For example, the anisotropy of anhysteretic remanent magnetization (AARM) (see *Magnetization, anhysteretic remanent (ARM), q.v.*) is a method unaffected by paramagnetic constituents. In many cases, a reasonable approximation of single mineral anisotropies can increasingly be obtained. These methods will continue to provide exciting opportunities to advance the state of research relating magnetic fabrics and rock fabrics.

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Cross-references

Magnetic Susceptibility, Anisotropy
Magnetization, Anhysteretic Remanent (ARM)

MAGNETIC ANOMALIES FOR GEOLOGY AND RESOURCES

Magnetic anomalies and geological mapping

Knowledge of the geology of a region is the scientific basis for resource exploration (petroleum, solid minerals, groundwater) the world over. Among the variety of rock types to be found in the Earth's crust, many exhibit magnetic properties, whether a magnetization induced by the present-day geomagnetic field, or a remanent magnetization acquired at some time in the geological past, or a combination of both. Mapping the patterns of magnetic anomalies attributable to rock magnetism has proved to be a very effective way of reconnoitering large areas of geology at low cost per unit area. The fact that most sedimentary rocks and surface-cover formations (including water) are effectively nonmagnetic means that the observed anomalies are attributable to the underlying igneous and metamorphic rocks (the so-called "magnetic basement"), even where they are concealed from direct observation at the surface. Anomalies arising from the magnetic basement are only diminished in amplitude and extended in wavelength through the extra vertical distance between source and magnetometer imposed by the nonmagnetic sediment layers. Thus *aeromagnetic surveys* (*q.v.*) are able to indicate the distribution of bedrock lithologies and structures virtually everywhere. Interpretation of magnetic anomaly patterns can then lead to maps of (hidden) geology that give direction to the exploration process (Figure M1/Plate 7b). In igneous and metamorphic ("hard rock") terranes, outlines of local areas promising for the occurrence of ore bodies can be delineated for closer follow-up studies. In the case of petroleum exploration, interpretation of the structure of the underlying basement can help understanding of basin development and help locate areas for (costly) seismic studies and drilling. Similar economies in the exploration process can be made through exploitation of aeromagnetic surveys in the systematic mapping of potential groundwater resources, of particular importance in the arid and semiarid areas of the world.

Mineral exploration

The amplitude, shape, and internal texture of magnetic anomalies may be used to indicate the likelihood of finding of certain ore types. Initially, aeromagnetic measurements were used in direct prospecting for magnetic iron ores and in the indirect detection of certain classes of magmatic-hosted Ni-deposits, kimberlite pipes for diamonds, and so forth. Hydrothermally altered areas in magnetic environments are often detectable as low magnetic zones and may be prospective for Au and Pb. The largest concentrated source of magnetic anomaly in terms of magnetic moment is the Kursk low-grade magnetic iron–quartzite ore formation in Ukraine that can be measured even at satellite altitudes. Most of the major satellite anomalies are, however, attributable to entire provinces of relatively magnetic rocks, such as Northern Fennoscandia, of which the Kiruna magmatic iron ore is but a tiny part.

Most ore deposits within the crystalline basement are, either in themselves or through their host rocks, accompanied by magnetic

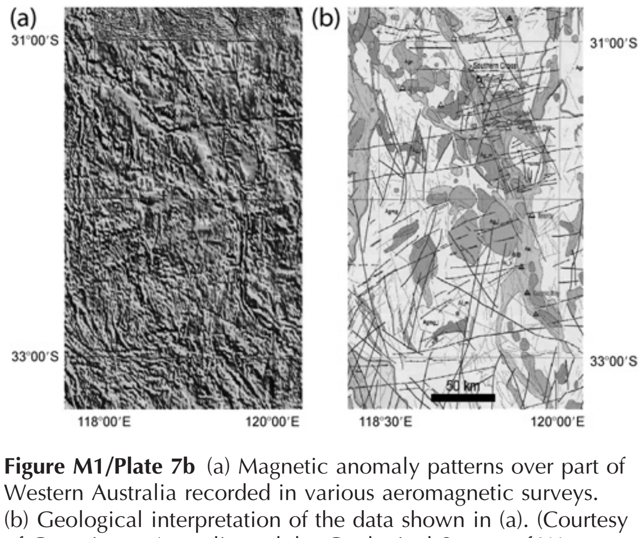

Figure M1/Plate 7b (a) Magnetic anomaly patterns over part of Western Australia recorded in various aeromagnetic surveys. (b) Geological interpretation of the data shown in (a). (Courtesy of Geoscience Australia and the Geological Survey of Western Australia).

anomalies. These anomalies are often used further in the closer evaluation of the extent and geometry of a deposit and in assessing the mineral potential of other comparable geological formations. At the reconnaissance stage of mineral assessment, area selection and prospecting—particularly of soil-covered areas of crystalline basement—geological mapping can be driven in large part by interpretation of detailed aeromagnetic anomaly maps. These provide, in a cost-effective and environmentally friendly way, a reliable picture of the underlying subsurface, including the location and extent of geological units and their lithology, structure, and deformation.

Continental and oceanic anomaly mapping

Given that most countries have a national program of mineral resource management, the foundation of which is the geological mapping program at an appropriate scale (say 1:1 000 000), ambitious national programs of aeromagnetic anomaly mapping have been instigated generally to supplement and accelerate geological mapping (for example Canada, Australia, former Soviet Union, the Nordic countries). National aeromagnetic anomaly maps, together with gravity anomaly maps, have therefore become preeminent in the geophysical support of geological reconnaissance. Given that gamma-ray spectrometer surveys are now usually flown simultaneously with aeromagnetic surveys at little additional cost, they form a third common type of geophysical support for geological mapping.

Over 70% of the Earth is covered by oceans. The geology here is totally obscured, even over the continental shelves. Until the advent of systematic ocean exploration in the second half of the 20th century, little was known of the geological evolution of the deep oceans. The patterns of magnetic anomaly stripes discovered, paralleling the mid-ocean ridges (Figure M2/Plate 9e from Verhoef *et al*., 1996), became one of the leading lines of evidence in support of continental drift and, eventually, global tectonics (see *Vine–Matthews–Morley hypothesis*). This revelation must count as one of the most profound advances in our understanding of the Earth's history and its mode of development.

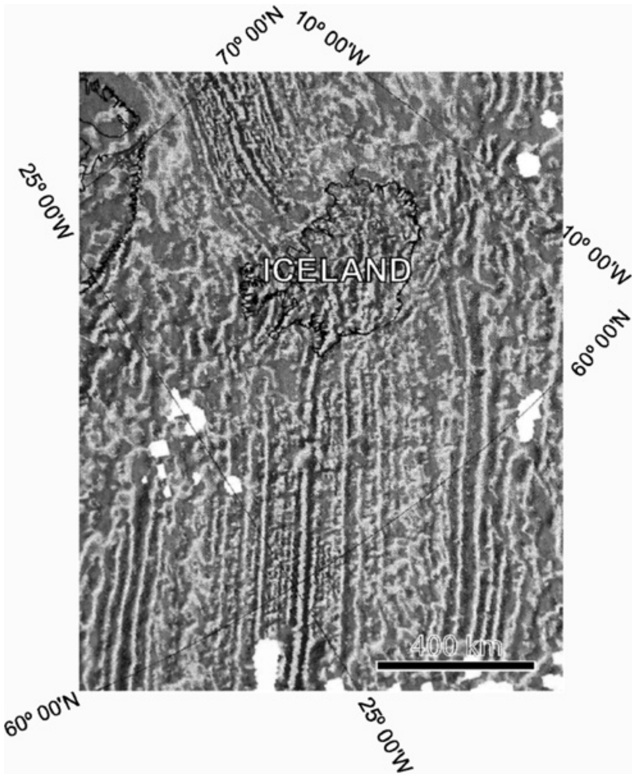

Figure M2/Plate 9e Magnetic anomaly patterns in the North Atlantic Ocean showing the symmetry of the anomalies either side of the mid-Atlantic Ridge in the vicinity of Iceland. (Detail from Verhoef *et al*., 1996, courtesy of the Geological Survey of Canada).

Being of igneous origin, the rocks of the oceanic crust solidify and cool at the mid-ocean ridge while inheriting a magnetic field direction from the erstwhile geomagnetic field. Repeated reversals of that field are recorded symmetrically either side of the ocean-spreading axis as new crust is relentlessly added, a few centimeters per year, at the axis itself. While people's interest in mineral resources of the deep ocean is still limited, understanding the previous locations of the continents, particularly during the past 200 Ma for which ocean floor can still be found, is central to our understanding of geological processes in this period. The sedimentary rocks laid down on the passive continental margins now separated by "new" oceans host a great deal of the world's hydrocarbon reserves.

Ocean crust is eventually recycled into the Earth's mantle via subduction zones with the result that ocean crust *in situ* older than about 200 Ma is no longer to be found. Evidence of the earlier 95% of geological history is therefore confined to the continents. Here a great deal of geological complexity is revealed (Figure M3/Plate 7d; Zonenshain *et al*., 1991), reflecting repeated orogenesis (mountain building) and metamorphism since the time of the oldest known rocks, dating from the Archean. The patterns of repeated continental collisions and separations evident from more recent geology can be extrapolated into this past. However, poor rock exposure in most of the oldest, worn-down areas of the world (Precambrian shields) hampers their geological exploration. Aeromagnetic surveys assist markedly here, though understanding at the scale of whole continents often necessitates maps extending across many national frontiers, as well as across oceans where present continents were formally juxtaposed.

What holds for investigations into geology and resources over regions or areas quite locally (say, scale 1:250 000, a scale typical for geological reconnaissance) also holds for national compilations of larger countries (say scale 1:1 000 000) and at continental scale (1:5 million or 1:10 million). Magnetic anomaly mapping is arguably even more useful at such scales since it represents unequivocal physical data coverage, part of a nation's (or a continent's) geoscience data-infrastructure. The view it offers to the geological foundations of continents is therefore of prime importance to improved understanding of global geology. Repeated cycles of continental collision, coalescence, and rifting-apart have led to the present-day arrangement of the igneous and metamorphic rocks of the continental crust, as revealed in continental scale images of magnetic anomalies, such as Australia (Figure M4/Plate 7a; Milligan and Tarlowski, 1999).

Continental and global compilations of magnetic anomalies

(Aero-)magnetic surveys usually record only the total strength of the magnetic field at any given point, thus avoiding the need for any precision orientation of the magnetometer. After suitable corrections have been applied for temporal field variations during the weeks or months of a survey, subtraction of the long wavelength (more than several hundred kilometers) components of the field leaves local anomalous values that should be comparable from one survey to another. Thus it is possible—though, in practice, challenging—to link many hundreds of surveys together to make national or continental scale coverages (Tarlowski *et al*., 1996; Fairhead *et al*., 1997).

The long wavelength components of magnetic anomalies must be defined in an internationally coherent way, for which purpose the *IGRF* (*q.v.*) was designed and is periodically updated by IAGA. Anomaly definitions still vary greatly between surveys for various

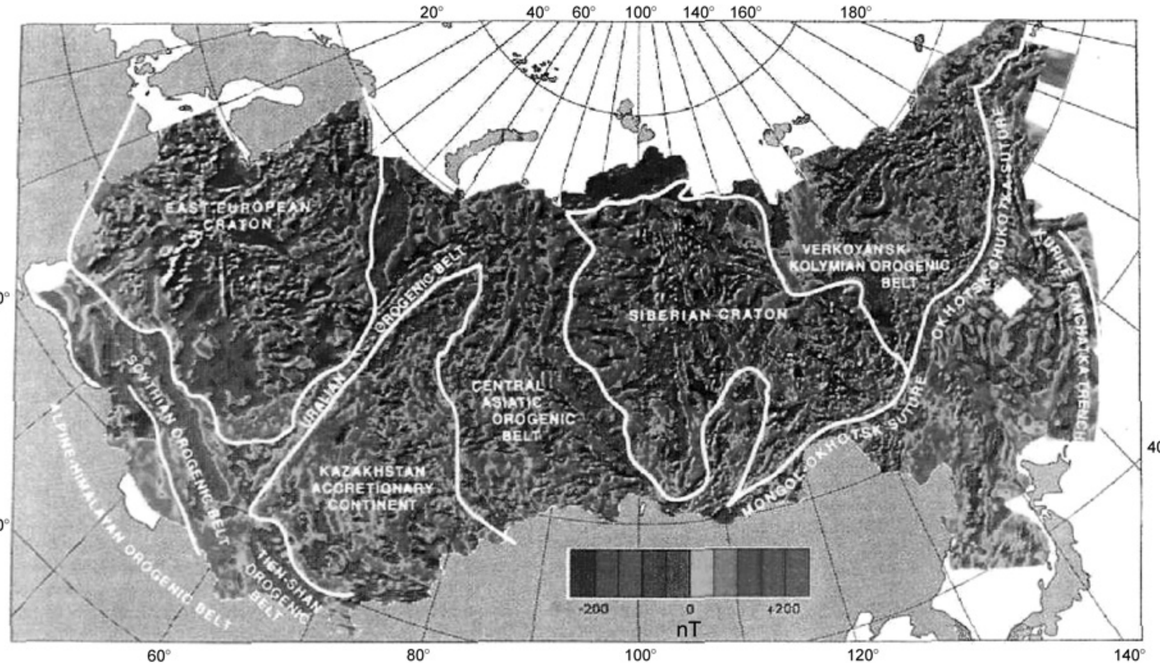

Figure M3/Plate 7d Magnetic anomaly patterns recorded in aeromagnetic surveys over the former Soviet Union with the outlines of some major tectonic domains added. Russia. (From Zonenshain *et al*., 1991, courtesy of the American Geophysical Union).

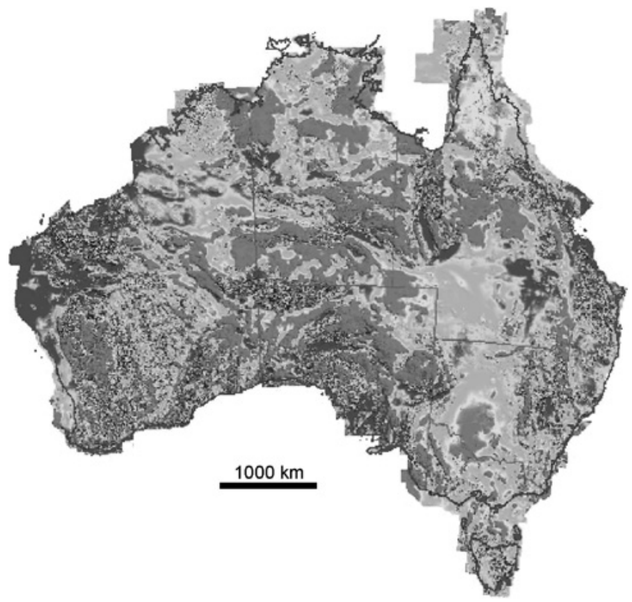

Figure M4/Plate 7a *Magnetic Anomaly Map of Australia*, 3rd edn (Milligan and Tarlowski, 1999). (Courtesy of Geoscience Australia).

reasons and, in addition to consistent use of the IGRF, national and international cooperation is required to link and level together the variety of magnetic surveys to a common level. Magnetic anomaly data exist over most of the Earth's surface, mostly a patchwork of airborne surveys on land and marine traverses at sea (Reeves *et al*., 1998). In 2003, IAGA appointed a Task Group to oversee the compilation of such a global magnetic anomaly map (www.ngdc.noaa.gov/IAGA/vmod/TaskGroupWDMAM-04July12s.pdf) that endeavors to complete its work in time for the 2007 IUGG General Assembly.

Magnetic mineralogy

The physical link between geological formations and their magnetic anomalies is the magnetic properties of rocks (Clark and Emerson, 1999). These are often measured, for example, in connection with Ocean Drilling Program (ODP) analyses, paleomagnetic studies, geological mapping, and mineral prospecting. ODP data provide local information at widespread oceanic locations giving a global coverage. International paleomagnetic databases represent the remanent magnetic properties acquired in the geological past (see *Paleomagnetism*). Magnetomineralogical studies reveal that by far the most common magnetic source mineral of Precambrian shield areas is magnetite. So far, the largest national campaign of magnetic property mapping was that carried out in the former Soviet Union. The results were presented as analog maps. Most of the world's resource of digital petrophysical data for the continents was collected in the Fennoscandian Shield by the Nordic countries (Korhonen *et al*., 2002a,b). Even so, these data represent only a small part of the crystalline basement of NW Europe. More, similar data sets are required if we are to understand how well this information represents crustal rocks more globally.

The results from Fennoscandia show that, when plotted on a diagram of induced magnetization against density (Figure M5a) the samples form two populations, A and B. Population A represents the paramagnetic range of susceptibilities defined by Curie's law. Compositional variation of Fe- and Mn-oxides correlates with density, the denser, more basic (mafic) rock lithologies being more magnetic than acid (silicic) ones by up to an order of magnitude. This population is only capable of causing anomalies less than about 25 nT, however. A second population of rocks (B), mostly acid in chemistry, represents the ferrimagnetic range of susceptibilities, mainly due to variations in the abundance and grain size of magnetite. This population is two

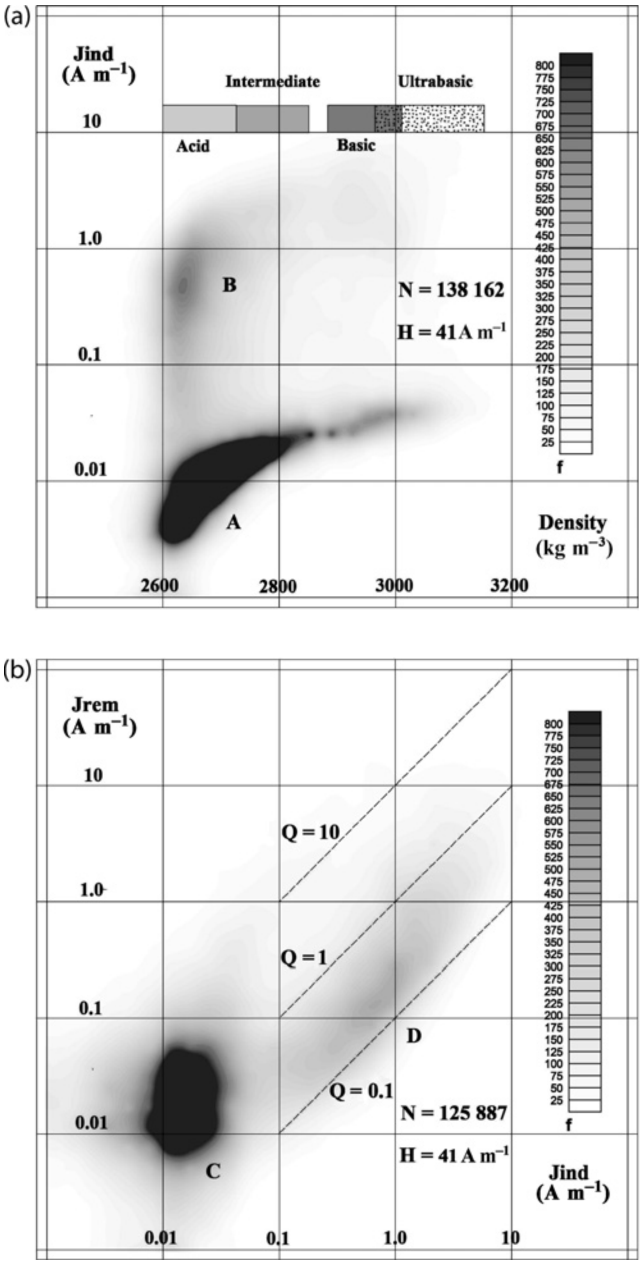

Figure M5 (a) Bulk density and induced magnetization in the Fennoscandian Shield (redrawn from Korhonen *et al.* 2002a). The lower population (A) contains the majority of rock samples, and represents the paramagnetic range of susceptibilities defined by Curie's law. A second population of rocks (B), mostly acid in chemistry, represents the ferrimagnetic range of susceptibilities, due mainly to variations in the abundance and grain size of magnetite. This population is two orders of magnitude more magnetic than the average of the first population (A). (b) Induced and remanent magnetization in the Fennoscandian Shield (redrawn from Korhonen *et al.*, 2002b). For the relatively few rock samples (D) that depart from a low level of magnetization (C), the Q-ratio is mostly less than 1.0, indicating the predominance of induced magnetization over remanent. A few exceptions are, however, highly magnetic. (Courtesy of Geological Surveys of Finland, Norway, and Sweden and the Ministry of Natural Resources of the Russian Federation).

orders of magnitude more magnetic than the average of the first population (A). Population B rocks represent most sources of local, induced magnetic anomalies. Average susceptibilities vary typically from 0.04 to 0.02 SI units for these ferrimagnetic geological formations, but much variation is found from one formation to another.

Another important parameter is the relative proportion of ferrimagnetic (population B) rocks to the effectively "nonmagnetic" paramagnetic (population A) rocks in any given area. For example, it is only a few percent in the magnetic "low" of central Fennoscandia but almost 100% in the northern Fennoscandian "high." Overall in Fennoscandia the average value is about 25%. In oceanic areas, by contrast, it approaches 100%.

Spatial contrasts in magnetic rock properties that give rise to the local magnetic anomalies encountered in mineral exploration are attributable to such factors as (a) the aforementioned bimodal nature of magnetic mineralogy (populations A and B), (b) the effects of magnetic mineralogy and grain size, (c) the history of magnetization and demagnetization, and (d) the variation between induced and remanent magnetization. These are related in turn to geological causes such as initial rock lithology, chemical composition, oxygen fugacity, and metamorphic history.

The ratio of remanent to induced magnetization varies typically from 0.1 to 20, corresponding to rocks containing coarse-grained fresh magnetite (most susceptible to induced magnetization) via altered and fine-grained magnetites to pyrrhotite (with a very stable remanent magnetization). Figure M5b shows the results for induced and remanent magnetization from the Fennoscandian Shield. For the relatively few rock samples (population D) that depart from a low level of magnetization (population C), the *Q*-ratio is mostly less than 1.0, indicating the predominance of induced magnetization over remanent as a source of magnetic anomalies. A few exceptions are, however, highly magnetic (above 1.0 A m^{-1}). For increasingly large source bodies, variations in the direction of all local remanent magnetizations cause the net remanent magnetization to sum up more slowly than the consistently oriented induced magnetization. Hence the effects of remanent magnetization are relatively more important in magnetic anomalies measured close to source bodies (such as on the ground) than farther away (from an aircraft or satellite). This effect is even more noticeable at magnetizations above 1 A m^{-1}, where *Q*-values tend to approach or even exceed 1.0 (Figure M5b).

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Cross-references

Aeromagnetic Surveying
IGRF, International Geomagnetic Reference Field
Paleomagnetism
Vine–Matthews–Morley Hypothesis

MAGNETIC ANOMALIES, LONG WAVELENGTH

Long-wavelength anomalies are static or slowly varying features of the geomagnetic field, and originate largely within the lithosphere. These anomalies stand in contrast to the rapidly time varying features characteristic of even longer wavelengths, which originate within the outer core. An inflection point, or change of slope, in the geomagnetic power spectrum (Figure M6) can be seen at degree 13 and is a manifestation of the relatively sharp transition from core-dominated processes to lithospheric-dominated processes. Long-wavelength anomalies (Figure M7a/Plate 5c) are most easily recognized from near-Earth satellites at altitudes of 350–750 km, and these altitudes define the shortest wavelengths traditionally associated with such geomagnetic features. The lithospheric origin of these features was firmly established by comparison with the marine magnetic record of seafloor spreading in the North Atlantic (LaBrecque and Raymond, 1985). Virtually identical features have now been recognized in satellite magnetic field records from POGO (1967–1971), Magsat (1979–1980), Ørsted (1999–), and CHAMP (2000–). Long-wavelength anomalies were first recognized by Cain and coworkers in about 1970 on the basis of total field residuals of POGO data.

Although electrical conductivity contrasts (Grammatica and Tarits, 2002) and motional induction of oceanic currents (Vivier *et al*., 2004) can produce quasistatic long-wavelength anomalies, the largest contributors to long-wavelength anomalies are induced (M_i) and remanent (M_r) magnetization in the Earth's crust. Contributions from the uppermost mantle may also be of importance, at depths where temperatures do not exceed the Curie temperature (T_c) of the relevant magnetic mineral. The earth's main field (H) is the inducing magnetic field responsible for induced magnetization of lithospheric materials. $M_i = kH$ expresses the linear relationship between the inducing field and induced magnetization, true for small changes in the inducing field. k is the volume magnetic susceptibility, treated here as a dimensionless scalar quantity, and reflects the ease with which a material is magnetized. If M does not return to zero in the absence of H, the resulting magnetic field is said to be remanent or permanent. Thus $M = M_r + M_i$, and the relative strength of the two contributions is referred to as the Koenigsberger ratio or $Q = M_r/M_i$.

Inversions of long-wavelength anomaly observations into lithospheric source functions, for example magnetic crustal thickness

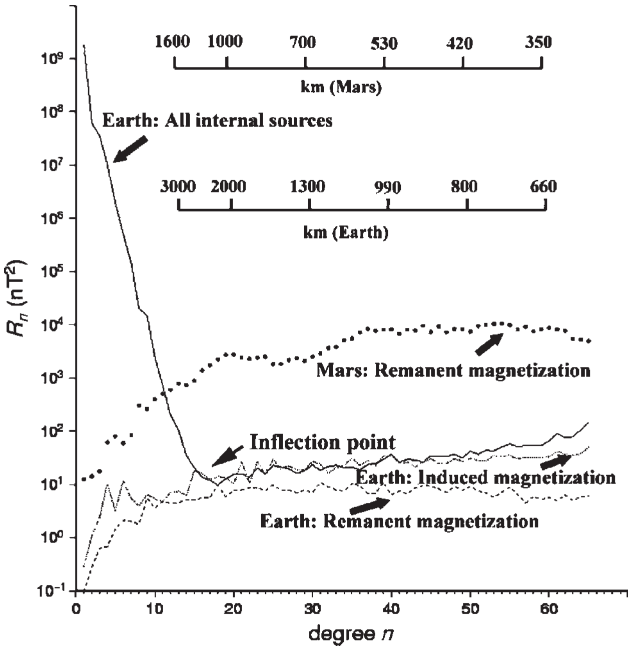

Figure M6 Comparison of the Lowes–Mauersberger (R_n) spectra at the surface of the Earth and Mars for a variety of internal fields. The inflection point in the terrestrial power spectra represents the sharp transition from core processes at low n to lithospheric processes at higher n. R_n is the mean square amplitude of the magnetic field over a sphere produced by harmonics of degree n. The terrestrial spectrum of all internal sources comes from Sabaka *et al*. (2004), the Martian remanent spectrum is derived from Langlais *et al*. (2004), the terrestrial induced spectrum is derived from Fox Maule *et al*. (2005), and the terrestrial remanent magnetization spectrum (of the oceans, and hence a minimum value) was derived from Dyment and Arkani-Hamed (1998).

(Figure M7b/Plate 5d) are subject to many caveats. Simple solutions are preferred, which also agree with other independently determined lithospheric properties. Specific caveats with respect to inversions of these magnetic field observations are that (1) direct inversion, in the absence of priors, can uniquely determine only an integrated magnetization contrast, (2) a remarkably diverse assemblage of magnetic annihilators (Maus and Haak, 2003) exist, which produce vanishingly small magnetic fields above the surface, and (3) the longest wavelength lithospheric magnetic signals are obscured by overlap with the core and it is formally impossible to separate them.

Unresolved research questions include (1) the continuing difficulty of signal separation, especially with respect to external fields (Sabaka *et al*., 2004), and the particular problem of resolving north–south features from polar-orbiting satellites, (2) the relative importance of magnetic crustal thickness variations and magnetic susceptibility variations in producing long-wavelength anomalies, (3) the relative proportions of induced and remanent magnetization in the continents and oceans, (4) the mismatch between the observed long-wavelength fields at satellite altitude, and surface fields upward continued to satellite altitude, (5) the separation of long-wavelength anomalies caused by motional induction of large-scale ocean currents, (6) the isolation and relative importance of shorter wavelength anomalies (between 660 and 100 km wavelength), and finally (7) the origin of the order of magnitude difference between the observed lithospheric magnetic fields of the Earth and Mars.

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