Earth's magnetic field complex: U.S. National activities during the Decade of Geopotential Field Research

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SUMMARY

The US geomagnetism community is supported by NASA, NOAA, USGS, NSF, DOD, and US universities. During the Decade of Geopotential Field Research, inaugurated in 1999 with the launch of the Danish satellite Ørsted on a US rocket, the US community has been involved in satellite mission development and analysis, instrument development, model development, and in the discovery and understanding of new processes with satellite magnetic signatures.

The ESA Swarm mission has been a primary focus of the US community, with three US scientists on Swarm's Mission Advisory Group. Swarm will measure, for the first time, the E-W gradient of the magnetic field. One of us (T. Sabaka) is involved with the development of a Comprehensive inversion scheme as part of the SMART consortium. This effort is an outgrowth of the Comprehensive Model [1]. Swarm will also provide valuable observations for ionospheric specification and forecast. The geomagnetism group at NOAA (S. Maus, P. Alken and C. Manoj) has developed algorithms to estimate the strength of the eastward electric field (EEF). As the driver of the equatorial plasma fountain, the EEF is an important space weather parameter. ESA is considering the implementation of the EEF as a dedicated inversion chain in the Level-2 Facility.

In 2006, NASA launched a minisatellite magnetometer constellation mission (ST-5) to test technologies and software. The ST-5 constellation featured the first along-track gradient measurements. NASA has also initiated efforts to study geomagnetism mission concepts after Swarm. One of the ideas under consideration is the systematic measurement of radial field gradients.

Instrument development, and geomagnetic observatories, are also an integral part of the US effort. The past decade has seen significant advances in the development of a self-calibrating vector helium magnetometer, and in the automation of the US observatory network. Working in coordination with Intermagnet, the USGS Geomagnetism Program has made operational 1-second data acquisition at 13 of its magnetic observatories. The Program is also developing a real-time 1-minute and 1-hour Dst service.

Within the past decade, US scientists have been leaders in the development of models that describe the global geomagnetic environment, including comprehensive models (the CM series), maps of the lithospheric field from satellite (MF-series), near surface maps of the lithospheric field (WDMAM-series), models of the thickness of the magnetic crust, the IGRF and World Magnetic Model series, ionospheric models such as the EEJM1, JVDM1, and the IRI, and data assimilation-based models (MoSST-series) that predict the future state of the geomagneic field.

THE GRADIENT METHOD IN THE COMPREHENSIVE INVERSION (CI) APPROACH

Fig. 1 illustrates different aspects of the superior recovery of the high-order crustal field spherical harmonics obtained by explicit use of Swarm gradient data (blue) versus just field measurements.

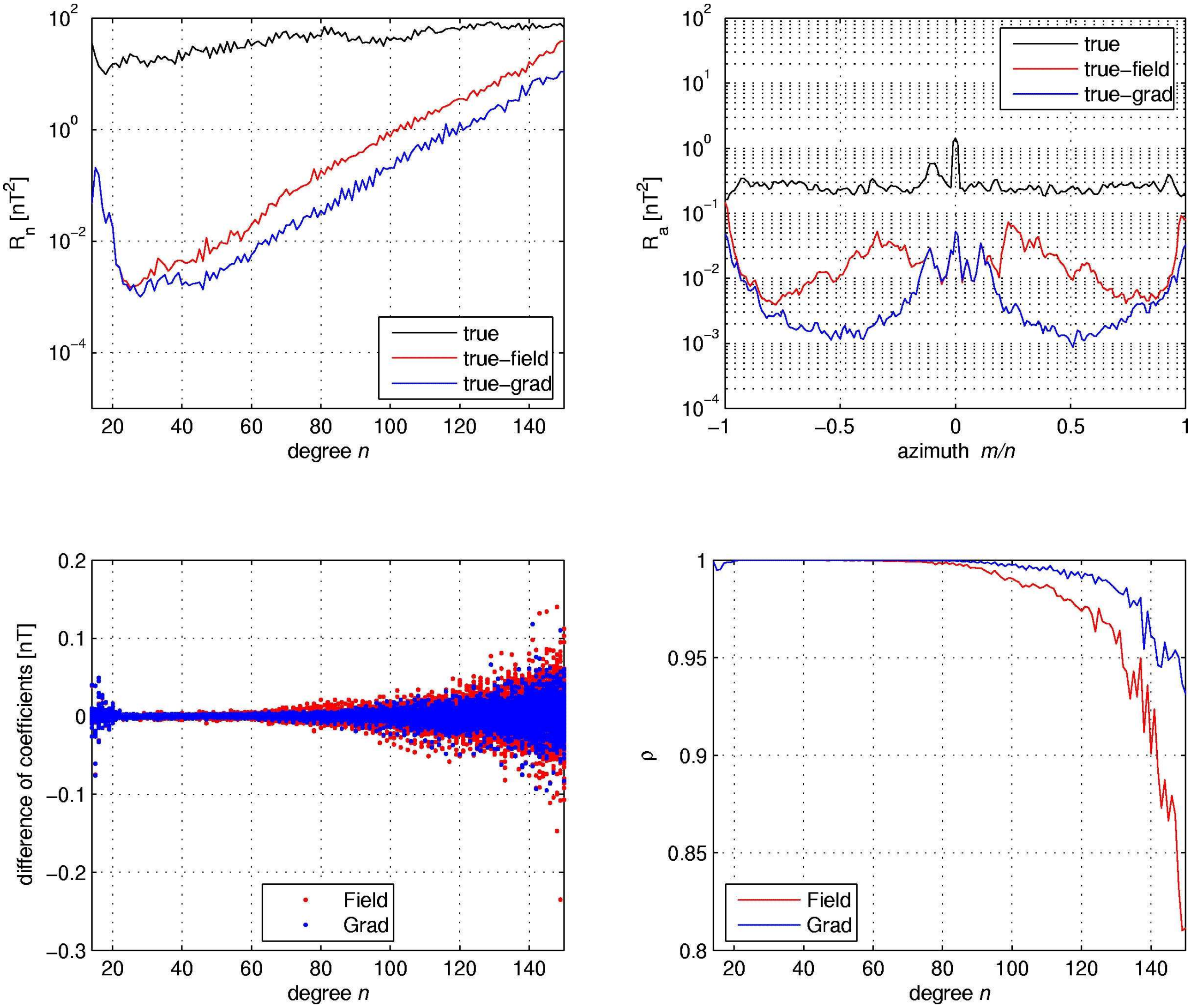

Fig. 1. The R_n spectra of the crustal signal and the error in its recovery (top left); the R_a (azimuthal) spectra of the crustal signal and the error in its recovery (top right); the actual coefficient errors (lower left); and the degree correlation of the recovered coefficients versus the true coefficients (lower right).

Fig. 2 shows that the intermediate wavelength gap existing between what typical satellite missions and near-surface surveys can see may at least be partially bridged by Swarm using a CI approach.

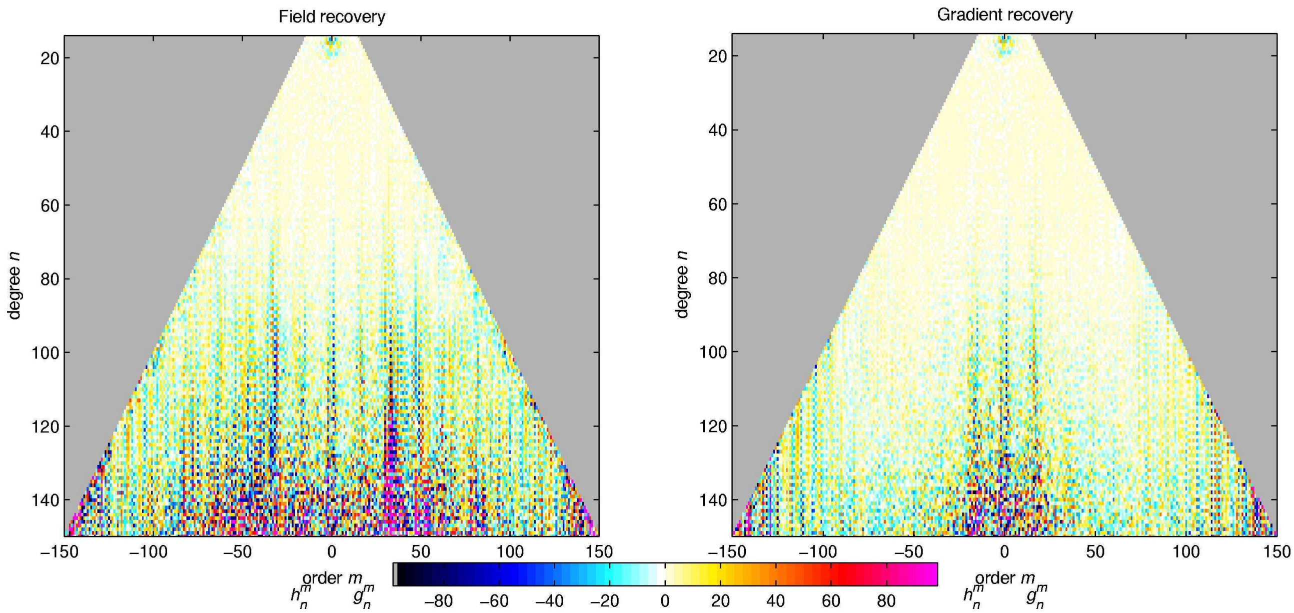

Fig.2. Degree-normalized relative error in crustal coefficients recovered from simulated Swarm magnetic field measurements (left) and their gradients (right) using a CI approach.

MAGNETIC INDEX DEVELOPMENT

The USGS Geomagnetism Program, working in cooperation with Intermagnet, has made available 1-second data at 13 of its magnetic observatories. The Program is also developing a real-time 1-hour Dst service. Fig. 3 illustrates magnetic index development using observatory data.

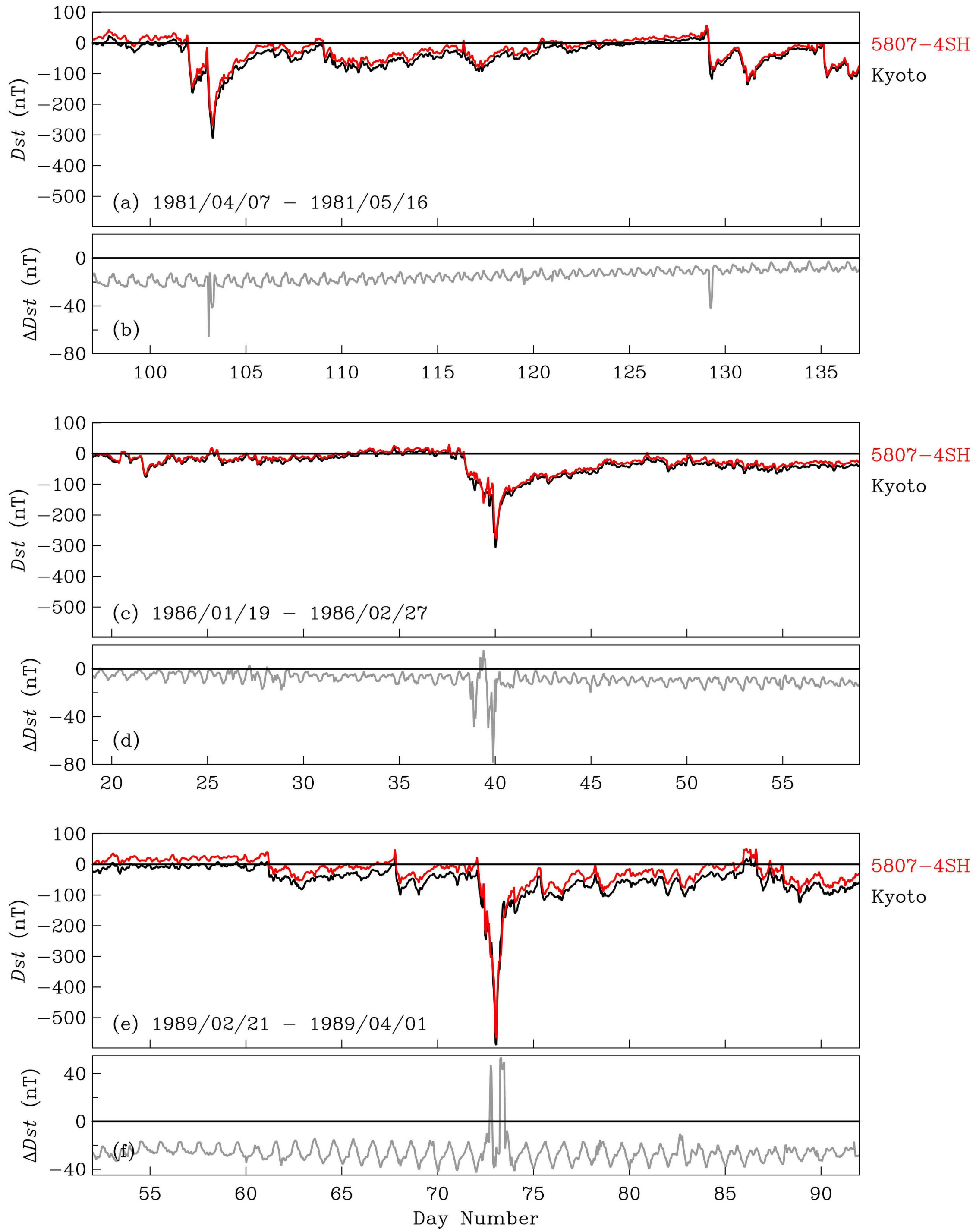

Fig. 3. Plot shows the difference between a new model of Dst (5807-4SH) compared to the traditional model [2]. The difference shows diurnal variation and abrupt problems with the traditional version of the index.

LITHOSPHERIC FIELD FROM SATELLITE

Fig. 4 shows the sixth generation lithospheric magnetic field model from CHAMP satellite magnetic measurements [3]. The model uses four years (2004-2007) of data from altitudes below 350 km to estimate the lithospheric magnetic field to degree 120, corresponding to 333 km wavelength resolution. This new model is the first satellite-based magnetic model to resolve the direction of oceanic magnetic lineations, revealing the age structure of the oceanic crust.

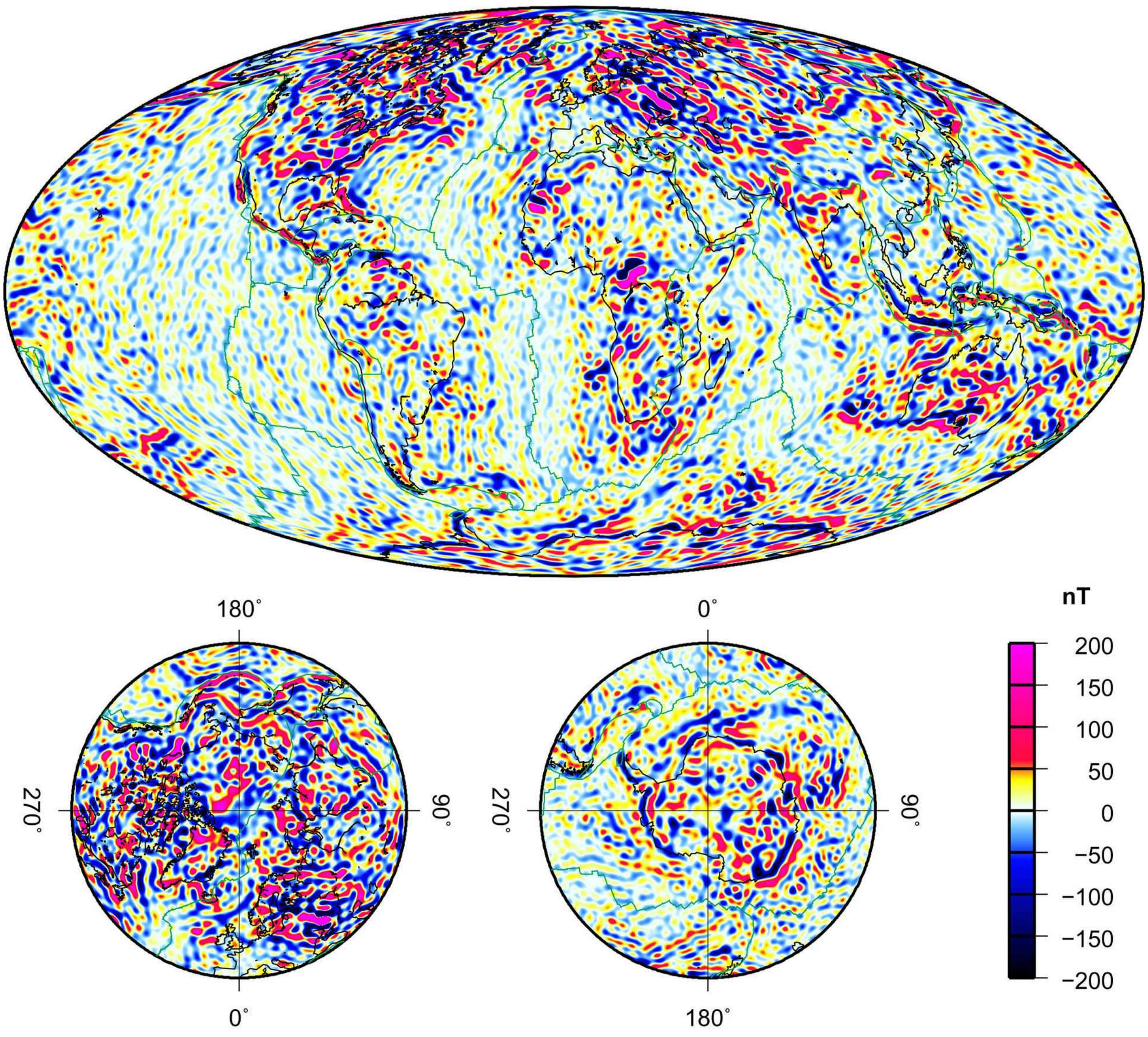

Fig. 4. The magnetic vertical component of the MF-6 model at geoid altitude.

MAGNETIC THICKNESS OF THE CRUST

The thickness of the continental magnetic crust can be related to tectonic and thermal processes. On the largest scale, diffuse plate boundary zones [4] within continents are seen to have thinner crust than continental regions away from these diffuse plate boundary zones zones. On intermediate scales, thickness variations are associated with crustal age variations, with rifting, and with enhanced heat flows. An estimate of the thickness of the terrestrial magnetic crust, and it's heat flow, can be made if certain conditions, and simplifying assumptions, can be made [5]. The technique requires a starting model to constrain the longest wavelengths because wavelengths in excess of S.H. Deg 15 (40000/15 ~ 2800 km) are dominated by core field processes [6].

The magnetic thickness map (Fig. 5) uses the global 3SMAC [7], supplemented by [8], compositional and thermal model of the crust and mantle as a starting point and is then modified in an iterative fashion with the satellite magnetic field map of the lithosphere (Fig. 4) until the magnetic field predicted by the model matches the observed magnetic field to within some specified error. The magnetic field is calculated from the starting model under the assumption of a constant magnetic susceptibility of 0.04 SI. A unique solution is obtained by assuming that induced magnetizations dominate over remanent magnetizations in continental crust, and that vertical thickness variations dominate over lateral susceptibility variations [9,10]. The solution shown was achieved after three iterations, and fits the observed magnetic field to better than 1 nT.

A comparison of the magnetic thickness map with the basement age map (Fig. 5) illustrates the utility of the map. The basement age map is based on surface and subsurface observations extended using seismic data. Seismic data covers much of the earth's surface, but significant gaps still exists (cf. Fig. 11 of [11]). Seismic data is spatially heterogenous, and of widely different quality. Magnetic data, on the other hand, are spatially homogenous away from the high latitude auroral zones. Seismic, and satellite magnetic models, have comparable resolutions of S.H. 120 (333 km wavelength) and so are amenable to direct comparison. Similarities between the two maps include the marked difference between the Eastern European craton and the younger Variscan terrane to the west. In general, magnetic crust with thicknesses of 16-27 km is associated with basement ages younger than Paleozoic. Exceptions are not uncommon, and one of the most striking is found in South Africa near the coast. Terranes with unrealistic thickness contrasts within a short distance, as in the southeast United States, often signal the presence of problems with the starting model. This thickness contrast dramatically decreases if the starting crustal thickness model has the boundary between thicker older crust, and younger thinner crust, moved to the Fall Line [9]. The maps differ in their assessment of the size of some of the older continental cores, for example the Omolon (3, Fig. 1) in eastern Siberia. The magnetic map suggests a much larger subsurface extent for this poorly surveyed province. Small older terranes set within younger ones often show up clearly, as for example the Colorado Plateau and the Tarim Basin. An alternative interpretation of the magnetic field observations would relate them to enhanced magnetic susceptibilities [12]. This in turn implies compositional differences. In the case of the Colorado Plateau, crustal compositions, as inferred from seismic velocities by [13], appear to be the same beneath the Colorado Plateau and the Basin and Range Province to the southwest, suggesting that magnetic thickness variations dominate over susceptibility variations in this region [10]. This undoubtedly varies from place to place, and we might expect that susceptibility variations would dominate over magnetic thickness variations in other places.

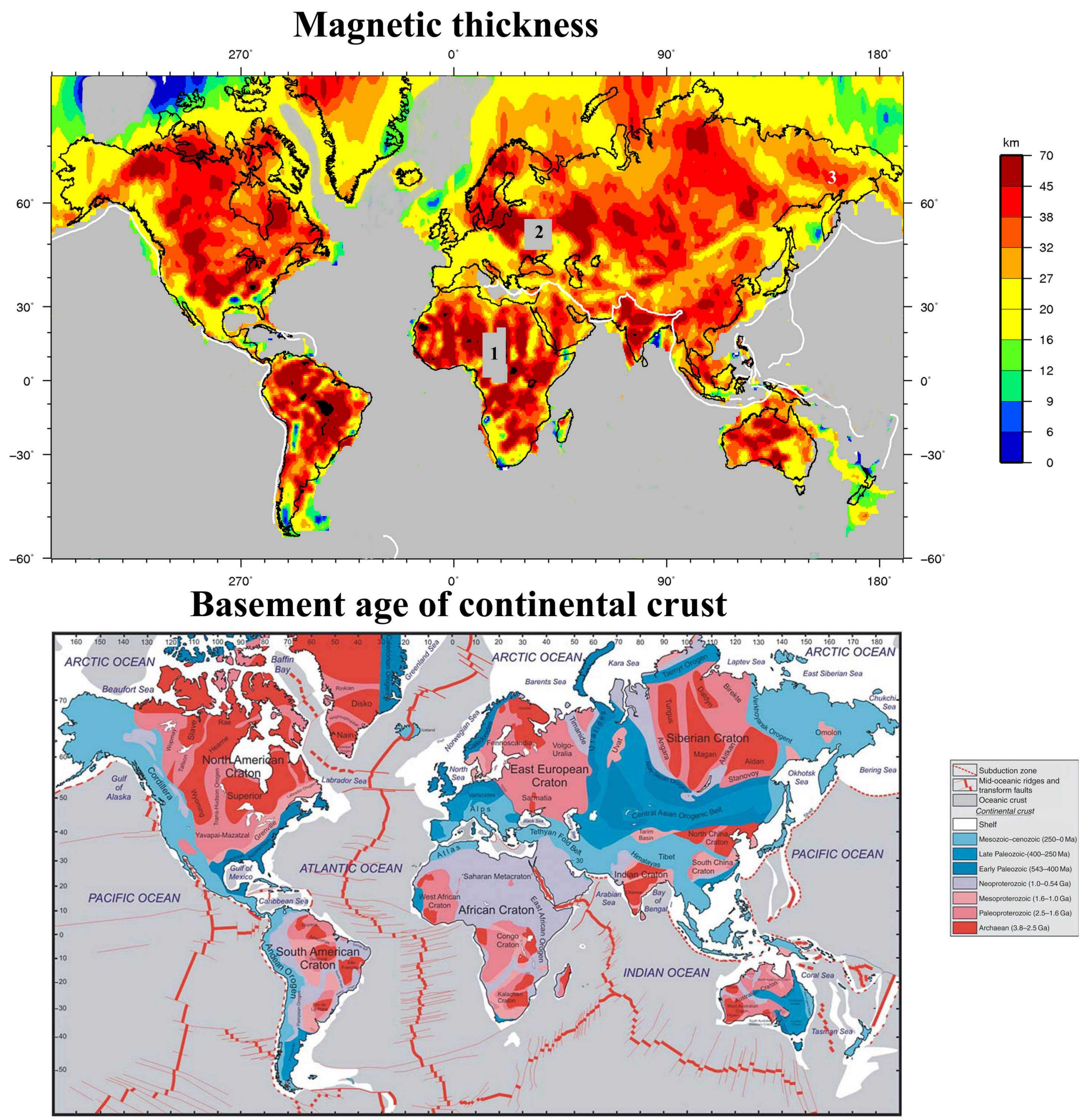

Fig. 5. Magnetic thickness of continental crust (updated from [10]) compared to basement age [11]. Basement age is determined from surface and subsurface measurements, and extrapolated under cover rocks using seismic measurements. Oceanic crust is masked on the magnetic thickness map because magnetizations are dominated there by remanent magnetizations. Also masked are two continental regions associated with the Bangui (1) and Kursk (2) anomalies, where remanent magnetizations, and/or enhanced magnetic susceptibilites, are known to dominate the magnetic signal. On the magnetic thickness map, 3 locates the Omolon terrane of Siberia.

CORE DYNAMICS MODEL

The MoSST core dynamics model (Fig. 6) has been used for geomagnetic data assimilation studies [14]. The extended system, the MoSST_DAS, combines both the dynamo model and the geomagnetic field models over the past 7000 years to predict geomagnetic secular variation. The current 5-year forecast accuracy at the Earth's surface is at least comparable to the IGRF prediction. But the MoSST_DAS can forecast the SV over 20 years.

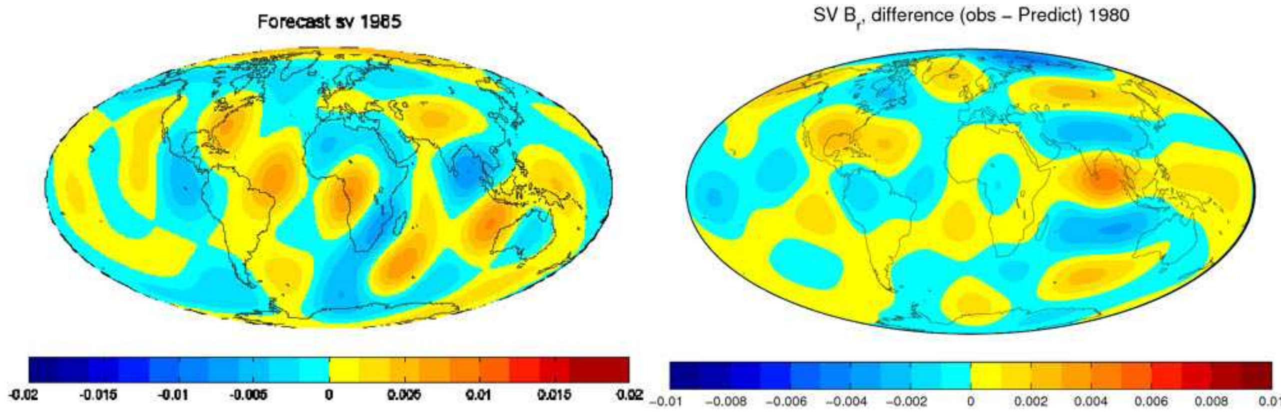

Fig. 6. A recent implementation of the MoSST core dynamics model.

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