# GEOMAGNETISM AND THE EXPLORATION OF GLOBAL GEOLOGY

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It is a testament to the ingenuity of scientists that the mere existence of a geomagnetic field has led to so much insight into four billion years of earth history. At or near the earth's surface, a small part of the geomagnetic field, usually no more than about 1 per cent, is attributable to rocks of the earth's crust, down to the depth of the Curie point isotherm – perhaps 40 km on land and 10 km at sea. The magnetization of any one element of rock may be considered as either induced or remanent, the former being in the direction of the present day field and the latter in the direction of the ambient field when the rock acquired its magnetisation. In practice, both effects may be present. The study of directions of remanent magnetization in rocks – paleomagnetism – was a significant contributor to the realization that the earth's crust is a dynamic rather than a static system. As a result of geomagnetic reversals and the relentless movements of the continents, the component of remanent magnetisation can, in principle, be in any direction and is demonstrably long-lived, even over geological time. Experimental studies show that induced magnetisation tends to predominate in the majority of rock specimens, while about 20 per cent of samples show predominantly remanent magetisation.

Rocks with significant magnetization are mostly igneous or metamorphic rocks – 'hard' rocks – while the sediments, weathering products, soils and overburden nearer the surface, are effectively non-magnetic. Patterns of magnetic anomalies or departures of the observed magnetic field from a standard global field model therefore reflect the lithology and structures of the bedrock even where, as in most places on earth, it is not exposed for direct inspection by the field geologist. The magnetic susceptibility of rocks tends to be bimodal with peaks separated by 2-3 orders of magnitude. Lithological boundaries in the rock body are therefore very often also magnetic property boundaries. This makes magnetic anomaly mapping an excellent tool in geological exploration that has been exploited since magnetometers first became portable instruments.

By measuring only the total strength (scalar magnitude) of the geomagnetic field it was possible to make anomaly measurements from an aircraft without solving technically difficult problems of directional reference and this discipline has evolved for more than 60 years. Instrumental and operational refinements over this period mean that variations as small as 0.2 nT are now recorded reliably and with suitable survey design (line spacing, sample spacing) the results can be imaged at the scale of a 50 m pixel, less than the wavelength of anomalies from even the shallowest sources. At ground speeds of 250 km per hour, large areas of territory can be covered at low unit cost. In Africa, where the geology is generally the least well explored, whole countries have be mapped in a few years at a cost of a few tens of millions of dollars – a mere fraction of the cost of traditional field geology and the coverage is continuous, not limited to the often isolated areas of outcrop to be found in the field. This has put aeromagnetic surveying in the forefront of geological reconnaissance, ahead of the more detailed and expensive survey methods employed for the detection of mineral and hydrocarbon resources which can, as a result, then be employed more selectively.

Resource exploration is still largely confined to the continents and the continental shelves and slopes. The remaining 70 per cent of our planet – the deep ocean – has a distinctly different geological history. Early oceanographic cruises with magnetometers (1950s and 60s) noted the symmetrical disposition of magnetic anomalies, mirror-imaged about the mid-ocean ridges that were already clear as topographic features. In the 1960s it became evident that new ocean crust was being continually created at these ridges and, as the two halves of the ocean were being separated by ever-younger crust, the sequence of geomagnetic reversals was being recorded in the remanent magnetization of the crust generated, mirror-imaged across the central ridge.

Elsewhere, primarily in subduction zones, oceanic crust is being consumed back into the mantle, the oldest oceanic crust currently still evident on earth being only about 200 million years old – no more than 5 per cent of the age of the oldest known continental rocks. While this principle could be established from limited magnetic anomaly data from early oceanographic cruises, thorough magnetic surveying of the oceans is still far from complete on account of cost, the enormous areas to cover and limited commercial interest. In the oceans of the southern hemisphere, areas the size of countries have yet to be crossed by a single marine magnetic profile. If a reliable model of ocean growth is available, however, the expected pattern of anomalies over large areas can be predicted and calibrated against the few existing traverses. In the North Atlantic, by contrast, the coverage of real data is reasonably complete.

The resolution attainable by magnetic anomaly patterns is related, through potential field theory, to the vertical distance between source and magnetometer. A survey aircraft can fly with safety as close as 60-80 m above terrain with low relief. A shipborne magnetometer is about 4 km above the ocean bottom. Even the lowest orbiting satellite magnetometer is still 350 km above the earth, affording resolution only four orders of magnitude less than an airborne survey. Such a satellite (in polar orbit) has the distinct advantage, however, of covering the whole earth, land and sea, uniformly. As with airborne and marine magnetic surveying, elimination of temporal variations in the field is challenging. The CHAMP satellite has achieved robust global coverage in the last 10 years largely through the repetition of orbits and 'stacking' those traverses collected at magnetically quiet times. The resulting global map of anomalies attributable to the lithosphere is reliable to a fractional nT accuracy and reveals local anomalies up to 30 nT in amplitude, even at satellite altitude.

Back at the scale of geological mapping of the continents (typically 1:250 000), individual airborne surveys usually cover areas of dimension no more than a few hundred km square. Large countries such as Canada and Australia that used aeromagnetic coverage as a strategic part of their geological reconnaissance in the second half of the twentieth century set about making a patchwork of individual surveys to build (eventually) a national coverage. While individual surveys lasting a few months may each be organised so as to eliminate short period temporal variations (e.g. diurnal) from the observations, a programme lasting decades needs also to eliminate secular variation from its results so that adjacent survey blocks may be stitched together objectively. It is a singular success for IAGA that the International Geomagnetic Reference Field (IGRF) has been adopted almost universally by magnetic anomaly surveyors to achieve this. The limited size of blocks, and any arbitrary warps still needed to make them join perfectly, means that the patchwork of data is still lacking real information at wavelengths of a few hundred km – somewhat short of the highest spatial frequency observed by satellite.

For many years IAGA was also active in promoting the patch-working of national magnetic anomaly maps into a global coverage. At first this unfolded as a series of continental scale coverages – North America, Australia, Africa, USSR, etc – produced mostly during the 1990s. Assisted by the advent of the CHAMP coverage and the ‘comprehensive’ geomagnetic field model in the past decade, to say nothing of new software and hardware capacity, the first global coverage map was realized in 2007 (IUGG Perugia) – a testimony to perseverance, new technology and, not least, diplomacy. Data was collected to populate a grid of about 5 km across the whole globe, a resolution that was considered a suitable compromise between the detail that should be visible on such a map and the confidentially still attached to data of a higher resolution by many national administrations. Fortunately, the Commission for the Geological Map of the World (CGMW) has protocols for the supply of outline data for the geological world map that could be invoked in support of these efforts.

Some of the geological and tectonic features evident in the world magnetic anomaly map will be illustrated in the presentation. This will be set in the context of the dynamics of continental movements and the history of the dispersal of the super-continents that existed in early Phanerozoic times to give the configuration of continents on the earth’s surface familiar today. Most recently, web-based techonology has been invoked to make geological and geophysical data more accessible generally through initiatives like Dapple and OneGeology. In Africa – 22 per cent of the world’s land area – initiatives like GIRAF and eGY-Africa have been launched to help accelerate the adoption of ICT in the geoscience community there.