Seismological investigations of Mars' deep interior

White Paper for the NRC Planetary Science Decadal Survey

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The last decade has seen a host of spacecraft missions to Mars, featuring orbiters as well as landers. Several of them have been extraordinarily successful and greatly enhanced our knowledge about this planet in a variety of fields. The orbiters have provided detailed information about the gravity and magnetic field, produced a comprehensive set of topographic and photographic information about the surface that is in some respect superior even to that available for Earth, and collected various kinds of data about the mineralogical and chemical composition of the surface. Landing devices have explored the surface close-up and made it possible to analyze surface composition and geological context on a small scale. It is fair to say that photos from the martian surface like those taken by the *Spirit* and *Opportunity* rovers are widely known and popular far beyond the planetary science community.

In blatant contrast to this abundance of data on the surface features and properties of Mars is the scarcity of knowledge about anything deeper than a few meters to a few kilometers. Perhaps the most drastic example of our ignorance is that we do not know the size of the martian core to a precision better than a few hundred kilometers, nor its state – liquid, solid, or both –, because the only constraints available come from the relatively low-resolution techniques of gravity and moment-of-inertia analysis. Likewise, our knowledge about the composition and the thermal and mechanical state of the mantle and core is fraught with considerable uncertainty, in spite of the information gleaned from gravity or meteorite analyses and inferences made from petrological experiments.

In this White Paper we make the case that long-term seismological experiments on Mars are indispensable for understanding the processes that have shaped, and possibly still shape, its interior and surface and for putting the information from past and ongoing missions into a comprehensive, meaningful context. This is because seismology, more than any other observational method in geophysics, has the potential of providing data on the structure and mechanical properties of a planet on a global scale, and it is these factors that control, through their influence e.g., on dynamo activity and magmatism, many of the processes and features at the surface and in the atmosphere, including the hydrosphere and a potential biosphere; related seismological applications and benefits from additional geophysical methods are also explained in an independent White Paper for this Decadal Survey by Banerdt *et al.* On Earth, such fundamental insights like the discovery of the core by Oldham in 1906, the discovery of the inner core by Lehmann in 1936, or the work of Wadati around 1930 and of Benioff in the 1950s that led to the discovery of subduction and hence to a basic understanding of earthquakes were made possible only by seismology. On Mars, the need for this basic type of information had been recognized when the *Viking 1* lander was equipped with a seismometer. However, the device did not operate correctly, and as no second attempt has ever been brought to completion, we are still lacking this fundamental knowledge.

Open questions to be addressed by seismology

Seismicity and current tectonics. Mars is a one-plate planet and therefore lacks the classic major seismic sources of earthquakes on Earth, which are related to plate boundaries. Nonetheless, fault systems are observed in many places (Dimitrova *et al.*, 2008) and are a potential seismic source (Golombek *et al.*, 1992). In case of ongoing magmatic activity, volcanic quakes would be another source. Lognonné (2005) suggests that although marsquakes are likely much weaker than earthquakes, about 100 events per year may be detectable and useful. The observation and location of marsquakes and even the mere quantification of their abundance would give information about several aspects of martian tectonics, e.g., the depth extent of the brittle lithosphere or at least of active faults and their geographic distribution, and the present-day magnitude of ongoing thermal contraction. It may also yield clues about potential volcanic or plutonic activity and hence about the thermal state of the crust and mantle.

Thickness and structure of the crust. Attempts have been made to derive crustal thicknesses from gravity and areoid data. Mean crustal thickness estimates range from $\sim$30 to 150 km (e.g., Nimmo and Stevenson, 2001; Wieczorek and Zuber, 2004), and numerical modeling indicates that the value is very sensitive to mantle temperature (Breuer and Spohn, 2006). Magnetic observations (e.g., Voorhies, 2008) can only provide a lower bound and depend on assumptions about induced magnetization and the timing of the demise of the dynamo. Seismograms, by contrast, would provide much tighter constraints on the thickness of the crust, and maybe also of the lithosphere. Furthermore, suitably placed seismometers would not only clarify the global structure of the planet, but can also deliver information about crustal structure in the neighborhood of the stations. Seismometers on both the northern and the southern hemisphere of Mars may therefore reveal differences in crustal structure that can elucidate the cause for the crustal dichotomy.

Melt and water in the mantle. Tidal dissipation studies (Bills *et al.*, 2005) find evidence for an extraordinarily low effective viscosity of the bulk planet that may require explanations in addition to a fluid core, and they offer the presence of partial melts and of volatiles as candidates. Seismological measurements are sensitive to the presence of melt and can, to limited extent if concentrations are high enough, also give some indication for the presence of water in mantle minerals (Sato *et al.*, 1989; Karato, 2003). If seismic velocities and maybe also attenuation can be deduced from martian seismograms, the extent of melting in the martian mantle could be determined. This would not only help to solve the dissipation problem, but can put much tighter constraints on the thermal history and current state of the mantle; moreover, it could test hypotheses about the presence of volcanism.

The water content of the martian mantle is controversial, and evidence has been put forth for an almost dry mantle (e.g., Wänke and Dreibus, 1994) as well as for a quite water-rich one (e.g., McSween *et al.*, 2001). Clarification of this issue has direct implications for water on the surface of Mars, because a major part of the surface water that is thought to be, or have been, there will have originated from the planet's deep interior. Seismological data do not offer unambiguous information about the water content of the medium traversed by seismic waves, although water does have an effect on seismic velocities and attenuation, but as water and other volatiles lower the solidus of mantle rock, it may be possible to put at least certain constraints on the water content by determining the depth range to which melt is present and comparing it with experimental determinations of the dry solidus (e.g., Schmerr *et al.*, 2001).

Iron content of the mantle. Analysis of martian meteorites indicates that the martian mantle has a higher bulk molar iron fraction X_{Fe} than Earth, but the precise value is not well known. While the most commonly used values lie around 0.25, some older studies proposed $X_{\mathrm{Fe}} \geq 0.3$; by contrast, recent work indicated that it may be as low as 0.15–0.2 (Musselwhite

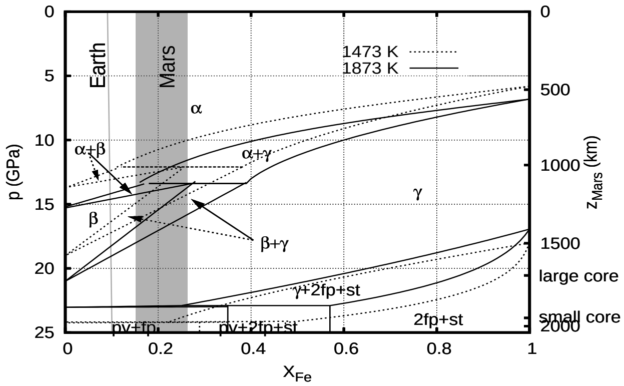

Figure 1: Isothermal phase stability fields of (Mg,Fe)$_2$SiO$_4$ at two different temperatures versus pressure and iron content. The depth scale corresponds to the martian mantle and is approximately valid within the "Mars" interval (shaded) of X_{Fe}. "Large core" and "small core" refer to bounds on the depth of the core–mantle boundary that include most of the published estimates.

et al., 2006). The more likely values are indicated by a gray strip in Figure 1 and show that in this range, small variations in X_{Fe} can alter substantially the succession of phase transitions and the pressure at which, and pressure range over which, they happen. Even though martian phase transitions may not yield such a sharp seismological response due to the much larger depth range they cover, seismological data can be expected to provide useful information about their position and depth extensions and thereby clarify the question about the iron content, which has major implications for mantle chemistry. They would also provide constraints on the areotherm over at least half of the depth of the mantle.

Size of the martian core. Seismological data would put tight constraints on the size of the core. The phase diagram of the $(\mathrm{Mg, Fe})_2\mathrm{SiO}_4$ system (Figure 1) shows that the bounds on the depth of the core–mantle boundary happen to bracket the phase transition from ringwoodite (γ-olivine) to perovskite+ferropericlase, which is the most important phase boundary in the Earth's mantle. From the exact position of the core–mantle boundary, it would be possible to tell if there is, or has been, the possibility of a basal perovskite layer in Mars' mantle. If it exists, the position of the phase boundary would also yield information about the temperature at that depth. Various numerical studies of mantle convection (e.g., Harder, 2000; van Thienen *et al.*, 2006) have demonstrated that solid-state phase transformations have a major impact on convection dynamics and that especially the transition to perovskite would alter convection patterns substantially and reduce heat flow from the core. This issue is therefore crucial for the thermal evolution and can give clues about the deep causes for the volcanic provinces of Tharsis and Elysium and the extent of present-day volcanism.

History of the magnetic field and state of the core. The magnetized crust (e.g., Acuña *et al.*, 1999) gives evidence for an ancient planetary dynamo in the martian core. The lack of an intrinsic large-scale field at present indicates that at some point in the planet's history the dynamo has ceased to exist. The extinction of the dynamo may have been caused by different factors. Vigorous thermochemical convection, necessary for the dynamo to function, depends on the state and thermal history of the core and its coupling with the mantle. While some studies lean towards a liquid-core model for Mars, this question is still undecided, and it is again seismology that can deliver the clearest answer. Martian core phases would provide information about the state of the core, and reveal the existence and, if applicable, the size of the inner core. Although seismological information is not sufficient to pinpoint values for the temperature of the core and the concentration of the light element (or indeed identify it), it can help to tighten the constraints on these properties.

Information about the structure and properties of the core is crucial for reconstructing the morphology, history, and strength of the dynamo and for understanding its extinction. The history of the dynamo is relevant not only with regard to the internal dynamics, but also because the presence of a magnetosphere stabilizes the atmosphere by protecting it from erosion by the solar wind (e.g., Chassefière and Leblanc, 2004).

Technical feasibility and expectations

The ability to address the science goals outlined above is highly dependent on the technical capabilities and geometry of seismometers deployed on Mars; here we discuss the details of instrumentation and several potential deployment geometries. At a minimum, seismometers on Mars must possess the capability to record seismic energy with the following criteria: 1) over a frequency range of 0.001 Hz–10 Hz, 2) on three orthogonal components, 3) over a dynamic range of at least 24 bits, and 4) with an effective sensitivity (measured in acceleration power spectral density units) of $< 10^{-9}\,\mathrm{m/s^2/Hz^{1/2}}$ (Lognonné *et al.*, 2000). An instrument with a sensitivity over a large frequency range will be capable of detecting surface waves, normal modes, and body wave arrivals, such as the direct P and S waves, as well as reflected (e.g., sS, ScS), and converted (sP, PKIKP) arrivals. The use of three orthogonal components is necessary for the proper seismic analysis of body and surface waves. A large dynamic range is required to allow the instrument to record both seismicity at large epicentral distances and still retain the ability to record events near the seismic station. A high sensitivity ensures the detection of the small number of seismic events expected for Mars (Lognonné, 2005). A high effective sensitivity is also necessary to observe body waves at teleseismic distances, as the martian mantle is predicted to be similarly highly attenuating as Earth's upper mantle or even more (Bills *et al.*, 2005). Due to these requirements for high sensitivity, the seismometers must be isolated from the diurnal and seasonal changes in the martian atmospheric pressure and temperature, decoupled from the spacecraft/lander, and shielded from the effects of wind energy. In addition to these technical challenges, multiple seismometers must be deployed in a systematic way to enable studies of the martian interior. We explore several potential deployment geometries below as first steps towards a permanent seismic network on Mars.

Option 1: Small Global Network. Our first proposed arrangement is a small global network of two seismometers, separated by at least 3000 km, and operating concurrently over a span of at least 1–2 martian years. This network arrangement is the minimum number of seismometers required to produce a sufficient seismology science return (ILN Final Report, 2009). At least one seismometer would need to be placed near a region of presumable seismic sources (such as the Tharsis volcanic region), and the other located at a teleseismic distance. The near-source station would provide source origin times and allow the measurement of travel times for mantle and core traversing body waves. If sufficient energy from the excitation of normal modes from atmospheric coupling is present, it may be possible to detect the state and size of the core (Kobayashi and Nishida, 1998; Van Hoolst *et al.*, 2000). This small network would provide preliminary estimates of the event magnitudes and amount of seismic activity on Mars, but give little information on the location of seismic events. The inclusion of a third, additional seismometer would allow for the location of seismic sources. The small network would also provide constraints on mantle attenuation and crustal scattering properties and establish the seismic noise environment of Mars.

Option 2: Global Network. A more desirable second option is a global network of four or more seismometers, each separated by 3000 km, and operating concurrently over a span of $\geq$2 martian years, a deployment similar to the proposed NetLander experiment (Lognonné *et al.*, 2000). This is the optimal arrangement for providing reliable event locations and timing and for the detection of a sufficient number of sources for studying the properties of the interior. The seismometers need to be distributed over large distances and preferably above provinces of current planetary geological interest to best provide detailed structure of the martian crust, mantle, and core. Ideally, each seismometer will be placed with an antipodal duplicate, with at least two seismometers placed in the northern hemisphere and two in the southern hemisphere. This geometry also provides accurate estimates for crustal thickness in each region and ensures the recording of core and mantle traversing phases. More seismometers naturally provide additional information on the interior and better constrain source location and timing. The deployment of a global network will allow the application of many of the advanced signal processing techniques used to determine Earth structure from terrestrial seismograms.

Option 3: Regional seismic array. Another option is the deployment of a dense, regional network ($<$500 km aperture) of four or more seismometers in a region of high seismicity, and operating concurrently over a span of $\geq$2 martian years. This option is similar in geometry to the Apollo Lunar Surface Experiment Package, which provided details of the lunar interior and location of surface and deep moonquakes (for a review, see Wieczorek *et al.*, 2006). On Earth, seismic arrays are used to increase the coherency of low-amplitude seismic arrivals, determine the location and timing of seismic sources, and to map the small-scale and detailed structure of the interior. The placement of such an array would require prior knowledge of martian seismicity and is therefore less desirable as an initial deployment geometry. However, a small regional array will return much more detailed images of local seismic heterogeneity (e.g., Rost and Thomas, 2002) and resolve regional structure of the core, mantle, and crust (e.g., the origin of volcanism beneath the Tharsis or Elysium regions).

Implications for interdisciplinary science

The information delivered by a seismological observation program will not only have important implications for the interpretation of results of many other branches of Mars research as explained above, but will also guide the development of models of martian dynamics, geology and evolution that integrate the knowledge from a broad spectrum of disciplines. For instance, numerical geodynamical models of the martian mantle and core will directly benefit from better knowledge of the planet's interior. At this point, general numerical investigations of the martian mantle always have to consider a case with and a case without the basal perovskite layer if the important effects of phase transitions are included. With seismological constraints, this necessity would disappear, and the range of several other basic model parameters like initial temperatures or rheological parameters could be narrowed considerably, making convection studies much less ambiguous with respect to the interpretation of their results. More realistic numerical models of the thermal and chemical evolution of the mantle may help to assess the current volcanic activity of Mars and contribute to resolve how much of any surface water can have come from the deep interior, and over which time span it was released.

The chemical evolution of the mantle is therefore linked to the evolution of the atmosphere and controls how long clement conditions on the surface may have persisted. Mantle and core dynamical models with improved constraints may also make it possible to explain the reason for the cessation of dynamo activity that set the stage for the erosion of the atmosphere, the concomitant increase of exposure of the surface to radiation, and the disappearance of those clement conditions. These processes are obviously directly related to the question of the possibility of early life on Mars. In a more direct form, seismology can also probe the potential existence of life on current Mars. As volcanically active regions provide energy, they are potential harbors of life. Seismologically detected and localized volcanic tremors can therefore help to identify regions at the surface where martian lifeforms are most likely to be discovered, if they exist; this approach is less dependent on assumptions about the properties of such lifeforms than e.g. inferences made from the detection of methane.

Finally, quantitative information about the spatial and temporal pattern of current seismicity and magmatic activity of Mars is also a matter of concern for future manned and unmanned missions with respect to the selection of mission target, but also for safety reasons.

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