

## Past as Prologue: Swarm and the Decade of Geopotential Field Research

The Decade of Geopotential Field Research, inaugurated in 1999 with the launch of the Danish satellite Ørsted on 23 February, was designed as an international effort to promote and coordinate a continuous monitoring of the geopotential (magnetic and gravity) field variability in the near-Earth environment. Combined with ground-based, marine, and airborne data, interpretation of the new data from the Decade has led to improvements in our understanding of the latest round of decay of the Earth's magnetic field that dates from about 1840, given us the first World Digital Magnetic Anomaly Map covering wavelengths from 10 to 2600 km, and potentially unmasked rapidly changing flows in the Earth's core-mantle boundary region. The data, and associated theory and modeling work, also suggest the existence of new processes with a satellite magnetic signature, amongst them oceanic tides, ionospheric pressure gradient currents and the magnetic signatures of plasma bubbles, and serpentinized mantle overlying subduction zones.

The CHAMP magnetic field satellite, sponsored by Germany and her international partners, continues monitoring the Earth's magnetic field today from altitudes below 330 km. Expected to reenter the atmosphere by the end of 2009, it will be succeeded in 2010 by ESA's Swarm mission, a novel constellation comprising three satellites under development by an international consortium. Two of the Swarm satellites will fly close together at lower altitudes, measuring the east-west gradient of the magnetic field, and one satellite will fly at a higher altitude. Swarm will improve upon its predecessors because it will carry identical, and improved, instrumentation to measure the vector and scalar magnetic fields, electric fields and plasma parameters, and the non-gravitational acceleration, all within a GPS-determined frame. The constellation's organization and evolution is designed to maximize the scientific return in the areas of core dynamics, lithospheric magnetization, and 3-D mantle conductivity. It will also benefit investigations of electric currents flowing in the magnetosphere and ionosphere, of relevance for quantifying the magnetic forcing of the upper atmosphere and for identifying the ocean circulation by its magnetic signature. The 2<sup>nd</sup> Swarm International Science Meeting, to be held at GFZ in Potsdam, Germany, from 24-26 June 2009, will provide the opportunity to present new scientific results from CHAMP and Ørsted, and discuss the upcoming Swarm mission.

Venus and Mars are often considered Earth's twins. But when it comes to Earth's magnetic field, it is to Mercury that we look first. Mercury is the only other terrestrial planet besides the Earth with a planet-wide intrinsic magnetic field. Two recent flybys of the Sun's innermost planet by NASA's MESSENGER spacecraft have revealed that the large-scale morphology of Mercury's internal magnetic field is similar to that of Earth, although Mercury's surface field is two orders of magnitude less than the Earth's. Dominantly dipolar and spin-aligned, the fields of both planets possess significant quadrupole moments, manifest as polar and equatorial magnetic "lows". In the case of Earth, the "low" is referred to as the South Atlantic anomaly (Fig. 1A), a region marked by a growing reverse flux patch at the underlying core surface.

The South Atlantic anomaly is an oval-shaped geographic region in the southern Atlantic Ocean east of Brazil. Because of the relatively weak magnetic field here at all altitudes, the Van Allen radiation belt descends to lower altitudes, and the associated increased radiation dose adversely affects satellites traveling through the region. This feature has existed since at least 1840, and is closely tied to the overall decrease of the strength of the Earth's dipole (5% per century) since that time (Fig 1B). Also closely related to this decay is the rapid motion of the north magnetic dip pole (where the field direction is vertical). Because the horizontal component of the magnetic field in the region of the north magnetic pole exhibits a very flat gradient in the direction of pole motion, small decreases in the field can cause significant displacements of the north magnetic pole.

Changes in the magnetic field occurring over a few months have been tentatively recognized as the signature of localized, rapidly changing flows in the Earth's core. Centered at 2003.5 and 2004.7 at the Earth's surface, these changes are seen over the Australasian and Southern African regions, respectively, and also have some expression in length-of-day variations. These changes are controversial because they imply accelerations 1-2 orders of magnitude faster than previously thought. Less controversial is the degree of improvement in our ability to describe core field variations. At the beginning of the Decade, secular variation could be resolved to spherical harmonic degree 11, whereas today models up to degree 15 are resolved. Associated with this improvement in the description of secular variation are improvements in the description of what is often referred to as the 'secular acceleration', the 2<sup>nd</sup> time derivative of the field of internal origin.

The Magnetic Anomaly Map of the World, published in 2007 by UNESCO, was the first global compilation of the wealth of magnetic anomaly information originating from the CHAMP satellite, aeromagnetic and sea-going surveys, supplemented by anomaly values derived from oceanic crustal ages. The measurement domain thus extends from the surface to satellite altitude. A new generation of the map is planned for 2011, and will include much new data from ocean-going surveys. In the interim, researchers are testing new methods of integrating marine survey data with model values derived from oceanic crustal ages. This integration is useful as a teaching tool, but sometimes leads to the mistaken impression that the oceans are completely surveyed, when in reality only a small fraction of the southern oceans are covered by marine magnetic surveys. The magnetic anomalies represented on the current map originate primarily in igneous and metamorphic rocks, in the Earth's crust, and locally, the uppermost mantle.

Complicating the isolation of the internal magnetic fields discussed above are a variety of magnetic fields from sources in Geospace, several of which have been recognized for the first time as a consequence of the high-resolution magnetometers, and the plasma instrument, flying on CHAMP. Examples include the magnetic fields associated with regions of dense plasmas or irregularities within the equatorial ionosphere (Fig 1C) and with gravity-driven electric currents in the ionosphere. Electron density anomalies are prominent north and south of the dip equator, especially after sunset. These enhancements lead to magnetic field changes of 1 part in  $10^4$ , which is why they were not previously recognized. The magnitude and scale-size of these features falls within the range of crustal anomalies, and earlier models of the crustal magnetic field

often contained these spurious features. These features can also cause artifacts in main field models, especially in high-degree secular variation and acceleration coefficients. Because the Swarm satellites will be at two different local times, external field effects, and corresponding induced effects, are more likely to be recognized and isolated. Extensive simulation studies have shown how satellites at multiple local times can be optimized to do the best job of separating internal, external and induced fields.

Newly recognized processes with magnetic signatures are not confined to external effects but include the oceanic lunar semidiurnal ( $M_2$ ) tide. The semidiurnal tide possesses a magnetic signature because seawater is an electrically conducting fluid. The flow of this fluid through the Earth's main magnetic field in turn generates magnetic fields, but does not affect the current flow to any significant degree. The tidal signature was easily recognized because of a clear  $M_2$  peak in the intensity spectra over the ocean data collected by CHAMP, in contrast to the land data where the peak was absent. Additionally, a global numerical prediction of these magnetic fields was in good agreement with CHAMP observations. Of more importance for climate modeling, the magnetic signal associated with oceanic currents should also be measurable by CHAMP, and Swarm. However, the spatial scale of these signals overlaps with those from the core and crust, and they have not yet been isolated.

The mantle is often considered to possess no remanent or induced magnetic signature, because of its mineralogy and elevated temperature. Recent work on subduction zones suggests that typical upper mantle rocks (peridotites) are often hydrated by release of water from the underlying, subducting oceanic plate (Fig. 1D). This hydration leads to the formation of highly magnetic serpentinite, and thermal models suggest that much of this mantle wedge is at temperatures where remanent and induced magnetism can still exist. Magnetic and gravity anomalies linked with subduction zones are commonly seen in satellite anomaly maps. In the Cascadian and Alaskan subduction zones, the depth of the sources of these long-wavelength anomalies has been estimated to be within the mantle. Because hydrated mantle responds differently to deformation than unhydrated mantle, and water release from the slab promotes brittle failure within the slab, models predict a causal connection between intraslab earthquakes and hydrated forearc mantle. Preliminary results suggest that this is true in some of the limited cases examined.

The discovery of new processes with satellite magnetic signatures is expected to continue apace with Swarm. In addition, by making it possible to access the detailed evolution of the field at the core surface over a significant time period, data assimilation procedures may be used to predict the future behavior of the Earth's magnetic field. Work has already begun using sequential assimilation, with promising results. Finally, the local time coverage of the Swarm satellites will significantly advance studies of the 3-D electrical conductivity of the mantle. Conductivity variations often correspond to large-scale variations in water content, and this approach may provide an alternative to seismic techniques for imaging subducted slabs within the mantle.

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<http://www.esa.int/esaLP/LPswarm.html>. For information from the European Space Agency on Swarm: the Report for Mission Selection SP-1279(6), science study reports, announcements of opportunity for data access and validation, and the 2<sup>nd</sup> Swarm International Science meeting from 24-26 June 2009 in Potsdam, Germany at GFZ. This meeting is open to all interested scientists and students, and there will be no registration fee.)

[http://op.gfz-potsdam.de/champ/index\\_CHAMP.html](http://op.gfz-potsdam.de/champ/index_CHAMP.html). The CHAMP home page, with links to data and mission-related pages.

<http://www.spacecenter.dk/data/magnetic-fields-models/magnetic-models>. Danish National Space Institute home page, including magnetic models.

<http://www.geomag.us/> NGDC geomagnetism web site for crustal and main field models, and updated versions of the World Magnetic Anomaly Map.

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NASA's web page on the Decade of Geopotential Field Research.

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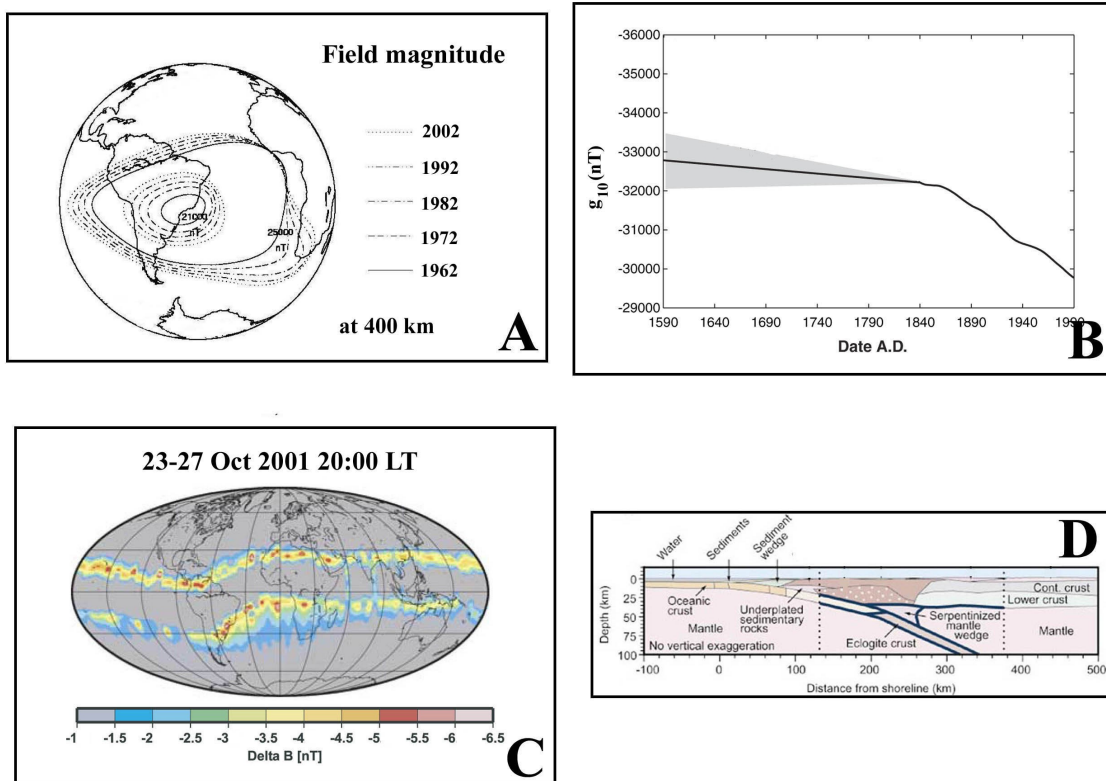


Figure 1: A) Change of the dimensions of the South Atlantic anomaly from 1962 to 2002. Adapted from Mandea and Purucker (2005), B) Decrease of the Earth's dipole ( $g_{10}$ , in nT) from 1590 to the present. Adapted from Gubbins et al., 2006, C) Magnetic effect of the Appleton anomaly, 23-27 Oct 2001, 20:00 LT, Lühr et al., 2003, D) Crust and upper mantle model of subduction zone and associated serpentinite wedge associated with magnetic and gravity anomalies. Adapted from Blakely et al., 2005.