Exploration geophysics on Mars: Lessons from magnetics

M. PURUCKER, Raytheon-ITSS/Goddard Space Flight Center, NASA, U.S.
D. CLARK, CSIRO Exploration and Mining, North Ryde, Australia

NASA's exploration of the solar system has often included magnetometers (e.g., Voyager, Mariner 10) to provide insight into the deep interior of the planets. Recently, however, a pair of magnetometers aboard the orbiting Mars Global Surveyor (MGS) satellite detected an unmistakable magnetic signature from the Martian crust. The magnetic signatures record tectonism from Mars' infancy—four billion years ago. The maximum magnetic field measured by MGS from the Martian crust is 20 times larger than that measured by earth-orbiting satellites at a comparable altitude. As on earth, interpretation of these magnetic fields aids in identification of provinces of interest for mineral exploration. With payload costs hovering around US$1 million/kilogram, it will become increasingly desirable to attempt to exploit local resources rather than relying on terrestrial resources for Martian exploration. The United States, Japan, and the European Space Agency all have active Mars exploration programs. France will join this club within the next few years to launch Mars micromissions (including a Martian seismic network) from its Arianne booster. What can the interpretation of the Martian magnetic fields tell us about resources potentially available at Mars?

The observations. Magnetic fields measured near Mars reveal that it has virtually no internal magnetic field of global scale at the present time. This is in contrast to earth, where a dynamo-generated internal field bathes the entire surface in fields of 23 000-67 000 nT (or gammas, for those brought up with cgs units). Exploration geophysicists on earth measure small (a few to a few thousand nT) deviations or anomalies from that internal field. Those anomalies originate from varying amounts of iron oxides and sulfides in the earth's crust. Most terrestrial explorationists use an Overhauser, proton precession, or optical pumping magnetometer that measures only the magnitude or total intensity rather than the direction of the magnetic field. They do this because it is very difficult to measure the orientation of a vector magnetometer to the arc-second level, necessary if nT-level magnetic field measurements are to be made. On Mars the task of making vector measurements of the crustal magnetic field is much easier because there is no large background field of internal origin.

The crustal magnetic field measured by earth-orbiting satellites and airborne surveys consists of both a permanent (remanent) magnetic contribution and a contribution from magnetic fields induced in crustal rocks by the large field of core origin. On earth there is a rough parity between the remanent and induced contributions, although many exploration texts (like Nettleton) maintain that induced contributions are dominant. Part of the uncertainty has to do with the difficulty of separating remanent and induced contributions on the basis of the magnetic fields they produce. For an example of a map made by assuming that induced contributions are dominant, see the Meter Reader in the March 1999 *TLE*. To first order on Mars, induced magnetizations will be absent because there is no large core field.

Interpretation of Martian magnetic fields is still in its infancy because observations have not yet been continued to a common altitude. This procedure is important because magnetic fields decay very rapidly with distance from their source. In the case of a simple dipole, representative of an isolated surface source on Mars, a magnetic field of 1000 nT at an altitude of 120 km will decay to a magnetic field of only 500 nT at 150 km. The Martian magnetic map in Figure 1 has not yet been continued to a constant altitude and shows observations acquired between 100 and 200 km. However, MGS continues to map the magnetic field of Mars from a circular orbit at an altitude of 380 km. This will soon yield a map at that altitude that can be more easily compared to the terrestrial map in Figure 1.

The strongest Martian magnetic fields are encountered in Terra Cimmeria and Sirenum in the heavily cratered uplands of Mars' southern hemisphere. With a telescope, one can observe these regions as darker than the terrane to the north. Modeling of magnetic profile data from this area by Connerney and colleagues suggests magnetization values of ± 20 A/m, assuming a magnetic crustal thickness of 30 km. Although it is not unusual to encounter terrestrial rocks like fresh basalts and banded iron formations (BIFs) with magnetization values in this range, only midocean-ridge basalts hold coherent magnetizations that extend for 2000 km as the Martian magnetic sources do. However, midocean-ridge basalts are very thin and produce small magnetic signals at terrestrial satellite altitude. Large terrestrial anomalies are primarily over continental crust, with its greater thickness. The near-surface expression of the largest terrestrial magnetic anomaly, Kursk in Russia, is dominated by a large BIF laid down horizontally and subsequently folded and faulted. However, this BIF extends only to depths of a few km and extends for a maximum of 100 km along strike. Measurements of the magnetized rocks here suggest that the remanent contribution dominates the induced contribution. However, we know little about the deeper and surrounding material that probably contributes substantially to the magnetic anomaly at satellite altitude. Connerney and colleagues argue that the long linear Martian sources may be the signature of a plate tectonic or crustal recycling process. The exact nature of this process is hotly debated.

Mineral exploration. Although high magnetization values are generally associated with high iron contents, other factors (e.g., oxidation state, magnetic mineral composition, and grain size/shape) often play a significant role. On Mars, Madsen and McSween summarize evidence that suggests that the iron content of the Martian crust may be some four to five times greater than that of the terrestrial continental crust. If large Martian magnetizations are a reflection of high iron concentrations, as they probably are, one can ask what other economically useful elements might be concentrated along with the iron. On earth, iron-rich, highly magnetic rocks host volcanogenic massive sulphide deposits, copper-gold-silver enriched ironstones, and lead-zinc-copper-silver enriched banded iron formations. Apart

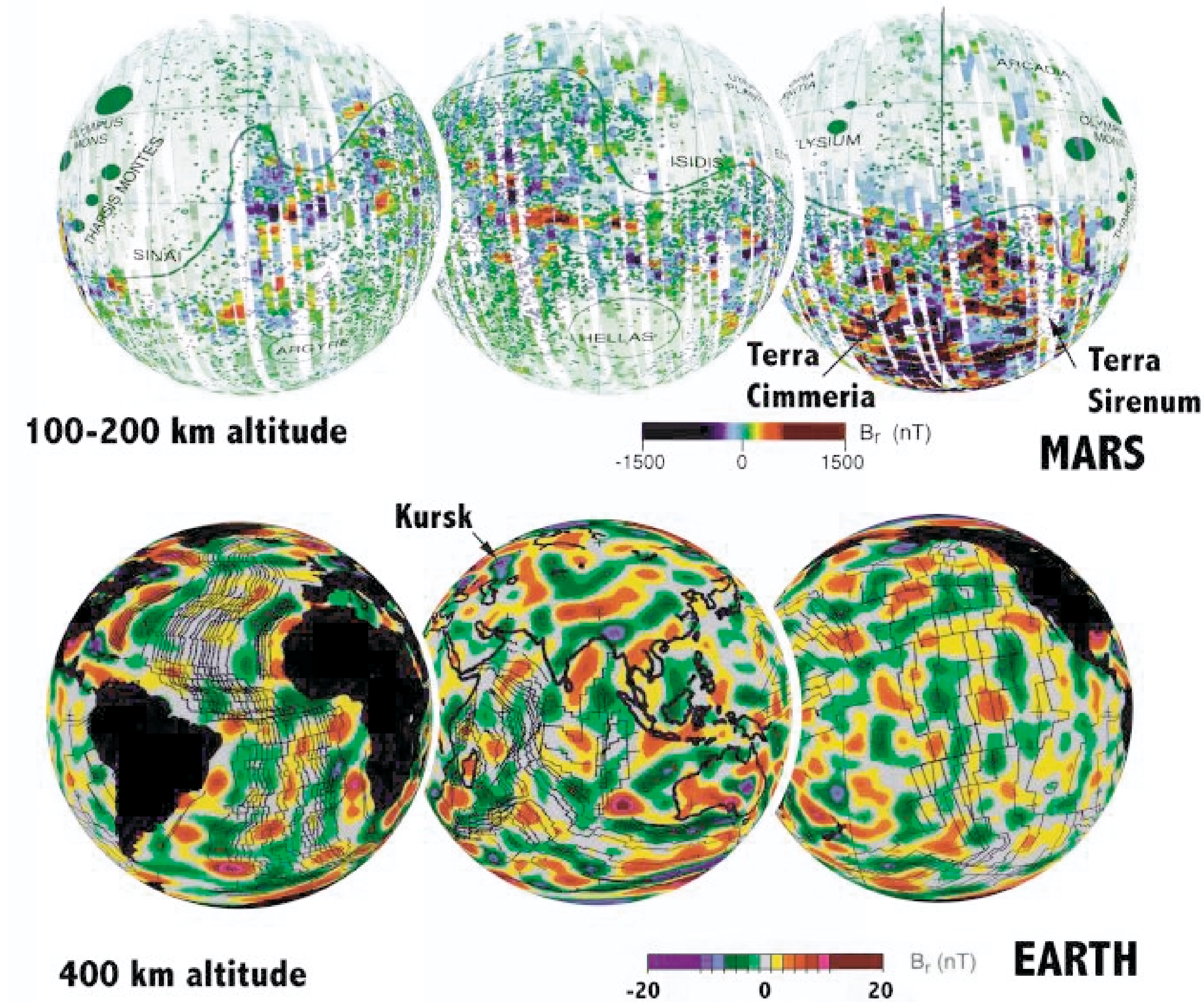

Figure 1. Global Martian crustal magnetic field from Acuna and colleagues compared with terrestrial magnetic field of Cain et al. (1990). In both cases, the radial (vertical) component of the magnetic field is shown. This component is less prone to contamination from magnetic fields of external origin. Note the difference in altitudes of the two maps. When measured at comparable altitudes, the largest magnetic fields over Mars are a factor of 20 larger than those measured over the earth. The Martian magnetic field map is not normalized for altitude, in contrast to the terrestrial map. The solid green line on the Martian globe is the approximate location of the crustal dichotomy, the boundary between the young northern lowlands and the old southern highlands. Note how most magnetic signatures are located in the older terrains. The solid and open green circles on the Martian globe locate large volcanos and impact basins. Note the absence of magnetic signatures associated with the Martian volcanos Olympus Mons and Tharsis Montes and with the large impact basins Hellas and Argyre. The ground track of the satellite below 200 km is illustrated with light green lines whose width approximates the satellite altitude above the surface. The color scale for the Martian crustal magnetic fields is a logarithmic representation. The Martian magnetic maps are made by windowing and reprojecting the image shown as Figure 3 in Acuna et al. (1999). The terrestrial magnetic field was measured by the Magsat satellite at an average altitude of 400 km. The map shows spherical harmonic degrees 15-40, whose origin lies largely within the earth's crust. The thin solid lines on the terrestrial globe are seafloor-spreading isochrons. The color scale for the terrestrial magnetic fields is a linear representation.

from the natural chemical association between iron and a number of other economically important metals, in many cases the mechanism behind these concentrations has to do with the reducing power of magnetite, relative to the mineralizing fluids, and the ability of these other economic elements to replace iron in the crystal structure. More generally, precipitation of ore metals in economic concentrations is facilitated by reaction of mineralizing fluids with rocks that act as traps because they are far from equilibrium with the fluids. Iron-rich rocks can be important traps for mineralization because iron is by far the most common element with variable valence, occurring as the native metal in highly reducing conditions, as ferrous (divalent) iron in somewhat reduced rocks, as ferrous plus ferric (trivalent) iron under intermediate oxidation states, and as ferric iron alone in highly oxidized rocks. Thus, precipitation of metals from relatively reduced fluids may be enhanced by reactions with oxidized hematite-rich rocks. We may expect these processes to be more common on Mars, where iron is much more abundant than on earth.

What's next? The present satellite magnetic survey effectively covers only 20% of the surface at altitudes below 200 km. A joint U.S.-French mission, called Dynamo microorbiter, has been proposed to complete the magnetic mapping of Mars below 200 km. This will allow for improvements in models of the magnetization distribution within the Martian crust and in turn improved explanations in terms of tectonic and geologic processes.

One question not answered by the present satellite magnetic survey of Mars is the depth of the source rocks below the surface—information critical to any assessment of the utility of potential Martian resources. For an accurate assessment of the depth of the source rocks, we need to be much closer to the surface. Magnetometers aboard superpressure balloons or aircraft 1-5 km above the surface should be capable of determining whether the source rocks are near the surface or deeply buried. With the upcoming centennial of human-powered flight in 2003, NASA has been seriously studying designs for a Mars Flyer that would be capable of flying in an atmospheric pressure only 1% that of the earth.

Suggestions for further reading. "Global distribution of crustal magnetization discovered by the Mars Global Surveyor MAG/ER experiment" by Acuna et al. (*Science*, 1999). "Numerical experiments in geomagnetic modeling" by Cain et al. (*Journal of Geomagnetism and Geoelectricity*, 1990). "Floating in space" by Smith and Cutts (*Scientific American*, 1999). "Magnetic petrophysics and magnetic petrology: Aids to geological interpretation of magnetic surveys" by Clark (*AGSO Journal of Australian Geology and Geophysics*, 1997). "Magnetic lineations in the ancient crust of Mars" by Connerney et al. (*Science*, 1999). *Origin and Thermal Evolution of Mars* by Schubert et al. (University of Arizona Press, 1992). *Martian meteorites in Planetary Materials*, by McSween and Treiman (Mineralogical Society of America, 1998). "The magnetic properties experiment on Mars Pathfinder" by Madsen et al. (*Journal of Geophysical Research*, 1999). *MarsAir* by Morton (Air and Space, 2000). *Elementary Gravity and Magnetics for Geologists and Seismologists* by Nettleton (SEG, 1971). LE

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Corresponding author: M. Purucker, purucker@geomag.gsfc.nasa.gov

Michael Purucker is employed by Raytheon ITSS in the Geodynamics Branch, Goddard Space Flight Center. He is a coinvestigator on the Oersted mission to map the terrestrial magnetic field (launched in February 1999) and a coordinating scientist for the proposed joint NASA-CNES Dynamo mission to map the magnetic field of Mars in 2005. Prior to moving to NASA, Purucker was involved in the interpretation of magnetic surveys for petroleum and mineral exploration.

David Clark is a principal research scientist with the CSIRO Australia Division of Exploration and Mining. His research interests include magnetic petrology, interpretation of potential-field surveys, and applications of rock magnetism to exploration.