NEWS & VIEWS

PLANETARY SCIENCE

Forming the martian great divide

Walter S. Kiefer

Early in its history, Mars suffered a convulsion that left a lasting geological and topographical scar. The latest work adds to evidence that the cause was external — a massive impact.

Mars is a divided planet. Its southern highlands cover about two-thirds of the planet and are on average about 4 kilometres higher than the northern plains, a difference that is known as the hemispheric dichotomy[1] (Fig. 1). Like an ice cube floating in water, the high topography is held up by the buoyancy of thicker crust (Fig. 2, overleaf) — the crust is about 25 km thicker in the highlands than in the lowlands[2]. On the basis of the number of impact craters in both the highlands and lowlands, the dichotomy is thought to have formed more than 4 billion years ago, during the first few hundred million years of martian history[3]. Moreover, the location of the boundary between the highlands and lowlands may have controlled the subsequent location of Tharsis[4], the largest and possibly longest-lived volcanic region in the Solar System.

Unravelling the processes that formed the hemispheric dichotomy is essential to understanding the earliest history of Mars. Previous explanations have invoked either the impact of a large asteroid or comet[5], or large-scale convective circulation in the martian mantle[6]. But observations by spacecraft have not yet permitted a clear choice between these possibilities.

Three papers in this issue[7–9] provide insight into this problem, and collectively strengthen the plausibility of the giant-impact model. One of the difficulties in testing the different hypotheses is that 30% of the boundary between highlands and lowlands is masked by later Tharsis volcanism. Andrews-Hanna *et al.*[7] (page 1212) used gravity observations to subtract the contribution of Tharsis volcanism from the crust and thus estimated the crustal signature of the dichotomy boundary in this part of Mars.

The key to their approach is that, because Mars has cooled with time, its elastic lithosphere (the strong, outermost layer of the planet) was thicker when the Tharsis volcanoes formed than when the hemispheric dichotomy formed. Assuming that the lithosphere was at least 100 km thick by the time the bulk of Tharsis volcanism occurred, Andrews-Hanna *et al.* show that the northern lowlands have an elliptical shape that is roughly 10,600 km by 8,500 km across. The statistical uncertainty in the basin dimensions is a few hundred kilometres. The authors conclude that the elliptical basin — known as the Borealis basin — is plausibly the signature of the largest impact in the Solar System. They also argue that this shape cannot be produced by convective flow in the mantle.

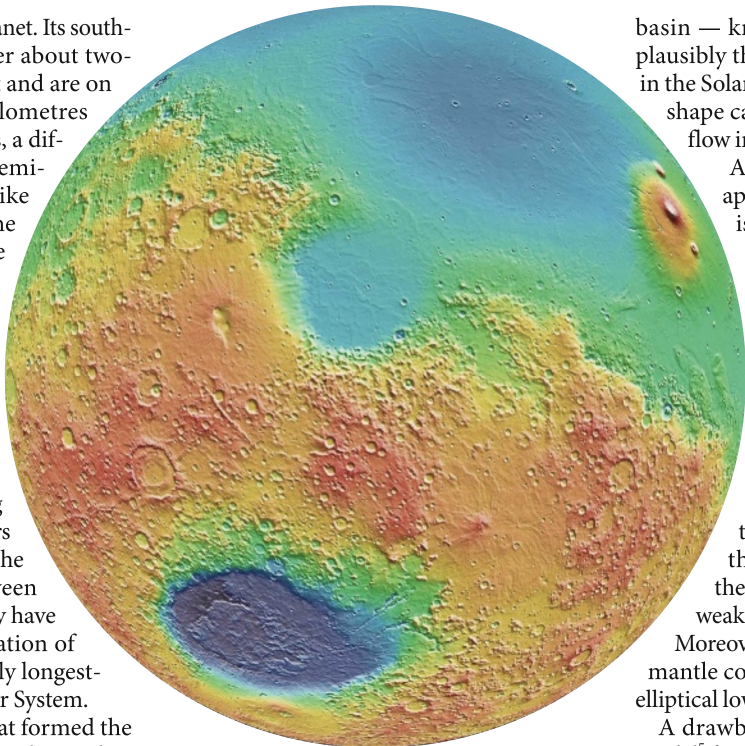

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Figure 1 | The martian hemispheric dichotomy. This image of Mars's eastern hemisphere provides a vivid depiction of the dichotomy, with the southern highlands appearing in red–yellow and the northern lowlands in blue. The hemispheric dichotomy may be due to the impact of a massive asteroid early in martian history[7–9], producing a proposed ~10,000-km-wide impact structure called the Borealis basin as the northern lowlands. The Hellas basin (lower left) is also an impact structure, but at 2,300 km across is much smaller. Another of Mars's geological structures, the Tharsis volcanic region, is on the opposite side of the planet to that shown here.

A potential problem with the approach of Andrews-Hanna *et al.*[7] is its sensitivity to the thickness of elastic lithosphere. Although some independent evidence[10] supports the assumption of a thickness of 100 km or more, other observations[11] suggest that the lithosphere was less than 20 km thick during the Noachian period, about 3.8 billion years ago, when Tharsis began forming. If the lithosphere was less than 50 km thick during Tharsis formation, the elliptical shape calculated for the dichotomy lowlands is degraded[7], weakening the case for an impact model. Moreover, no calculations have shown that mantle convection is unable to produce an elliptical lowland basin.

A drawback of the original giant-impact model[5] for the dichotomy is that the resulting basin was assumed to be circular, as are the vast majority of small impact craters in the Solar System. By contrast, the northern lowlands are clearly elongated, with an eccentricity of ~1.2 (ref. 7). Three-dimensional hydrodynamic impact simulations by Marinova *et al.*[8] (page 1216) now show that the original reasoning was incorrect. Small impact craters are essentially formed on a flat surface, and thus are not sensitive to the spherical shape of the planet. But in an impact large enough to form the hemispheric dichotomy, one must consider the interaction of the impactor with the spherical planet. Marinova *et al.* show that, for planet-scale impacts, an oblique impact angle of 30–60° from the horizontal can produce the observed basin eccentricity. This range of impact angles is the statistically most likely range, and the authors' inferred impact velocity of 6–10 km s^{-1} is reasonable for a body intersecting the orbit of Mars. If the impactor was a rocky or metallic asteroid, it would have had to have been between 1,600 km and 2,700 km

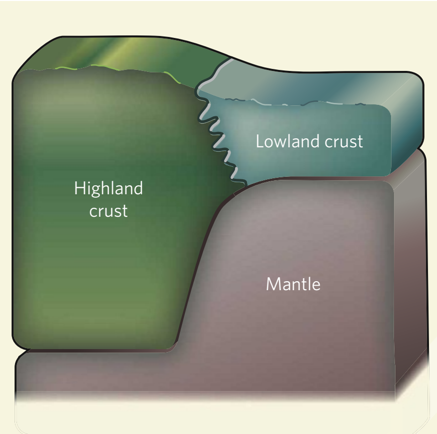

Figure 2 | Crust with a difference. **The southern highlands (left) consist of relatively thick crust and high-standing topography. The northern lowlands (right) consist of thinner crust and lower topography. In the impact model for dichotomy formation, which is supported by the new work[7–9], the crust also differs in composition. According to this model, the highland crust formed early in martian history, and consists primarily of basalt rock. The lowland crust formed by shock melting of the mantle during the impact event, and so is both younger and different in composition compared with the highland crust.**

in diameter to produce the observed basin size. For comparison, Mars itself is 6,780 km in diameter.

A limitation of the three-dimensional simulations done by Marinova *et al.*[8] is that the vertical resolution is 118 km. This is about twice as large as the estimated average crustal thickness[2], and thus details of crustal excavation and the resulting basin shape are not well resolved in these simulations. Nimmo *et al.*[9] (page 1220) have developed a complementary set of numerical models with a vertical resolution of 25 km in the crust and upper mantle. This provides a much better resolution of the behaviour of the crust during an impact, although the models are two dimensional and thus limited to vertical impacts.

In Nimmo and colleagues' models, almost all of the pre-existing crust is excavated from the centre of the impact basin, and a new, thinner crust is generated by shock melting of the martian mantle. The inferred impact energy is a factor of 3–5 lower than in the simulations of Marinova *et al.*[8]. This disparity is probably due mostly to the difference between vertical and oblique impacts. Nevertheless, the overall concordance of the two sets of models suggests that we now have a reasonable first-order understanding of the dynamics of the proposed impact event.

These three papers[7–9] strengthen the plausibility of the impact model for the hemispheric dichotomy on Mars, but they do not rule out mantle convection as the primary cause. One way to further test the impact model would be to gain a better understanding of the topographical variability along the proposed impact basin rim. In some places, the transition between highland and lowland occurs over just a few hundred kilometres, whereas in others a gradual change in elevation occurs over several thousand kilometres. The two boundary types also have distinct patterns in the gravity data. These differences have been proposed to be consequences of post-impact flow in the crust and mantle[7,12]. Development of quantitative models for these processes would be a great help in understanding the overall geological evolution of the proposed Borealis basin.

Another test relates to crustal composition in the highlands and lowlands. In the giant-impact model, most of the lowland crust formed by shock melting of the mantle[9] (Fig. 2). Extraction of the highland crust from the mantle modified the mantle's initial chemical composition. Impact-shock melting of the modified mantle is likely to have produced a lowland crust that differs in composition from that of the highlands. Some differences in composition between highlands and lowlands have been proposed on the basis of spectroscopy measurements made by orbiting spacecraft[13]. Impact-cratering statistics also suggest that the lowlands are slightly younger than the highlands[3]. Both observations are consistent with the impact model.

A more precise test of possible differences between highlands and lowlands would involve comparative analysis of bedrock composition in the two regions by future robotic landers. Landers could also measure how seismic-wave velocities vary with depth, which would provide a more comprehensive test of possible variations in composition throughout the entire thickness of the crust. Seismic measurements of crustal structure could also directly probe the proposed location of the dichotomy boundary in southern Tharsis.

Meantime, the main cause of Mars's great divide must remain a story without an ending. But appropriately enough, given the hundredth anniversary of the Tunguska event in Siberia celebrated elsewhere in this issue, these three sets of authors[7–9] have shortened the odds that it was produced when a huge impactor collided with a young Mars in what would have been an event of awesome proportions. ■

Walter S. Kiefer is at the Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, Texas 77058, USA.
e-mail: kiefer@lpi.usra.edu

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See Editorial, page 1143.

BEHAVIOURAL NEUROSCIENCE

Out of sight, but not out of mind

Seth M. Tomchik and Ronald L. Davis

Flies are cleverer than previously thought. They can remember their original destination even if distracted en route by another landmark. This behaviour depends on a specific group of neurons.

You are walking down a street to meet a friend at the end of it. You are early; so to kill time, you go into a café. After this brief detour, you continue on your way to meet your friend. While in the café, your original destination was out of sight, yet your brain held that goal in memory. Many such distractions occur during our daily tasks, yet in most cases we can remember and complete the original task. On page 1244 of this issue, Neuser *et al.*[1] demonstrate that the fruitfly *Drosophila melanogaster* can perform a similar task, and elucidate some of the mechanisms that the fly brain uses for this type of memory.

To determine whether flies can retain memory of a landmark when presented with a distraction, the authors used a modified version of Buridan's paradigm[2]. For the original paradigm, each fly is placed in a circular arena with two opposing black, vertical stripes on its walls. Normally, a fly will pace back and forth between the two stripes (Fig. 1a). But if the stripes are removed as the fly crosses the midline of the arena, it will maintain its heading, which suggests that it remembers the location of the stripes or its own trajectory[3].

Neuser *et al.*[1] devised a variation called the detour test. They removed the original target stripes as the fly was halfway through its second crossing, and immediately presented a distracter stripe on the arena wall either to the left or the right of the insect (Fig. 1b). Once the