# *Planetary science*

## Mars, planet of 2004 (*January 2005*)

As 2004 was but a few days old, there was much cheering at NASA's Jet Propulsion Laboratory as the two Mars landers touched down safely and unleashed the two Rovers to deploy their instruments. Celebrations at ESA were not so universal, as the Beagle-2 miniature geochemistry laboratory vanished without trace. Beagle could in principle have proved the existence or otherwise of Martian life, had it survived and landed on suitable ground. Still, ESA's Mars Express orbiter was safe and promised oodles of highly detailed pictures and other data. What followed was an embarrassment of riches from both the US and EU missions, more or less throughout the year. Then ESA had real cause for partying as 2005 opened, as its Huygens probe landed on the largest and most enigmatic moon in the solar system, Saturn's Titan, but that is a story that will run this year, and it *was* carried courtesy of NASA's Cassini mission. *New Scientist* featured an excellent summary of the achievements on Mars in its 15$^{th}$ January 2005 issue (Chandler, D.L. 2005. Distant shores. *New Scientist* 15 January 2005, p. 30-39). Everything has worked better than expected, Rovers Spirit and Discovery having the benefit of sand blasts that cleared the dust off their solar cells. They are still functioning, though not exactly prancing – it has taken a year for them to travel just over 5 km between them. But the treasures they have unfolded have delighted lots of geologists.

There is ample evidence at least for the former influence of liquid water at the surface, which has both weathered the Martian surface to produce iron minerals that witness both water and highly acid conditions and also laid down sediments in layer after layer. Some hint at the former existence of a large shallow, salty sea where Discovery landed. Mars Express's imaging devices have produced high-resolution pictures that confirm the influence of water's sculpting, seemingly late in its history, and the presence of recent glacial deposits. The orbiter also carries a deeply penetrating radar device (MARSIS) capable of finding water up to a kilometre beneath the surface, though it has yet to be deployed. Perhaps the most intriguing find is that Mars' atmosphere has more methane in it than seems possible, unless something is continually emitting it. That "something" could be volcanism (2004 also revealed signs of previously unknown, recent eruptions), methane may be leaking from sub-surface gas-hydrates similar to those beneath Earth's sea floor, it could be emitted by icy material from comet debris, and maybe it signifies some primitive, methanogen life forms that are respiring. The last needs to be tied down very rigorously before scientists get over excited. Even if it matches up with signs of emitted water vapour, which it does, that could still be an abiogenic phenomenon. There can be little doubt that Mars is proving irresistible as a political draw, riding on its kudos to hammer out the old message that "Man Must Go There!". But consider this: had today's robotic technology and analytical miniaturisation been possible 35 years ago we would know vastly more than we do about the evolution of our neighbour the Moon. Instead of carrying astronauts and their weighty life support systems, the Apollo missions would have brought back an equivalent mass of lunar rock. The same goes for Mars, surely, on the old basis of getting "more bangs for your buck". But that is a scientific outlook, and maybe the bucks can only be raised by the romantic notion of some brave souls treading where Edgar Rice Burrough's John Carter once rode astride his 10-legged banth. But of course, robotic science can also ride on that "vision", for what could be more catastrophic to whichever US president succeeds in making George W. Bush's dream come true to find that it is not safe enough out there, and the astronauts do not come back.

### Plotting meteorite falls (*January 2005*)

Museums host collections of thousands of meteorites donated by collectors over more than a century. Although they are the source of much of our understanding about the timing and processes involved in the origin of the solar system and of the Earth itself, the collections are biased towards those that are most easily spotted on the ground. Metallic meteorites show up much more readily than do those made of silicate minerals, which resemble ordinary terrestrial rocks in colour and density. Only when collectors pore over very uniform, light coloured surfaces, such as ice caps, deserts and bare limestone plateaux, can they be assured of a truly representative selection of types. Also, many meteorite samples are weathered and contaminated with earthly materials, because they have lain around on the ground for a long time. Improved precision and detection limits of the chemical analytical tools that meteorite specialists use demand fresh material, as do researchers interested in organic materials carried from space – the embarrassment of having an announcement of a fossil bacterium in a meteorite and then finding that it is some common bug from soil is career threatening. Most important are trying to overcome the compositional bias and to see from which part of the sky different kinds of meteorite come.

Phil Bland of Imperial College, London is trying to solve all problems at a stroke. His idea is to set up a network of wide-angle sky cameras to record meteor trails, so that computer analysis of the film will triangulate the point of impact and also work out the precise orbit of the offending body. The ideal place - easy to get to, safe, flat, dry unvegetated and dominated by pale rock – is the infamous Nullarbor ("No Tree") Plain of SW Australia, which is one of the most featureless places on Earth. Bland already has one sky camera in place that has sensors that only turn it on if the sky is clear, and an internet connection that e-mails him if something as malfunctioned. In one year it spotted 12 trails bright enough to have resulted in meteorites falling to the surface. With three cameras, he hopes that results will be sufficiently accurate to narrow search areas to a square kilometre. If funded, the extended project will even incorporate e-mail alerts to teams of local collectors, whenever a trail exceeds a certain brightness. They should then be able to pristine recover material in a few days.

**Source:** Muir, H. 2004. Catch a falling star. *New Scientist*, 25 December 2004, p. 45-47.

### Curiously low-velocity material at the core-mantle boundary (*March 2005*)

One of the oddities of the deep Earth is the presence of zones of the order of 1 to 10 km thick close to the core-mantle boundary (CMB) that have seismic wave speeds well below those expected at such depths. Because wave speed is inversely proportional to density, the chances are that they are "ponds" of extremely dense solid materials. Denser in fact than basalt might become in the form of eclogite, even compressed appropriately to these extreme depths. The zones have been a puzzle, but that may have been resolved, albeit controversially, by work from University College, London (Dobson, D.P. & Brodholt, J.P.

2005. Subducted banded iron formations as a source of ultralow-velocity zones at the core-mantle boundary. *Nature*, v. **434**, p. 371-374; DOI: 10.1038/nature03430).

The densest materials found commonly at crustal levels are iron oxides and hydroxides, but today they are disseminated through much larger volumes of quartz-rich sediments. Up to about 1.8 billion years ago, they were produced in huge abundance in sedimentary rocks, along with interbedded cherts, to form banded iron formations (BIFs). That is widely agreed to have been a phenomenon only possible when the ocean was oxygen free so that iron could be dissolved in the oceans, and that they were precipitated when that Fe(II) came into contact with oxygen being produced by photosynthesising blue-green bacteria in shallow water. Without any shadow of doubt, BIFs are the densest sediment that the Earth has ever produced, with a 50:50 mix of iron oxide and chert having a density of 3900 kg $m^{-3}$ at near-surface pressures, compared with 3100 for the upper mantle. Long ago, Bob Newton of the University of Chicago suggested to me that they "didn't ought to be still around": Precambrian BIFs are so vast and so dense that they are even more likely to be subducted than oceanic basalt converted to eclogite. And they would not even need to be metamorphosed to do that. So, it has taken a long time for someone to cotton on to Newton's typical prescience.

Quite possibly, BIFs were a tectonic driving force at a time when the basalt-eclogite transformation was thermodynamically unlikely. Dobson and Brodholt observe that BIF density can only get larger (much larger; 6600 $kgm^{-3}$ at CMB pressure) if they sink. This is a nice hypothesis, for BIFs fit the bill exactly for the ultra-low velocity zones, and carries some interesting corollaries. BIFs contain a great deal of oxygen, in fact probably the entire productivity of the early Precambrian biosphere; and it would have a biogenic isotope signature. Could that be added to any plume material emanating from the CMB? Equally, BIFs contain unusually high concentrations of transition metals, and there is another possibility for deep-mantle geochemists to juggle with. The authors also observe that iron-oxides have high electrical conductivity compared with silicates, and ponder on the electromagnetic consequences of that so close to the core. One thing seems certain; iron oxides probably would not melt, but, depending on the amount of oxygen in the core, they might dissolve in the molten outer core.

### Mineral maps of Mars (*March 2005*)

Lots of space has been devoted in science journals to results from NASA's robot rovers on Mars. Well, haven't they been exciting? Iron-oxide "blueberries, a cliff with bedded sediments and some iron-aluminium sulphate in a combined traverse of a kilometre at most. Imagine a geologist coming back from a terrestrial field trip costing a year's GDP for a small country and writing a report for the funding agency! That is a bit cruel, for in planetary exploration the themes are context, context and context, but we did know that Mars is red and orange, which is enough for most of us to feel happy with a lot of iron coloration. At the same time as the rovers were deployed, the European Space Agency's Mars Express was going into orbit (so named because it was assembled in something of a hurry). It bristles with the geoscientist's other modern tools; those aimed at sensing materials from their electromagnetic spectra. There is the High-Resolution Stereo Camera that produces images to rival high-altitude aerial photos of the Earth, and with stereoscopic overlap from which accurate models of Mars' topographic elevation can be calculated, of which more in the next item. The principal mineral and rock mapping tool is the Observatoire pour la Minéralogie, l'Eau, les Glaces, at l'Activité (OMEGA), that builds on the spectral mapping by NASA's Thermal Emission Spectrometer deployed by the earlier Mars Global Surveyor and a similar instrument aboard Mars Odyssey. OMEGA is every remote sensing geologist's dream machine. Its coverage of the short-wave end of electromagnetic radiation by 350 narrow bands can match spectra reflected from rocks and soils with those for several hundred minerals measured under laboratory conditions. Research geologists don't get much of that quality of data from Earth, mainly because it is commercially successful in mineral exploration, and very expensive (for much of the Earth, such hyperspectral data is not very useful, because vegetation masks most mineral signatures). But data are free from Mars Express (or will be when the main investigators have had a reasonable time to satisfy their curiosity) and has a terrestrially useful resolution down to 100m. They also cover an awful lot of the planet's surface and should eventually give 100% coverage.

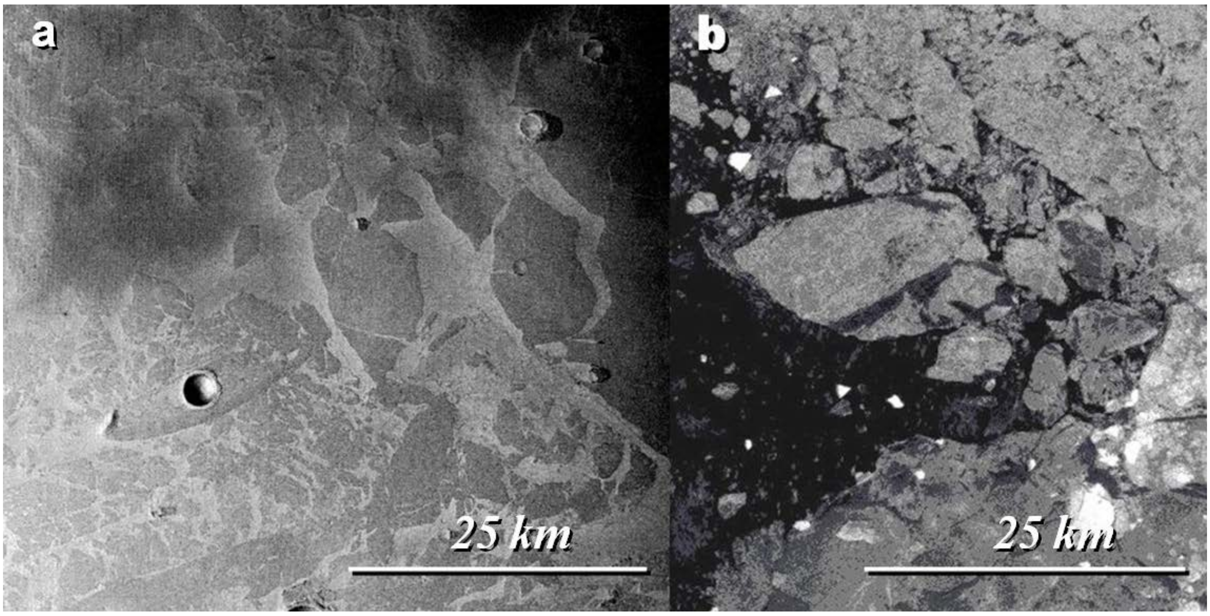
False-colour image of an area on Mars near Syrtis Major that shows olivine-rich surface materials in magenta (Credit: NASA/JPL/ASU)

The 11 March 2005 issue of *Science* devotes 24 pages (p. 1574-1597) to summarising OMEGA results. Various papers reveal variations in the composition of pyroxenes in the predominantly mafic Martian surface rocks, those minerals, such as the sulphates gypsum and jarosite, which contain water and signs of weathering by water, and an awful lot about water and $CO_2$ ices around the poles. But this is not the geology in full of course, but driven by the search for potential habitability. Common rocks are not made of sulphates and ice, but silicates, which can be assessed best by multispectral thermal emission data that prove very useful on Earth. The lack of information about such fundamental divisions of Martian igneous rocks as ultramafic, mafic, intermediate and felsic is a great disappointment, but perhaps the thermal instrument aboard Mars Odyssey will eventually come up with those more mundane goodies. Oddly, the planetary treasures of Mars are not being revealed by such sophisticated instruments, but by what is still the work horse for a great deal of geological image interpretation, black and white stereo images.

## The triumph of an antiquated technique on Mars (*March 2005*)

Except perhaps for some of the current generation of geology students, immersed in their remote sensing training by interpreting false colour images of spectrally revealing multispectral image data, a great many professionals who engage in mapping cut their teeth on what is known simply as photogeology. And it is simple. Provided images are taken of an area from slightly different angles, most people's innate stereoscopic vision enables them to see startling illusions in three dimensions by using a stereoscope. Stereoscopy has been to geologists of the mid to late 20$^{th}$ and early 21$^{st}$ centuries what the binoculars were to those earlier scientists who discovered the great nappes of the Alps and thrust belts of the Rockies. A stereoscope of some kind is the latter-day analogue of that "Swiss Hammer". Two stereo images reveal a great deal more than twice the information of one flat image, no matter how detailed.

Using complex software, which converts the parallax differences that enable us to see 3-D to the differences in topographic elevation that cause relative shifts in the position of features on overlapping images creates accurate models of the elevation itself. That enables quantitative measure of many features related to topography, and allows the images to be viewed in perspective, as if they were indeed captured by binoculars from a high view point. Results from the Mars Express High-Resolution Stereo Camera (HRSC) have proved able to revolutionise our understanding of the Martian surface. The 17 March 2005 issue of *Nature* reports three important new results that stem from HRSC data. For several years the possibility of glaciers having carved some features on Mars have been suspected from lower resolution elevation data. Now it is certain from exquisite perspective views of debris aprons that record the flow of smashed rock from large mountains, almost certainly because the debris was once extremely dirty glacial ice (Head, J.W. *et al*. 2005. Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars. *Nature*, v. **434**, p. 346-351; DOI: 10.1038/nature03359). The flows are reminiscent of rock-rich glaciers in the hyper-arid Dry Valleys of Antarctica. These authors present evidence that suggests that the flows are as young as 130 Ma, and may yet contain water ice. A second paper also reveals the influence of near-surface ice on Mars (Hauber, E. *et al*. 2005. Discovery of a flank caldera and very young glacial activity at Hecates Tholus, Mars. *Nature*, v. **434**, p. 356-361; DOI: 10.1038/nature03423). In its case it seems to have been mobilised by an explosive volcanic eruption, possibly as young as 20 Ma, to produce debris flows and also very well preserved drainage channels at a much smaller scale than those known from Mars' earliest history. The drainages might have resulted from subsurface ice melting by high heat flow and emergence of the "groundwater" to carve the meandering channels. There is an important caution: any dating on Mars depends on assuming a timescale based on counting impact craters and noting their relations to each other and different kinds of surface. The third paper observes something very different (Murray, J.B. *et al*. 2005. Evidence from the Mars Express High Resolution Stereo Camera for a frozen sea close to Mars' equator. *Nature*, v. **434**, p. 352-356; DOI:).




Platy features on Mars (left) resemble Antarctic pack ice (right) (Credit: John Murray)

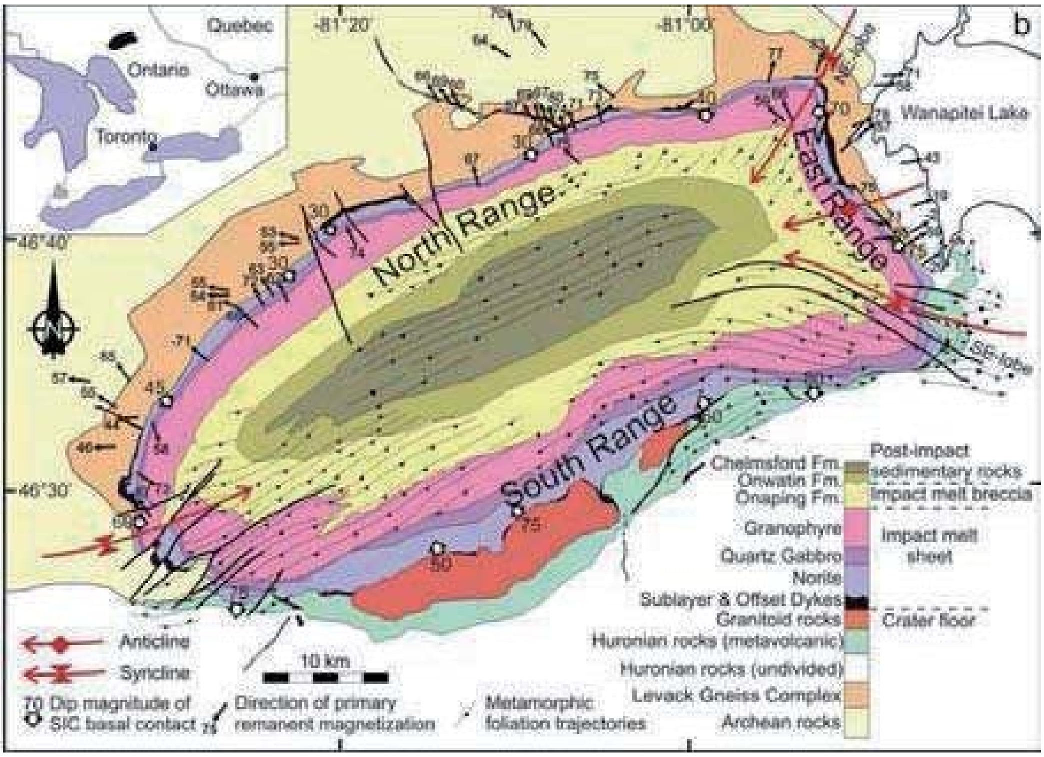
HRSC images reveal an area about the same size as the North Sea that is not only completely flat, but shows features very like those associated with pack ice in the Arctic and around Antarctica. They are plates whose edges can be fitted together, and in some cases islands have resulted in pressure ridges very like those seen where terrestrial pack ice meets land. There are even examples of impact craters that have been flooded. Murray and colleagues attribute all this to a large volume of subsurface water released by very recent volcanism along fissures close to the Martian equator. Basalt floods had been identified in the region before, but not evidence for a possible sea-sized, frozen lake. Similar, but not so revealing features elsewhere on Mars have been interpreted as lava rafts that once floated on flood basalts. Naturally, Mars scientists are very excited about the possibility of a large ice sheet at the equatorial surface, which may be as much as 45 metres deep. Unfortunately, the observations are from an area not yet covered by spectral data that would resolve whether the surface is ice-rich or more mundane lavas.

**How the core controls Earth's magnetic field reversals (*April 2005*)**

While most geoscientists are well aware that past changes in the geomagnetic field are useful as a means of timing sea-floor spreading and stratigraphic correlation, and that records of the direction of palaeomagnetism are keys to ancient plate movements. Most, however, understand only vaguely why Earth has a magnetic field that flips polarity from time to time: there is some kind of self-sustaining dynamo due to motion in the liquid-metal outer core. That aspect of geomagnetism involves tough theory and maths. So for *Scientific American* to present an up-to-date review of how that dynamo might work is both surprising and welcome (Glatzmaier, G.A. & Olson, P. 2005. Probing the geodynamo. *Scientific American* April 2005, p. 33-39; DOI: 10.1038/scientificamerican0405-50). The review covers what is currently known about convective motion in the outer core, both laminar and turbulent, and how the simpler laminar convection has been used in computer modelling that simulates how the geodynamo works. It is complex even at that level of simplification, because thermal convection is affected by the Coriolis effect: much like that in the atmosphere. Even though the idea of a dynamo inducing magnetic flux is a basic principle of physics, one based on fluid circulation is in constant motion and change. Surface monitoring of shifts in the magnetic field help to chart that aspect. The issue of reversal is, literally, the knottiest problem for geomagnetists, and they have to resort to the old idea of lines of flux and the effect of contortions by motion at the core-mantle boundary to grapple with how polarity flips might occur. Computer simulations show the development of what can only be described as chaos in the geomagnetic field at the core-mantle boundary, and much smoothed, but nonetheless odd variability at the surface, as the poles prepare to reverse. For a period of around 6 000 years the field wobbles like a massive jelly as it lurches across the planet, sometimes splitting into several "blobs" of different polarity. Eventually it settles down into its new configuration. To some extent this strange behaviour is matched by what little is known in detail about the progress of reversals from the geological record (see *Magnetic polarity reversals* May 2004).

**Ejecta from the Sudbury impact (*April 2005*)**

Sudbury in Ontario, Canada hosts one of the world's largest nickel and platinum-group metal deposits. It is associated with the world's second largest impact structure (260 km diameter), dated at 1850 Ma. About 650 km to the WNW is another of Canada's Precambrian treasures, the Gunflint Chert beds that contain the earliest incontrovertible fossil cells. Those cherts are also roughly the same age as the Sudbury impact structure, so what better place to seek material excavated and ejected by the offending meteorite? No need either to thrash around the bush to collect rocks; the succession has been penetrated by 5 drill cores near Thunder Bay and in northern Minnesota. Sure enough, all the cores show signs of impact ejecta (Addison, W.D. *et al*. 2005. Discovery of distal ejecta from the 1850 Ma Sudbury impact event. *Geology*, v. **33**, p. 193-196).




Geological map of the Sudbury Basin, Ontario Canada. (Cedit

The proof takes the form of shocked quartz and feldspar grains and melt spherules, but in a sequence of silicified carbonates above the level of the Gunflint Chert. Ejecta material is about 0.6 m thick. Because the carbonates contain no volcanic horizons, establishing the age of the ejecta depends on a thin volcanic ash 5 m above it, which yielded zircon U-Pb ages between 1827 to 1832 Ma. There are no other known impacts around this time, so Sudbury is the most likely source of the ejecta. Apart from being the oldest impactite layer known that can be tied to a source, there are a couple of intriguing features. The ejecta layer occurs almost at the top of the Gunflint Formation famous for its cellular remains, yet the overlying strata contain no sign of fossils. The authors wonder if this might represent mass extinction, but these slightly younger sediments are clastic rocks in which cell microfossils are unlikely to have been preserved. However, they do show signs of anoxia, including high organic carbon content and sulfide minerals. Hopefully carbon isotope data from the section might throw light on how impacts in a world exclusively that of single-celled organisms affected the biota: an interesting comparison with the K-T boundary. The other puzzle is that the ejecta are in shallow-marine sediments. Being only a few hundred km from the linked impact structure, some sign of disturbance by tsunamis or water-release by huge seismic shocks might be expected within the sediments. No signs of such disturbances have been reported.

**Mars: the best may yet be to come (*May 2005*)**

The NASA and ESA satellites orbiting Mars have so far deployed remote sensing instruments that detect visible to thermal infrared radiation from the planet's surface. Ultimately their energy source the Sun: these are passive instruments. Engrossing as they are, images from these sensors reveal only details of surface mineralogy and the Martian topography. So far, virtually nothing is known about what lies buried beneath it, apart from inferences about ground ice. The ESA Mars Express has one last imaging trick up its sleeve, which uses energy generated on board and beamed obliquely down to the surface. This is the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS). Radar remote sensing on Earth generally uses high-frequency microwaves in the wavelength range from 0.01 to 0.1 metres, and the images produced show how much energy is scattered by surfaces of varying roughness, to be received by antennae deployed from an aircraft or satellite. The longer the wavelength the greater the height of small-scale surface irregularities that cause scattering and therefore a received signal. Smooth perfectly surfaces reflect all the energy away from the antennae, like a mirror, so no energy returns to be sensed. How microwaves interact with the Earth's surface depends on the electrical properties of the materials. Good electrical conductors, such as metals and liquid water are extremely efficient reflectors, whereas minerals are poor conductors and tend to absorb microwaves to some extent.

If soils are extremely dry, with less than 1% moisture content, as in some deserts, some of the absorbed energy is scattered by materials below the surface and images show subsurface features. This lies behind the principle of ground penetrating radar, but since many soils are damp, only radar waves generated at the surface give good signals in most areas, to be exploited by civil engineers and archaeologists. Ice is very different from liquid water, being so poorly conductive that it is almost transparent to microwaves. Consequently it has proved possible to sound the depth of terrestrial glaciers and ice sheets using ground penetrating radar deployed from aircraft. The depth of penetration, and of course that involves energy returning to the surface in order to get a signal, is governed by the radar wavelength. For instance, unknown former courses of the River Nile's tributaries have been detected by 0.25 m radar waves beneath the hyperarid eastern Sahara through about 3 metres of dry sand.

MARSIS can transmit microwaves with 4 wavelengths 170, 100 , 80 and 60 m; much longer than those used in terrestrial remote sensing. Given rocks and soils free of liquid water, which comprise most of Mars's surface, or ice, MARSIS can penetrate as deep as almost 5 km. The multi-wavelength arrangement can also potentially discriminate water ice from rock and soil. A great deal of speculation and some evidence suggest that parts of Mars may be underlain by permafrost, that is melted only under unusual conditions, such as after meteorite impacts. There are also suggestions that glaciogenic-like landforms may still be underlain by ice, and bizarrely that there are frozen seas (see *The triumph of the old on Mars* above). MARSIS may well throw Mars investigations into a turmoil, but maybe not. The delay in sparking it up has been caused by fears that deploying its antennae might damage the whole spacecraft, and the first attempt seems to have got stuck. It's other drawback is limited power so that horizontal resolution will be between 5 to 10 km and vertically only 100 m, so results may be so blurred as to be inconclusive. NASA plans a similar device aboard its Mars Reconnaissance Orbiter (launch date August 2005). The Shallow Subsurface Radar (SHARAD) will use microwaves with 12 to 20 m wavelengths that give penetration to 1 km, but horizontal and vertical resolutions of 300 and 15 metres.

**See:** Reichhardt, T. 2005. Mars exploration: going underground. *Nature*, v. **435**, p. 266-267; DOI: 10.1038/435266a.

**New data on starting point for Earth evolution (*June 2005*)**

Slowly, geochemists as well as planetary scientists have been taking up the implications of a probably infernal origin for the Earth-Moon system, which resulted from a Mars-size planet colliding with the proto-Earth shortly after planetary accretion. The chemistries of both Earth and Moon have sufficient similarities for a common origin to be almost certain. There is one difference: lunar rocks are more depleted in volatiles than those accessible on the Earth. Terrestrial rocks were at some stage in their evolution purged of some volatile elements. The Moon's early history seems to be extraordinarily simple. It is recorded in the pale rocks of the lunar highlands that are made dominantly of feldspars. Their low density and abundance suggest that feldspars floated to the top of completely molten rock, in much the same way as similar anorthosites on Earth seem to have formed in large magma chambers. The difference is that lunar anorthosites probably once formed the entire crust of the early Moon, and formed by simple differentiation of a deep, all-encompassing magma ocean. The late Dennis Shaw applied this simple notion to the Earth's earliest evolution during the 1970s, but his vision was largely ignored by his geochemist peers. A mantle-wide zone of complete melting was resurrected when William Hartmann's giant impact theory appeared: the energy involved seems to make this an inevitable corollary of his idea.

Indirect analysis of the mantle from the geochemistry of its basaltic products has shown that the mantle is not homogeneous. Some has been partially stripped of basalt-forming elements, and there are other chemical heterogeneities. However, examined from the standpoint of isotopes of neodymium ($^{142}Nd$ and $^{144}Nd$) more or less every magmatic rock has been considered to have been ultimately derived from material with the same isotopic composition as chondritic meteorites, and by extension, that of the Galaxy in the vicinity of what became the Solar System. That observation has been a major counter argument to the notion of an early terrestrial magma ocean. Differentiation of such a fundamentally molten Earth would have separated some of the samarium-146 (the source of $^{142-}$Nd through radioactive decay) from $^{144}$Nd, thereby imparting different growth histories for $^{142}$Nd/$^{144}$Nd ratios to different mantle 'reservoirs'. The half-life of $^{147}$Sm is about 100 million years, so that radiogenic $^{142}$Nd would accumulate most in Earth's early history, thereafter tending towards a constant proportion of neodymium, unlike the $^{143}$Nd used in radiometric dating that accumulates much more slowly from decay of $^{147}$Sm (half life about 100 billion years).

There was a flaw in this counter argument. The similarity of chondritic and terrestrial Nd isotope patterns might have stemmed from isotopic measurements that were insufficiently precise to detect significant differences. Mass spectrometry has undergone a leap in precision. Applied to the chondrite-Earth rock comparison, the neodymium data for chondrites remains as determined earlier, but the $^{142}$Nd/$^{144}$Nd ratios of terrestrial rocks turn out to be 20 parts in a million higher than for chondrites (Boyet, M & Carlson, R.W. 2005. $^{142}$Nd Evidence for Early (>4.53 Ga) Global Differentiation of the Silicate Earth. *Science Express*, DOI: 10.1126/science.1113634). That doesn't seem very much, but quite sufficient to suggest plausibly that indeed the Earth's mantle did indeed evolve from a magma ocean. Its upper part was enriched in samarium by its fractionation as a solid that probably crystallised downwards. Whatever was left of the original liquid would be at the base of the protomantle, and in it many other elements that favoured melt over crystals – so-called 'incompatible' elements – would have been enriched. Boyet and Carson suggest that such a deep, enriched layer may amount to between 5 to 30% of the current mass of the mantle.

The implications, if the ideas are confirmed, are enormous, because geochemists up to now have taken the bulk of the mantle that supplies basalt magmas – and whose composition is quite well constrained - to represent the whole silicate Earth. That may satisfy geochemical parameters, but worries geophysicists. The 'standard' Earth has insufficient radioactive uranium, thorium and potassium to account for the heat that flows to the surface. In fact it generates about a half, leaving the rest to speculation. One school looks to supposed gravitational potential energy locked in the core when it formed by inward collapse of iron-nickel alloy and slowly released thereafter. Another theorises about radioactive potassium-40 combined in sulphides of the core, which also 'leaks' out.

The possible existence of the last dregs of an early magma ocean, near the core-mantle boundary (CMB), would not only account for 43% of surface heat flow, but might also drive convection in the liquid outer core as a means of generating Earth's magnetic field. Even more important, it might fuel the rise of plumes from the CMB that are increasingly implicated in periodic repaving of the Earth's surface by flood-basalt volcanism. Since flood basalts are a popular source for mantle geochemists' data, why are the signs of such a peculiar source region not clear in their analyses? Either they are not looking with the requisite precision, or the source itself does not move with plumes, merely setting them in motion. Eminent geochemists see a bit of a hectic time ahead…..

**See also:** Kerr, R.A. 2005. New geochemical benchmark changes everything on Earth. *Science*, v. **308**, p. 1723-1724; DOI: 10.1126/science.308.5729.1723.

**Modelling the core (*August 2005*)**

Judging by the growing procession of research grant proposals aimed at computer modelling of the inner workings of the Earth's core, it would be easy to assume that a major breakthrough was just over the horizon. What you need is some kind of supercomputer to handle the massive complexity of core fluid dynamics and then channel that through one of several concepts of a geodynamo, first towards simulating the present field and then to how the geomagnetic field swirls and occasionally flips. The fourth biggest there is belongs to the Japanese geophysical community; the Earth Simulator, which is certainly well ahead, in terms of power and speed, of facilities available to less endowed scientists. Recently, about 10% of its power was let loose for a 9 month modelling run that focussed on complex motion in the liquid outer core that theory should generate (Takahashi, F. *et al*. 2005. Simulations of a quasi-Taylor state geomagnetic field including polarity reversals on the Earth Simulator. *Science*, v. **309**, p. 459-461; DOI: 10.1126/science.1111831). Hitherto, modelling had produced pictures of varying magnetic intensity that bore some resemblance to the real magnetic field at the Earth's surface, and did indeed come up with reversals. Yet a variety of models all produced similarly plausible patterns in space and time. The snag was the limit to matching the viscosity of liquid iron with spin rate. Geomagnetists suspect that the Ekman number, which represents that relationship, is very low in the Earth's core, i.e. there is very low drag in core circulation, and that adds to complexity. Until the Earth Simulator was built, no power on Earth could deal with the high spatial resolution needed to simulate properly motions at low Ekman numbers. Takahashi and colleagues were able to drop the Ekman number 10 times below any previous simulation.

Real-looking features did begin to emerge in the time sequence for the field at the core's surface. The most interesting was the formation of zones of opposed polarity at high latitudes, soon (in about 1000 years of simulated time) to be followed by a reversal. The zones move progressively polewards to coalesce, when the overall magnetic polarity all but disappears, and then a reversed field becomes established. However, this is not real but a model dependant phenomenon, even though it is possible to see patterns akin to those observed today – many geophysicists believe the Earth is on a magnetic cusp before a reversal. Will it ever be real is an obvious question, in the same way that related climate simulations may flatter to deceive. The problem is not a lack of models, nor conceivably computing power, but a lack of real data. The ocean floor contains masses of information on past reversals, and cunning analyses of palaeomagnetism in lavas that cooled slowly through the Curie point at the time of a reversal show astonishing things that happened. Excellent maps of the modern field are available, but reality in a reversal is a time series of that mapped field. Without such data, and the time to collect it (the modelling simulates evolution over 5200 years) before the next order-of-magnitude jump in computing power (perhaps 10 years off), it is very difficult to see a justification for this kind of modelling, as opposed to that for climate, which does have a more rapid response time.

**See also:** Kerr, R.A. 2005. Threshold crossed on the way to a geodynamo in a computer. *Science*, v. **309**, p. 364-365; DOI: 10.1126/science.309.5733.364a.

**Martian methane: a bit of a blow (*September 2005*)**

In Joseph Heller's *Catch 22*, Hungry Joe is noted for '…snorting, stamping and pawing the air in salivating lust and grovelling need'. That is a close metaphor for reactions among some scientists (and astronauts) to observations that seem to support the notion that indeed, there is life on Mars. Remember the meteorite ALH84001? In 2004, a spectrometer carried by ESA's Mars Express probe detected methane in the Martian atmosphere above areas that probably carry sub-surface water ice. Many exobiologists attributed this to exhalations by methanogen bacteria perhaps living in the ice, which seemed plausible. Sadly, it seems that hydrous alteration of the mineral olivine, widespread at the Martian surface, to serpentine is even more likely. The reaction can yield hydrogen, which generates methane by reducing carbon dioxide. Exobiologists are keeping their options open… Meanwhile, it is not implausible that hydrogen from this simple reaction might be used to resolve global warming: olivine is the most abundant mineral in the rocky planets. Incidentally, it is serpentinisation of ultramafic rocks that best explains methane exhalation from the deep ocean floor and from crystalline basement, which Thomas Gold thought had a deep-mantle origin and was responsible for all hydrocarbon deposits.

**Source:** Schilling, G. Martian methane: rocky birth then gone with the wind? *Science*, v. **309**, p. 1984.

**Where do impactors come from? (*September 2005*)**

All the rocky bodies in the Solar System (the Moon, Mars, Mercury, Venus, Earth and some moons of the giant planets) preserve to some extent the signs of collisions with errant bodies. One period stands out dramatically: the Late Heavy Bombardment or LHB (4.0-3.8 Ga) that produced the lunar maria, and left its signature in Archaean rocks on Earth (see *Tungsten and Archaean heavy bombardment*, August 2002). The planet Venus was entirely resurfaced about 500 Ma ago, and its plains record the later flux of impactors in much smaller more widespread craters, as do the lunar maria, parts of Mars and to a very limited degree the Earth. The LHB stopped abruptly, having appeared equally out of the blue. The influence of astronomical collisions on planetary histories may be an established fact, but is still something of a mystery as regards its pace and intensity. High resolution images of large rocky bodies sustain a thriving cottage industry of measuring, counting and dating craters; the latter from stratigraphic evidence of relative age, such as craters that have been cratered, and ejecta mantles that bear signs of impact themselves.

Hidden inside such statistics are clues to the astronomical processes that lead to impacts (Strom, R.G. *et al*. 2005. The origin of planetary impactors in the Inner Solar System. *Science*, v. **309**, p. 1847-1850; DOI: 10.1126/science.1113544). The crater-size distributions for the early events and those after 3.8 Ga are very different. Those of the later generation show features very like the size distribution of objects whose orbits intersect that of the Earth (near-Earth Objects or NEOs) and largely reflect the element of chance in a more or less stable late Solar System. The LHB pattern extends to craters more than an order of magnitude larger than the younger one, and resemble the size distribution of bodies that now orbit quite happily in the Main Belt of asteroids. It seems that during the period between 4.0 and 3.8 Ga, some main belt asteroids were flung out of their orbits to enter the Inner Solar System in large numbers. The analysis by Strom et al. suggests that the gravitational disturbance during that period might have been due to gradual migration of the giant Outer Planets before they took up their present stable orbits.

**A dialogue concerning world-shattering events (*October 2005*)**

Scottish Gaelic mythology includes the 'Dread Coruisk', the largest of the *each uisge*, or water horses. " 'Tis a thing we dinnae care tae speak aboot", say locals of the Isle of Skye, whose shores it nightly stalks. The same could be said of one of the most daring, and amusing, hypotheses of modern geosciences: that of the 'Verneshot' (see *Mass extinctions and internal catastrophes* Palaeobiology June 2004). Phipps Morgan, Reston and Ranero explored the possible consequences of a build-up of volatiles in plume-related magmas at the base of thick continental lithosphere beneath cratons, prior to the eruption of continental flood basalts. The suggested that pressure would eventually result in an explosive release at a lithospheric weak point, followed by collapse above the plume head that would propagate upwards, at hypersonic speeds. Modelling the forces involved, the authors of the novel idea considered that they would be sufficient to fling huge rock masses into orbit. The notion neatly might explain the circumstances around mass extinctions: coincidence of CFB events; large impact structures, most likely at the antipode of the event; global debris layers containing shocked rock, melt spherules; unusual element suites and compounds (including fullerenes); and enough toxic gas to cause biological devastation. As with the 'Dread Coruisk', little has been said, neither in support nor in dispute over the last year. My comment at the time was, "As with all departures from "accepted wisdom", the Geomar group's ideas will come in for a lot of stick, quite possibly from the fans of giant impacts, who not so long ago were themselves dismissed as "whizz-bang kids" by many geoscientists.

It is good to be proved perceptive once in a while. One of the original butts of adverse opinion in the early days of impact hypotheses, Andrew Glikson of the Australian National University, has been the sole commentator (Glikson, A.Y. 2005. Asteroid/comet impact clusters, flood basalts and mass extinctions: Significance of isotopic age overlaps. *Earth and Planetary Science Letters*, v. **236**, p. 933– 937; DOI: 10.1016/j.epsl.2005.05.007). He points out that Phipps Morgan *et al*. overlooked 6 overlaps of impact clusters and CFBs, three of which were associated with mass extinctions. Rather than adding grist to their mill, he goes on to say that it is the geochemical blend associated with impactite layers that points unerringly to an extraterrestrial source for the mass involved in creating large impact craters, rather than any known terrestrial rocks. Moreover, the extreme shock-metamorphism that is the hallmark of impactites has never been observed near any gas-rich volcanic structure formed by explosive venting. He returns to the view that impacts of alien origin have sufficient energy to *induce* large-scale partial melting of the mantle, and thereby generate large igneous provinces.

Unsurprisingly, the original authors were onto Glikson's comment, in leopard-like manner (Phipps Morgan, J., Reston, T.J & Ranero, C.R. 2005. Reply to A. Glikson's comment on 'Contemporaneous mass extinctions, continental flood basalts, and 'impact signals': Are mantle plume-induced lithospheric gas explosions the causal link?'. Earth and Planetary Science Letters, v. **236**, p. 938– 941; DOI: 10.1016/S0012-821X(03)00602-2). First they emphasise that their concept of the tremendous power of a 'Verneshot' is not based on the explosive release of volatiles, but on the shock pressures associated with the collapse of ~80 km tall pipes due to gas venting, in a very short period of time. As regards the geochemical blend in impactite-related layers, dominated by iridium yet a dearth of other platinum-group metals, they cite evidence that very similar element proportions are released in the carbon- and sulfur-rich gas phases of plume-related volcanoes, as in Hawaii and Reunion.

They are not crustal, but of mantle origin, carried by escaping volatiles, and fall in the field normally said to be meteoritic. Phipps Morgan *et al*. also dispute the likelihood of extraterrestrial-impact induced magmatism from its statistical unlikelihood – the chances of a one in 100 Ma bolide coinciding with 1 in 30 Ma CFB events is, on their count, 1 in 3000 Ma – and from the standpoint of the powers and work involved. They agree that indeed there are extraterrestrial impact structures.

Surely, their well-argued idea is worth bearing in mind and considering as evidence continues to emerge – they do list a plausible set of characteristics that a 'Verneshot' would probably produce. There is some essential philosophy that has a good track record in the history of the geosciences, that of plate tectonics for one: the absence of evidence is not evidence of absence.

**Movies of Mars (*November 2005*)**

One of the most exciting geoscience websites that you can find is hosted by Arizona State University in Tempe. It centres on the capture of thermally emitted infrared radiation from the Martian surface by the Thermal Emission Imaging System (THEMIS) aboard NASA's Mars Odyssey orbiter. The opening 'splash' of the THEMIS website features thermal images gathered on the fly by THEMIS, as if you were peering down from the spacecraft as it orbits the planet. The movies are not really live, but about 2 weeks old. Nevertheless, they have a hypnotic appeal as one waits to see what is going to turn up – mainly small craters, but sometimes oddities such as the strange terrain of the northern Tharsis Basin that is a tangle of extensional faults that might well be on the floor of the Afar Depression in north-eastern Ethiopia. THEMIS acquires data in several thermal wavelengths, and this is its scientific importance: the multiple channels span the very different emission spectra of silicate minerals.

Using different thermal bands to control the red, green and blue colour guns of a computer screen produces vivid images that are colour-coded for a variety of rock compositions. The great advantage of thermal sensing is that it works at night as well as during the day. So THEMIS images can also tell us a great deal about the way in which rocks heat up and cool, which is another clue to their composition. Having no clouds – there are seasonal dust storms – Mars can be mapped in great geological detail without geologists having to traipse across space and the inhospitable Martian surface. All that a human touch could add would be to bring back some rock samples for geochemists to get their teeth stuck into. What those rock are – basalts, andesites and various sediments – is already becoming known in greater detail than for huge tracts of the Earth's surface. Fortunately, a sister instrument to THEMIS, called ASTER does orbit the Earth to deploy a similar multispectral thermal imaging system. What is hugely annoying is that the Martian data are 5 times sharper than those of the infinitely more interesting Earth. Yet again, NASA has priorities that that are far from those of most of humanity. One excuse regularly given for better resolution from other planets is that of security issues for Earth images…

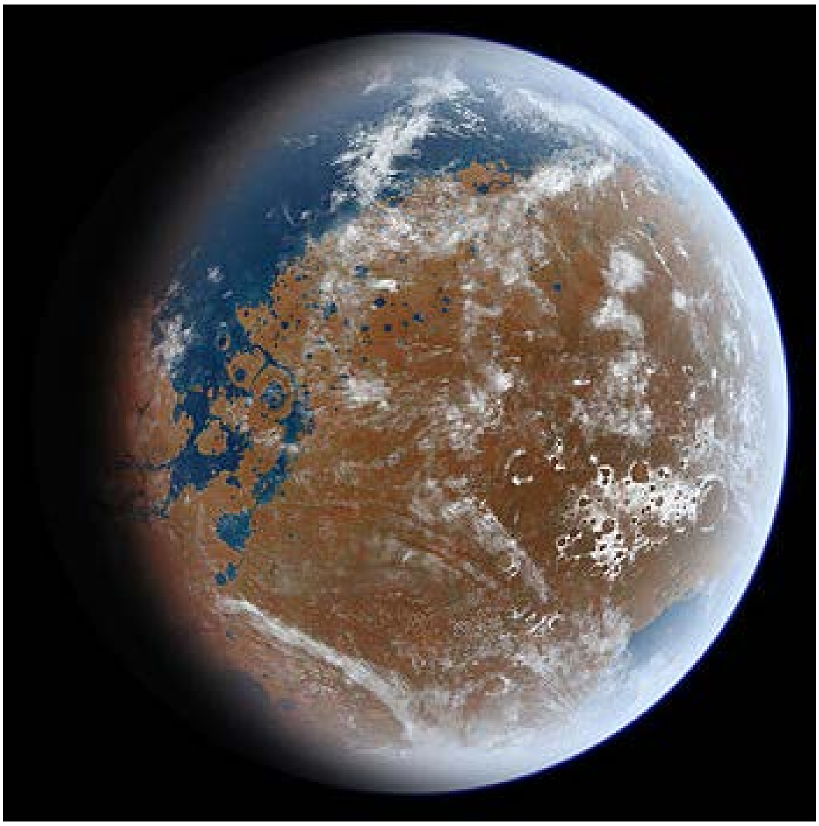
**Helium and how the Earth convects (*December 2005*)**

In the last ten years the new technology of seismic tomography that produces ghostly images of high and low density mantle has convinced many geoscientists that two major dynamic features extend to almost to the core mantle boundary (CMB). Dense, high-velocity zones descend from subduction zones, suggesting that the slabs continue to fall through the entire mantle below the ~700 km maximum depth of the earthquakes that Bennioff and Wadati used to define subduction. Some hotspots seem to be above diffuse zones of low seismic velocity that are supposed to signify hot, low density plumes that rise from the CMB. An inkling of a grand theory of mantle convection might then be that the descending slabs ruck up the deepest and hottest mantle layers to set them rising as narrow diapirs. Yet, other tomographic features appear to be restricted to the uppermost mantle, less than the 660 km depth of a major discontinuity long considered to be due to a mineral phase change at high pressure. A whole-mantle theory of convective heat transfer should transfer some geochemical trace of an exchange between core and silicate mantle. Osmium isotopes from plume-related magmatism suggest that there might be an exchange, but those of tungsten do not (see: *Mantle and core do not mix*, February 2004). The oldest and perhaps most convincing evidence against whole-mantle convection comes from study of helium in volcanic rocks, neatly reviewed by Francis Albarède (Albarède, F., 2005. Helium feels the heat in Earth's mantle. *Science*, v. **310**, p. 1777-1778; DOI: 10.1126/science.1120194).

Helium is generated by the decay of radioactive uranium and thorium isotopes as alpha particles ($^4$He), which generates much of the Earth's geothermal heat flow. There should be a close correlation between helium and helium, but at mid-ocean ridges the amount of $^4$He is only 5% of that expected from the associated heat flow. One explanation for this is that somewhere in the mantle there is a barrier to upward movement of helium, yet is allows heat to pass through: a thermally conductive layer that bars convective mass transfer. Albarède cites recent work that uses the flow of heat and helium through groundwater in an aquifer (Castro, M.C. *et al*., 2005. 2-D numerical simulations of groundwater flow, heat transfer and $^4$He transport — implications for the He terrestrial budget and the mantle helium–heat imbalance. *Earth and Planetary Science Letters,* v. **237,** p. 893-910; DOI: 10.1016/j.epsl.2005.06.037) as analogy of mantle processes. There too helium is less than might be expected, the reason being that the aquifer is recharged by rainwater, low in He. Likewise, ocean-floor basalts are probably affected in the same way by hydrothermal circulation of seawater, thereby diluting the flux of helium from the mantle and perhaps helping to account for anomalously low helium flux. Another widely accepted view that the high $^3$He/$^4$He ratios of hotspot basalts is evidence for their source in primitive mantle – $^3$He is probably a product of nucleosynthesis and therefore primordial as far as the Earth is concerned – is challenged by a recent paper that shows that helium is dissolved in mantle minerals (Parman, S.W. *et al*., 2005. Helium solubility in olivine and implications for high $^3$He/$^4$He in ocean island basalts. *Nature*, v. **437**, p. 1140-1143; DOI: 10.1038/nature04215). Parman *et al*.'s measurements suggest that the high $^3$He might result from residues of earlier melting in the mantle, rather than coming from parts that have remain in the state they were when the Earth accreted.

### Vanished Martian sea or not? (*December 2005*)

The Mars Rover data from the Opportunity site, which showed up masses of sulfate minerals in the large depression that it has roamed for 2 years, prompted the notion that they formed as a sizeable body of surface water evaporated. The Rover Opportunity scientists have also speculated on Mars once having had highly acidic 'weather', in the form of sulfuric acid rain from $SO_2$ emitted by volcanoes. The sediments at the Opportunity site also show signs of fluid transport in the form of bedding and cross stratification, ascribed to moving water. Most independent-minded scientists confronted by a united front of vast teams of highly focused scientists sometimes feel that there is more than one way of skinning a cat. Such is the case of Paul Knauth and Donald Burt of Arizona State University and Kenneth Wohletz of the Los Alamos National Laboratory in New Mexico. They visualise the dramatic evidence from Opportunity in an altogether more mundane scenario (Knauth, L.P. *et al*., 2005. Impact origin of sediments at the Opportunity landing site on Mars. *Nature*, v. **438**, p. 1123-1128; DOI:10.1038/nature04383). Their main point of departure is quite simple; acidic water full of hydrogen ions is a powerful means of weathering and the production of clay minerals. Clays are very uncommon on Mars, particularly at the Opportunity site, and have only shown up rarely on hyperspectral remote sensing images.



Artist's impression of ancient Mars and its postulated ocean (Credit: Wikipedia)

Layered sediments are evidence for fluid deposition, but not only water produces them. As well as wind transport and deposition, they are also formed by gas-rich base surges from explosive volcanism and meteorite impacts – and also during surface nuclear explosions that mimic impacts, hence the Los Alamos connection. Knauth *et al*. explain the Opportunity deposits as debris originally made of rock, sulphides brines and ice flung from a massive impact. They explain the sulfates as products of interaction between melted ices and sulfides. The extension of the Opportunity team's hypothesis of evaporating surface water is that it would have been long-lived, perhaps sufficiently so for the emergence of acid-loving organisms, similar to those that infest groundwater in terrestrial massive sulfide deposits. Should the deposit prove to have formed during an extremely rapid event, such as an impact, the idea of it having hosted primitive life forms becomes extremely unlikely. Gleefully, Knauth *et al*. almost exactly match the Opportunity image mosaic of layered sediments with a photograph of a New Mexico layered, volcanic surge deposit. Surges from large impacts, and Mars was intensely bombarded in its early history, can extend hundreds of kilometres from the crater rim. Many other examples of layered sequences are being revealed by high-resolution orbital images of Mars, and interpreters regularly ascribe them to wind, flowing water or volcanic processes. Ockham's Razor demands the most likely and simplest explanation for phenomena, and impacts could have formed the lot. The earliest detection of features that only flowing water could have carved – the sinuous canyons on Mars, originally prompted such a simple explanation, that water was released *en masse* by early massive impacts. Perhaps there is a much wider link between many Martian features and the most common geological agent in the Solar System.