Planetary science

Icy martian mysteries

Victor R. Baker

Both Mars and Earth have experienced ice ages in geologically recent times. Coincidence of the phenomenon on two planets will further the scientific quest to answer the question of how ice ages originate.

Among the grandest of mysteries about planet Earth is the origin of its ice ages and related climate change. Human civilization developed during a warm, 'greenhouse' climatic interlude of several thousand years within the overall 'ice-house' conditions of a major ice age that became most intense during the past two million years. On page 797 of this issue, Head *et al.*[1] present evidence that this same period coincides with an occurrence of martian ice ages. They develop a convincing case that these geologically recent ice ages were induced by episodes of higher tilt (obliquity) in the axis of Mars' planetary spin. The resulting warming of the martian polar caps increased the sublimation of water ice, the water vapour migrating to the then cooler lower latitudes where it was emplaced as ice-rich deposits.

Head *et al.* advance scientific arguments that are mainly geological in nature, not theoretical. By this I mean that the various indicators of past processes, consistent with appropriate physical principles, are used to infer the causes. This contrasts with scientific arguments that postulate principles, deduce predictions and then compare those predictions with observed features. Whereas theoretical arguments are corroborated by successful predictions, the geological approach derives its support from a full suite of evidence — in this case from the appropriate interpretation of landforms (Fig. 1) that indicate the presence of near-surface ice, emplaced or mobilized at the appropriate times over parts of the planet.

This means that the geologist is more an investigator than a theorist[2]: like a detective at a crime scene, the geologist relies on the evidence and knowledge of the operative processes to conclude what causes led to that evidence. The overall assemblage of evidence, and the explanatory surprises that it may generate ('consilience'), are used to suggest fruitful lines of inquiry. These tentative hypotheses are then subject to additional testing against new evidence. In other words, the geologist lets the planetary landforms tell their own 'story', just as the evidence at a crime scene reveals its story to an experienced detective.

Since the first orbital Mars missions of the 1970s, the geological evidence for ice- and water-related environmental change on Mars accumulated into a strong circumstantial case[3]. Nevertheless, it was the detection of abundant near-surface hydrogen, made by neutron and γ-ray detectors aboard an orbiting spacecraft and published last year[4], that provided the 'smoking gun': this indication of water ice at high martian latitudes finally convinced a majority of the planetary science community that Mars was indeed a water-rich planet. A physically plausible means for emplacing this water, consistent with what is known of the martian climate, is the exchange of water vapour between the atmosphere and the pore space of the martian soil[5].

However, Head *et al.*[1] describe numerous attributes of landforms that indicate the direct emplacement of a mantle of ice and dust, possibly as dirty snow from the atmosphere. Such attributes include the regional smoothing of terrain by internally layered, and locally eroded, deposits a few metres thick; extensive, small-scale polygonal or patterned terrains (similar to the ice-wedge phenomena of Earth's polar regions); gullies and the mobilization of rocky debris on slopes (presumably by ice deformation); and even the likely remnants of glaciers, now mantled by dust or other debris (Fig. 1). Reinterpretation[6] of the neutron and γ-ray measurements indicates that although sublimation and re-condensation of ice in pore spaces is probably active on Mars today, the measurements also require the emplacement of nearly pure near-surface ice — just as is indicated by the climate changes proposed by Head *et al.*[1].

Earth's present ice age, known as the Quaternary period, is only the latest and coldest phase of a progressive cooling over the past 43 million years. Earlier major ice ages occurred about 260 to 340 million years ago (during the Carboniferous and Permian periods), about 430 to 445 million years ago (during the Ordovician and Silurian periods), several times between about 520 and 950 million years ago (during the late Proterozoic era), about 2,250 million years ago (during the early Proterozoic era) and about 2,900 million years ago (during the Archaeozoic era)[7]. As with Mars, the climatic changes of Earth's latest ice age had a pacemaker that operated through variation in the astronomical parameters of the planet's orbit and axis[8]. However, there is also a very strange element in this comparison. During its recent ice age, the martian poles had to warm up to release their store of frozen water into the atmosphere. For Mars, the episodes of ice

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Figure 1 **Ice age evidence. This image shows a striking, tongue-shaped feature, 4 km in length and an average of 800 m wide, taken by the Mars Orbiter Camera. The feature can be interpreted as a glacier of ice and rock flowing down the northern wall of a crater, 70 km in diameter, in the eastern Hellas region of Mars — and so of the occurrence of geologically recent ice ages on the planet.**

accumulation ('glaciations') are warm phases for a planet that seems to be most stable in an ice-house condition. For Earth, the stable state seems to be the warm greenhouse condition, with cold phases corresponding to metastable periods of glaciation.

There is the controversial possibility that, for short periods, Earth might have become like Mars in this respect. This derives from the so-called 'snowball' conditions of the late Proterozoic, when glaciation reached Earth's equatorial latitudes[9]. How is it that such major instabilities are induced in the planet's climate? Mars also has very ancient landforms that are consistent with the incidence of epochs of past glaciation[3]. It

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would seem that there are other causes that tip climatic stability from icehouse to greenhouse for Mars, and from greenhouse to icehouse for Earth. Although the orbital parameters can be the pacemakers for change within one of these states, they are not powerful enough to tip the balance between them.

The major causes of change could be volcanic or tectonic activity — which can, respectively, release radiatively active gases such as carbon dioxide, or alter the land and water configurations of the planetary surface, thereby altering heat distribution. Or they could be astronomical, for instance a change in the flux of interplanetary dust related to large-scale movements of the galaxy. With two planets on which to explore this puzzle, we should have a better chance of resolving it than we would have by limiting our investigations to only one. ■

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Cell cycle

Passenger acrobatics

Toru Higuchi and Frank Uhlmann

Chromosomal passenger proteins undergo spectacular changes in localization during cell division. We now have molecular insight into how and why these changes occur.

Of all the cellular proteins, chromosomal passengers display some of the most visually striking patterns of behaviour. These proteins associate with chromosomes as cells prepare to segregate them during nuclear division (mitosis). Later, when chromosomes are aligned on the filaments that do the mechanical work of segregation, the passenger proteins become concentrated in distinct foci between paired kinetochores — the protein-based structures on chromosomes to which the filaments attach. Then, as chromosomes split, the passengers abruptly dissociate from the kinetochores and instead localize to the filaments in the area midway between the separating chromosomes[1] (Fig. 1a). Quite how these proteins relocate in this way has long been a mystery. Pereira and Schiebel[2] propose a solution in a paper in *Science*.

The first protein[3] found to display such striking changes in localization during mitosis was named INCENP, for 'inner centromere protein' — the centromere being the DNA sequence onto which the kinetochore assembles. Two further proteins were later discovered to show a similar localization pattern: aurora B kinase, which regulates the activity of target proteins by transferring phosphate groups onto them, and a protein called survivin (reviewed in ref. 1). It has since become clear that these three proteins together form a stable aurora B kinase complex[4]. Earlier this year[5], a fourth protein showing passenger behaviour was identified and named TD-60. This protein is required to 'recruit' the aurora B kinase complex to kinetochores, and might regulate its activity.

So what does this kinase complex do? In the phases of the cell-division cycle that precede mitosis, the chromosomes are duplicated, producing pairs of 'sister chromatids'. The sisters must then be pulled apart to opposite poles of the cell by the mitotic spindle — an array of so-called microtubule filaments (see Fig. 1b). For this to happen successfully, sister kinetochores must attach to microtubules emanating from opposite poles of the spindle. The aurora B kinase complex is responsible for correcting the erroneous attachments that inevitably occur during the 'search-and-capture' mechanism that establishes bipolar attachment[6]. Later, as the chromosomes pull apart and aurora B kinase relocates to the region between them — the spindle's 'midzone' — it recruits microtubule-binding proteins. These stabilize the midzone, serving as a guide for the final step of cell division, the pinching off of the two daughter cells[7].

The aurora B kinase complex, then, is clearly important at several stages of mitosis. But what lies behind its acrobatics? It was known that the timing of relocalization coincides with the splitting of the chromosomes. So does relocalization actually depend on this process? Apparently not. Chromosome segregation is triggered when the cohesive link between sister chromatids — a protein complex aptly named cohesin — is destroyed by the separase protein. But preventing chromosome segregation, by making cohesin resistant to destruction by separase, does not stop aurora B kinase from relocating from the kinetochores to the spindle[8].

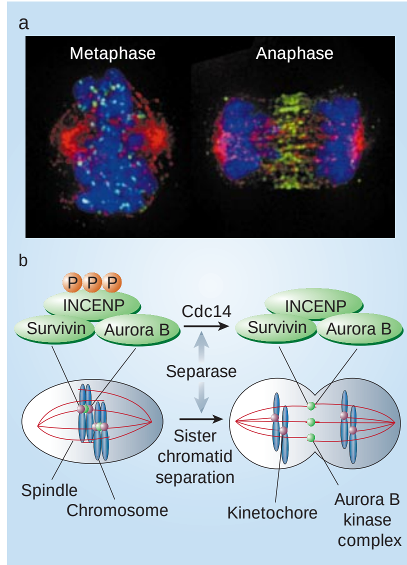

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Figure 1 **Moving passengers about. Chromosomal passengers include the INCENP protein, and together they make up the aurora B kinase complex.** a, **During mitosis, this complex shows dramatic changes in localization, as these micrographs of dividing chicken DT40 cells reveal. In the metaphase of mitosis, INCENP (green) is found at kinetochores, the structures on chromosomes (blue) to which the mitotic spindle (red) attaches. As chromosomes split at the onset of anaphase, INCENP dissociates from kinetochores and moves to the midzone of the elongating spindle.** b, **Relocalization as explained by Pereira and Schiebel[2]. It was known[9,10] that, at the onset of anaphase, separase cleaves the cohesin protein (not shown) to separate sister chromatids, and at the same time activates the phosphatase Cdc14. Pereira and Schiebel find that Cdc14 removes phosphate (P) groups from INCENP, and that this triggers its relocalization to the spindle.**

Could passenger relocalization and chromosome segregation instead be caused by the same regulator? The answer is a clear 'yes' (Fig. 1b). Studies in budding yeast[9,10] have shown that separase serves double duty: at the same time as separating sister chromatids, it also activates the protein phosphatase Cdc14. During the cell cycle, various proteins need to be phosphorylated so that cells can enter mitosis; once active, Cdc14 removes the phosphate groups, allowing cells to exit mitosis. Pereira and Schiebel[2] have now discovered that one of Cdc14's targets is the INCENP subunit of the budding yeast aurora B kinase complex. The authors show that INCENP dephosphorylation is both necessary and sufficient for the complex to relocalize to the midzone of the mitotic spindle. The simple model, then, is

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