surveyed by near-surface data. Thanks to the satellite data and indirect geophysical methods, the general shapes of the magnetic anomalies in these regions can be predicted (*CCGM/CGMW, 2007*). The most important features discussed in Part 2 and Part 3 are indicated: 1) Chicxulub crater (Figure 2.2); 2) Bangui anomaly (Figure 2.3); 3) Thromsberg anomaly (Figure 2.5); 4) Richat structure (Figure 2.4); 5) Atlantic ridge (Figure 2.7); 6) Bay of Biscay (Figure 2.10); 7) Sumatra-Java arc (Figure 2.13); 8) Paris Basin (Figure 3.3).

The lithospheric magnetic field deduced from data measured by the CHAMP satellite is shown in Figure 3.5-a. At 400 km altitude, the lithospheric field is characterised by large anomalies extending over several thousand kilometres with magnitudes between ±25 nT. This map is thus fully complementary to the WDMAM as it highlights the large and deep structures of the field but completely misses the magnetic field details due to the altitude of the measurements. These large anomalies are explained by lateral and vertical magnetisation variations of a few $\mathrm{A\,m^{-1}}$ distributed through a continental crustal thickness of 40 km and an oceanic crustal thickness of 7 km, on average. The magnetic anomalies are heterogeneously distributed, with stronger anomalies mostly located over continents: the strongest ones are situated over Kursk (Ukraine) and Bangui (Central Africa), for instance.

Over continents, the anomaly field is prominent over the main continental masses, Africa, Antarctica, Asia, Australia, Europe, Greenland, India, North America and South America. A comparison with the geological map shows that large magnetic anomaly features correlate well with Precambrian and Paleozoic provinces although a significant portion of old crust is probably hidden by Phanerozoic cover (Figure 3.5-b). If the strongest and largest positive magnetic anomalies are associated with shields and cratons, large subduction zones are also outlined (Indonesia) showing that the magnetic anomalies also correlate with the plate boundaries and thus the seismotectonic activity around the world (Figure 3.5-c). Moreover, each large structure includes diverse geological features of smaller extension like mobile belts or collision zones with comparatively lower magnetisation (Tibetan Plateau). In some places, continental magnetic anomalies seem to extend in oceanic regions along continental margins and island arcs (South Argentina).

Oceanic areas offer a big contrast and are characterised by weaker magnetic fields at satellite altitude. The Pacific Ocean, in particular, is very weakly magnetised. Compared to Figure 3.3 it may appear inconsistent. In fact, this situation is identical to the one illustrated by Figure 3.4 and the oceanic stripes of alternating sign discussed previously, and dominating at near surface altitudes in oceans, mostly cancel out at satellite level and magnetic anomalies correlated with oceanic ridges are scarce and weak. Only the widest seafloor stripes, like those associated with the Cretaceous Quiet Zones, and the magnetisation associated with spreading ridges are detectable at 400 km altitude. Comparatively higher positive anomalies are noticeable over oceanic plateaus while basins or abyssal plains are associated with negative anomalies. Other anomalies of larger extension and weaker magnitude are difficult to interpret as a result of our poor understanding of oceanic crust.

The physical parameters characterising the lithospheric magnetic field at global scales

Visual comparisons offer a good reconnaissance tool for gaining an understanding of magnetic sources but are always oversimplified as they have either too many possible explanations or no explanation at all. Ambiguities in interpretation are omnipresent in geomagnetism.

According to the qualitative descriptions above, the observed magnetic anomalies can reveal very different physical processes, but the clear dichotomy between oceanic and continental magnetic strengths hints that crustal thickness is an important parameter. The reasoning can be pushed further and we may even venture that lateral variations in magnetisation are subordinate to thickness variations.

A physical model aims precisely at finding a theoretical relationship between the physical parameters, like the magnetic field in [nT], the rock magnetisation in [$\mathrm{A\,m^{-1}}$], and the thickness of the crust in [km]. Such investigations tell us which parameter dominates over the others and they provide us with a higher level of knowledge by quantifying, confirming or undermining our hypothesis about the origin of lithospheric magnetic anomalies. When these mathematical relationships are confronted with real measurements, they tell us something about puzzling

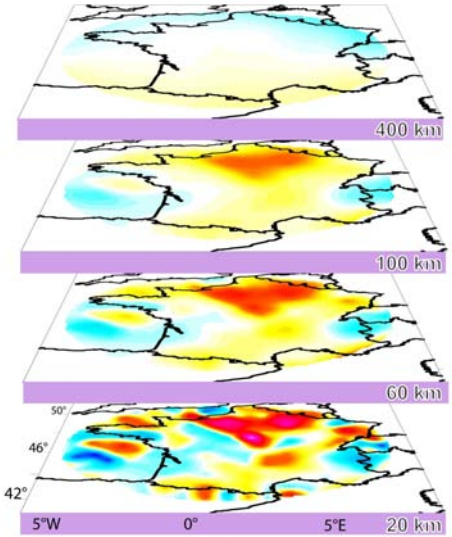


Figure 3.4: With an appropriate modelling technique, vector magnetic components can be calculated at any altitude between ground and satellite levels from essentially scalar data. Note the importance of having data measurements at various altitudes. In this case, of the French magnetic anomaly map, the Paris Basin anomaly decreases so quickly that it is invisible at satellite altitude (After *Thébault et al., 2006*).

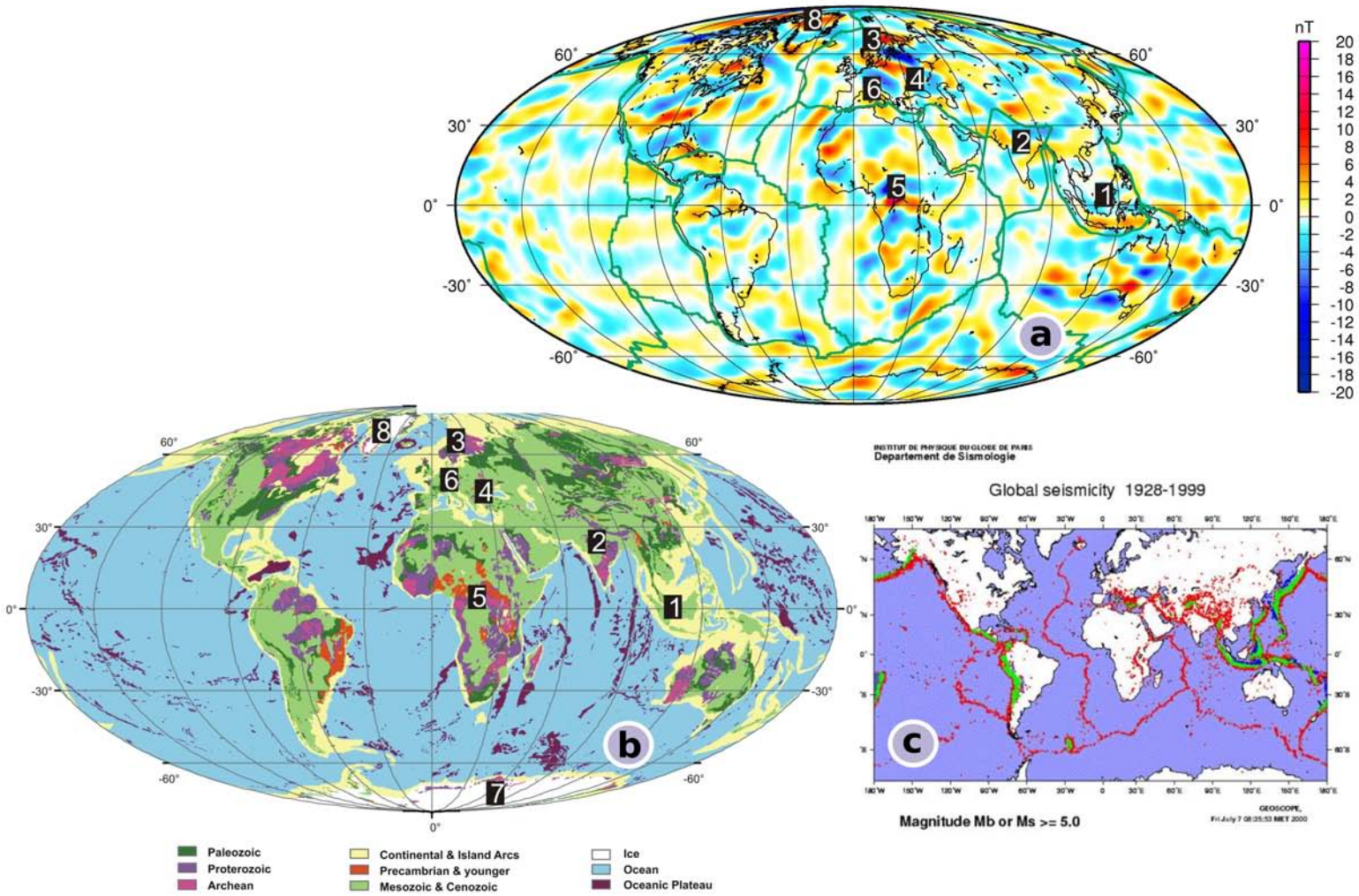


Figure 3.5: The magnetic anomaly field sketched at satellite altitude shows magnetic anomalies of large dimensions (a; After *Maus et al., 2007*). High positive magnetic anomalies are correlated with the geology and the age of rocks (b, After *CCGM/CGMW, 2000*). Many features are correlated with active tectonic events (c) like the Java Trench (1) or the Himalayan fold belt (2), for instance. Occasionally, strong positive magnetic anomalies lie over large iron ore mines as in Kiruna (3) or Kursk (4). This could reflect a slight enhancement in iron content over large horizontal and/or vertical dimensions. Some anomalies remain poorly understood like the prominent anomaly of Bangui (5). The large negative anomaly over Europe defines the terminus of the East European Craton (6). Magnetic anomaly maps are useful when the geology is poorly known, like over Greenland (7) and Antarctica (8).

anomalies, like Bangui, and explain why regions are not magnetised. For instance, oceanic and continental crusts have different thicknesses and properties. We thus intuitively expect a magnetic signal at their common boundaries. However, measurements do not show systematic magnetic anomalies at the ocean-continent boundaries (Figure 3.5-a). Such an intriguing problem can be addressed by setting up relationships between the physical parameters of the lithosphere and the magnetic signal recorded at satellite altitudes.

These experiments exceed the focus of lithospheric magnetic field studies. The lithospheric magnetic features larger than 2500 km are invisible to observation because, in order to obtain our lithospheric field image, a core field masking these contributions was removed. This procedure hampers the correct analysis of the main field. If we are able to predict these large structures independently from data, it will be possible to better characterise the main field. We could thus access the smaller dynamo structures that better guide our physical understanding of the terrestrial dynamo.

1. Is the farfield induced or remanent? The crust carries both induced and remanent magnetisation but, at satellite level, further assumptions are justified. The Earth's crust is 40 km thick in average and appears as a thin layer at satellite level. Furthermore, considering magnetite to be the dominant mineral in the crust, the farfield over continents is assumed to be mainly induced by the core magnetic field. Many geomagnetic results are inferred by playing with the rock susceptibility and the magnetic crustal thickness. The oceanic crust is somehow different in nature from the continental crust, it is thinner, younger and remanent magnetisation plays a prominent role.

In the following, we assume purely induced magnetisation in the continental crust but a combination of induced and remanent magnetisation in the oceanic crust. We illustrate, step by step, how to make use of these physical hypotheses to eventually obtain a satisfying understanding of the lithosphere on a global scale that fits satellite observations.

2. Oceanic magnetisation model Remanent magnetisation is important in the oceanic domain, but it first is neglected, in order to estimate how well the induced field hypothesis accounts for the observed lithospheric magnetic field. Two different, but uniform, magnetisations for rocks, respectively over oceans and continents, are set. This assumption is less drastic for oceans than for continents as the oceanic crust has a remarkably uniform composition (mostly silicates) and thickness (7 km $\pm$1 km). This bimodal magnetisation distribution implies a magnetisation contrast, and thus induces a magnetic signal, at the continent-ocean boundary (Figure 3.6-a). The depth at which rocks are no longer magnetic is not directly known but one may further consider the topography of ocean floor instead. Adding the ocean topography is fruitful, and positive magnetic anomalies over oceanic plateaus (see Figure 3.5-a) can roughly be explained by an excess of thickness (Figure 3.6-b). Such a simple model is sufficient to explain a few strong oceanic anomalies and demonstrates that the field variations indeed depend on the crustal thickness.

This basic model satisfies our intuitive expectation by predicting a magnetic anomaly at the ocean-continent boundary. However, this anomaly is not systematically seen in satellite data. Moreover, it is clearly observed in the satellite data ridge-parallel anomalies due to remanent magnetism of oceanic superchrons in the North Atlantic and Indian Oceans that are still missing. At this stage, the model remains too approximate.

Let us now include remanent magnetisation to the induced contribution over oceans. Adding the remanent magnetisation of oceanic basalt is a difficult step as the direction and strength of remanent magnetisation is significantly different from that of the present field. However, the digital age map obtained from the extrapolation of marine data can be used to set a prior remanent magnetism direction (see Figure 2.8).

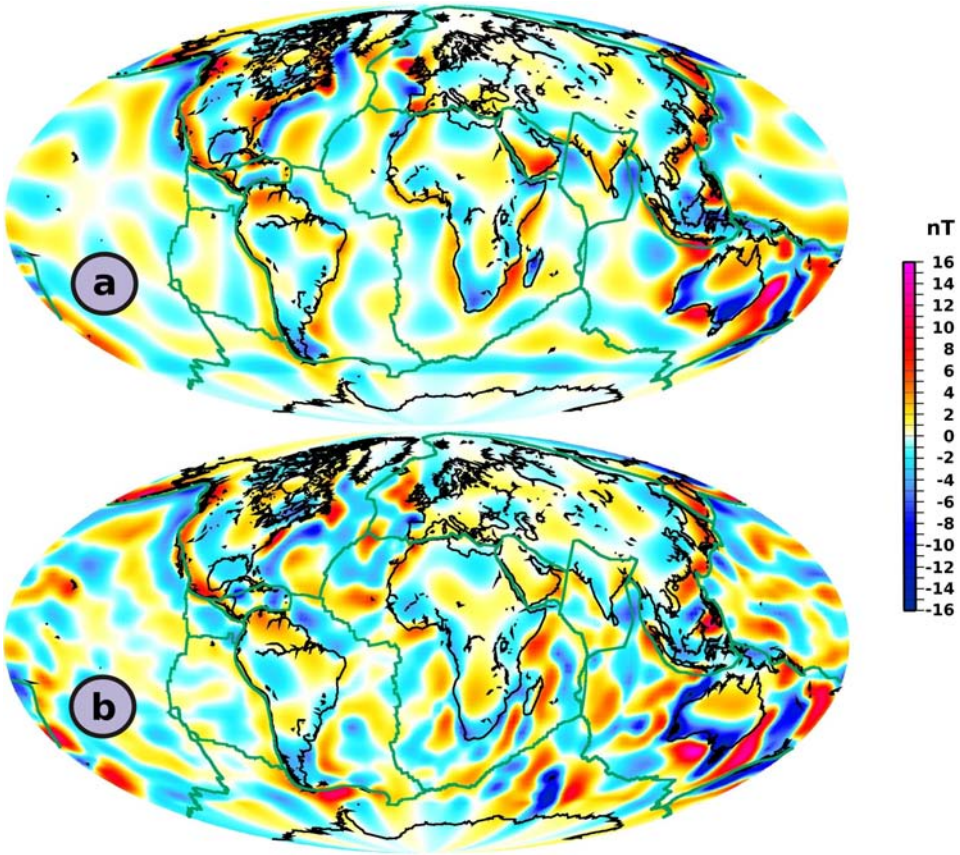


Figure 3.6: The anomaly field at satellite altitude is estimated by considering magnetisation contrasts between oceans and continents only (a). The correlation with real data is rather weak although a few magnetic anomalies are clearly recognised. When considering also the sea-floor topography, the shapes of the magnetic anomalies resembles those measured at satellite altitude (b). It means that most of oceanic anomalies can be explained by induced magnetisation and crustal thickness variations (After *Cohen and Achache, 1994*).

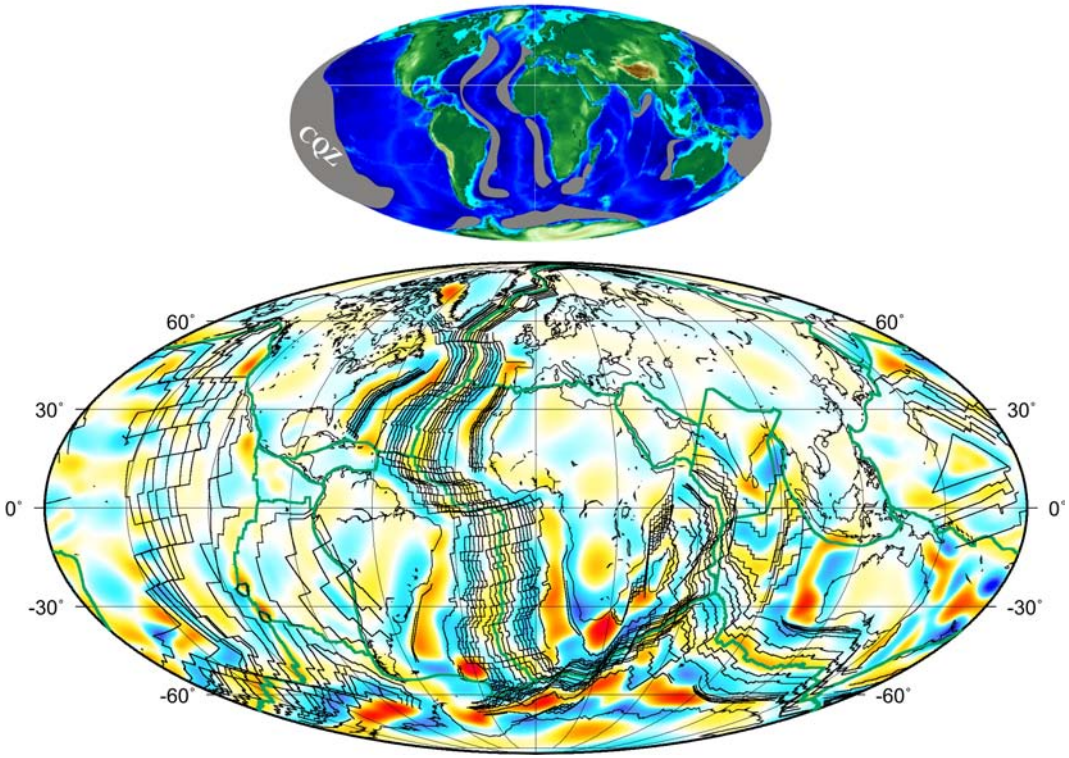


Figure 3.7: This magnetic anomaly field represents the estimated contribution of remanent magnetisations in oceans. Black thin lines are isochrons. In this calculation, the largest oceanic magnetic anomalies are associated with the Cretaceous Quiet Zone (top), a long period of geomagnetic normal polarity (Figure 2.7). The predicted anomalies correlate generally well with the observed data in the oceans, particularly well for Northern Antarctica (After *Dyment and Arkani-Hamed, 1998*).

In oceanic domains, core drillings and seismic tomography distinguish three different layers of different magnetisation values. An upper extrusive basalt layer of 0.5 km thickness forms directly at the ocean ridges. This layer is highly magnetic and has an average Natural Remanent Magnetisation (NRM) of $4.0\,\mathrm{A\,m^{-1}}$. A layer of intrusive basalt solidifies below the surface and is about 1.5 km thick. This layer has a negligible NRM. At last, the lowermost layer is 5 km thick and has an NRM of $0.25\,\mathrm{A\,m^{-1}}$. It consists of gabbro coming from the partial melting of peridotite, the rock constituting the Earth's mantle.

Familiar shapes over oceans are identified (Figure 3.7). At this stage, satellite data can be used to refine the magnitude of the average magnetisations by comparing the forward model with the real data.

It is difficult to improve the magnetic field prediction in the oceanic domain without a more elaborate hypothesis. In particular, anomaly strength disagreements and shifts between measured and predicted data are a common problem that is difficult to address.

Three important conclusions may be drawn from the prediction of the field in oceanic domains. Firstly, magnetic anomalies over oceans cannot be modelled without combining induced and remanent magnetisations. Secondly, we are able to explain magnetic data observed at satellite altitude, but all our knowledge is not sufficient yet to explain in detail the presence, or the absence, of some magnetic anomalies. At last, considering thickness variations in the oceans also produces anomalies over continents. Magnetic sources have also an effect away from the vertical of the source and it is crucial to consider the magnetic field in a more global context. The reverse holds true, we probably missed anomalies in the ocean because the continental sources were neglected.

3. Global magnetisation model The situation over continents is slightly more intricate because rocks and geological layers underwent tectonic deformation. The continental crust is older and much more heterogeneous than the oceanic crust. Lateral and vertical thickness and rock nature variations are thus important. The anomaly field at satellite altitudes is complex and requires accurate prior information to be predicted. Using independent ground geophysical measurements is inevitable. The most important contributions to the study of crustal magnetism are offered by the philosophy of the Geographical Information System (GIS) that aims to integrate all geophysical realms.

The continental crust is disparate but magnetic anomalies correlate well with geological maps that offer a priori information about unit contours of magnetic sources. Different susceptibility values, measured from laboratory rock experiments, may be associated with each geological unit. Moreover, the crust is transformed and deformed at large scales, thickened or thinned, and the same geological unit can be separated by tectonic activity over large distances. A seismic crustal model not only supplies a priori thickness variations of each geological layer but also the lower boundary of the lithosphere; the depth at which rocks are no longer magnetic (Figure 3.8). Continental and oceanic GIS data are merged together and compared with satellite observations.

The major anomaly features visible at satellite altitudes, mainly associated with Precambrian provinces, are largely reproduced (Figure 3.9). The forward modelling also answers the important startling question already evoked before. Recently, it has been shown that a continent ocean anomaly is not expected everywhere but only where oceans are flanked by continental provinces, Precambrian in age. The continental thickness is thus mainly balanced by the weakly magnetised sediment, Phanerozoic in age (compare Figures 3.5 and 3.9).

Despite the confrontation between the model and the data, discrepancies remain. The beauty of the GIS approach is that the system can adjust itself to better fit satellite measurements. By allowing some freedom to the prior model, the geological map, the geological layers or the crustal thickness map can be refined.

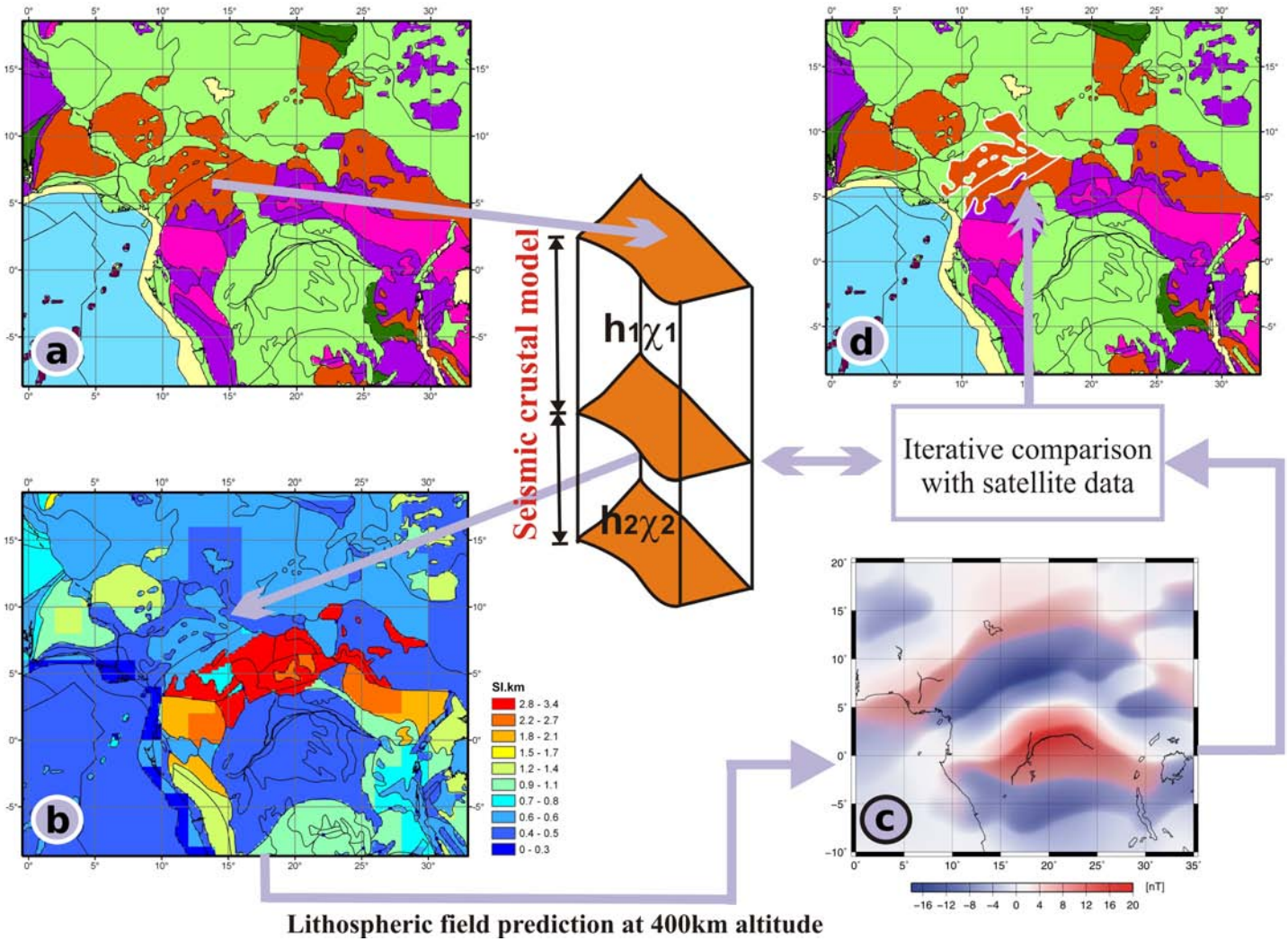


Figure 3.8: Contours of geological units and rock types at the Earth's surface are supplemented with tectonic and geological maps (a). Global seismic velocity models and stratigraphic information are then used to separate vertical geological layer and to define the crustal thickness. The Earth's surface is thus entirely divided into geometrical blocks of polygonal sections with different vertical layers. Each layer is associated with susceptibility value provided by laboratory rock experiments. At satellite altitude, this provides an average susceptibility value for each polygon (b) that respond more or less to the inducing core field. The expected magnetic field at 400 km (c) is iteratively compared with real satellite data and the geometry and physical parameters are modified (d). The example shows that the Bangui magnetic anomaly can be better explained if the geological boundaries are modified (white lines in d). (After *Hemant and Maus, 2006*; Courtesy of *K. Hemant, NASA*).

This can be obtained by assuming that Precambrian crust has larger extensions hidden below Phanerozoic covers and focusing on improving the geological map boundaries. Redefining the subsurface limits of the Precambrian provinces provides better agreement with satellite data. This is insufficient in detail and other parameters are also to be changed. In Bangui, for instance, one assumption is to allow basalts in the lower crust to account for the observed discrepancy. This increases the averaged susceptibility and thus, the induced magnetic field predicted at satellite level (Figure 3.8-d). The main result in this latter example being that the Bangui magnetic anomaly can be explained without resorting to the impact cratering hypothesis (see Part 2).

4. Crustal thickness In the quest of making predictions more in agreement with satellite measurements, it is possible to let the magnetic crustal thickness vary instead of the geological boundaries. Indeed, if the non-uniqueness is an outstanding problem, comparing the average susceptibility over oceanic (0.04) and continental regions (0.035) suggests that thickness variations dominate susceptibility variations. The magnetic crustal thicknesses, indicating the depth to which magnetised crust is cooler than the Curie temperature, could be deeper or shallower than the Mohorovičić transition given by seismic tomography.

Figure 3.10 shows the estimation of the magnetic crustal thickness. In many places, the estimated crustal thickness significantly differs from the Mohorovičić discontinuity. Interestingly, negative or highly elevated thickness values reveal either inaccuracies or flawed initial assumptions. The Bangui anomaly, again, displays erroneous high or negative magnetic thickness values, which probably means that remanent magnetisation cannot be neglected in this region (Figure 3.10-b).

5. Geothermal flow The example of crustal thickness under Sumatra or Tibet, demonstrates that there is a relationship between magnetic anomalies and temperature in the crust (Figure 3.10-c and 3.10d). Indeed, the Curie isotherm* and the surface heat flows are related by analytical equations and an original way of investigating Earth's heat flow is to use geomagnetic lithospheric field measurements.

The heat flow at the Earth's surface is the amount of heat transfer between the crust and its surface per element of surface ($\mathrm{W\,m^{-2}}$) and per unit of time. It is a convenient measure of the Earth's cooling and thermal regime. The heat transfer from the crust is realised by conduction and, again, also depends on rock properties such as the thermal conductivity of crustal rock. The geothermal heat flux depends on many geologic conditions such as a global cooling of the Earth's core, friction of tectonic plates, plate motion, and radiogenic heat production. The latter, coming from radioactive isotope decay of uranium, thorium and potassium, represents the largest amount of heat production from the crust. Old crust is generally colder as a result of a longer cooling of rocks and relatively inactive tectonics, and thus has a low heat flux. Magnetic older crust is thus thicker than younger provinces. The Earth's average heat flow is about $65\,\mathrm{mW\,m^{-2}}$ over continents but local heat flows anomalies are recorded in many places. The effect of crustal thickening could be regionally balanced by the excess of heat in the crust. Such thermal anomalies are found, over volcanoes, hotspots and young fold belts, or in slow-spreading ridges in the oceans where mechanical constraints accumulate.

Ground heat flow measurements are scarce and globally poorly distributed. As a result, global estimation of heat flux, especially, in remote regions is very valuable. Antarctica, for instance, is the largest uninhabited area in the world. Almost 98% of the continent is hidden by ice sheet cover about 2 km thick. The study of Antarctica has been greatly hampered by the extreme climate conditions that hinder systematic ground or aeroplane geophysical measurements. The geology of the continent is poorly known although about 200 Ma ago it was part of the Pangea supercontinent (see Part 2). In this region, the geothermal flux is an important factor that may explain the occurrence of sub-glacial lakes and affect the thickness and dynamics of ice sheets (Figure 3.11).

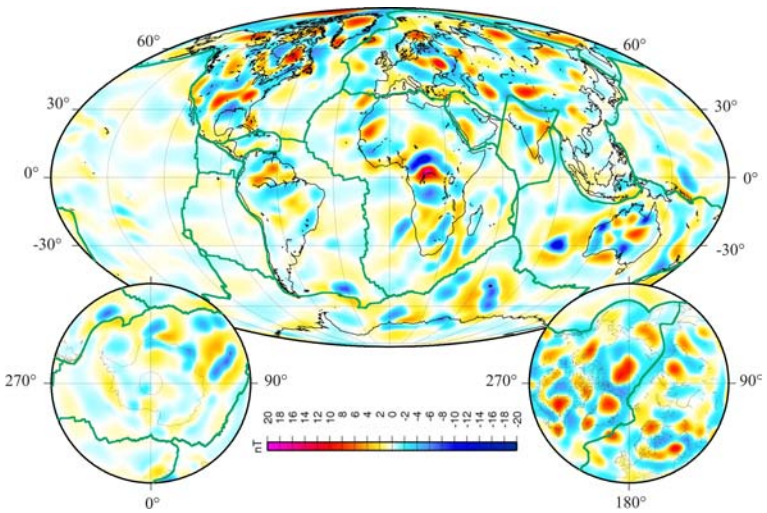


Figure 3.9: This magnetic anomaly field prediction derives from the joint analysis of a large amount of geophysical data. This result represents the current state-of-the-art of the so-called "forward modelling technique", purpose of which is to exploit all possible geophysical knowledge (it has to be compared with the spherical harmonic model sketched in Figure 3.5-a). The agreement is generally good although noticeable disagreements suggest that our understanding of the Earth's lithosphere remains incomplete. In the future, a main issue will be to include the contributions of the remanent magnetic field over continents (After *Hemant and Maus, 2006*).

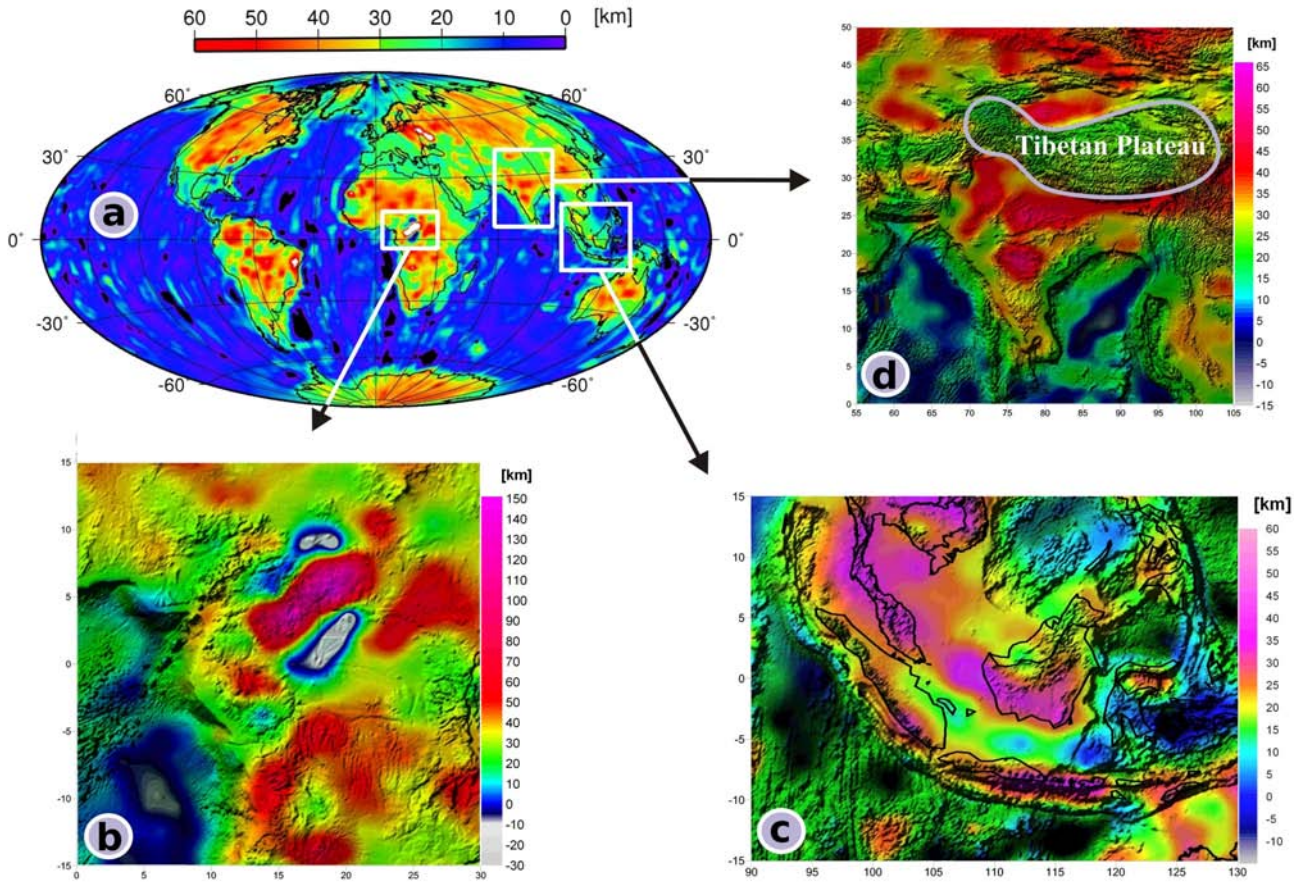


Figure 3.10: a) The world magnetic crustal thickness gives an estimate of the depth at which magnetic rocks loose their magnetic properties (After *Purucker et al., 2002*). b) Over Bangui, the magnetic crustal thickness model fails, probably because of a non-negligible contribution of remanent magnetisation. c) The strong negative magnetic feature observed over the entire Tibetan plateau seems paradoxical as an excess of crustal thickness should induce a positive magnetic anomaly (see Figure 3.5). The low magnetisation is here explained by a shallow Curie-temperature under the entire stretch of the Himalayan belt. Thus, the effective magnetic crustal thickness is thin due to the high heat flows in the region. d) In areas where subduction is occurring, as in the Sumatran region (see Figure 2.1), the subducting plate is descending so quickly that the Curie temperature is reached deep within the Earth's mantle (After *Purucker and Ishihara, 2005*). Hence, the magnetic thickness increases markedly in an easterly and northeasterly direction along the subduction zone.

The future is promising

We could not end without an important discussion about uncertainties made in these analyses. Merging our knowledge into a single problem proved to be encouragingly satisfactory and suggests that our understanding of the Earth's lithosphere is fairly accurate. Nevertheless, puzzling questions remain when scrutinising the differences between predicted and measured data, especially when examining the details. It is not surprising then, to notice that this question becomes more acute as more and higher quality magnetic data become available.

Here we have decided to restrict ourselves to the static part of the magnetic lithospheric field, but the near future will require more and more attention of its temporal variations at global and especially regional scales. An example illustrating this aspect is given by the recent identification of magnetic field signal generated by ocean circulation. This signal is perceived by satellite as internal and close enough to the Earth's surface to be wrongly interpreted as a signal of crustal origin, especially its quasi-stationary part (Figure 3.12). Moreover, if the lithospheric field is mainly induced, it also varies with the secular change of the inducing field. To which proportion remains a debated question and this requires long term monitoring of the magnetic field.

It should now be clear to the reader that the Earth's magnetic field is composed of a multitude of sources having overlapping temporal and spatial characteristics. In order to achieve a comprehensive view inside the crust, it is important to envision all possible physical processes driving the Earth's dynamics at all spatial and temporal scales. It cannot be accomplished without the understanding of all kinds of interactions, from rock magnetism and thermodynamic rules, geochemistry, Earth's interior composition, heat in the upper mantle, core dynamo, mantle convection, plate tectonics, or even Sun and Earth coupling... all these being very different areas of practical geophysical applications.

In addition, it was discussed that far-field and near-field measurements only partly correlate because measurements themselves provide us with partial views only. We are thus currently bound to miss information essential for our comprehensive understanding unless we improve our remote sensing devices together with our mathematical models to jointly analyse all kinds of magnetic data.

The high-resolution magnetic field monitoring from space will continue after the end of the current satellite missions. The European Space Agency's (ESA) Swarm mission consists of three CHAMP-like spacecraft planned to be launched in 2010. The Swarm concept consists of a constellation of three satellites in three different polar orbits: two satellites will fly at 450 km mean altitude with a West-East separation being of 1-1.5° and one will fly at 530 km mean altitude. High-precision and high-resolution magnetic measurements complemented by precise navigation, accelerometer and electric field measurements, will provide the necessary observations that are required to separate and model various sources of the geomagnetic field. This will result in a unique view inside the Earth from space, helping to study the composition and processes in the interior.

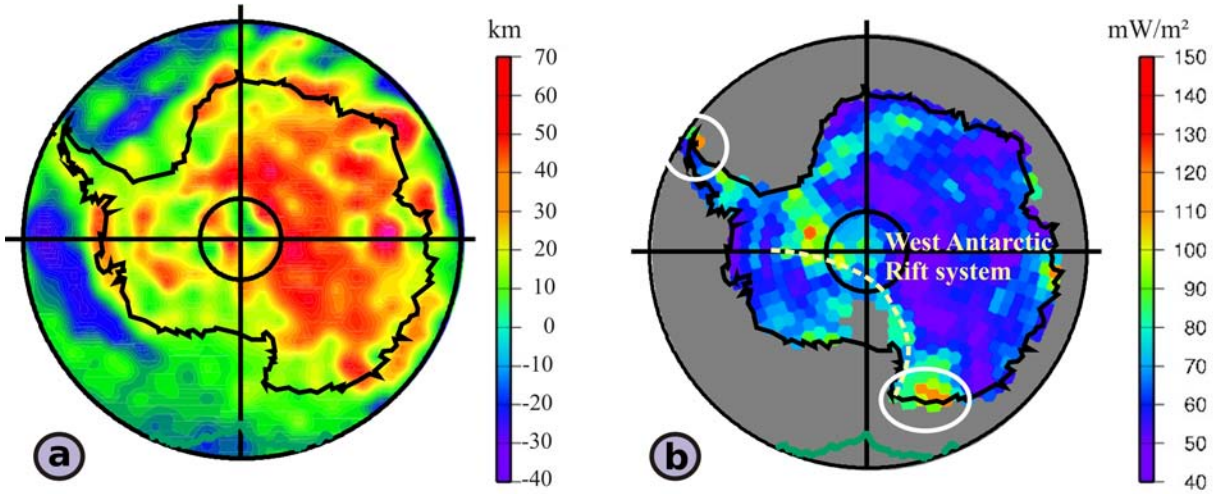


Figure 3.11: a) The magnetic crustal thickness over Antarctica is thicker in its eastern part than in its western part. b) The heat flux estimated shows two separated regions with an average heat flux in Antarctica in agreement with ground surface measurements. The western part of Antarctica has higher heat flux that coincides with volcanic activity in the south and north-west (white contours). Areas of high heat flux are found close to the west Antarctic rift system (yellow dashed line), which is a major active rift valley moving east and west Antarctica (After *Fox-Maule et al., 2005*).

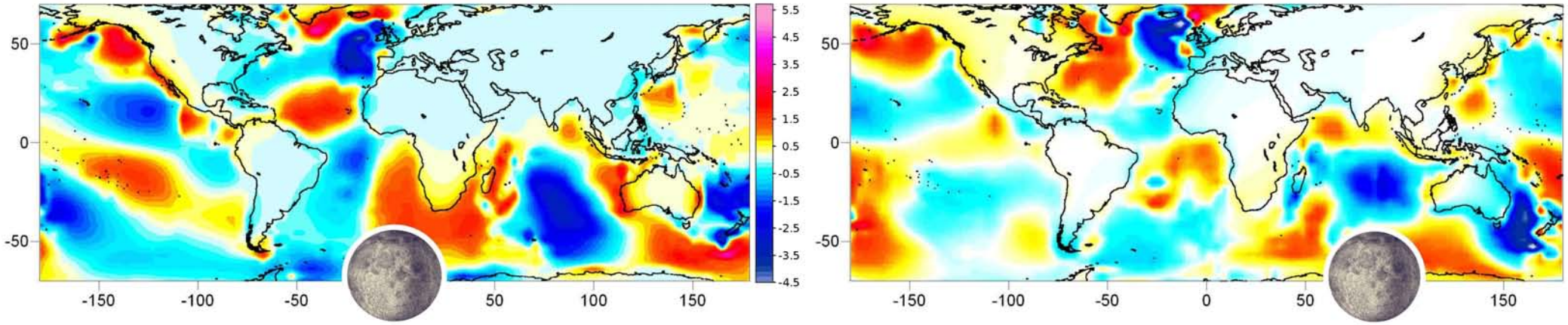


Figure 3.12: Sea water is a fairly good conductor and moves periodically in the ambient geomagnetic field generating secondary electric and magnetic fields. Both pictures show the secondary magnetic field generated by the tides for two Moon locations. Such signals, with different periodicity, could be easily confused with the lithospheric magnetic field.

Fourth Part: Earth-like planetary magnetism

The discipline of comparative planetology is a fruitful domain teaching us about the history and the possible future of our own planet. All planets represent a natural laboratory with different physical conditions that lead to various planetary evolutions and compositions. In that respect, the Earth is unique but, since it also shelters life, the necessity of understanding how fragile its stability is represents a serious matter at the very least. Some terrestrial planets and moons, like Mars, Mercury and our own Moon show evidence of heavy impact cratering and thus record the history of early solar system activity and formation. Martian large volcanoes indicate for a past cooling of the planet through convection, Venus' atmosphere turned out to be unbearable as a result of the most powerful greenhouse effect found in the Solar System. Most of these bodies lack a detectable core magnetic field but seem to have had one in the past... Can we extrapolate these observations to reconstitute the past and to predict the future evolution of the Earth? Common to all terrestrial planets (the Earth and its Moon, Mars, Mercury and Venus) is the existence of several magnetic field contributions of internal and external origin. The magnetic field of a planet can be sensed remotely, even through clouds, and can be used to probe the planet's interior and composition and to evaluate resources.

As already discussed, a few spacecraft have been able to monitor the Earth with full global coverage, thus making it possible for a good knowledge of the lithospheric field and its present and past morphology. We should always keep in mind that we are missing something as near surface geophysical observation and long term measurements are lacking. Thus there is no hindsight concerning other planet's time evolution and most models are derived using the Earth's experience.

In the following, after a short tour of the magnetic fields of the Moon, Venus and Mercury, the emphasis will be on the Martian magnetic field, the one that can most profit from the expertise gained in studying the Earth's lithospheric magnetic field. It is likely that in turn our comprehension of the Earth's lithospheric magnetic field will also be enriched.

Moon, Venus, Mercury

Early measurements have shown that the Moon has no global, core magnetic field. To create a magnetic field, the moon must have core magnetic material such as iron that is melted enough to form currents within the planet. The absence of a detectable core field suggests a possible frozen lunar core. However, the Moon possesses a weak remanent magnetic field of lithospheric origin. The lunar magnetic lithospheric field has been studied via the natural remanent magnetisation of the returned lunar samples, and directly not only with magnetometers carried to the surface but also with those placed in orbit at low altitude above the surface on the Apollo and, more recently, on the Lunar Prospector spacecraft. Apollo measurements have revealed widespread anomalies with scale sizes ranging up to many tens of kilometers. Paleointensity measurements on the returned samples suggest that the lunar surface field was comparable in intensity to the present-day terrestrial surface field from about 3.6 to 3.8 Ga ago. Such a field is most easily understood if a lunar core dynamo existed at that time. Relatively weak lithospheric fields (up to some tens of nT at spacecraft altitude) have been highlighted, mostly at the antipodes of the largest lunar basins. This suggests that the magnetic anomalies are linked to impact processes, in which ejecta would deposit at the antipodes in the presence of an impact-amplified magnetic field. Moreover, linear features and anomaly cut-crossing were observed that reveal a series of eruptions and lava solidifications on the surface. This would mean that a core inducing field was present during the period of these basalts emplacement, during the Late Imbrian according to the Lunar geological chronology, which is about 3.5 Ga. This also implies a tectonic activity on the Moon in its early ages.

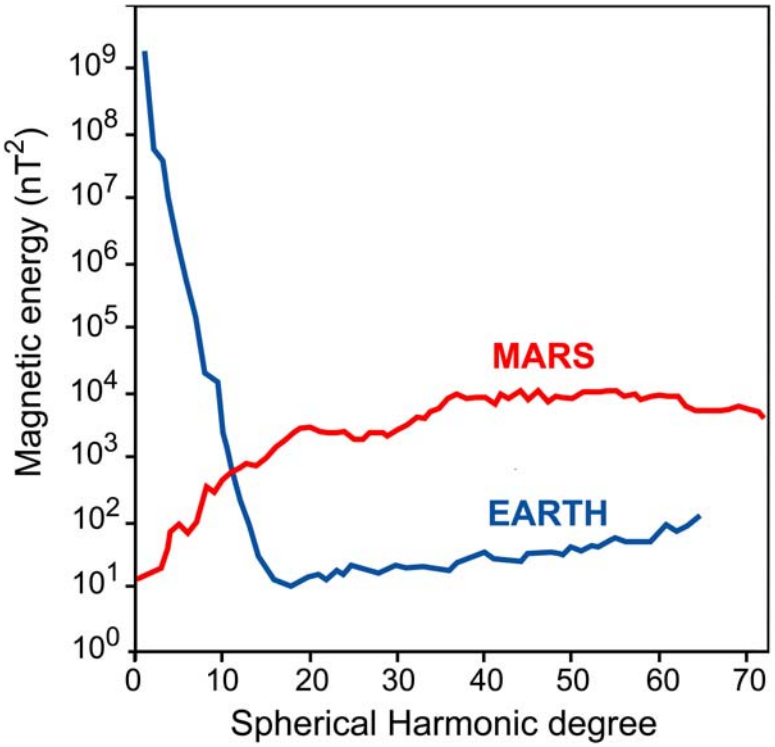


Figure 4.1: Comparison of the magnetic power spectra at the surface of Earth (blue) and Mars (red). The inflection point, i.e. change of slope, in the geomagnetic power spectrum can be seen at degree 13 and is a manifestation of the relatively sharp transition from core-dominated processes to lithospheric-dominated processes. The Martian spectrum shows only the signature of the lithospheric field, which is remanent in origin.

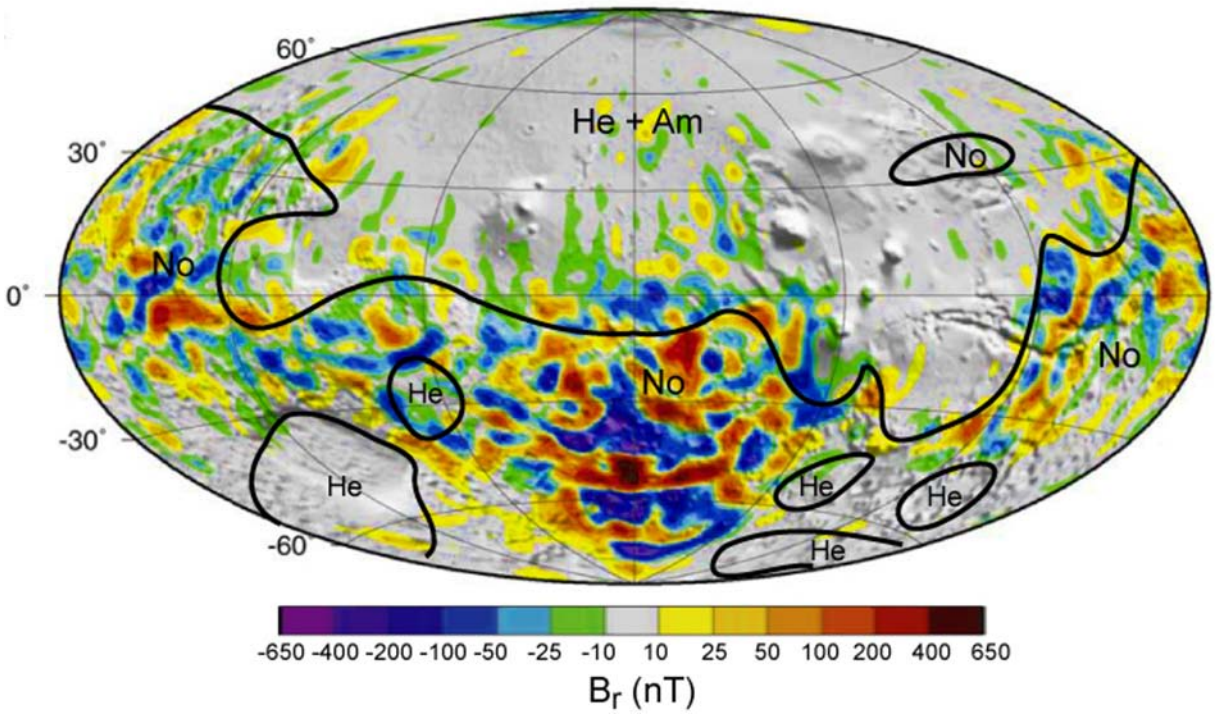


Figure 4.2: Radial component of the Martian magnetic field at 200 km altitude, with a shaded relief shown as background. Black lines roughly delimit the Mars geological scale: Noachian (No; 4.5-3.7 Ga), Hesperian (He; 3.7-3.2 Ga) and Amazonian (Am; 3.2 Ga - actual) units.

Venus has long been considered the Earth's twin planet as a result of its proximity, composition and density. Despite its relative similarity to the Earth, Venus is devoid of any detectable intrinsic magnetic field. Low-altitude observations (∼150 km) on both the night and day sides proved the insignificance of a field of internal origin in near-Venus space, as it seems that this planet is not able to maintain any remanent crustal magnetic fields because the temperatures in the crust are estimated to be above the Curie point. In contrast to the Earth, where lithospheric anomalies betray a past core field activity, the absence of crustal magnetism on Venus leads to a controversial problem. It is indeed difficult to tell if Venus ever had a core magnetic field, and thus a convecting iron core, that cooled down or if the present Venus core is still melted but is missing adequate physical condition to convect and to produce a dynamo. So, the observed fields near Venus may be explained by solar wind interactions with the planet.

Mercury was thought to have no active, planetary scale, magnetic field. Because of the relatively small size of the planet, it was assumed that the metallic core of Mercury was solid. Mariner 10 showed that Mercury has a magnetic field that is 1% as strong as Earth's. The weakness of Mercury's internal magnetic field has the consequence that external and internal contributions are harder to separate than in the Earth's case, where they differ by orders of magnitude. The information about the magnetic field were obtained from the first and third Mariner 10 flybys. These measurements demonstrate that the magnetic field of Mercury has a planetary scale, and that at the surface, it appears to be mostly dipolar. The source of Mercury's magnetic field is controversial: it might be from remanent magnetisation of iron-bearing rocks, magnetised when the planet had a strong magnetic field during its younger years or it might be produced by a partially molten iron core in the planet's interior, so a magnetic dynamo might be possible. A combination of these two sources might be also possible. Messenger (NASA mission, launched in 2004) and BepiColombo (ESA mission, planned to be launched in 2013) data will allow us to discriminate between the various models in terms of the spatial structure of magnetic fields, its degree of axisymmetry, and its secular change.

Mars

In contrast to the Earth's dynamic magnetic field, the magnetic field of Mars corresponds to the relics of an ancient magnetic field, frozen in the upper tens of kilometres of the lithosphere. This is one of the major discoveries from the NASA mission Mars Global Surveyor (MGS), launched in 1996. Amplitudes of up to 250 nT were measured at 400 km altitude by the MGS magnetometer. External contributions are weaker and result from the interaction between the solar wind and the thin Martian atmosphere. Most of these interactions take place on the day side, creating a highly variable dynamic magnetosphere, both in intensity and in altitude. More interestingly, the MGS mission answered the question about the intrinsic Martian magnetic field: there is no more significant planet-wide magnetic field, only a patchy, remanent, crustal field.

Mars shows no sign of a core-source magnetic field and, again, no unambiguous results prove the existence of a past dipolar core field. When the magnetic spectra of Earth and Mars are compared (Figure 4.1), it illustrates the dominance of the internal static magnetic field of lithospheric origin on Mars, in contrast to the dominant role played by the core field on the Earth. Strong magnetic fields of lithospheric origin in near-Mars space are restricted to a broad sinuous region spanning almost entirely the Southern Hemisphere. A clear crustal dichotomy is observed that is largely coincident with the heavily cratered, hence ancient southern highlands (Figure 4.2). There are two large terrains with no large magnitude magnetic fields within the magnetic region, one centred in the younger northern lowlands, and one centred in the older highland terrain around Noachis Terra in the south. Large impact craters such as Hellas, Isidis, and Argyre puncture the highlands and

manifest themselves magnetically by the absence of large scale magnetic fields. The process is assumed to be the same as on Earth, large impact craters are likely to have locally demagnetised the uppermost part of the crust. The absence of magnetism in large craters is believed to support the assumption of an early cessation of the Martian dynamo more than 3.5 Ga ago. The ancient Martian dynamo may have operated for only a few hundred million years between the accretion of Mars and the formation of the Hellas, Argyre, and Isidis impacts. However, the imprecise correlation between the relative age of the terrain and its associated magnetic field hinders our ability to determine the timing and duration of the postulated Martian dynamo.

The Martian magnetic field of lithospheric origin is a factor of 10 larger than the terrestrial lithospheric field, when directly measured at comparable altitudes above the planet (400 km). The most intense sources are observed in the Cimmeria region (Figure 4.2), where fields in excess of 1500 nT were observed near Mars periapsis at 100 km altitude.

The terrestrial lithospheric field contains a significant component of induced magnetisation from the large terrestrial core field. This component is largely absent at Mars, where remanent magnetisations dominate. This remark is of importance as on Earth we usually assume the remanent magnetisation to be rather weak. Moreover, such a high lithospheric field would not occur if highly magnetised rock were not present in the Martian crust. Only a crustal mineralogy rich in iron can acquire and, above all, preserve a large remanent field over such a long time. If we restrict our comparison to regions of Earth where remanent magnetisation is dominant (the oceanic basins), then the Earth-Mars contrast increases by a factor of 5, to 50. We said that the longest wavelength lithospheric fields over the Earth are masked by the core field, and best estimates suggest that this hidden field may double the strength of the lithospheric field. So if we could measure all wavelengths of the terrestrial lithospheric magnetic field resulting from stable remanent magnetisation, we might expect that the observed Martian magnetic field would be a factor of 25 larger. This raises the question about the past Martian core field, the Martian crustal thickness and the planet's composition.

Mars could have become an Earth-like planet rather than the present dry and cold planet. It is believed that the absence of a global magnetic field for billions of years contributed to the erosion of Mars' atmosphere by the solar wind. Since liquid water may have been the birthplace for life on Earth, the fate of Martian water is one of the major key and yet unanswered question to be solved. The recently proposed and selected Mars missions will cover the complex relations between early magnetic field, atmospheric escape, Martian upper and middle atmospheres and solar conditions. A complete low altitude characterisation of Martian magnetic field signatures will allow the past active magnetic field to be fully described and its influence upon the surface conditions and planetary evolution to be understood. Moreover, the role of the superficial magnetic field currently shielding Mars' surface and lower atmosphere from high-energy ions cannot be addressed without new measurements by a dedicated mission. Knowledge of the dependencies of the present atmospheric processes on solar activity will enable the past atmospheric escape to be traced back to the wet Mars period...

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* *This is a non-exhaustive list of relatively new references, covering more than those indicated in the figure captions.*

Glossary

Aeromagnetic survey - Measurements of the Earth's magnetic field intensity gathered from aircraft with a magnetometer installed on a boom.

Aurora - A bright display of constantly changing light mainly at high latitudes, created by the radiant energy emission from the Sun and its interaction with the Earth's upper atmosphere. This phenomena is most intense at times of magnetic storms (when it is also observed farthest equatorward) and shows a periodicity mainly related to the 11-year Sunspot cycle.

Axial dipole - An imaginary axial (along the Earth's rotation axis) geocentric (located in the centre of the Earth) dipole.

Core - Innermost zone of Earth, consisting of an outer liquid core (about 2200 km thick) and an inner solid core (about 1250 km thick), both chiefly of iron and nickel with about 10 percent lighter elements.

Crust - The constitutive rocks of the crust are primarily igneous, metamorphic and sedimentary. The rocks of the continental crust underlie the continents, and range in thickness from about 35 km to as much as 60 km under mountain ranges. The oceanic crust underlies the ocean basins and is about 5 to 10 km thick, with a higher density then continental crust.

Crustal/lithospheric magnetic field - The term *lithosphere* is used in a thermal sense, to include crust and upper mantle rocks whose temperature is below the Curie point of the dominant magnetic phase, typically about 600° C. The term *crust* is often used instead of *lithosphere* when magnetisations are thought to be restricted to the crust.

Curie Isotherm - The significant thermal surface beneath which any rock magnetisation is destroyed. Mapping its depth contributes to evaluating geothermal resources and oil maturation processes within sedimentary basins.

Geomagnetic field - The magnetic field observed in and around the Earth, composed of magnetic fields from various sources of which the main field, generated in the core of the Earth, is the most significant. Its intensity, at the Earth's surface, varies approximately from 30 000 nT at the equator to more than 60 000 nT in polar regions.

Induced magnetisation - Any magnetised body inside a magnetic field becomes magnetised by induction, which is due to a statistical reorientation of electrons and atoms along the inducing field. The degree to which a rock responds to an induced field depends on its mineral properties, structure and is determined by its magnetic susceptibility.

Ionosphere - The region of the Earth's upper atmosphere, at altitudes from around 70 to some 1500 km, containing partly ionised plasma, i.e. free electrons and ions produced by photoionisation of the atmosphere constituents due to solar ultraviolet radiation at very short wavelengths as well as incident X-rays.

Lithosphere - The solid portion of the Earth, as compared with the atmosphere and the hydrosphere. In plate tectonics, a layer of strength relative to the underlying asthenosphere. It includes the crust and part of the upper mantle and is of the order of 100 km in thickness.

Magnetic anomaly - The difference between observed and the prediction of the field originating in the core. The shape of a magnetic anomaly depends on the geometry of a body, the magnetic inclination, the direction of the Earth's magnetic field with respect to the direction of the line of observations, and the direction and intensity of the body's remanent magnetism.

Magnetic power spectra - A quantity computed as the squared magnetic field in each spherical harmonic degree averaged over a spherical surface, consisting of two components on the Earth, long wavelengths being dominated by fields originating in the core, and short wavelengths by fields originating in the crust; the cross-over occurs around wavelengths of 3600 km.

Magnetic storm - A worldwide major disturbance of geomagnetic field arises when strong solar winds hit the Earth's magnetic field in the upper atmosphere.

Magnetic susceptibility - The measure of the ability of a sample to acquire a magnetisation in a magnetic field, and defined as the ratio of the magnetisation induced in the sample over the inducing magnetic field.

Magnetosphere - The region of near-Earth space, with a comet-like shape, controlled by the geomagnetic field which dominates the interplanetary magnetic field. On the sunlit side, the magnetosphere is nearly hemispherical with a radius ∼10 Earth radii under quiet conditions and ∼6 Earth radii during solar storms, and on the opposite side it extends in a "tail" of several hundred Earth radii.

Moho - The seismic boundary between the crust and mantle. The location of the Mohorovičić discontinuity varies between about 5 km beneath mid-ocean ridges to approximately 75 km beneath continental crust.

Paleomagnetism - Paleomagnetism is based on the principle that magnetic particles, in molten igneous rocks or sediments, align with the Earth's magnetic field. When rocks cool and sediments become lithified, the magnetic field is fossilised and preserved. This discipline studies the strength and orientation of the remanent magnetic field recorded by the rocks.

Remanent magnetisation - The magnetisation retained by rocks from previous magnetic fields, recording the Earth's magnetic field as it existed at the time that the rock formed, such as when magnetic crystals in igneous rocks solidified (also known as thermal remanent magnetism) or at the time of deposition of sedimentary rocks (known as depositional remanent magnetism). The remanent magnetisation does not change with the reorientation of the rock sample, but is "frozen" into the rock.

Reversal - A change in the polarity of the Earth's magnetic field from its present polarity (named normal polarity). This has occurred a number of times in the Earth's history and provides a method for age dating.

Spherical harmonics - Mathematical expressions (functions) that depend on location in space, used in expressing the magnetic (scalar) potential, and which represent the field as the sum of "dipoles" (2-pole, like a bar magnet) whose strength decreases with distance r like $1/r^3$, plus a "4-pole" decreasing like $1/r^4$, plus an "8-pole" decreasing like $1/r^5$, and so forth.

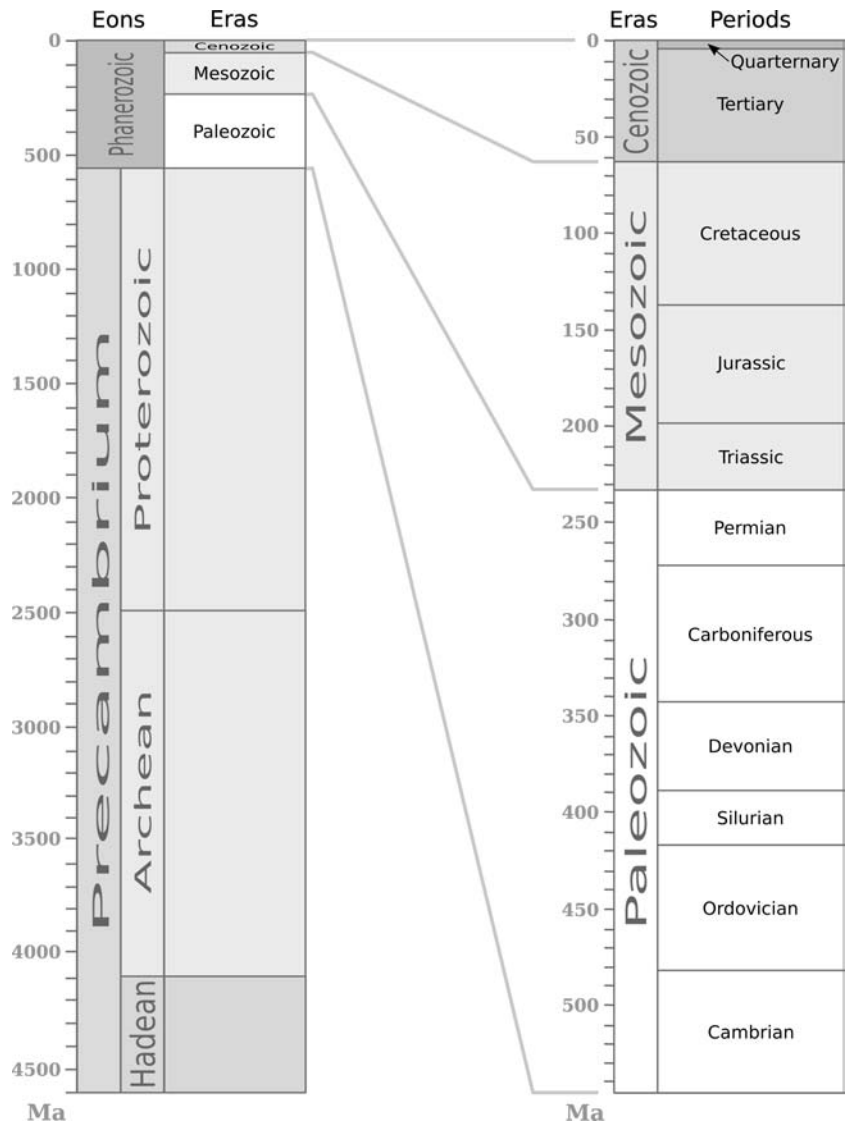
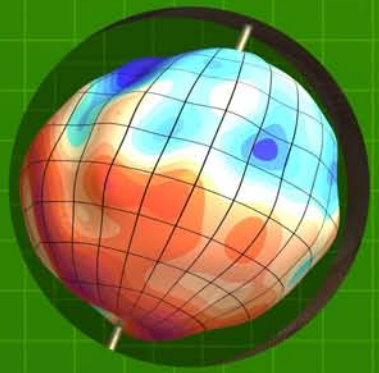
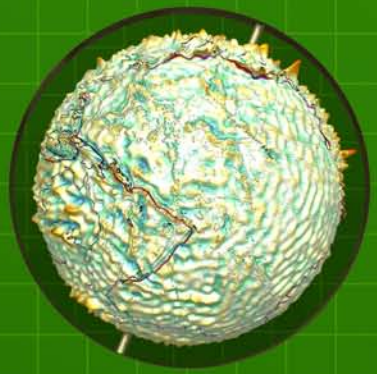
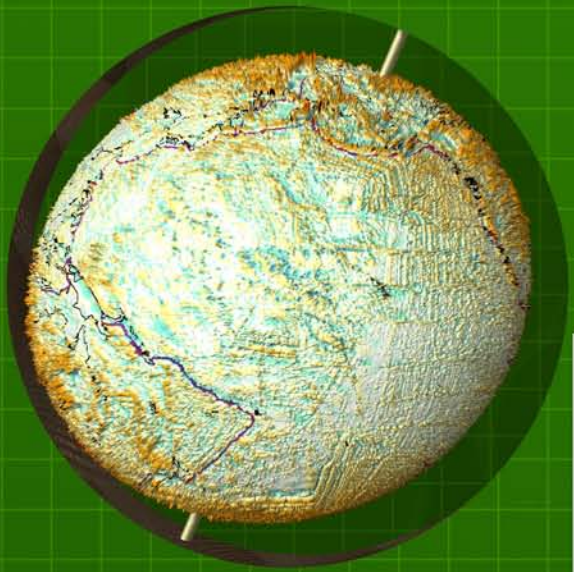


Figure Glossary: Geological time scale

1. The Earth's magnetic field and its complex behaviour
2. The use of magnetic anomalies at regional scales
3. Towards a global view of magnetic crustal anomalies
4. Earth-like planetary magnetism







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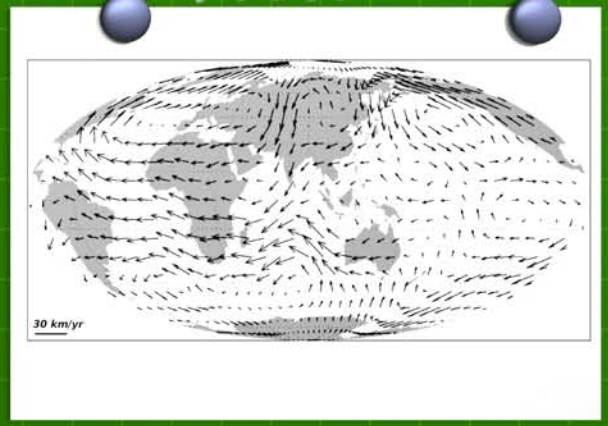

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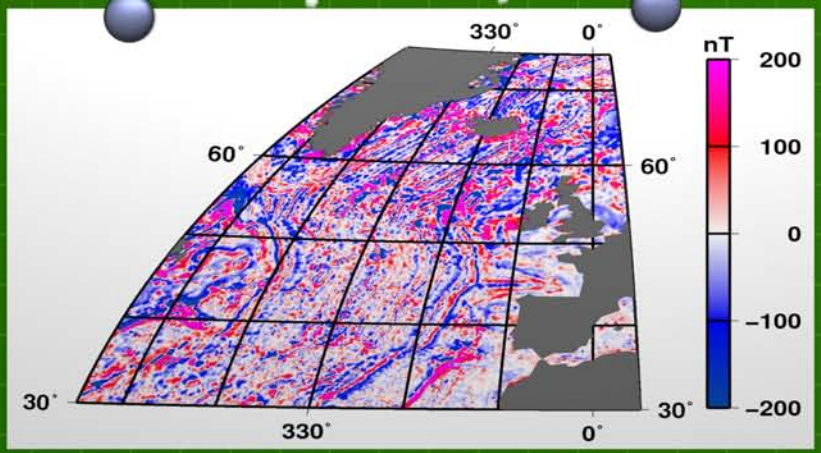

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