fast propagating planetary or synoptic wave packet, (2) the life cycle of a tropical storm, including extratropical transition and redevelopment, and (3) orographically induced mesoscale phenomena, all in the global environment.

Our ocean general circulation model (OGCM), named OFES (OGCM for the ES), was adopted from MOM3 (Modular Ocean Model version 3) developed at the Geophysical Fluid Dynamics Laboratory of the U.S. National Oceanic and Atmospheric Administration. OFES has also been highly optimized for the ES architecture. A snapshot of horizontal current speed shown in Figure 2 demonstrates the great ability of OFES in representing mesoscale features in the Antarctic Circumpolar Current region; these features include a number of local meanders embedded in the strong and complicated eastward currents reflecting frontal structures as well as realistic mesoscale eddies such as the Agulhas Rings off the southern tip of Africa.

The significance of this simulation may be recognized by analyzing the OFES outputs, especially in the following research topics: (1) interannual variability caused by interaction between large-scale and mesoscale circulations, (2) effects of eddies on formation of near-surface ocean climate, and (3) topographic effects on the ocean circulations. OFES may also be used as a reference for low-resolution models.

Preliminary outcomes of these simulations are reported in the new, peer-reviewed semi-online Journal of the Earth Simulator [*Ohfuchi et al.*, 2004; *Masumoto et al.*, 2004]; see http://www.es.jamstec.go.jp/esc/images/journal200404/index.html).

In *Geophysical Research Letters*, Sasai et al. [2004] report preliminary results of tracer transport in an OFES simulation.

The AFES and OFES Task Teams are planning to open the results of these and ongoing simulations to the research community under mutual agreement. For more information, contact the corresponding author.

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MEETINGS

Hemispheres Apart: The Martian Crustal Dichotomy

PAGES 46–47

Mars is a world divided—divided into ancient, heavily cratered highlands in the southern hemisphere and relatively featureless lowland plains in the northern hemisphere (Figure 1). This hemispheric dichotomy is manifested not only in the topography, but also in the geology, the tectonics, the cratering record, the gravity and magnetic field, and the crustal structure. The contrast between hemispheres has been brought into sharp focus by the unprecedented amount of new data returned by the fleet of operational spacecraft in Mars orbit (Mars Global Surveyor, Mars Odyssey, and Mars Express) and on the surface (Mars Exploration Rovers).

However, the origin of perhaps the most fundamental feature of the crust of Mars remains uncertain. The formation of the crustal dichotomy may have set the course for most of the subsequent geologic evolution of Mars, including the Tharsis volcanic and tectonic province.

Since the discovery and initial characterization of the Martian crustal dichotomy in the 1970s, two opposing classes of models for its origin have emerged. Exogenic (externally driven) models invoke either one giant impact or multiple impacts to remove crust from the northern lowlands. Endogenic (internally driven) models form the northern lowlands through either subcrustal transport of lowlands crust by mantle convection, the generation of thinner crust by plate tectonics, or as a consequence of an early magma ocean. In the decades that followed, no consensus on the origin of the dichotomy was reached.

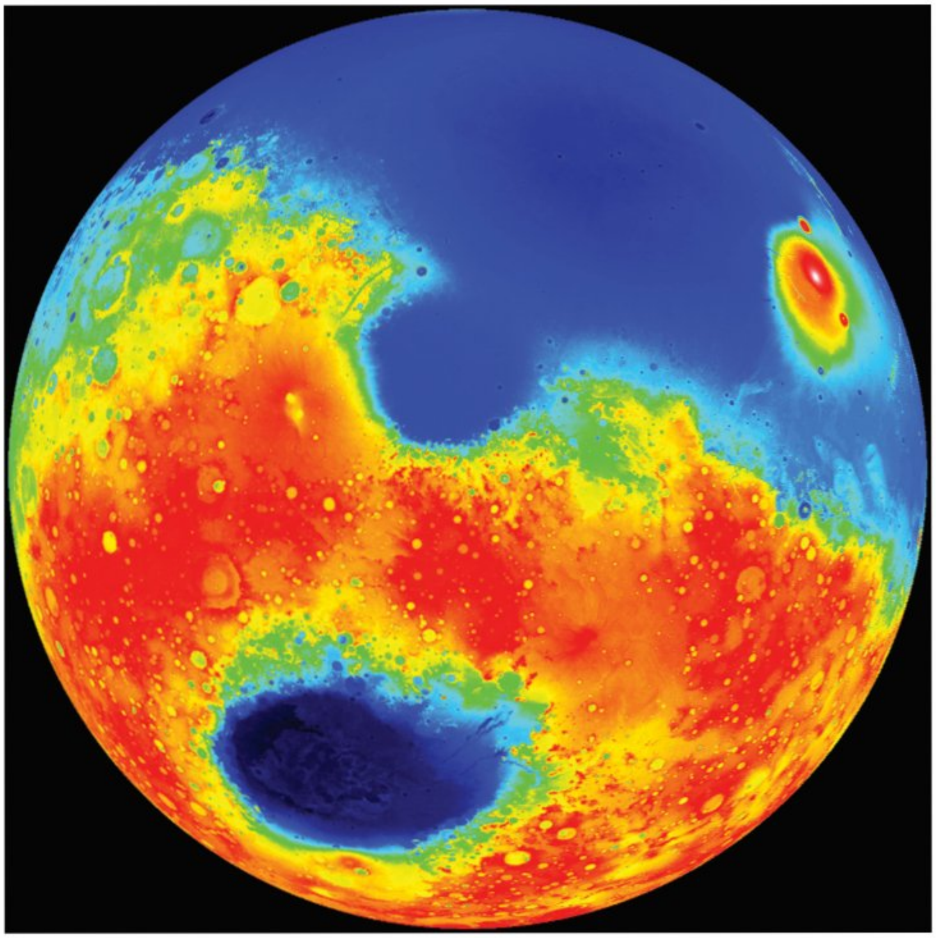

Fig. 1. Color-coded digital elevation model combined with a shaded relief map of the eastern hemisphere of Mars. The topographic data were obtained by the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor spacecraft. The Martian crustal dichotomy in the eastern hemisphere is expressed by the dramatic change in elevation between the southern highlands and the northern lowlands.

A new view of the hemispheric dichotomy is now taking shape. The identification of quasi-circular depressions in the northern lowlands suggests a population of buried impact craters and basins. Thus, the northern lowlands crust may be about the same age as the ancient southern highlands crust.

New evidence also points to later tectonic modification of an ancient dichotomy boundary, the deposition and erosion of material along the dichotomy boundary by fluvial, aeolian, and glacial processes, and widespread resurfacing of the northern lowlands by volcanism and sedimentation.

In an effort to assess the current understanding of the origin and evolution of the dichotomy, a two-day workshop was held last fall in Houston, Texas. "Hemispheres Apart" brought 37 scientists together to discuss both observational and theoretical viewpoints and to foster future research directions. The workshop consisted primarily of contributed talks and posters and was kicked off by four invited overview talks. Time was allowed for extended discussion, and the exchanges were so lively that an impromptu discussion session continued until it was preempted by the first U.S. presidential debate. The workshop ended with a panel-led discussion of current issues, new directions for investigation and modeling, and upcoming data sets and future mission opportunities.

Workshop Highlights

The following is a brief summary of some of the contributions to the workshop (the abstracts are available at http://www.lpi.usra.edu/meetings/hemispheres2004/).

One of the most significant outcomes was the convergence of opinion that the hemispheric dichotomy is an ancient feature of the crust of Mars. The populations of buried and exposed impact basins in the highlands and lowlands suggest early Noachian ages (the Noachian epoch is from planet formation to ~3.7–3.5 Ga, where Ga = 1 billion years B.P.) for the crust, and are consistent with dichotomy formation by "lowland-making" impact basins before 4 Ga (H. Frey). Further, isotope data from the Shergottites, Nakhlites, and Chassigny (SNC) meteorites, and predictions from planetary accretion models, suggest that the Martian crust (and, by inference, the global-scale dichotomy) formed very early in the geologic history of the planet, perhaps within 50 million years after the formation of the solar system (S. C. Solomon).

Plate tectonics is responsible for the contrast in crustal thickness between continental and oceanic crust on Earth. An early phase of Martian plate tectonics could account for the dichotomy in crustal thickness and an ancient lowlands crust. Alternatively, transport of crustal material by degree-one mantle convection may have thinned and thickened the crust above zones of upwelling and down-welling, forming a lowlands crust not much younger than the highlands crust (S. Zhong et al.).

A very early age of formation of the Martian crust and the dichotomy presents a challenge to these endogenic models because both require timescales of the order of several hundred million years to either recycle the crust or to establish convection patterns after solidification of a magma ocean (S. C. Solomon).

One endogenic process that can satisfy early-rapid formation of the dichotomy is heterogeneous development of a magma ocean (S. C. Solomon). The problem then is how to localize a dichotomy in crustal thickness to its largest possible scale: hemispheric. Crystallization of an early magma ocean could result in a gravitationally unstable mantle that rapidly overturned (L. T. Elkins-Tanton et al.). This overturn event could have triggered the formation of the crustal dichotomy if the scale of mantle overturn was hemispheric (degree-one).

An exogenic origin by many giant impacts satisfies the constraint that the dichotomy must have formed very early in the geologic evolution of Mars (H. Frey). A significant portion of the northern lowlands can be correlated with the Utopia, Acidalia, and Chryse quasi-circular depressions. However, broad expanses of the lowlands lack the topographic or gravity signature of buried basins. Also, impact-related topographic depressions that formed very early when the heat flow was high and the mechanical lithosphere was thin must survive removal by magmatism and crustal flow (S. C. Solomon).

The dichotomy is also expressed in the crustal magnetization data. Although the strong remanent magnetic field preserved in the southern highlands extends beyond the dichotomy boundary, it is weak to absent throughout much of the northern lowlands. The most recent map of the magnetic field suggests that the northern lowlands crust also recorded an early magnetic field. It was suggested that this record may have been lost by widespread volcanic resurfacing of the northern lowlands after the magnetic dynamo shut down (J. E. P. Connerney et al.). The formation of the crustal dichotomy may also be directly related to the demise of the early dynamo. The overturn of the magma ocean may have moved cold cumulates to the core-mantle boundary, facilitating rapid cooling of the core (L. T. Elkins-Tanton et al.).

The expression of the boundary between the highlands and lowlands is most dramatic in the eastern hemisphere (Figure 1). There is growing evidence supported by new geologic mapping that the present-day dichotomy boundary in the eastern hemisphere has evolved from an ancient, poorly understood transition zone between the hemispheres (J. A. Skinner et al.).

Knobby and fretted terrain along the dichotomy boundary indicates a long and complex history of erosion. Groundwater flow and sapping exploited fractures and faults to modify the boundary in the Noachian and Hesperian (the Hesperian epoch is from ~3.5–3.7 to ~2.9–3.3 Ga) until the emergence of the global cryosphere in the Amazonian (the Amazonian epoch is from ~2.9–3.3 Ga to present). Degradation continued in the Amazonian by ice-assisted creep and glacial activity, possibly during Martian ice ages (J. W. Head et al.). Fretted terrain is generally interpreted to be erosional remnants of highland materials. However, there is evidence that fretted terrain may have formed in a thick sequence of aeolian sediments deposited along the dichotomy boundary in the late Noachian-early Hesperian while fluvial activity was in decline (R. P. Irwin et al.).

Extensional troughs and fault-controlled fretted valleys in the lowlands along the dichotomy boundary and lobate scarp thrust faults in the adjacent highlands suggest tectonic modification of the ancient boundary during the late Noachian-early Hesperian. Extension may have resulted in down-dropped blocks of highland material expressed by cryptic faults in the lowlands (G. E. McGill et al.) that may correlate with gravity and magnetic field anomalies along the dichotomy boundary (S. E. Smrekar et al.).

Analytical and numerical modeling suggests that the long-wavelength topography of much of the dichotomy boundary in the eastern hemisphere is consistent with flexure of the southern highlands lithosphere (T. R. Watters et al.). While these models can account for the location of the extensional and compressional tectonic features associated with the dichotomy boundary, global contraction must be invoked either to fit the long-wavelength topography or to obtain large enough compressional stresses to generate thrust faults (P. J. McGovern and T. R. Watters).

Alternatively, the elevated highlands near the dichotomy boundary may have relaxed over time (A. Guest and S. E. Smrekar). Relaxation by lateral flow of the lower crust may result in highland compression and lowland extension, consistent with the location of the tectonic features (F. Nimmo). However, in some regions the observed topography of the dichotomy boundary is not well matched by relaxation models.

The dichotomy boundary in the eastern hemisphere is reminiscent of a terrestrial continental margin. If the dichotomy boundary can be viewed as the edge of a large craton, large lateral thermal gradients there may give rise to "edge-driven convection." Modeling suggests that edge-driven convection may have initiated formation of the long-lived Tharsis volcanic province (S. D. King and H. L. Redmond).

New Opportunities and Data

It will come as no surprise that the array of new data for Mars has raised as many questions about the crustal dichotomy as it has answered. The discovery of subtle, quasi-circular topographic depressions in the northern lowlands that may be ancient buried impact basins, the suggestion that lowlands crust was demagnetized by volcanic plains, and the discovery of subdued ridges buried by sediments of the Vastitas Borealis Formation that may be wrinkle ridges like those in exposed early Hesperian ridged plain volcanics have punctuated the need to characterize the subsurface geology.

The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) on Mars Express may be capable of probing the subsurface to depths of 3–5 km, particularly in the northern lowlands where the surface roughness is low. MARSIS deployment in March 2005 will provide the best opportunity to collect subsurface data for much of the northern lowlands.

Understanding the deep internal structure will ultimately require seismic data and a mission like the now defunct Mars NetLander. A critical area for future work that was identified is modeling of basin-scale impacts to determine if the observed difference in crustal thickness can be accounted for by multiple impacts. Our understanding of the effects of giant impacts on crustal structure is in an embryonic stage.

The "Hemispheres Apart" Workshop was held on 30 September–1 October 2004 at the Lunar and Planetary Institute in Houston, Texas.

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The International Water Cycle Workshop

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Scientists from Japan, Europe, and the United States met at the International Water Cycle Workshop, in Seattle, Washington, last summer. The goals of this workshop were to review a draft implementation of the water cycle component to the Global Earth Observing System of Systems (GEOSS), and to develop a companion "water cycle road map" that would provide specific actions and timetables for its implementation.

This meeting was an outcome of the 10th U.S.-Japan Workshop on Global Change, Climate and Water, held in Irvine, California, in January 2003, and the Group of Eight (G-8) Earth Observing Summits I and II. The meeting was timed to align with the G-8 GEOSS Implementation Plan expert review period (15 July to 25 August 2004).

Earth Observation (EO) Summit I, held on 31 July 2003 in Washington, D. C., promoted the development of a comprehensive, coordinated, and sustained Earth observation system, including the conceptual framework and implementation plan for such a system (http://www.earthobservationsummit.gov/). This summit was followed by the G-8 Action on Science and Technology for Sustainable Development, which included a commitment to strengthen international cooperation on global observations and strategies for the next 10 years; to identify new observations to minimize data gaps; to build on existing work to produce reliable data products on atmosphere, land, fresh water, oceans, and ecosystems; to improve the worldwide reporting and archiving of these data and fill observational gaps of coverage in existing systems; to favor interoperability with reciprocal data-sharing; and to develop an implementation plan to achieve these objectives.

EO Summit II, held on 25 April 2004 in Tokyo, Japan, began to develop a 10-Year Implementation Plan (TYIP) that will be presented at Earth Observation Summit-III in Europe in early 2005. At EO Summit-II, a framework document was developed, agreed upon, and adopted for Earth observations. The document includes an implementation of in situ measurements, satellite observations, and modeling systems for "achieving comprehensive, coordinated, and sustained Earth observations for the benefit of humankind."

The International Water Cycle Workshop reached the following overarching conclusions and recommendations with regard to the water cycle activities of GEOSS, all of which were incorporated into the expert review.

1. The GEOSS must have international data-sharing and exchange agreements with all nations that wish to be members. These agreements would specify that the GEOSS-required data and related metadata be made available in a timely manner to GEOSS regional and central data centers that would then distribute the data to the GEOSS community. There would be no costs borne by GEOSS for the acquisition of these data.

The members of the workshop noted that global hydrologic data are at present neither freely nor openly available, and that this is a major impediment to global water cycle research and affects the exchange of information about the status of the world's water resources. GEOSS has been encouraged to adopt an open data policy and to consider this workshop's option as one way to achieve this goal.

2. For GEOSS to fulfill its goals of providing data products for water decision-making, it must establish data and modeling synthesis centers. These centers would receive data from national data centers operating in situ data networks, climate data from national and international climate data centers, remote sensing data and products from operational remote sensing data centers, data from the GEOSS water reference sites, and experimental data collected under international programs such as the WCRP.

GEOSS needs to work with space agencies in developing priorities and specifications for new and enhanced space-based observations. The GEOSS synthesis centers would host process and management water cycle models; assimilate the above data into models; develop data products, including real-time data-based products; and make predictions in support of water-related decision-making. The workshop recognized the potential of the Coordinated Enhanced Observing Period (CEOP) data center at the University of Tokyo to serve as one of these GEOSS synthesis centers but encouraged governments and GEOSS to develop more centers.

3. To better ensure that the GEOSS 10-year implementation plan goals are met, demonstration projects need to be funded in the early stages of the implementation period. These projects need to test components of the end-to-end GEOSS data, modeling, and decision support system. The projects need to show the relevance of the GEOSS products to local and regional water management decision-making, with an emphasis on value-added data products for data-poor locations. GEOSS and the IGOS-P Global Water Cycle Observations (IGWCO) theme have been encouraged to use demonstration projects as part of their capacity-building activities.

4. GEOSS should give capacity-building a central role in its implementation. Capacity-building is essential for GEOSS to ensure the commitment of developing countries and maximize the benefits that humanity derives from its implementation. Through early pilot capacity-building projects, the benefits of GEOSS data will be demonstrated. Capacity-building will also include major upgrades in the hardware and software available in developing countries. It will provide training programs that will allow their water managers to acquire the training and "hands-on" experience needed to improve regional observing networks, and to analyze and interpret the products developed from these observations. GEOSS has been encouraged to adopt a comprehensive capacity-building strategy.

5. The workshop recognizes that many of the water cycle issues raised above are relevant to other GEOSS groups, and a framework for discussion with these groups needs to be developed by GEOSS. Participants at the workshop expressed a willingness to assist GEOSS by participating in such a framework.

GEOSS must facilitate the enhancement of data products for decision makers by utilizing a greater range of data and by increasing the interaction and collaboration between data providers, modelers, and users. The needs for data exchange and regionalization must be adopted as a critical underpinning for the GEOSS agreements and its governance process.

GEOSS should establish mechanisms that will give users a voice in indicating their priorities and provide them with opportunities to participate in GEOSS applications. Furthermore, the GEOSS structure must also facilitate the improved coordination of responsibilities and activities between the large number of international water projects and programs such as