hundreds to thousands of meters of ice can be deposited in some locations (*9*).

Recent geological mapping shows features at low latitudes best interpreted as glacial in origin (see the figure). Features occur in isolated low-latitude locations such as the flanks of the Tharsis volcanoes that are reminiscent of moraines, knobs formed as a residual similar to terrestrial water-ice sublimation hills, and flow-line morphology (*10*). Remarkably, these are the same locations for which dynamical models show preferential deposition of water ice (*9*).

Thus, the geological evidence supports the dramatic climate changes that would be induced by the changing obliquity. Indeed, large changes in the climate appear to be the natural consequence of the temporal oscillations of the system.

Surface features and geomorphology can also tell us much about the ancient climate. The occurrence of valley networks on the oldest surfaces and high erosion rates inferred from crater degradation and removal have long argued for a warmer and wetter environment on Mars earlier than about 3.7 billion years ago. The Sun was 30% less luminous then than it is today, increasing the greenhouse warming required to raise temperatures enough to allow liquid water. A thick CO_2 greenhouse atmosphere would have saturated at temperatures that were still too low, making a martian greenhouse problematic (*11*), and the radiative effects of dust or clouds may not have alleviated this problem (*12*). Impacts at the end of planetary formation may have mobilized water for brief periods, producing rainfall that might have formed the valley networks without requiring a sustained greenhouse (*13*). However, the timing of large impacts, the long tail in the decline of moderate-sized impacts and their climatic effects, and the requisite thickness of the atmosphere still need to be better understood.

Recent spacecraft results provide important new constraints on the history of liquid water. The Meridiani landing site for Opportunity has sulfate-rich deposits that require liquid water to have been present for sufficiently long times to have had significant geochemical effects (*14*). Mapping of these deposits from orbit (*15*, *16*) shows that they occur as regional rather than local deposits. Thus, the conditions allowing liquid water likely were produced by global rather than local conditions. In addition, clay minerals that are indicative of chemical weathering in the presence of liquid water occur only on the ancient surfaces (*16*).

These new results appear to have required the prolonged occurrence of liquid water during the early epochs. One possible mechanism is a relaxation of the constraints imposed by the faint young Sun (*17*). The early Sun would have been more luminous if it had been even slightly more massive; subsequent mass loss would have brought the Sun to its current mass. Allowable values of the early Sun's luminosity require less greenhouse warming, and a CO_2 greenhouse atmosphere is plausible. The measurements are few and the uncertainties large, however (*18*). And, if the faint young Sun problem is mitigated, the role of impacts in also mobilizing water is unclear.

The changes in our understanding of martian history and implications for climate and volatile evolution are not just minor tweaking of existing hypotheses; rather, they are changing our view of what the important processes have been. Admittedly, much uncertainty still surrounds the nature of the earliest climate and of the processes responsible for controlling it are still very uncertain. On the obliquity and the seasonal time scales, though, the evidence is both compelling and dramatic. As the history of liquid water is written in Mars' geological history, these new results, when properly digested, will be important for deciphering Mars' biological potential.

References

1. Planet Mars II workshop, Les Houches, France, 23 May to 1 June 2005.
2. P. C. Thomas *et al.*, *Icarus* **174**, 535 (2005).
3. J. P. Bibring *et al.*, *Nature* **428**, 627 (2004).
4. A. Colaprete *et al.*, *Nature* **435**, 184 (2005).
5. M. T. Mellon, B. M. Jakosky, *J. Geophys. Res.* **100**, 11781 (1995).
6. J. F. Mustard, C. D. Cooper, J. F. Rifkin, *Nature* **412**, 411 (2001).
7. J. Laskar *et al.*, *Icarus* **170**, 343 (2004).
8. B. M. Jakosky *et al.*, *Astrobiology* **3**, 343 (2003).
9. B. Levrard *et al.*, *Nature* **431**, 1072 (2004).
10. D. E. Shean, J. W. Head, D. R. Marchant, *J. Geophys. Res.* **110**, 10.1029/2004JE002360 (2005).
11. J. F. Kasting, *Icarus* **94**, 1 (1991).
12. F. Forget, R. T. Pierrehumbert, *Science* **278**, 1273 (1997).
13. T. L. Segura O. B. Toon, A. Colaprete, K. Zahnle, *Science* **298**, 1977 (2002).
14. S. W. Squyres *et al.*, *Science* **306**, 1709 (2004).
15. B. M. Hynek, *Nature* **431**, 156 (2004).
16. J. P. Bibring *et al.*, *Science* **307**, 1576 (2005).
17. I. J. Sackmann, A. I. Boothroyd, *Astrophys. J.* **583**, 1024 (2003).
18. B. E. Wood *et al.*, *Astrophys. J.* **628**, L143 (2005).

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GEOPHYSICS

The Ghost of an Earthquake

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Unlike the shadowy remains of departed souls, past earthquakes can leave traces that are detectable today with modern geophysical instrumentation. If large enough, a seismic event in the upper crust (less than about 15-km depth) can change the state of stress in the Earth to mantle depths (depths greater than about 30 km. These stresses subsequently relax over time scales of weeks to decades. The length of time needed to fully equilibrate depends on the material properties of the lower crust and upper mantle, and the size and style of the earthquake. On page 1473 of this issue, Gourmelen and Amelung (*1*) report evidence that relaxation following large earthquakes in the early to mid-20th century is presently observable in central Nevada. Because it is transitory, the presence of this signal has profound implications for our interpretation of geodetic data with respect to crustal deformation in the western United States.

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When subjected to loads, Earth's deep layers are thought to behave viscoelastically. Viscoelastic materials exhibit a component of viscous flow in their response to stress, in addition to an instantaneous (elastic) deformation. Therefore the response to an instantaneous stress change is drawn out in time, and in the specific case of Maxwell viscoelasticity used by Gourmelen and Amelung (*1*), decreases with time toward zero. Loads of sufficient size include sudden stress changes that occur in earthquakes (*2*), or the more gradual and/or time-variable loading owing to removal of continental ice sheets (*3*), or draining of large Pleistocene lakes (*4*, *5*).

Identifying and correcting for postseismic effects may be necessary when geodetic measurements, such as those that are frequently made with the Global Positioning System (GPS), are used to map the slow, inexorable motion of tectonic blocks. Such measurements have helped show that the Basin and Range province of the interior western United States is a part of the wide (~1000 km) and diffuse plate boundary deformation zone that accommodates the relative motion between the Pacific and North American plates (*6*). In these regions, GPS measurements are used to quantify seismic hazard by estimating deformation rates near active faults. Thus, the existence of transient deformation features that are hundreds of kilometers wide, with deformation rates up to several millimeters per

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