Planetary science and meteoritics

Interstellar carbonates and "fossils" from Mars (*January 2002*)

Part of the argument used to support the notion that life may have arisen on Mars early in its history depends on the presence of carbonates in the notorious meteorite ALH84001 found in Antarctica. Supposedly having been ejected by an impact on the Martian surface (based on its oxygen isotope composition and the blend of noble gases trapped within it), ALH84001 also contains the minute structures that were prematurely announced in a blaze of publicity as fossilized alien life forms by US and British meteorite specialists in 1996. The discoverers claimed that carbonate minerals within it clearly evidenced the rotting of silicates by liquid water containing dissolved CO_2; so they do in terrestrial rocks. However, carbonates also occur in meteorites that by no shred of the imagination can have formed within sizeable planets. Many probably accreted in a near vacuum from dusts that occur in clouds within our galaxy, while the solar system was forming.

Using infrared spectra to assess the mineral composition of dust clouds surrounding stars, a team of European and American cosmochemists has found that in two cases such dust contains calcite and perhaps dolomite (Kemper, F. *et al*. 2002. Detection of carbonates in dust shells around evolved stars. *Nature*, v. **415**, p. 295-297; DOI: 10.1038/415295a). Because liquid water cannot exist in a near vacuum, production of these carbonates cannot have taken place by the familiar silicate-rotting process. More likely, they formed on the surfaces of silicate dust or ice grains by reactions between calcium and magnesium ions and those in which carbon and oxygen were combined.

Magnetic reversal on the way? (*April 2002*)

Over the last 150 years, the Earth's dipolar magnetic field has been declining so fast that it will vanish in around a thousand years. Breakdown of the dipole is known to have characterized past reversals in magnetic polarity, together with a decrease in the field to very low values. That is a worrying prospect, because the strength and polarity of the Earth's magnetic field serves to deflect the flux of energetic particles from the Sun, which would otherwise bombard the surface with potentially disastrous effects.

The likely source of planetary magnetic fields is turbulent circulation of a liquid iron core. Movement of such an electrical conductor is bound to generate such a field, in the manner of a self-sustaining dynamo - movement of a conductor in a magnetic field that the motion itself generates results in current flow that sustains the magnetic field. Perturbation of core motion would give rise to continual deviations from a perfect dipole. Charting such deviations is therefore a means of sensing how the core's circulation behaves. There have been two satellites devoted to monitoring the global magnetic field - The US Magsat in 1978 to 1980 and the Danish Oersted launched in 2000. Comparing results from the two reveals a remarkable patchiness, the largest being one to the south of Africa in which the field points downwards, opposite to the upward-pointing field of the main dipolar field in the southern hemisphere (Hulot, G. *et al*. 2002. Small-scale structure of the geodynamo inferred from Oersted and Magsat satellite data. *Nature*, v. **416**, p. 620-623; doi: 10.1038/416620a). The Earth contains "anti-dynamos", and if they merged and grew, the overall polarity might flip. Not only that, but for a while at least the poles of the reversed state need not line up with the rotational axis.

Gauthier Hulot of the Institut de Physique du Globe de Paris, with French and Danish colleagues, have modelled the generalized magnetic maps as proxies for core circulation. The dominant features, other than a slow westward drift, are probably vortices close to the rotational poles, akin to those induced in the atmosphere by large-scale variations in air temperature. But there are asymmetries, of which that south of Africa is the largest.. They too are probably vortices, perhaps related to convection columns. Those showing a likely fluid motion linked to the Earth's rotation cluster beneath the Pacific, whereas counter flows dominate the hemisphere centred on the Atlantic.

See also: Olson, P. 2002. The disappearing dipole. *Nature*, v. **416**, p. 591-594; doi: 10.1038/416591a.

A basaltic meteorite, but from where? (*April 2002*)

The vast majority of meteorites represent bodies in the Solar System that never became parts of planets; they are fragments of planetesimals. Of the 20,000 collected meteorites, only about 50 have been suggested from their geochemistry to hail from existing planetary bodies. They travelled to Earth as fragments that violent impacts on these bodies ejected from their surfaces. Since most meteorites have been recovered either from glacial ice or the surface of deserts, such suspected planetary fragments arrived recently in geological time, but had probably been travelling for immense periods of time since an impact dislodged them. Oddly, there are few if any meteorites with Earthly compositions, and only the Moon and Mars seem to be represented in collections. Suspected planetary meteorites have basaltic compositions, but so too do some likely to have originated from planetesimals. One of the keys to sorting them is analysis of their oxygen isotopes, as well as conventional element analyses and noble-gas composition. It was the resemblance of noble gases in the notorious Antarctic meteorite ALH84001, and others like it, to the very imprecise measurements made by the Viking lander in the 1970s that encouraged the view that it was from Mars. Their odd oxygen-isotope composition has also been said to indicate a Martian origin, mainly because they don’t fit with other specimens most likely to have originated from planetesimals.

In these uncertain times for manned and unmanned space missions, basaltic meteorites are probably as close as planetary scientists, especially geochemists, will ever get to the objects of their longing, perhaps for several generations. It is hardly surprising that collectors seize on petrogenetically evolved meteorites with glee. Such a desirable chunk from a desert surface in NW Africa has been analysed comprehensively by scientists from Japan and the USA (Yamaguchi, A. *et al*. 2002. A new source of basaltic meteorites inferred from Northwest Africa 011. *Science*, v. **296**, p. 334-336; DOI: 10.1126/science.1069408). Its chemistry fits with no planetesimal or suspected planetary meteorite class, although for the most part it does resemble the eucrites, considered to originate from the large asteroid Vesta. Rare-earth elements, siderophile metals and oxygen isotopes put it in a class of its own. Although the authors are content to conclude that it probably evidences a range of planetesimals that underwent differentiation to produce basaltic magmas, some have been tempted to speculate on a planetary origin, perhaps on Mercury (Palme, H. 2002. A new Solar System basalt. *Science*, v, **296**, p. 271-273; DOI: 10.1126/science.1070768). I am left wondering why the supposed Martian meteorite class, with all the kudos that such a suggested origin brings, has not been tempered by the likelihood of origin in a large planetesimal; but I am no specialist.

Early Argentineans did not witness a meteorite impact (*May 2002*)

Ten years ago, planetary scientist Peter Schultz and Argentinean pilot Ruben Lianza observed several depressions shaped like tear drops while flying over the Pampa. Because they also found meteorites and tektite glass when they examined the structures on the ground, it seemed certain that the depressions had formed by the impact of bodies travelling almost parallel to the Earth's surface. The structures were clearly no more than a few thousand years old, and the discovery encouraged lurid artistic impressions of terrified native South Americans cowering from an extraterrestrial firestorm. The Rio Cuarto structures were a godsend for those who fear social and economic disaster from Earth-bound NEOs (near-Earth objects), and have been lobbying for a sky watch for impending doom.

In reality, the Pampas of northern Argentina has hundreds of similar structures over an area of more than 50 thousand square kilometres, and their long axes parallel the prevailing wind direction (Bland, P.A. and 10 others 2002. A possible tektite strewn field in the Argentinian Pampa. *Science*, v. **296**, p, 1109-1111; DOI: 10.1126/science.1068345). They are “blow-outs” developed in the fine loess soils of the Pampa, and much the same structures affect most loess plains. Being formed of wind-blown silica and clay dust, loess is not well known for its content of objects above a millimetre in size, so any larger objects found on wind-deposited plains stand a high chance of having arrived by some extraterrestrial process. Meteorites and tektites are rare, but ablation concentrates them in wind-blown depressions as they are too heavy to be blown away. That is the likely origin of the objects that Schultz and Lianza used in support of their hypothesis of impact devastation wrought on early South Americans. Phil Bland of the Open University, and his colleagues from Brazil, the USA, Australia, Russia, Argentine and Britain, were able to date organic matter in the Rio Cuarto structures using the C-14 method at 4000 years. Yet Ar-Ar ages of the meteorites range from 52 to 36 thousand years, so the two are unconnected. The glassy tektite fragments provided yet another age of 57 thousand years. Along with similar glasses at a couple of other sites in Argentina, these support melting of the homogeneous loess by an impact around that time, although no crater from which they might have been ejected is known. The search is on for the source of a hitherto unknown field of strewn tektites, although it seems strange that in the featureless plains of southern South America one hasn’t shown up long before now.

The mantle’s breath and Earth's early evolution (*May 2002*)

Many lavas contain bubbles, which form when gases dissolved under pressure in magma froth out at low pressures. For the most part the gas is water vapour, carbon dioxide and sulphur dioxide. It comes from mantle peridotite, and represents the volatile fraction of the deep Earth. But there are traces of other gases, the most revealing of which are the noble gases helium, neon, argon, krypton and xenon, because some of their isotopes originate from radioactive decay of other elements (mainly potassium, uranium and thorium. Noble gases in basalts offer important insights into how the mantle has evolved since the origin of the Earth. Chris Ballentine of the University of Manchester, reviews how such trace-gas isotopes in basalts help resolve some otherwise intangible challenges (Ballentine, C.J. 2002. Tiny tracers tell tall tales. *Science*, v. **296**, p. 1247-1248; DOI: 10.1126/science.1070399).

Water on Mars (*July 2002*)

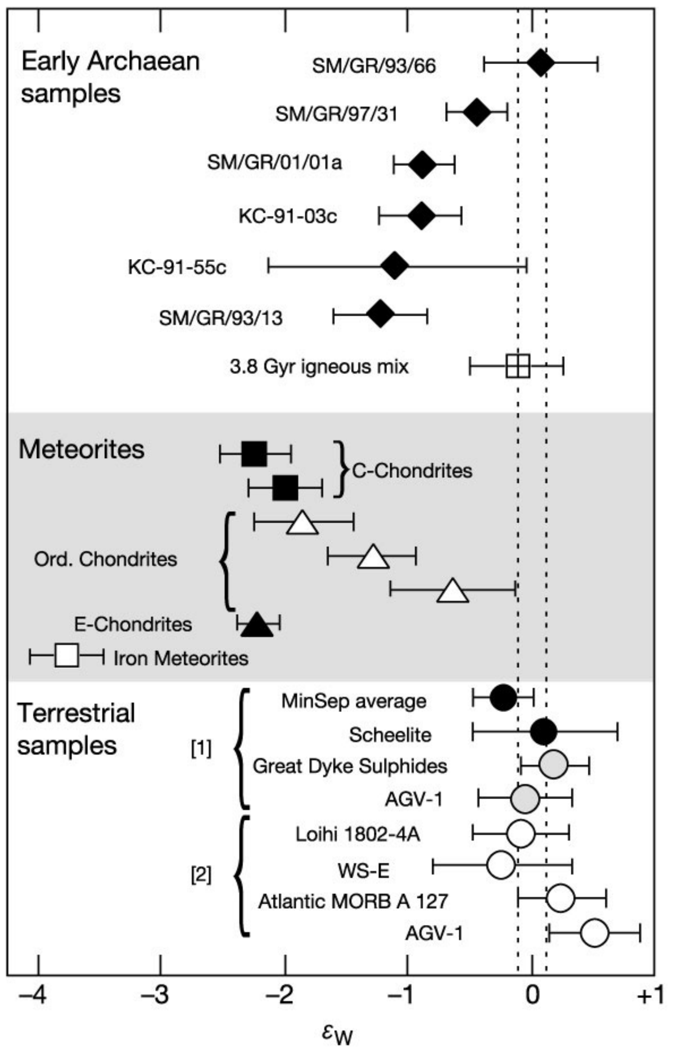
From time to time I have tried to temper the flood of papers that seek every which way to support the notion that Mars is still well-endowed with water. That is what NASA seeks in order to fuel its bid for the vast funds needed to launch a crewed mission to the Red Planet. The evidence in each case was ambiguous. I have always thought that attention and money would be better directed towards the one sixth of the human population who have no access to safe and abundant water supplies. That remains my view, but the appearance of 10 pages of *Science* forces me to accept near proof of Martian water in abundance (Feldman, W.C. and 12 others 2002. Global distribution of neutrons from Mars:results from Mars Odyssey. *Science*, v. **297**, p. 75-78; DOI: 10.1126/science.1073541. Mitrofanov, I. and 11 others 2002. Maps of subsurface hydrogen from the high energy neutron detector, Mars Odyssey. *Science*, v. **297**, p. 78-81; 10.1126/science.1073616. Boynton, W.V. and 24 others 2002. Distribution of hydrogen in the near surface of Mars: evidence for subsurface ice deposits. *Science*, v. **297**, p. 81-85).

The neutron and gamma-ray detectors aboard Mars Odyssey only needed to operate for a month to reveal the abundance of hydrogen across the surface of Mars. It varies a great deal, the highest levels showing up at high northern and southern latitudes. Preliminary modelling suggests that these regions have at least several metres of ice-rich debris, containing between 25-35 % water ice. Quite possibly the modelled ice-rich layer could reach a kilometre in thickness. High anomalies at lower latitudes are modelled as being due to hydrated minerals in the Martian soil.

More results at higher precision are to come from Mars Odyssey, and experts emphasize that the reported modelling of neutron fluxes and those of gamma rays emitted by neutron-capture reactions is complex and preliminary. However it does look like NASA scientists will soon by selecting sites for future landings on Mars. Even more certain, it will have sent a frisson of excitement through those intent on the glory of finding signs of life there.

Tungsten and Archaean heavy bombardment (*July 2002*)

One of the major revelations that arose from the Apollo missions to the Moon is that the vast *maria* basins, filled with basalt, formed when a series of huge impacts wracked the lunar interior. Surprisingly, they formed between 4 to 3.8 Ga ago, rather than in the earlier evolution of the Moon, and this “late heavy bombardment” (LHB) spans the period when the oldest rocks were forming on the Earth. Controversy has raged for 3 decades about whether the LHB had a major influence on early Archaean geology. The problem was that direct evidence has been hard to find, and difficult to get across to critics of such outlandish notions. A careful investigation by geochemists from the Universities of Queensland and Oxford seems likely to force some critics to eat hat (Schoenberg, R. *et al*. 2002. Tungsten isotope evidence from ~3.8-Gyr metamorphosed sediments for early meteorite bombardment of the Earth. *Nature*, v. **418**, p. 403-405; DOI: 10.1038/nature00923).

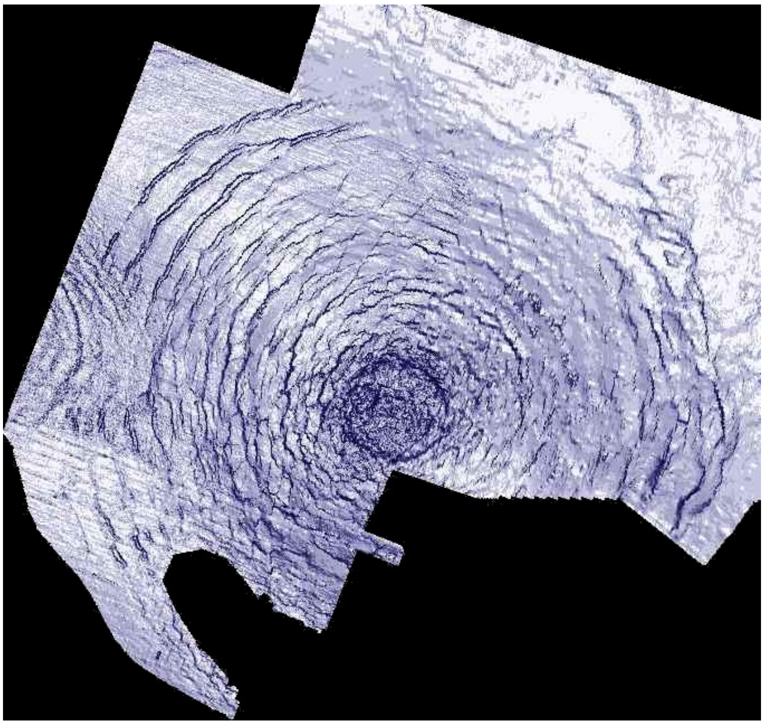


Values of εW for terrestrial rocks, meteorites and early Archaean samples. The top 6 are from early Archaean metasediments (Credit: Schoenberg*et al*. 2002; Fig. 1)

Because stable ^{182}W forms by the decay of ^{182}Hf, with a short (9 Ma) half life, virtually none will have formed since the Earth accreted. The $^{182}W/^{183}W$ (ε_W) ratio of objects from different parts of the Solar System should show distinct differences, and so they do. Different classes of meteorites show tungsten isotopes that are significantly different from one another, and from products of mantle melting on Earth. Ronny Schoenberg and co-workers analysed tungsten from two early-Archaean sources: the dominant grey gneisses, which are probably calc-alkaline igneous rocks formed at mantle depths, and metasediments from the famous Isua area in Greenland and another around the same age (~3.8 Ga) in Labrador. The gneisses show no difference from later products of mantle processes, but the metasediments deviate significantly from the terrestrial isotopic composition of tungsten, towards that characteristic of meteorites. They conclude that the metasediments mix debris formed by weathering and erosion of normal early Archaean crustal rocks with that formed in major blankets of ejecta from meteorite-induced impacts.

Bizarre impact structure beneath North Sea (*August 2002*)

The increasing use of finely-resolving 3-D seismic surveys in offshore exploration for hydrocarbons reveals exquisite detail of structure in strata beneath the sea floor. So it is no surprise that oil-company geophysicists are able to image features that would otherwise remain hidden to researchers in universities. If such discoveries are of little interest commercially, their finders are free to publish. During routine surveys in the southern North Sea, an array of seismic profiles gradually built up a picture of something more reminiscent of the surface of an icy moon of Jupiter than a sequence of basinal sediments (Stewart, S.A. & Allen, P.J. 2002. A 20-km-diameter multi-ringed impact structure in the North Sea. *Nature*, v. **418**, p. 520-523; doi:10.1038/nature00914). The circular feature, known as Silverpit, found in strata at the top of the Cretaceous, might have been passed off as the product of deeper rise of salt diapirs from the widespread Permian evaporites of the North Sea basin, but for several features. The surveys revealed no signs of the low-density Permian salt having bulged upwards below the structure, and disruption stops at depth.



Seismic data showing the crater and its concentric ring structure (Credit: Wikipedia, Phil Allen (PGL) and Simon Stewart (BP))

The feature consists of at least 10 concentric rings extending to 20 km diameter, and at its centre is a bowl-shaped depression around a clear peak. Not only is it an impact structure, but one of a particular class known as multi-ringed basins. Those known from the Moon, are vastly bigger and are thought to have formed by such immense energy that the lunar surface rippled to fail along large concentric faults. Lunar and terrestrial craters of the size of the North Sea structure usually have no concentric structure, being circular pits with rims and occasionally a central peak cause by rebound of the crust after impact. The only similar features known are from moons of the Giant Planets that are made mostly of ice. It is surprising that the North Sea example closely resembles them. Modelling of such craters on Callisto suggests that they form when surface materials are underlain at depth by weaker ones; possibly an ice-liquid slush on ice moons. The North Sea impact was into the Upper

Cretaceous Chalk, whose upper strata are more homogeneous than those at deeper stratigraphic levels, which contain layers of mudstone. Had impact occurred while the strata were not completely lithified, then the clays would have allowed inward movement to fill the crater excavated by impact, the more rigid upper Chalk having fractured during this movement.

Whether or not the impact accompanied the Chicxulub crater, implicated in the end-Cretaceous mass extinction, is not certain, although it does seem to predate Tertiary sedimentation in the North Sea. There are probably many more impact structures on the sea floor, buried by marine sediments, but only in hydrocarbon-rich basins are they likely to be unmasked by seismic surveys.

Note: Later consideration suggests that Silverpit was indeed a result of salt diapirism triggered by intrusion of Palaeocene basaltic dykes beneath the North Sea

Evidence builds for major impacts in Early Archaean (*August 2002*)

Impact spherule bed from the Archaean of Barberton South Africa (Credit: Callan Bentley)

Following the discovery that anomalous tungsten isotope compositions of some Early Archaean rocks suggest a major component of extraterrestrial material in them (see *Tungsten and Archaean heavy bombardment* above), geochemists from Louisiana State and Stanford universities report evidence of debris from very large impacts in the same period (Byerly, G.R. *et al*. 2002. An Archean impact layer from the Pilbara and Kaapvaal cratons. *Science*, v. **297**, p. 1325-1327; DOI: 10.1126/science.1073934). Their case rests on the occurrence of layers of rock containing spherules of what formed as molten silicate droplets, in Early Archaean greenstone belts of the Barberton and Warrawoona areas of South Africa and Australia. Zircons from a single layer in both areas yield identical ages of 3470 Ma, suggesting that the layers formed during a single impact event. The authors speculate that a major unconformity in the Archaean of the Pilbara province in Australia, which is around the same age, may be the result of tsunamis induced by the impact. It seems as if the responsible impact had a global effect, and may have released 1 to 2 orders of magnitude more energy than that responsible for the K/T event. Judging by the lunar cratering record, this and previous finds help confirm expectations of similar bombardment on Earth during the Early Archaean.

Very early differentiation of planetary bodies (*August 2002*)

The radioactive decay of ^{182}hafnium to ^{182}tungsten seems likely to resolve the influence of impacts on the Earth 's evolution (See *Tungsten and Archaean heavy bombardment above*). It is even more useful in refining ideas about the evolutionary pace of the parent bodies of meteorites. The half-life of ^{182}Hf is only 9 million years (all of it has decayed away in the Solar System by now), so the amount of radiogenic ^{182}W associated with hafnium in a meteorite is a guide to pervasive geochemical processes early in the history of their parent bodies. Hafnium has an affinity for silicates, whereas tungsten is siderophile and likely to enter planetary cores, should they form. Because ^{182}Hf decays so quickly, it is not easy to work out its original abundance, relative to stable ^{180}Hf, in the source material for the Solar System. That is a prerequisite for estimating when the hafnium-tungsten differentiation took place in a planetary body. Two papers in the final August 2002 issue of Nature agree on this initial ratio (Yin, Q. *et al*. 2002. A short timescale for terrestrial planet formation from Hf-W chronometry of meteorites. *Nature*, v. **418**, p. 949-952; 10.1038/nature00995. Kleine, T. *et al*. 2002. Rapid accretion and early core formation on asteroids and the terrestrial planets from Hf-W chronometry. *Nature*, v. **418**, p. 952-955; • DOI:10.1038/nature00982), which has important connotations; it is less than half the previously assumed value. They determined this initial ratio using Hf-W data from independently dated carbonaceous-chondrite meteorites, whose parent bodies were never fractionated.

The two research groups, from Harvard University and the French Laboratoire des Sciences de la Terre, and the universities of Münster and Köln, Germany, respectively, use the new initial ratio to estimate the age of core formation from a range of meteorites. Their estimates dramatically shorten the time between original accretion and core formation in a variety of bodies whose Hf-W isotopes have been studied previously. The parent of the eucrite class of meteorites, probably the asteroid Vesta, differentiated within only 3 to 4 Ma, whereas the cores of the Earth and Mars took a little longer - about 29 and 13 Ma respectively. In geological terms, accretion and core formation probably accompanied one another. Of course, such estimates based on isotopic decay systems assume that the initial ratios existed at the time of accretion. That may not be valid if the pre-Solar nebula took millions of years to evolve to the stage of self-collapse under gravity, which is the prerequisite for the formation of a planetary system. However, there is evidence from short-lived decay systems involving other radioactive isotopes, such as ^{26}Al, in meteorites, that points to the influence of a nearby supernova that triggered the formation of our Solar

System. Such an event is required to synthesize short-lived isotopes anyway. Moreover, the shock from a supernova could accelerate collapse to mere few tens of thousand years.

See: Cameron, A.G.W. 2002. Birth of a Solar System. *Nature*, v. **418**, p. 924-925; doi: 10.1038/418924a.

Britain's own impact (*November 2002*)

While evidence has been accumulating for the influence of asteroid and comet strikes elsewhere, the British geological community has had a disproportionate share of sceptics; those who thought it was all a matter of "whizz-bang" science. It is welcome news that we now have our own "piece of the action", for geoscientists from Aberdeen University and the Open University have a discovered a well-preserved impact horizon in Late Triassic terrestrial sediments that contain both devitrified glass spherules and shocked quartz grains (Walkden, G. *et* al. 2002. A Late Triassic Impact Ejecta Layer in Southwestern Britain. *Science*, v. **298**, p. 2185–2188; doi: 10.1126/science.1076249). It is not associated with the Triassic-Jurassic boundary, which witnessed on of the "Big Five" mass extinctions, but is dated at 214±2.5 Ma, within error of the major impact at Manicougan (~100 km diameter; Quebec; 214±1 Ma) the lesser Rochechouart structure (~25 km diameter; France; 214±8 Ma). The Ar-Ar dating did not use spherule glass, but authigenic potassium feldspar that postdates the spherules, but may have formed from potassium released when they became hydrated. Given its size and position relative to Britain on a Triassic plate reconstruction, Manicougan is a likely culprit. However, despite its considerable size, there are no signs of significant faunal changes at the time of the Manicougan impact. The host Triassic rocks in Somerset rest directly on Carboniferous limestones, and primitive mammal remains are known from infillings of a palaeokarst surface in the Mendip Hills. Now the deposit has come to light, the search is on for similar materials in Late Triassic marine sediments.

Water recycling in the mantle (*December 2002*)

The cold, dense oceanic lithosphere that descends subduction zones is also rich in water. These features result from the circulation of seawater through young basaltic crust, the exothermic hydration of originally anhydrous minerals in basalt and efficient convective cooling through hydrothermal processes. Because of this, it might seem as though subduction is a means of re-introducing water into the mantle, thereby enhancing the ability of rising mantle plumes to melt. The critical process that destines subducted lithosphere to sink inexorably is the conversion of oceanic crust to eclogite by high-pressure, low-temperature metamorphism in the subduction zone. Eclogite consists mainly of garnet and the pyroxene omphacite, which confer its higher density than mantle peridotite, and the reactions which form them involve dehydration. Rise of hydrous fluids from the descending slab is implicated in partial melting of the over-riding wedge of mantle to form the volatile-rich magmas that build volcanic arcs. The higher gas content of arc magmas, compared with those at constructive margins and above mantle plumes, makes them explosive and able to build volcanoes high above sea level. Most eclogites found at the Earth's surface are accompanied by still hydrous metamorphic rocks of basaltic composition - blueschists - and others that clearly formed from the sedimentary veneer of the oceanic crust. So, it might seem that blueschists and metasediments could carry a substantial amount of water into the mantle. Eventually, its recycling through the mantle could influence later magmatic processes.

Testing this seemingly reasonable extension of the hydrological cycle depends on assessing the water content of newly erupted magmas. This is virtually impossible for eruptions at the Earth's surface, because low pressure results in water escape within the higher parts of the volcanic plumbing system, before lavas can be sampled. However, eruptions onto the ocean floor deeper than a kilometre experience pressures high enough to keep gases in solution, which is why pillow lavas of true oceanic crust contain no signs of gas bubbles. Crystallised oceanic basalts soon react with percolating water, and their volatile contents are meaningless. Only the rapidly chilled margins are likely to retain their original composition, locked into quenched basaltic glass. Even then, a direct measurement of water content can be misleading. A cunning approach is to consider H_2O as if it behaved like a single element, based on its bulk distribution coefficient between melt and residual solid mantle. That is close to the values for light rare-earth elements, such as cerium. So a check for either degassing or contamination of basaltic glass with seawater is the glass's H_2O/Ce ratio (decreased by the first and increased by the second process). Jacqueline Dixon of the University of Miami, and co-workers from Harvard and the University of Rhode Island have used this method to assess the probable water content of the mantle source for mid-Atlantic Ridge basalts, whose lead and strontium isotopes suggest that their source was contaminated by older, recycled crust (Dixon, J.E. *et al*. 2002. Recycled dehydrated lithosphere observed in plume-influence mid-ocean-ridge basalt. *Nature*, v. **420**, p. 385-389; DOI: 10.1038/nature01215). The surprising conclusion of their work is that oceanic basalts formed from mantle with a recycled component have considerably less water in them than those formed by melting of pristine mantle. This suggests that subduction processes are extremely efficient (>92%) at removing volatiles from the subducted slab; lithosphere descending to depth is almost anhydrous.

Incidentally, the paper begins with an excellent explanation of the somewhat arcane distinctions between different mantle sources affected by lithosphere recycling and mixing.

See also: White, W.M. 2002. Through the wringer. *Nature*, v. **420**, p. 366-367; doi: 10.1038/420366a.

Mantle avalanches and length of the day? (*December 2002*)

One of the most fascinating spin-offs of detailed palaeontology is that the growth layers in corals and the carbonate shells of other organisms can record how many days there once were in a year. Records of shell growth can even chart variations in the lunar cycle, backed up by subtle features in cyclical sediments. Such data infer that the speed of the Earth's rotation has changed (Ravilious, K. 2002. Wind up. *New Scientist*, 23 November 2002, p. 30-33). As well as the general slowing through the Phanerozoic, from a rate that gave 420, 21-hour days in a Cambrian year, there have also been times when the rate has strangely speeded up again. Such curious events occurred at 400 Ma and again around 180 Ma.

Planetary spin can be set in motion or changed by very large impacts, in the manner of whipping a spinning top. But there is little sign for such drama at those times. Another possibility is a change in the Earth's moment of inertia by a shift of mass relative to the spin axis, in the manner of a skater speeding up a spin by pulling in her arms. What could induce such an effect at the scale of our planet? Cold, dense lithosphere continually sinks at subduction zones, but that is normal behaviour in balance with rotation. One possible trigger for sudden changes in moment of inertia is the breaking away of a substantial chunk of the mantle that lies above the discontinuity 670 km beneath the surface to sink to deeper levels. This dramatic suggestion stems from modelling by Philippe Machetel and Emilie Thomassot of the University of Montpellier in France (Machetel , P. & Thomassot , E. 2002. Cretaceous length of day perturbation by mantle avalanche. *Earth and Planetary Science Letters*, v. **202**, p. 379-386; DOI: 10.1016/S0012-821X(02)00785-9). Their model focussed on the transition zone between lower and upper mantle around the 670 km discontinuity, and how it might respond to the fluid dynamics of Earth's convective heat transfer, particularly that involving heat originating in the core. The transition, they claim, acts as a "lid" to efficient heat transfer between lower and upper mantle. Their model suggested that additional deep-mantle heat flow might destabilise the transition's strength, so that it would no longer support the mass of cooler and more rigid mantle above it. Failure could then allow a massive slab of upper mantle literally to fall to the core-mantle boundary, spreading out to displace material there upwards as the precursor of a superplume.

The link to day-length comes from Machetel and Thomassot's search for evidence that such collapses might have occurred, and they concentrated on the 180 Ma change (Mid Jurassic). Around 170 Ma the current round of continental drift began in earnest. In the Early Cretaceous (130 Ma) the geomagnetic field became locked into quiescence, remaining with the same polarity for an unprecedented 40 Ma during which the giant Ontong Java oceanic flood volcanism took place. Their explanation for both is that upper mantle avalanched, eventually to reach the core-mantle boundary. When the mass "bottomed out" it cooled the outer core, settling it into regular motion, so that the geomagnetic field became constant. Coincidence? I am reminded that when skaters wish to stop their spins, they throw out their arms. The law of conservation of angular momentum also demands that the Earth behaves in the same way. In fact it applies to the Earth-Moon system, so that the general slowing of Earth's rotation has been accompanied by the Moon receding into ever more distant orbit, and gaining momentum.