Geohazard assessment from satellite magnetic data modeling—with examples from the Arctic Margin along the Canada Basin and the Korean Peninsula along 40°N (latitude) parallel

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Long-wavelength, relative high-amplitude-magnetic anomalies obtained at satellite altitudes have provided an understanding of the nature of the deeper crust of the Earth. We have studied two such long-wavelength anomalies in regions of high stress—one with a large and one with a lower amplitude anomaly. The first feature is on the Canada Basin continental margin in the Northwest and Yukon Territories, Canada (magnetic anomaly range: 19 nT to −6 nT at 350-km altitude). This area is also the focus of significant stress and earthquake activity. We interpret this anomaly and associated tectonic activity with this region's position at or near the fulcrum of the scissors-like opening of the Canada Basin in the mid-Mesozoic Era. The second is a section along the 40°N (latitude) parallel crossing the Korean Peninsula (magnetic anomaly range: <-2 nT to >3 nT at 350-km altitude), where an east-west fracture zone has been proposed to extend from northeastern China, across the Korean Peninsula, Sea of Japan and (Northern) Japan.
Key words: Magnetic anomalies, Arctic Margin, Korean Peninsula, stress, tectonics.

1. Arctic Margin along the Canada Basin

We will discuss these regions beginning with the Canada Basin margin of the Arctic. Even in the 21st Century the Arctic remains a largely inaccessible and poorly understood region of the Earth. Geophysical information on a regional scale in this large area is most easily obtained by remote means, such as aircraft and satellite observations. Therefore, recognizing that the magnetic anomaly field data is essential to an understanding of the structure and evolution of the Arctic and given the logistical difficulty of working there, airborne surveys were initiated in 1946 by agencies of the former Soviet Union. Extensive magnetic surveys have been made since this time (see, for example, Coles and Taylor, 1990). Scientists from the USA and Canada soon joined in the effort of conducting airborne surveys of this region. Arkady Karasik, in particular, was a pioneer in using aeromagnetic methods in the 1970s for determining the structure and development of the Arctic Basin (Karasik, 1980).

A new perspective was added with the advent of satellite data, initially from the Polar Orbiting Geophysical Observatory (POGO) satellites and subsequently from the Magnetic Satellite (Magsat) (Coles and Taylor, 1990; Langel and Hinze, 1998). At satellite altitudes a complete coverage, over both land and water, of the polar region could be obtained on a more regional scale, with admittedly a lower resolution than that obtained by aeromagnetic means. For the example of a Magsat compilation from the Arctic, see Alsdorf *et al.* (1998). Satellite altitude magnetic anomaly surveys reveal the long-wavelength (>500 km) structures that are most indicative of deeper crustal features.

Our study area is the northern sectors of the Yukon and Northwest Territories, Canada. This region borders the southern Canada Basin in the vicinity of the Mackenzie River Delta. It extends from 90° to 180°W longitude and from 60° to 80°N latitude. We will use geological and other geophysical information to interpret one of these long-wavelength Magsat anomalies from this northwestern part of Canada (Figs. 1 and 2).

1.1 Background

Based on low-level aeromagnetic profiles, Taylor *et al.* (1981) suggested that the Canada Basin was formed by a rotational spreading event beginning in Late Jurassic (M-25) and continuing until Early Cretaceous (M-12). This scissors-like opening of the Canada Basin was first proposed by Carey (1955) and developed by Tailleur (1973). According to their model, after initial rifting, a sliver of the Canadian shelf would have been rotated in an anticlockwise arc of some 70°, eventually docking against northern Alaska and easternmost Chukota. Several re-

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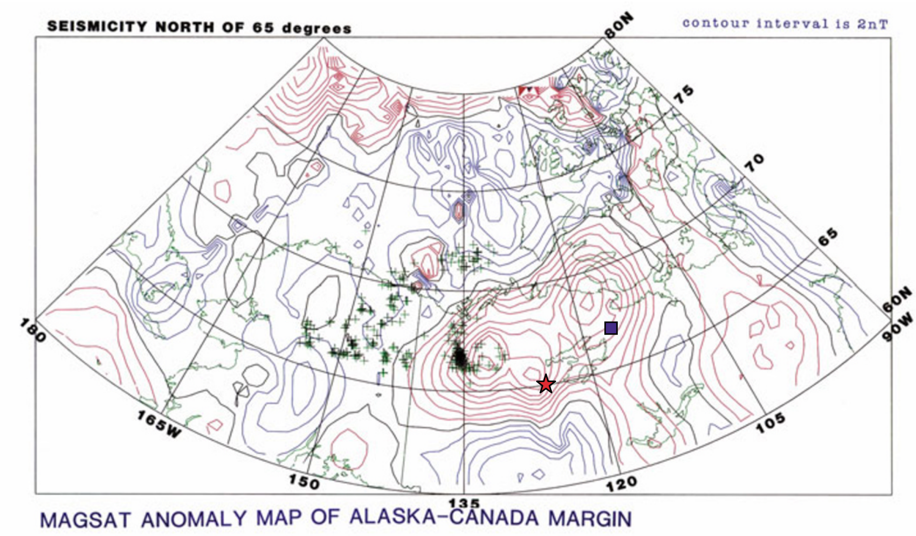

Fig. 1. Magsat anomaly map of Alaska-Canada margin with superimposed earthquake epicenters and heat flow data.

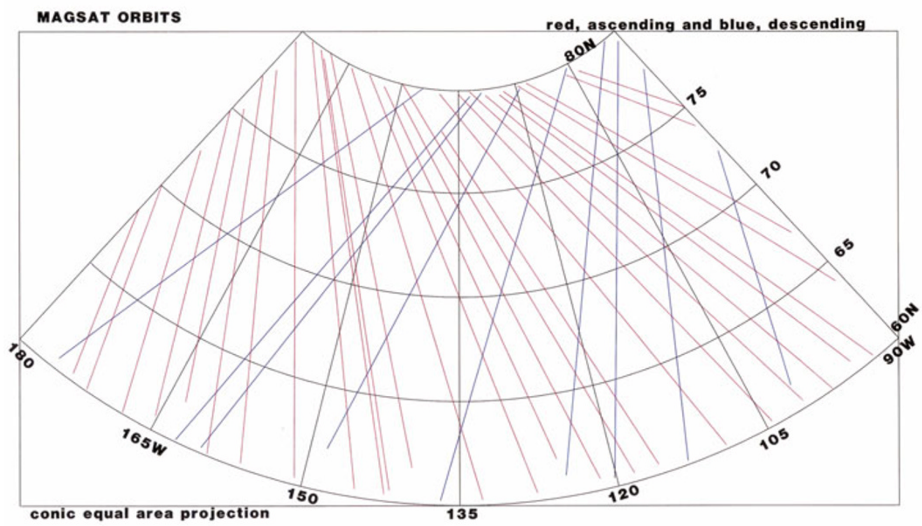

Fig. 2. Arctic Magsat profiles used in the construction of the anomaly map.

searchers have calculated the pole of rotation to be in the MacKenzie River Delta region. Extending the aeromagnetic anomalies of Taylor *et al*. (1981) back to their convergence point would place the axis of rotation at approximately 69.25°N, 142.50°W. Grantz *et al*. (1979), based on matching the 1000-m isobath, suggested a pole of 69.1°N, 130.5°W in the eastern MacKenzie Delta. In a subsequent study, Grantz *et al*. (1990) matched the tectonic hinge lines in the eastern and western Beaufort Shelves that placed the paleo-pole near 68.5°N, 135°W. Norris (1983), however, studied the regional geology in the lower Mackenzie River valley and sited the paleo-pole at the southern apex of the Rapid Depression (Fig. 3) near 68°N, 138°W. The location of these postulated poles of rotation are depicted in Fig. 3 together with the tectonic elements, which are shown to illustrate the regional structures. Jones (1980), however, proposed that this area was a locus of the complex interaction of several transcurrent faults (see Jones, 1980, his figure 1).

1.2 Data processing and analysis

Polar regions present special problems for magnetic studies because of the extensive external fields, most dramatically displayed by the auroral phenomena. External fields combine with the internal field and make it difficult to separate these static and dynamic components. All methods designed to isolate the crustal field from the total field observation begin with a rigorous selection of data based on visual correlations of adjacent orbits and/or on the planetary and polar indices, such as Kp, Ae. The orbital profiles used to produce the Magsat anomaly map of our study region are shown in Fig. 2. Thirty-six orbits (28 ascending-dusk and eight descending-dawn) were utilized in the orbit-crossing analysis technique described in detail by Taylor and Frawley (1987). Briefly, this method employs data from a restricted altitude range (350 ± 10 km), and the errors at the orbit crossing points are reduced to a minimum by the fitting of a bias and low-order polynomial surface. In this man-

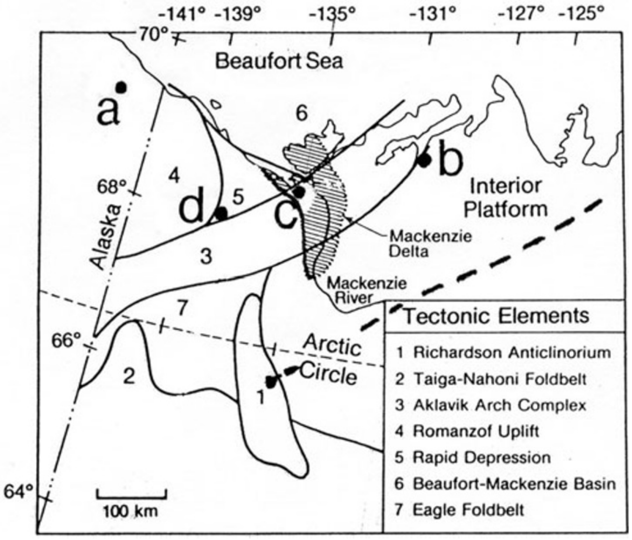

Fig. 3. Tectonic elements of the region with postulated poles of rotation. Modified from Jones *et al.* (1988). The localizations of four poles of rotation for the opening of the Canada Basin have been proposed. The lower case letters indicate the proposed pole of opening as given by the referenced authors: (a) Taylor *et al.* (1981); (b) Grantz *et al.* (1979); (c) Grantz *et al.* (1990); (d) Norris (1983). The heavy dashed line indicates the trend of the Magsat anomaly through this region. The series of closely spaced horizontal lines below the number 6 indicates the extent of the Mackenzie River Delta.

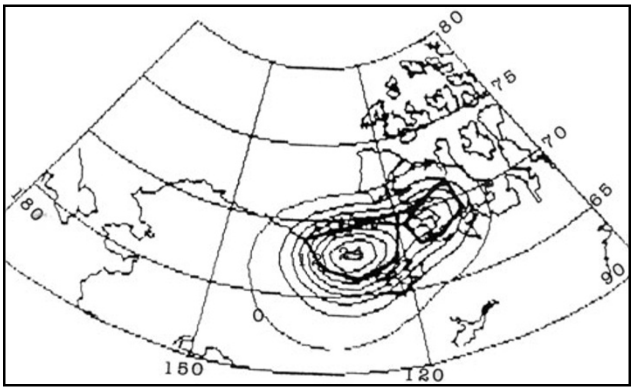

Fig. 4. Mathematical model study of magnetic anomalies.

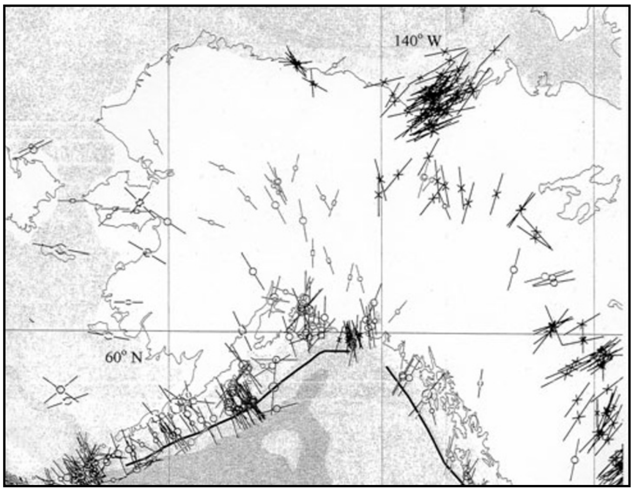

Fig. 5. Section of The World Stress Map (Zoback, 1992).

ner, all cross-over point errors are treated at once, whether they are from external fields, secular variation or instrument noise. A more recent method of noise removal that involves computing the spectral analysis of each orbit and subsequently correlating adjacent orbits is discussed by Alsdorf *et al.* (1998).

1.3 Magnetic anomalies

Figure 1 illustrates the large northeast-southwest-striking Magsat anomaly present between 110° and 140°W longitude and 64–72°N latitude. At its maximum, the elongated anomaly has 19- and 16-nT positive peaks. On regional scale compilations, such as the magnetic anomaly map of North America (Geological Society of America, 1987), this anomaly is revealed as a large positive feature. Coles *et al.* (1976) also confirmed the presence of this Magsat anomaly from high-level airborne data. They described it as a wide belt of intense anomalies that may be evidence for a Precambrian orogenic zone. Coles *et al.* (1976) further suggested that the crystalline continental basement (Fig. 3, Interior Platform) extends far to the west beyond the exposed and known buried shield. Three-dimensional seismic reflection profiling also favors the idea that the structural basement is composed of Proterozoic strata (Cook and Coflin, 1990). The magnetic anomalies support these conclusions and imply that there are major contrasts between the basement beneath the MacKenzie Fold belt and that of the craton. Taylor and Frawley (1986) suggested that the source for this large positive (peak to trough) anomaly (25 nT at 350-km altitude) might be a Precambrian rift.

Plouff (1976) developed a three-dimensional magnetic model of these anomalies (Fig. 4). This model duplicates both the 25- and 13-nT (positive peak-to-surrounding negative trough) highs of the Magsat map. We used a 15-km-thick body (depth extent 5–20 km) for the larger anomaly and a 13-km-thick body (depth extent 5–18 km) for the smaller anomaly. Both were given a vertical polarization and magnetization of 5 A/m. These models provide an estimate of the geometry and depth extent of the geologic units producing these magnetic anomalies and indicate that an intra-crustal source is likely.

1.4 Other geophysical data

1.4.1 Seismicity and horizontal stress The region of the poles of rotation is located close to a region of enhanced seismicity and horizontal stress (Figs. 1, 3, 5). Earthquake epicenters are plotted (as small crosses) in Fig. 1 based on 1986 data obtained from the U.S. Geological Survey (USGS). It is evident that a N-S-trending group of earthquakes form the western boundary of the Magsat anomaly and may be related to a fundamental crustal discontinuity. The seismicity may denote an offset in the Aklavik Arch (Fig. 3, number 3), as it trends southwest toward Alaska. Stress measurements from bore holes reveal high levels of horizontal stress (Fig. 5) even though no directionality could be determined (World Stress Map, Zoback, 1992). These stresses indicate that there is a significant amount of horizontal tension and/or compression centered on the Magsat anomaly high and the region of maximum earthquake activity. While the World Stress Map does not indi-

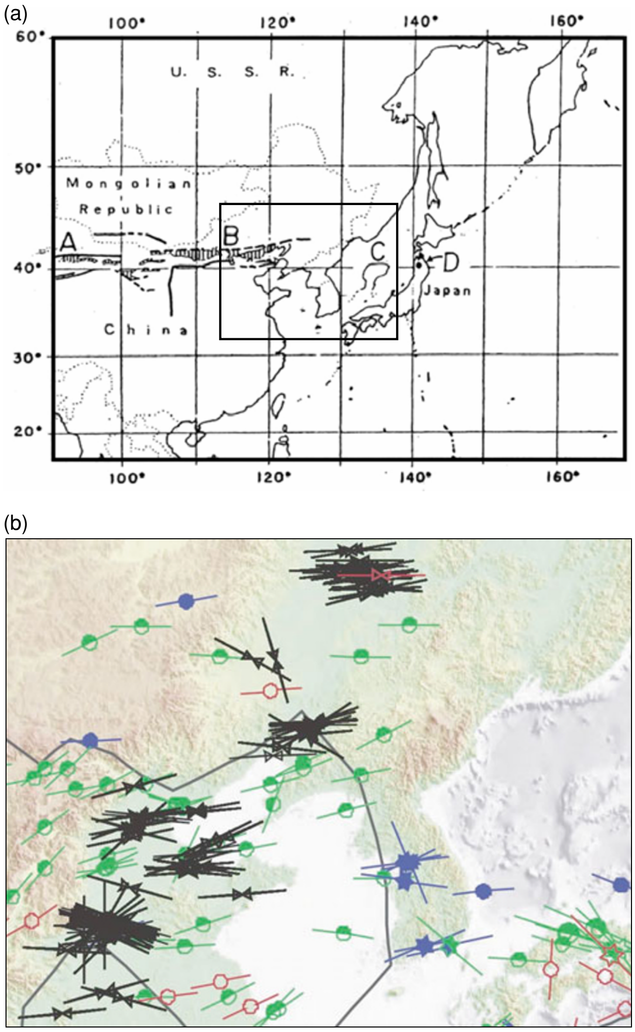

Fig. 6. (a) A part of map defining the "Forty-North Fracture Zone" in Asia (after Kutina, 1974). A–B: East-west-trending structural belts bounded by major east-west fracture zones in northern China (after Tectonic Map of Eurasia by Yanshin, 1966). C: Bathymetric lineament in the East Sea. D: The main concentration of "Kuroko ores" in northern Honshu, Japan. (b) Portion of the new World Stress Map (Heidbach *et al.*, 2007) where the solid line is delineated as in Fig. 6(a).

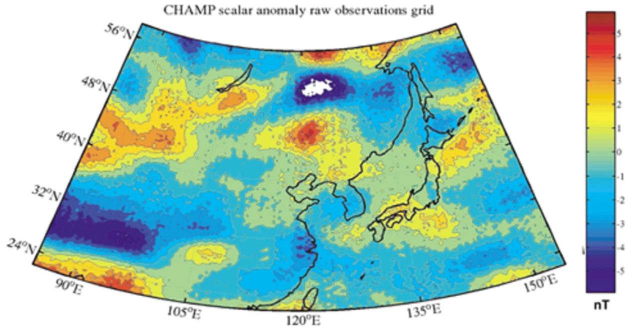

Fig. 7. A CHAMP total intensity magnetic anomaly map at 350-km altitude over a region of East Asia (85°∼155°E, 22°∼58°N).

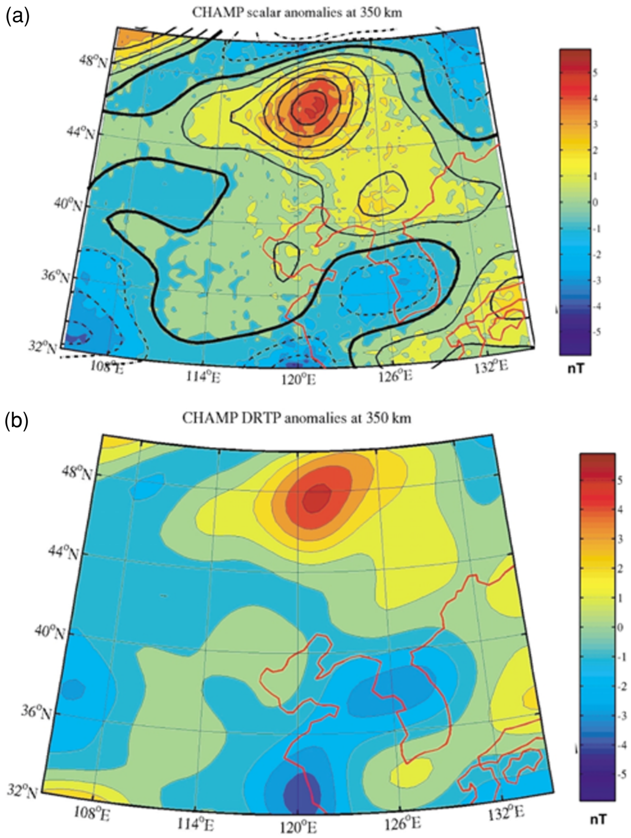

Fig. 8. (a) Enlargement of the magnetic anomalies centered at the Korean Peninsula from Fig. 7. (b) Differentially-reduced-to-pole (DRTP) magnetic anomalies for the same area using equivalent point source inversion. Color-filled contours are the same as in Fig. 7.

cate the nature of this stress regime, it is interesting to speculate that this current focal point of stress is centered near the opening of the Canada Basin. Since the motion of the Alaska block that formed the Canada Basin ceased at least 80 m.y. ago, then this relic stress regime would certainly be very long lasting. It seems obvious that the stress regime and the earthquakes are related, even if it is not clear how these are associated with the pole of opening of the Canada Basin.

1.4.2 Heat flow Low heat-flow values (<40 mW m^{-2}) occur in the Beaufort-MacKenzie Basin and Rapid Depression (Fig. 3). Both of these areas are characterized by thick successions of Upper Devonian, Cretaceous and Tertiary clastic sedimentary strata. High heat-flow values (>60 mW m^{-2}, Jones *et al.*, 1988) are found on the northeastern part of the Aklavik Arch Complex (Fig. 3, number 3). Langseth *et al.* (1990) present two land heat-flow measurements within the area of the positive magnetic anomalies: 65°18′N, 126°52′W (red star in Fig. 1) and 66°59′N, 115°16′W (blue square in Fig. 1). The former (83 mW m^{-2}) is within the 16-nT contour, and the latter (54 mW m^{-2}) is within the 12-nT contour. These high heat-flow values are consistent with this region being associated with exothermic tectonic processes such as those which may have been produced by the proposed opening of the Canada Basin.

1.5 Summary

Satellite-derived magnetic fields are valuable for determining regional geologic variations and tectonic deformation (Alsdorf *et al.*, 1998). The Magsat anomaly illustrated in this paper and apparent from other geophysical data represents a major discontinuity in the crustal structure and is most likely the westward continuation and termina-

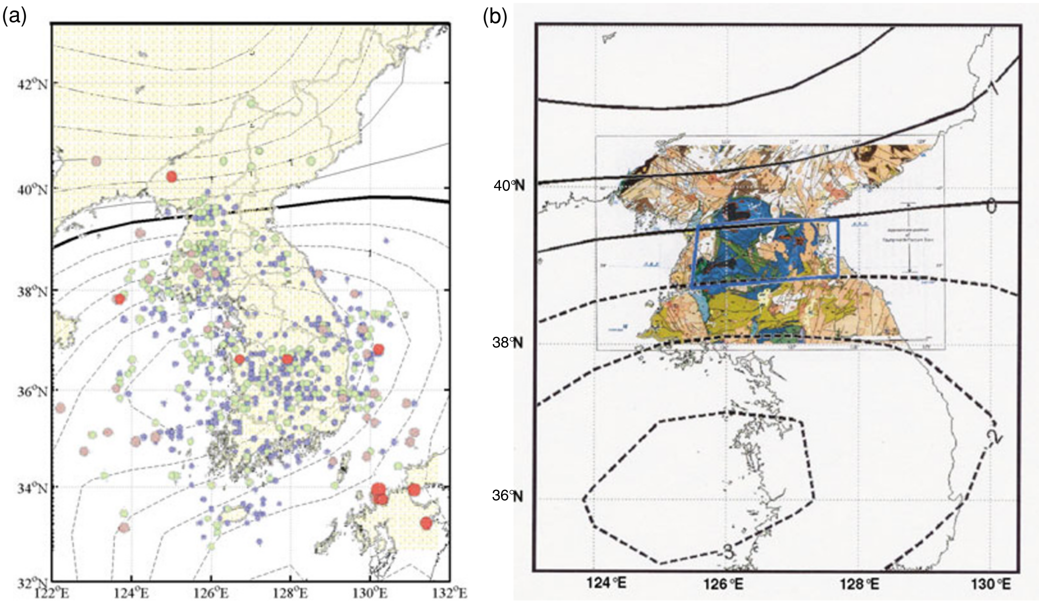

Fig. 9. (a) Magnetic anomalies at 350-km altitude. Earthquake epicenters from 1978 to 2006 (adapted from the epicenter image of Lee and Yang (2006) (http://www.kmaneis.go.kr/eng/eng05.htm)) are superposed. (b) CHAMP anomalies at 350-km altitude superposed with Korean geology map from KIGAM (Korean Institute of Geology and Mining; Chwae *et al.*, 1995). The blue line from the prism-shaped model delineated with the geology map represents Cambrian Pyongnam Basin.

tion, at 135°W, of the Proterozoic Canadian Shield. The Aklavik Arch may indicate the front of an orogenic belt during the Devonian Ellesmerian orogeny (Cook and Coflin, 1990). The geologic map of Canada (GSC Map 1860A, 1996) shows the region of the prominent Magsat positive anomaly to be upper Devonian sediment on a Precambrian basement. The occurrence of earthquakes and stress data compilation indicate that stress is still present in the region of the discontinuity. One may speculate if this long-term geologically activity can be correlated with the region having acted as the fulcrum of the pole of rotation for the opening of the Canada Basin. For example, the opening hinge or fulcrum region would be a locus of exothermic activity, and this could produce the source of these large magnetic anomalies.

2. Korean Peninsula along 40°N Latitude

2.1 Regional geology

The second study region is the Korean Peninsula, more specifically along the 40°N parallel of latitude (Fig. 6(a) from Kutina, 1974). Based on geologic and tectonic data, Kutina (1974) and Kutina *et al.* (2007) proposed that this region is part of a large fracture zone extending from northern China across the Yellow Sea, Korean Peninsula, Sea of Japan and the island of Honshu, Japan, which they called the "Forty-North Fracture Zone." A more recent three-dimensional study of the Yanshan area in northeastern China provided data important for checking the eastward continuation of the 40°N discontinuity across the Korean Peninsula and extending this trend to the east of the Yellow Sea (Cui *et al.*, 2002). Figure 6(a) shows a map defining the Forty-North Fracture Zone in East Asia. The latitudinal structures that extend into China along the 40°N latitude are noted as regions of ore deposits as well as of strong earthquakes associated with the significant stress concentrations. For example, in China, many important ore deposits, including the rare earth element (REE)-Fe-Nb deposit of Bayan Obo, occur within this region. Kutina *et al.* (2007) examined the geology of the Korean Peninsula within the latitudes corresponding to the belt of east-west fractures in northeastern China and found a difference in the geology and fracture patterns across the band of latitudes 39°–40°N. The new World Stress Map (Heidbach *et al.*, 2007) (Fig. 6(b)) supports the eastward extension of the 40°N discontinuity to the Korean Peninsula.

2.2 Satellite altitude magnetic anomaly data

We wanted to determine if such a large fracture zone had a signature in the long-wavelength satellite altitude magnetic anomaly data that could be detected in the more recent CHAMP mission measurements. We collected CHAMP satellite observations during June to December in 2005 over the study area and reduced these data to obtain the lithospheric magnetic intensities at the altitude of the satellite (∼350 km). For this reduction, we removed the main field component derived from an IGRF 2005 model and the external field components by wavenumber correlation filtering (von Frese *et al.*, 1997). Figure 7 shows a reduced gridded total scalar anomaly map over the East Asia region (85°∼155°E, 22°∼58°N). We enlarged the Korean Peninsula and its surroundings (105°–135°E, 32°–50°N), as shown in Fig. 8(a), and transformed the total scalar anomalies into the differentially-reduced-to-the pole (DFTP) anomalies (Fig. 8(b)) using the point source (von Frese *et al.*, 1981) method. Note that the anomaly pattern along the 40°N parallel is divided into a small positive anomaly (>2 nT) to the north and a small negative anomaly (< −3 nT) to the south. Both dipolar anomalies are extended in an easterly direction (Fig. 8(a)). While this anomaly pattern does not establish the existence of the east-west fracture zone through this region, it is, nevertheless, consistent with an east-west fracture. The DFTP anomaly map (Fig. 8(b)) also displays a similar pattern.

2.3 Magnetic model

Our next procedure was to construct a geologically reasonable mathematical body or model and then compute the anomaly field produced by such a structure at the altitude of the observed CHAMP magnetic data, 350 km. This is called forward modeling and usually requires several attempts to achieve a match. We used a rectangular block centered roughly on the peak of the DRTP anomaly and delineated the Cambrian Pyongnam Basin area just to the south of the 40°N parallel in the approximate region of the "Forty-North Fracture Zone". The rectangular mathematical model is shown in Fig. 9(a, b). The magnetic body was 20 km thick and extended from the surface to a depth of 10 km, and we assigned an induced inclination and declination of 56°N and 8.9°W, respectively, with a main field intensity of 52,390 nT. The model magnetization is 3.2 A m^{-1} (SI unit). These model contours closely resemble the observed data; however, modeling is not a unique process, and other shapes with different magnetizations could also produce a similar anomaly.

2.4 Geologic and seismicity data

Figure 9(a) shows a map of an anomaly pattern at 350-km altitude from a forward modeling of the source body; this pattern is delineated with blue lines superposed on the distribution of earthquake epicenters from 1978 to 2006 (an epicenter image taken from http://www.kmaneis.go.kr/eng/eng05.htm; Lee and Yang, 2006). Note that the zero contour of our model divides the seismicity of the peninsula into two parts: north of this contour, the seismicity is relatively low, while to the south of this contour, the seismicity is relatively high. Figure 9(b) shows the scalar CHAMP anomaly pattern over the study area at 350-km altitude superposed with the Korean geology map from KIGAM (Korean Institute of Geology and Mining; Chwae *et al.*, 1995). The blue area in the geology map represents the Cambrian Pyongnam Basin bounded by late Proterozoic basins (brown) and Achaean basins (peach) and outcrops (white). The Forty-North Fracture Zone bounds the basin model used to represent the magnetic anomaly data to the north.

2.5 Summary

We have produced a long-wavelength magnetic anomaly map of the region of the Korean Peninsula in order to determine if a signature could be found that was produced by the proposed Forty-North Fracture Zone of Kutina *et al.* (2007). The anomaly map indicated a relatively small dipolar anomaly dividing the seismicity and geology of this region. These correlations are consistent with the fracture zone hypothesis, but the data are not irrefutable.

3. Conclusions

We have shown that there are two large regions where a potential correlation exists between significant tectonic elements and long-wavelength magnetic anomalies. The first example is the Arctic margin of the Canada Basin, an extensive concentration of stress, most likely related to the opening of the Canada Basin, is associated with a large magnetic anomaly. The second example involves the Korean Peninsula where a much smaller, but still distinct, east-west-trending magnetic anomaly tends to support the occurrence of a major fracture zone running along the 40° parallel (Kutina, 1974; Kutina *et al.*, 2007). This fracture zone crosses the northern edge of the Pyongnam Basin and the region of Korea that is most active seismically. We are proposing that the stress of each of these regions produced both of the observed tectonic elements and the enhanced magnetization required to form long-wavelength magnetic anomalies.

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References

Alsdorf, D., P. T. Taylor, R. R. B. von Frese, R. A. Langel, and J. J. Frawley, Arctic and Asia lithospheric satellite magnetic anomalies, *Phys. Earth Planet. Inter.*, **108**, 81–99, 1998.

Carey, S. W., The Orocline Concept in Geotectonics, *Papers and Proceedings of the Royal Society of Tasmania*, **89**, 255–288, 1955.

Chwae, U. C. and nine others, Geologic Map of the Republic of Korea, Korean Institute of Geology, Mining and Materials, Republic of Korea, 1 sheet (1:1,000,000), 1995.

Coles, R. L. and P. T. Taylor, Magnetic anomalies, in *The Arctic Ocean Region*, edited by A. Grantz, G. L. Johnson, and J. F. Sweeney, Boulder, Colorado, Geological Society of America, The geology of North America, v. L, 119–120, 1990.

Coles, R. L., G. V. Haines, and W. Hannaford, Large Scale magnetic anomalies over western Canada and the Arctic: a discussion, *Can. J. Earth Sci.*, **3**, 790–802, 1976.

Cook, F. A. and K. Coflin, Experimental three-dimensional imaging of crustal structure in the northwestern Canadian Arctic, *Tectonophysics*, **173**, 43–52, 1990.

Cui, S. and others, *Mesozoic and Cenozoic Intracontinental Orogenesis of the Yanshan Area, China*, 386 pp., Geological Publishing House, Beijing, China, 2002.

Geological Society of America, A Gravity Anomaly Map of North America, B. Magnetic Anomaly Map of North America in The geology of North America-An overview, Boulder, Colorado, Geological Society of America, The Geology of North America, v. A, Plate 1, 1987.

Grantz, A., S. Eittrim, and D. Dinter, Geology and tectonic development of the continental margin north of Alaska, *Tectonophysics*, **59**, 263–291, 1979.

Grantz, A., S. D. May, P. T. Taylor, and L. A. Lawver, Canada Basin, in *The Arctic Ocean Region*, edited by A. Grantz, L. Johnson, and J. F. Sweeney, Boulder, Colorado, Geological Society of America, The Geology of North America, L, 379–402, 1990.

Heidbach, O., *et al.*, World Stress Map Published, *EOS*, **88**(47), 504, 2007.

Jones, F. W., J. A. Majorowicz, and J. Dietrich, The Geothermal Regime of the Northern Yukon and Mackenzie Delta regions of Northwest Canada-Studies of Two regional Profiles, *Pure Appl. Geophys.*, **127**(4), 642–658, 1988.

Jones, P. B., Evidence from Canada and Alaska on plate tectonic evolution of the Arctic Ocean Basin, *Nature*, **285**, 215–217, 1980.

Karasik, A. M., Basic specifics of the history of development and the structure of the Arctic Basin bottom according to aeromagnetic data: Marine Geology, Sedimentology, Sedimentary petrography, and Geology of the Ocean, Academy of Sciences of the U.S.S.R, Ministry of geology of the U.S.S.R, National committee of Geologists of the Soviet Union, Leningrad, 178–193 (Translated 1981: NASA GSFC-07), 1980.

Kutina, J., Structural control of volcanic ore deposits in the context of global tectonics, *Bull. Volcan.*, **38**, 1039–1069, 1974.

Kutina, J., S. Cui, R. Pei, and M. Jiang, A deep-seated E-W trending structural boundary indicated as extending across the Korean Peninsula at a latitude close to 40° N, *Glob. Tectonics Metallogeny*, **9**, 2007 (in press).

Langseth, M. G., A. H. Lachenbruch, and B. V. Marshall, Geothermal observations in the Arctic region, Chapter 9 in The Geology of North America, Vol. L, p. 133–151, 1990.

Langel, R. A. and W. J. Hinze, *The Magnetic Field of the Earth's Lithosphere*, 429 pp., Cambridge University Press, 1998.

Lee, K. and W.-S. Yang, Historical Seismicity of Korea, *Bull. Seismol. Soc. Am.*, **96**, 846–855, 2006.

Norris, D. K., The structural link among the Columbia, Innuition, and Alaska Orogens, *Geol Assoc Canada-Mineral Assoc Canada Geophysical Union Program with Abstracts*, 8, A51, 1983.

Plouff, D., Gravity and magnetic fields of polygonal prisms and application to magnetic terrain corrections, *Geophysics*, **41**, 727–741, 1976.

Tailleur, I. L., Probable Rift Origin of Canada Basin, Arctic Ocean, 526–535, *American Association of Petroleum Geologists*, Tulsa, Oklahoma, 1973.

Taylor, P. T. and J. J. Frawley, MAGSAT anomaly map of the Alaska-Canada Arctic continental margin, *EOS Trans. Am. Geophys. Union*, **67**, 920, 1986.

Taylor, P. T. and J. J. Frawley, Magsat anomaly data over the Kursk region, U.S.S.R., *Phys. Earth Planet. Inter.*, **45**, 255–265, 1987.

Taylor, P. T., L. C. Kovacs, P. R. Vogt, and G. L. Johnson, Detailed aeromagnetic investigations of the Arctic basin, 2, *J. Geophys. Res.*, **86**, 6323–6333, 1981.

von Frese, R. R. B., M. Jones, J. Kim, and J. H. Kim, Analysis of anomaly correlations, *Geophysics*, **62**, 342–351, 1997.

von Frese, R. R. B., W. J. Hinze, and L. W. Braile, Spherical earth gravity and magnetic anomaly analysis by equivalent point source inversion, *Earth Planet. Sci. Lett.*, **53**, 69–83, 1981.

Yannshin, A. L., editor, *Tectonic Map of Eurasia, 1:5,000,000*, Nauka Press, Moscow, 1966.

Zoback, M. L., First- and Second-Order Patterns of Stress in the Lithosphere: The World Stress Map Project, *J. Geophys. Res.*, **97**, 11,703–11,728, 1992.

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