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Interpretation of the lithospheric magnetic field

Michael E. Purucker[1] & David A. Clark[2]
[1]*Raytheon at Planetary Geodynamics Lab, Goddard Space Flight Center, Greenbelt, MD 20771 USA, michael.e.purucker@nasa.gov*
[2]*CSIRO Materials Science and Engineering, PO Box 218, Lindfield 2070, NSW Australia, david.clark@csiro.au*

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SUMMARY
We review some of the controversial and exciting interpretations of the magnetic field of the earth's lithosphere occurring in the four year period ending with the IAGA meeting in Sopron in 2009. This period corresponds to the end of the Decade of Geopotential Research, an international effort to promote and coordinate a continuous monitoring of geopotential field variability in the near-Earth environment. Among the products of the Decade has been the first edition of the Digital Magnetic Anomaly map of the world, the first global map of the magnetic field of the earth's lithosphere. In this article we review interpretations of the lithospheric magnetic field that bear on impacts, tectonics, resource exploration, and lower crustal processes.

Key words: Earth's magnetic field – Lithosphere

1 INTRODUCTION

The magnetic field originating in the earth's lithosphere is part of the earth's magnetic field complex, a dynamic system (*Friis-Christensen et al.* 2009) dominated by the interaction of the earth's magnetic field dynamo with that of the sun's. The lithospheric field is dominated by static (on a human time scale) contributions that typically represents less than 1% of the overall magnitude of the magnetic field complex, and originate from rocks in the crust and locally, the uppermost mantle. Interpretation of the lithospheric magnetic field is used in 1) structural geology and geologic mapping, and extrapolation of surface observations of composition and structure, 2) resource exploration and 3) plate tectonic reconstructions and geodynamics.

This article is designed as a review describing recent progress in interpreting the lithospheric magnetic field, and also includes some highlights from the 2009 IAGA meeting in Sopron, Hungary. Since IAGA meets every four years, we have designed this review to highlight progress in the four year period from 2005 through 2009. Several reviews of this and related subjects have appeared in this time. Review articles within books and encyclopedias have included those within the Encyclopedia of Geomagnetism and Paleomagnetism (*Gubbins and Herrero-Bervera* 2007) and the Treatise of Geophysics (*Schubert* 2007). The Encyclopedia included articles on the Crustal Magnetic Field (D. Ravat), Depth to Curie temperature (M. Rajaram), Magnetic anomalies for Geology and Resources (C. Reeves and J. Korhonen), Magnetic Anomalies, Long Wavelength (M. Purucker), Magnetic Anomalies, Marine (J. Heirtzler), and Magnetic Anomalies, modeling (J. Arkani-Hamed). The Treatise of Geophysics included articles on 'Crustal Magnetism' (*Purucker and Whaler* 2007), on the 'Source of Oceanic Magnetic anomalies and the geomagnetic polarity timescale' (*Gee and Kent* 2007) and on 'Plate Tectonics' (*Wessel and Müller* 2007). A series of workshops at the International Space Science Institute (Bern, Switzerland) in 2008 and 2009 on Planetary Magnetism (2008) and Terrestrial Magnetism (2009) has resulted in a review article on the earth's magnetic lithosphere (*Langlais et al.* in press). Reviews in journals in this time frame include those of *Nabighian et al.* (2005) and *Mandea and Purucker* (2005).

This review will highlight some of the controversial and exciting areas relating to the interpretation of the lithospheric magnetic field. We first discuss impact processes, and the magnetization and demagnetization processes involved. After briefly reviewing the magnetic record of terrestrial impact craters, we discuss recent quantitative and theoretical work in the area, both terrestrial and extra-terrestrial. We then go on to review some of the new interpretations at the Vredefort, Lonar, and Sudbury structures, with possible implications for the extraterrestrial record, especially at Mars. We next review some of the interpretations of magnetic data for tectonics, and structural geology and geologic mapping. Included within this section is recent work suggesting that parts of the uppermost mantle, especially in the vicinity of subduction zones, may be magnetic. If true, this may have important implications as a predictive tool for the spatial localization of large megathrust earthquakes and associated tsunamis. Following this is a review of interpretations for resource exploration, especially minerals, geothermal resources, and water. We also highlight some of the new developments in predictive mineral exploration models. This is followed by a review of the interpretation of lower crustal processes, motivated by exciting new work on ilmenite-hematite intergrowths by S. McEnroe and colleagues, and on the effects of pressure on magnetization by S. Gilder and colleagues.

2 IMPACTS

Impact cratering produces two classes of craters, the smaller 'simple' and the larger 'complex' (*Melosh* 1989). The two types can be distinguished based on their morphologies, and the transition between the two occurs at diameters of between 2 and 4 km on the Earth. Complex craters have central peaks, wall terraces, and a much smaller depth/diameter ratio than simple craters. They have undergone more collapse than the simple craters, and the transition diameter is inversely proportional to the local (planetary) gravitational acceleration. At even larger diameters the central peak evolves into a central peak ring. Multi-ring craters are a type of complex crater characterized by multiple, large inward-facing scarps, and are most clearly developed on the Moon. Unlike the transition from simple to complex, or from complex to peak ring, multi-ring craters do not seem to scale with the local gravitational acceleration. The other crater type worthy of mention on the Earth is the 'inverted sombrero' often seen in km-size terrestrial craters and characterized by a disturbed central zone surrounded by a shallow moat. Atmospheric interactions may contribute to this distinctive shape, as discussed by *Melosh* (1989).

The magnetic signature of impact craters can be complex, but in general two types of features are often apparent (*Pilkington and Hildebrand* 2003). Short-wavelength, relatively intense magnetic anomalies that occur near the center of the structure are the first of these types of features. Impact craters also disrupt the preexisting magnetic signature, and that disruption is the second feature that can sometimes be recognized (*Spray et al.* 2004). The relatively intense magnetic anomalies occuring within the crater can be attributed to 1) uplifted magnetic lithologies, often basement, 2) magnetized impact melt rocks or breccia, 3) hydrothermal activity, 4) shock remanent magnetization or demagnetization, or 5) some combination of the above. Although variable, it is often the case that terrestrial impact structures are characterized by broad magnetic lows (*Grieve and Pilkington* 1996). Two useful guides to the variability of the magnetic signature are provided by the works of *Ugalde et al.* (2005), and *Cowan and Cooper* (2005). Numerical modeling using 2-D hydrocodes predict the distribution of pressure and temperature from which inferences can be made about the final magnetization distribution (*Ugalde et al.* 2005). While very useful, this model does not take into account later hydrothermal processes, which can significantly alter the magnetization distribution, and are often the source of significant ore deposits (*Grant* 1984; *Clark* 1997, 1999).

Recent work on the utility of the magnetic method over terrestrial impacts includes the work of *Pilkington and Hildebrand* (2003) on estimating the size of the transient and disruption cavity. These sizes can be directly related to the energy release associated with impact. Weak lower and upper bounds are placed on these quantities by establishing the sizes of two parameters: 1) the size of the relatively intense features in the interior of the crater, and 2) the size of the region where magnetic features have been disrupted. The authors suggest, based on 19 complex terrestrial structures, that the collapsed disruption cavity is about half the size of the crater diameter.

Of critical importance to the interpretation of the magnetic signature is the coherence scale, or size of a region of coherent magnetization (*Lillis et al.* in press; *Carporzen et al.* 2005). The high-frequency and relatively intense magnetic features seen in the interior of impact basins, when upward-continued, often result in broad magnetic lows because adjacent coherently magnetized regions effectively cancel out. To complicate matters further, the coherence scale is often asymmetric. A simple example comes from the terrestrial oceans, where strongly magnetized sea-floor 'stripes' are often very narrow (kms) in a direction perpendicular to the spreading axis, but very wide (thousands of kms) in the direction parallel

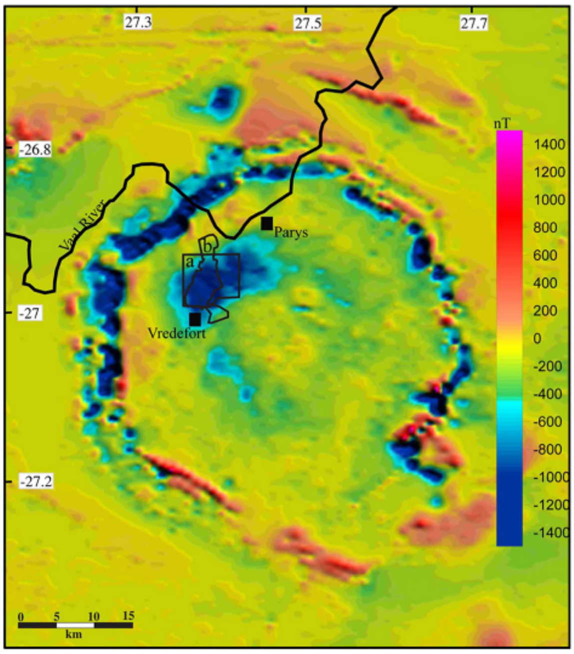

Figure 1. Aeromagnetic anomaly map of the Vrededort impact structure, from *Muundjua et al.* (2007).

to the spreading axis. When marine magnetic surveys of the oceans are upward-continued to satellite altitude they 'reveal' that oceanic magnetic fields are much weaker than continental magnetic fields (*Hinze et al.* 1991). The reality is more complex. Typical oceanic basalts are much more magnetic than typical continental granitic rocks. Another example, discussed in depth below, comes from the Vredefort impact crater (*Carporzen et al.* 2005) where aerial measurements of the magnetic field are lower than over surrounding regions, but surface magnetizations from within the crater are large and variable on the cm scale. Finally, it should be noted that there may not be a single coherence scale for a particular region. The coherence scale is dictated by the physical process or processes at work, and multiple processes may result in multiple coherence scales. In certain idealized cases, it is often useful to employ the concept of a matched filter (*Syberg* 1972; *Phillips* 1997) to estimate the depths of the principal magnetic sources, and to estimate crudely what a map of the magnetic fields from those sources would resemble. Certain parameters are independent of coherence scale. Ideal body theory helps to establish bounds on quantities such as the magnetization strength required to explain a magnetic field distribution (*Parker* 1991, 2003; *Purucker et al.* 2009b).

The Vredefort impact in South Africa, Earth's oldest and largest impact crater, has been the subject of several recent studies (*Carporzen et al.* 2005; *Muundjua et al.* 2007) and commentary (*Dunlop* 2005; *Reimold et al.* 2008; *Muundjua et al.* 2008). *Carporzen et al.* (2005) explain the elevated NRM intensities and Q-ratios typical of many of the exposed rocks at Vredefort as a consequence of short-lived plasmas produced during the impact. They find that paleomagnetic directions from the shocked but unmelted bedrock exposed to these hypothetical plasmas have directions which vary on scales of 10 cm or less. They explain the broad aeromagnetic low over the central portion of the impact (Figure 1) as a consequence of viewing this spatially incoherent magnetic signal from an altitude of 150 m. *Carporzen et al.* (2005) also find

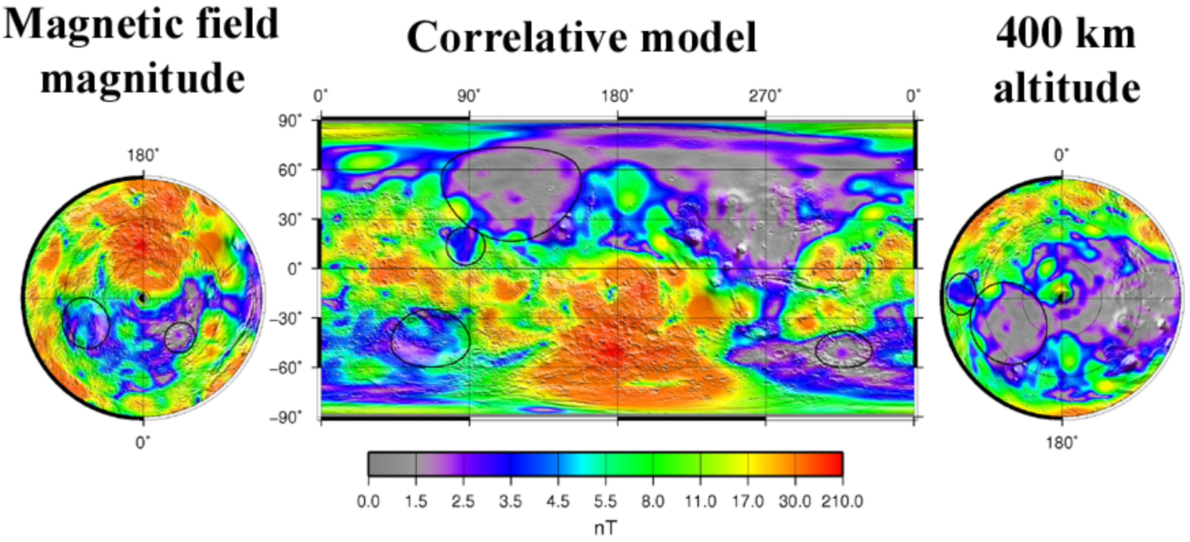

Figure 2. Magnetic anomaly map of Mars, adapted from *Lillis et al.* (in press). The circles represent the visually determined locations of the youngest large impact basins on Mars.

magnetic evidence for lightning in the surface rocks at Vredefort, another example of a plasma phenomenon. According to the authors, lightning can reproduce many, but not all, of the magnetic features of the surface rocks. As many as a quarter of their samples have been affected by lightning. *Graham* (1961) was the first to document the pervasive magnetic effects of lightning on surface rocks in South Africa. *Carporzen et al.* (2005) extrapolate their Vredefort results to the five youngest large impact basins on Mars (*Lillis et al.* in press) where very weak magnetic fields have been measured. They suggest that a much smaller coherence wavelength characterized these basins, and the measured magnetic fields do not require the absence of a planetary dynamo when they were created. The Martian observations had previously been taken as evidence (*Acuña et al.* 1999) that these basins had been demagnetized by the impact, and that the magnetic dynamo had ceased by this time. In addition, it has been observed that the 14 oldest large impact basins on Mars have significant magnetic fields associated with them (*Lillis et al.* 2008), suggestive of the presence of a magnetic dynamo at this time (Figure 2). To explain the difference in terms of coherence wavelength, and not in terms of the presence or absence of a magnetic dynamo, suggests that another process is at work, perhaps changes in the aqueous alteration enviroment *Lillis et al.* (in press).

The 1.85 Ga impact that produced the Sudbury structure struck a region of the southern Canadian shield characterized by late Archean and early Proterozoic faulting, and dike implacement. *Spray et al.* (2004) document the termination of the magnetic signature of the 2.47 Ga Matachewan dike swarm as it reaches Ring 2 of the impact structure, some 65 km from the center of the impact (Figure 3). Post impact magnetic dikes at 1.24 Ga are not terminated. The authors interpret these observation in terms of shock demagnetization, and further interpret Ring 2 to correspond to a shock isobar pressure of between 1-10 Gpa, depending on whether the magnetism of the dikes is dominated by induced or remanent magnetization.

A recent magnetic study of the Lonar impact structure (*Louzada et al.* 2008) document the magnetic processes active at this simple, young (<50 ka) crater formed in the Deccan basalts. In this 1.88 km diameter crater, shocked ejecta blocks exhibit a

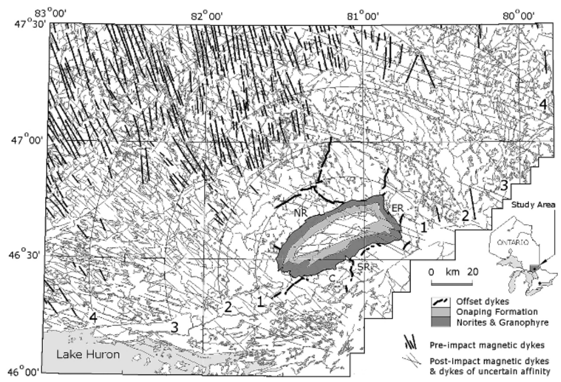

Figure 3. Distribution of magnetic dikes, and ring structures, from Spray et al.(2004).

slightly elevated coercivity. No evidence of shock remanent magnetization (*Gattacceca et al.* 2008), shock demagnetization, or transient, plasma-related processes, such as have been suggested around larger impact structure, were identified.

3 TECTONICS

Interpretations of magnetic field observations for tectonics, structural geology, and geologic mapping have a long history (*Reeves* 2007). One of its leading practioners, the US Geological Survey, has an ongoing program to evaluate seismic hazards in the Seattle (USA) region. The shallow earthquakes in this active forearc basin can be devastating, and paleoseismology studies indicate the presence of a M7+ earthquake some 1100 years ago on the Seattle fault, accompanied by a tsunami. Integrated magnetic studies (*Blakely et al.* 2002) have focused on recognizing these shallow faults, and tracing them in areas of poor exposure. Recent work in the Puget lowland (*Sherrod et al.* 2008) and to the west in the Olympic peninsula (*Blakely et al.* 2009) continues to unravel the complexities, and highlights the advances that can be made by an integrated geolog-

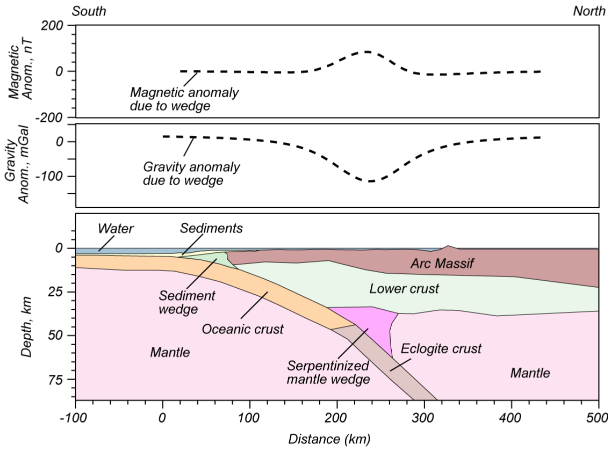

Figure 4. Highly simplified crust and upper mantle model of the Aleutian subduction zone and related serpentinite mantle wedge, showing predicted near-surface contributions of the wedge to magnetic and gravity anomalies.

ical and geophysical approach, which includes LIDAR, magnetics, gravity, and paleoseismological studies. For example, the Saddle Mountain deformation zone (*Blakely et al.* 2009) in the Olympic peninsula has been shown to have been active at approximately the same time as the Seattle fault, some 1100 years ago, suggesting a kinematic linkage between the two fault zones. The interpretation favored by the authors suggests that the Seattle and Saddle Mountain zones form the boundaries of the northward advancing Seattle uplift.

Recent work (*Blakely et al.* 2005) suggests that parts of the uppermost mantle, especially in the vicinity of subduction zones, may be magnetic. At critical depths of 40 to 50 km, subducting ocean crust goes through important metamorphic changes that release large amounts of water into overriding mantle rocks. Introduction of water into the mantle produces serpentinite (*Peacock et al.* 2002), a highly magnetic, low-density rock (Figure 4).

Thermal models (*Oleskevich et al.* 1999) indicate that, in many of the subduction zones of the world, this part of the mantle is cooler than the Curie temperature of magnetite, the most important magnetic mineral in serpentinite, and thus large volumes of mantle in subduction-margin settings should be magnetic. The World Digital Magnetic Anomaly Map (Figure 5) does indeed show large-amplitude magnetic signatures over many of the worlds subduction forearcs, including the Aleutian Islands, southern Alaska, Cascadia, Central America, and the Kurile Islands. Certainly these near-surface magnetic anomalies are caused in large part by upper crustal lithologies, and they have been recognized since the time of the U.S satellite MAGSAT (*Frey* 1982). However, detailed analysis of a number of these subduction zones (Cascadia, Nankai, southern Alaska, Aleutians, and Central America) indicates that the magnetic anomalies also include long-wavelength components originating from mantle depths. These mantle-depth anomalies are thought to be caused by highly magnetic serpentinite in the mantle above the subducting slab (*Blakely et al.* 2005; *Manea and Manea* 2008).

Not all subduction zones exhibit high-amplitude magnetic anomalies, reflecting geothermal and geochemical complexities. The World Digital Magnetic Anomaly Map (*Purucker* 2007) , which forms the background of several of the illustrations here, is in many respects a highly detailed artist's rendering of the magnetic signature of the earth's lithosphere. For example, the oceanic component of the map has been supplemented by models derived from the Digital Age map of the oceans, and the polarity reversal timescale. The details of the map, even in places where marine magnetic surveys have been conducted, are compromised by the inability to separate spatial from temporal variations, a consequence of the absence of base stations in marine magnetic surveys. Future generations of this map will result in a more objective and useful product.

The presence of serpentinite in subduction margins has two important links to large and giant earthquakes, and associated tsunamis. First, dewatering the subducting slab is thought to embrittle the slab, reactivate pre-existing faults and other structures, and produce within-slab earthquakes (*Kirby et al.* 1996; *Peacock et al.* 2002).Thus, we expect to see a spatial association between this type of earthquake and mantle magnetic anomalies (*Hyndman and Peacock* 2003; *Blakely et al.* 2005). Second, in cool subduction margins, the down-dip limit of megathrust earthquakes (M 8.0-9.6) is controlled by the slabs first encounter with serpentinized mantle (*Oleskevich et al.* 1999). Again, we expect to see a spatial association between these devastating earthquakes and mantle magnetic anomalies. For example, the devastating 2004 and 2009 Sumatra-Andaman earthquakes are spatially associated with long-wavelength magnetic anomalies and thus consistent with the predicted pattern. Long recurrence intervals on megathrust earthquakes make current seismic compilations an unreliable guide to the location of past earthquakes, although non-volcanic tremors can be used, at least in part.

The existence of serpentinized mantle is well demonstrated in a few subduction margins. At Cascadia, for example, anomalously low mantle velocities have been interpreted as evidence for serpentinization of the mantle wedge (*Bostock et al.* 2002; *Brocher et al.* 2003), and these low-velocity zones are located directly beneath static long-wavelength magnetic anomalies (*Blakely et al.* 2005). However, in many of the subduction zones of the world, including the Aleutian Islands (Figure 6), where a proposed magnetic survey (Serpent) would be conducted, seismic data appropriate for these studies are unavailable. If it can be demonstrated that long-wavelength magnetic anomalies are a reliable predictor of the presence of serpentinized mantle, then high-altitude magnetic surveys, such as the Serpent survey proposed to NASA by *Purucker et al.* (2009a) provide the promise of mapping hydrated mantle at subduction zones worldwide, thereby illuminating zones spatially and causally associated with both megathrust and within-slab earthquakes.

In the Antarctic, aeromagnetic surveys play a much larger role than elsewhere in deciphering tectonics because exposures of basement rocks are rare. The interpretation of a new survey over the Admiralty Block of the Transantarctic Mountains by *Ferraccioli et al.* (2009b) adds to our understanding of the relationships there between Cenozoic magmatism, faulting, and rifting. Fault zones here are defined by magnetic lineaments, and these help to define transtensional fault systems which may have served to localize the McMurdo volcanics. Farther inland, interpretations of high-frequency aeromagnetic anomalies within the Wilkes subglacial basin (*Ferraccioli et al.* 2009a) suggest the presence of large volumes of Jurassic tholeiites which may be related to rifting. By analogy with the Cordillera of North America, the authors infer that the Wilkes basin contains fold and thrust belts and a former backarc basin. These features may represent the transition between the Precambrian East Antarctic craton and the Ross orogenic belt. On the other side of the Antarctic continent, *Shepherd et al.* (2006) delineated subglacial geology via a combined aeromagnetic and radio echo sounding survey over three tributaries of Slessor Glacier in

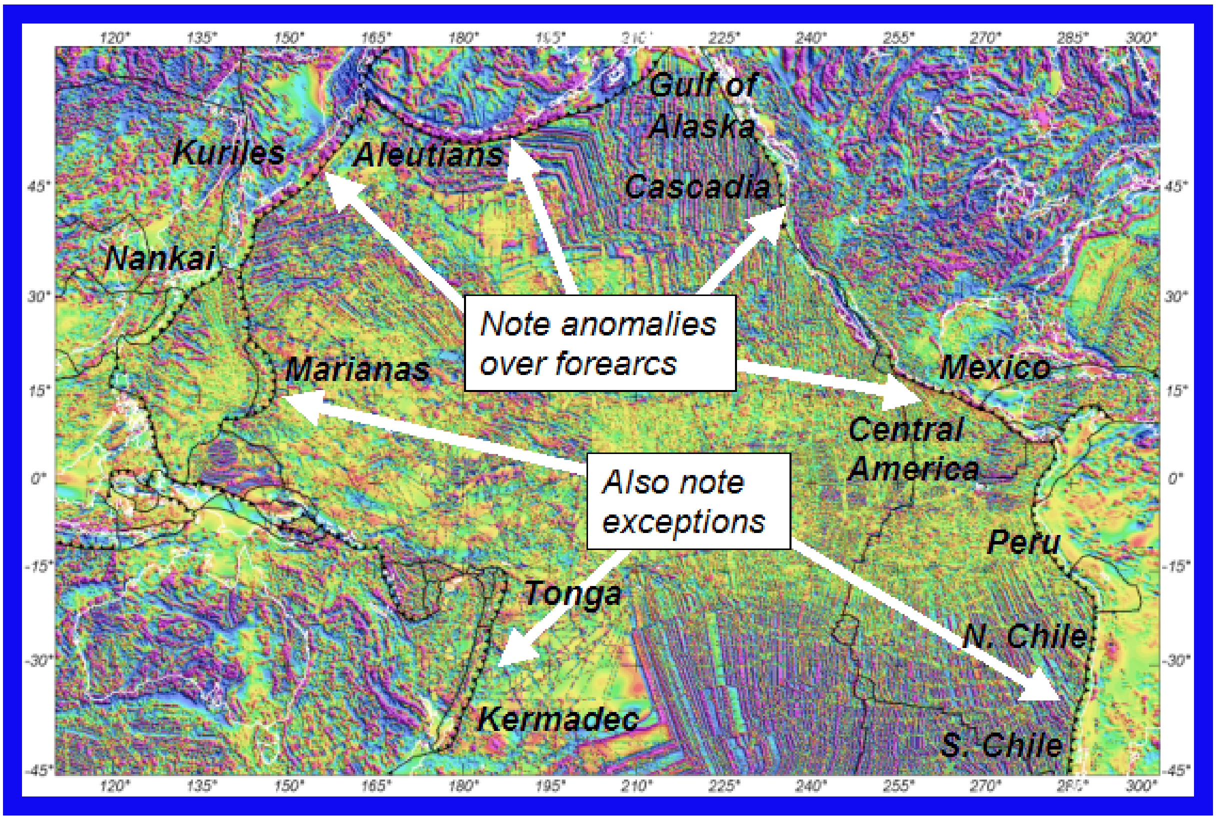

Figure 5. Magnetic anomalies of the Circum Pacific, showing the location of subduction zone magnetic anomalies. Source: World Digital Magnetic Anomaly Map (*Korhonen et al.* 2007)

the East Antarctic. They tentatively identified Jurassic dikes and sills intruding the Precambrian block here, and a post-Jurassic(?) sedimentary basin with a significant accumulation of sediment. Ice motion above the inferred sedimentary basin is seen to be different in character, comprising basal sliding and/or a deforming layer of sediment, than that above the remainder of the survey area.

In the Sinai peninsula, *Rabeh and Miranda* (2008) interpret a new high-resolution aeromagnetic survey, in conjunction with GPS and seismic data. They find systematic trends in the depth to the magnetic basement, and in the magnetically defined structural trends. The depth to basement increases to the west and north, reaching some 4 km deep at the north end of the study area.

Aeromagnetic, gravity, geologic, and remote sensing data were combined in the Eljufra region of Libya by *Saadi et al.* (2008) to define geologic structures and outline hydrothermally altered basalt. Analytic signal determinations of the magnetic field were used to estimate the location and depths of magnetic contacts.

Aeromagnetic surveys often provide unparalleled views of faults in sedimentary basins. For example, *Grauch and Hudson* (2007) find that prominent low-amplitude (5-15 nT) linear anomalies are often associated with surficially hidden faults that offset basin-fill sediments in the central Rio Grande rift of north-central New Mexico (USA). They also find that the linear anomalies are not the consequence of chemical processes acting within the fault zone, but rather due to the tectonic juxtaposition of magnetically different strata across the fault. They develop a set of simple graphical, mathematical, and conceptual models to help them determine parameters of direct interest to structural geology.

Drenth and Finn (2007) have also recognized hidden faulting in the Pine Canyon caldera of Big Bend National Park, along the US-Mexico border. The caldera-filling Pine Canyon rhyolite can be used as a magnetic marker because it is reversely magnetized. The authors use this marker to assess the thickness of the caldera fill, and suggest that it is controlled by buried faults evident in the magnetic survey.

Magnetic surveys, interpreted in conjunction with gravity and radiometric data, can also delineate basin architecture and tectonic evolution, as illustrated by the study of the Neocomian Rio do Peixe basin of NE Brazil (*de Castro et al.* 2007). The Rio do Peixe is a tripartite basin developed during the opening of the South Atlantic Ocean. Many pre-existing faults within the basement complex were reactivated during basin development, and the magnetics also serves to delineate the thickness of the sedimentary packages in these asymmetrical half-graben basins.

The utility of high-resolution airborne magnetic data in the interpretation of tectonic processes is borne out by the analysis of such a survey along a 120-km-long section of the Dead Sea Fault in Jordan and Israel (*ten Brink et al.* 2007). This fault is poorly delineated on the basis of surface morphology, or micro-seismic activity, although damaging earthquakes have struck along this fault as recently as AD 1458. The fault is clearly seen on maps of the first vertical derivative, indicating a shallow source for the anomalies. The authors interpret these 5-20 nT anomalies as originating from the alteration of magnetic minerals due to groundwater within the fault zone. Based on modeling of the magnetic observations, the width of the shallow fault zone is several hundred meters wide. On a regional scale, the authors observe no igneous intrusions related to the fault zone, and confirm previous interpretations of 107-111 km of left-lateral offset across the fault.

Magnetic techniques continue to play a major role in delin-

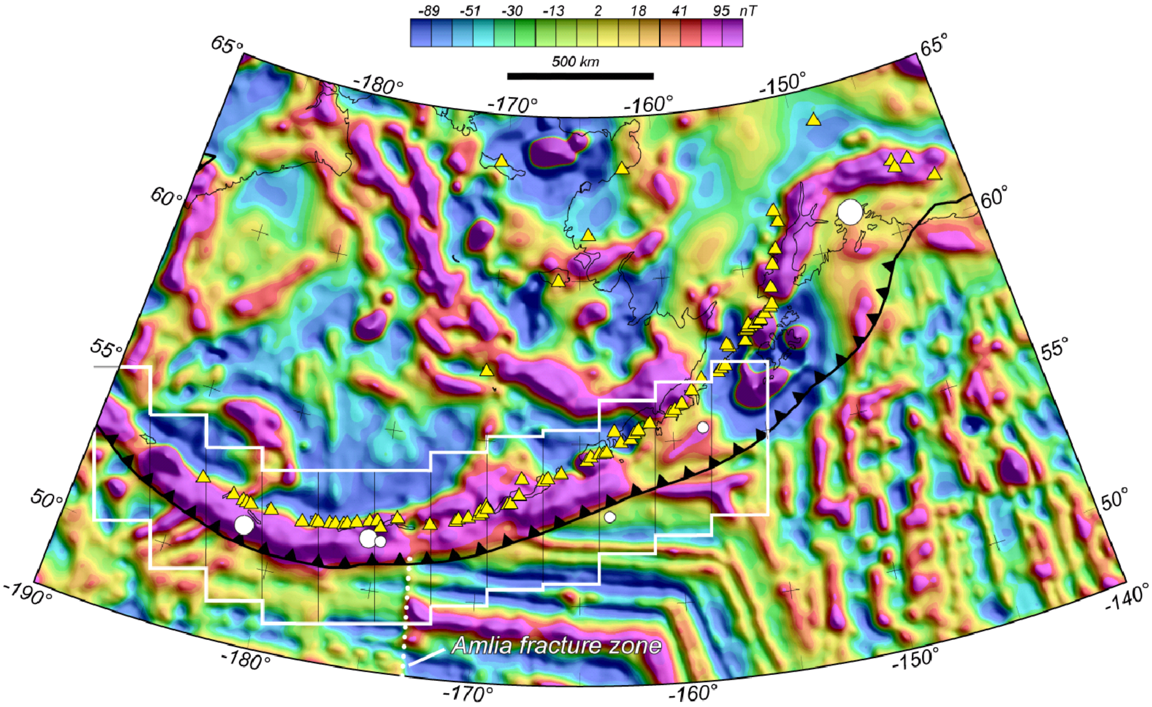

Figure 6. Proposed high altitude Global Hawk magnetic surveys (*Purucker and SerpentTeam* 2010) over the Aleutian Islands and surrounding regions, outlined by the white polygon. Yellow triangles locate arc volcanoes, and white circles are historic megathrust earthquakes with magnitude greater than 8.0. The Amlia fracture zone is indicated by the dotted white line. The color base map shows an approximation of magnetic anomalies observed at 20 km altitude. Anomalies were calculated by analytically continuing the World Digital Magnetic Anomaly Map to 20 km altitude, from its nominal 5 km altitude.

eating plate tectonic processes in the marine realm. *Maia et al.* (2005) document the interaction between the Foundation hotspot and the Pacific-Antarctic ridge within the South Pacific. Analysis of the magnetic anomaly data document a difference between the age of hotspot-related seamounts, and the underlying oceanic crust. This difference suggests that the ridge has approached the hotspot at a rate of 40 km/Ma. This is in good agreement with published radiometric dates.

4 RESOURCE EXPLORATION

Tectonic and structural interpretations derived from aeromagnetic and Landsat thematic mapper (TM) data sets form the basis for an ambitious program of groundwater exploration (*Ranganai and Ebinger* 2008) in the arid southern Zimbabwe craton (Africa). The lack of primary permeability and porosity in this crystalline basement terrain results in poor overall groundwater potential. However, available groundwater is localized by the presence of faults, fracture, dikes, and deeply weathered regions. These features are often recognizable through enhanced aeromagnetic and/or thematic mapper observations, and the authors utilize these to identify lineaments, and place them in the context of the regional structural geology. They develop a model in which the aeromagnetic data is used to map faults and fractures of considerable depth extent which may be open to groundwater (under tension) while the TM lineaments are typically closed to groundwater (under compression) and define recharge areas. The authors predict that coincident magnetic and TM lineaments, and continuous structures associated with large catchment basins, will be most favorable for groundwater. The sparse record of existing borehole data, some of which is of questionable quality, suggest a relationship between productivity and spatial proximity to faults and dikes, but proximity does not guarantee productivity. The trends of the NNE and NW sinistral faults in the Chilimanzi plutons can be traced from higher elevation areas in the north that represent the watershed, to lower areas in the arid south. Since regional groundwater flows mostly follow the dominant topographic gradient, these structures were identified as the most promising in terms of sustainable ground water resources.

By utilizing magnetic and gravity data in an integrated geological and geophysical study, *Blakely et al.* (2007) establish that the White River area of Washington exhibits many similarities to the Goldfield mining district of Nevada, home to one of the largest epithermal gold deposits in North America. To date, White River has produced only silica commercially, but deep weathering, young surficial deposits, and dense vegetation have hindered the evaluation of its economic potential for base and precious metals in the near surface. The magnetic data was invaluable in defining structural controls on hydrothermal alteration in both areas, but especially at White River because of poor exposures. The deposits are pene-contemporaneous products of the Cascade Arc some 20 Ma ago. Gravity and magnetic data were instrumental in locating the intrusive body beneath both regions that presumably was the source of fluids and heat to the overlaying calc-alkaline volcanic rocks. Magnetic susceptibility measurements at White River demonstrate the destruction of magnetic minerals in the altered rocks, and provide a way of estimating the depth extent of alteration (230-390 m). The White River altered area is located between two magnetically identified faults, in a temporary extensional stress regime.

Aeromagnetic data can also be utilized to infer heat flow within the crust, via determination of the depth to the Curie isotherm, the depth at which rocks lose their permanent and induced magnetism. When these determinations are from active geothermal areas, they provide important constraints on the depth to the heat source, and its extent. *Espinosa-Cardena and Campos-Enriquez* (2008) make such a determination from the Cerro Prieto geothermal area of NW Mexico. They find that the Curie point ranges from 14 to 17 km depth, slightly deeper than previous studies, but supported by seismic, gravity, and heat flow measurements.

5 INTERPRETATION OF LOWER CRUSTAL PROCESSES

Lower crustal processes are dominated by increasing temperatures, and an important temperature is that associated with the Curie point of magnetite (580°C), above which it loses its permanent and induced magnetism. To the extent that other magnetic minerals dominate in the lower crust, the temperatures of those other magnetic phases will be important for interpretation. Ilmenite-hematite, hematite-magnetite, or titanomagnetite-rich, phases exhibit different Curie, Néel, or unblocking temperatures from pure magnetite (*McEnroe et al.* 2004), and they extend to 670°C for hematite-rich compositions. Fine-scale exsolution of ilmenite-hematite phases (*McEnroe et al.* 2009), and possibly also magnetite-hematite phases (*Schmidt et al.* 2007), significantly increases the magnetic remanence and coercivity from typical multi-domain values. If these lamellae are not resorbed by temperature and pressure conditions in the lower crust, then a much greater range of magnetic mineral phases may be present. Experiments by *McEnroe et al.* (2004) suggest that the lamellae may be stable at lower crustal temperatures and pressures.

Increasing pressures also have an effect on the magnetic properties of single and multi-domain magnetite (*Gilder et al.* 2004) and titanomagnetite (*Gilder and Le Goff* 2008). Both saturation remanent magnetization and coercivity increase markedly in titanomagnetites at typical lower crustal pressures. The percentage of Ti in the titanomagnetite structure seems to control the increase in magnetization and coercivity, with the highest increases associated with the highest amounts of Ti.

Much work continues to be devoted to the difficult question of determining the depth to the Curie and Néel isotherms, and with comparing results from different approaches. Works utilizing standard approachs (*Spector and Grant* 1970) include those of *Bilim* (2007), *Bektas et al.* (2007), and *Maden* (2009) in Turkey, *Trifonova et al.* (2009) in Bulgaria, *ChunFeng et al.* (2009) and *Xu-Zhi et al.* (2006) in China, *Prutkin and Saleh* (2009) in Egypt, and *Stampolidis et al.* (2005) in Albania. A fractal approach based on the formulation of *Maus et al.* (1997) was used in the western United States by *Bouligand et al.* (2009), and a similar approach was used in California by *Ross et al.* (2006). *Ravat et al.* (2007) compares several spectral approaches, while *Rajaram et al.* (2009) compares the spectral approach with an approach that integrates seismic, heat flow, and satellite magnetic data sets (*Purucker et al.* 2007).

6 SUMMARY

The integrated interpretation of terrestrial impact structures continues to garner much attention because of its relevance to the interpretation of extraterrestrial impacts which are the targets of robotic exploration by NASA, ESA, and the national space agencies of Japan, India, and China. The importance of the coherence scale, or size of a region of coherent magnetization, can not be overemphasized, both in the terrestrial and extraterrestral examples. It is often the case that observations of a feature are made from only a single altitude. A change in that altitude can often make a dramatic difference in what features are available for interpretation, and 'color' the interpretation in subtle ways.

7 ACKNOWLEDGMENTS

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