Sedimentology and stratigraphy

A shocking discovery, for sedimentologists (*January 2008*)

Every introductory geology course hammers home the message that the finer the grains in a sedimentary rock, the lower the energy under which it was deposited. This ‘received wisdom’ links to the ways in which grains move in moving fluids: rolling; bouncing and in suspension. A reductionist view sees this as the influence of Stokes’ Law in the boundary conditions between turbulent and laminar flow, close to the bed of flow and higher up in the fluid respectively. Stokes’ Law is invoked as it explains how spheres falling through fluids reach a steady speed related to the fluid’s viscosity. The larger the radius of the sphere, the greater that settling speed is. For the smaller size ranges settling speed is proportional to the square of the radius (laminar flow conditions), whereas for large objects it is proportional to the square root of radius (turbulent flow). This nicely explains the upward decreasing grain sizes in graded beds, formed when a mixture of grain sizes settles from moving fluids when their speed slow, as in turbidites and the on the lee sides of sand dunes. Since we often see silts and muds being deposited in low-energy lagoons and estuaries on the coast that too seems to verify the theory. However, muds that contain clay mineral particles are quite different from scaled-down spherical grains: they are platy; often have unbalanced electrical charges and are subject to Brownian motion that helps keep them in suspension. When clays suspended in fresh river water meet the sea, ions in sea water encourage the plates to clump together as aggregates or floccules that are much larger than the clay particles themselves. Another oddity is that, once deposited, clays are not as easily eroded as uncemented sands, partly due to their hosting biofilms that hold the particles together.

Despite the accepted explanation of mudstones as indicators of past low-energy conditions based on reductionist notions, suspicion of awkward complexity dates back to Henry Clifton Sorby, one of the founders of geology, who suggested that the study of mudstones and shales was a great challenge for sedimentology. In reality there are probably more than 30 parameters that govern the shifting and deposition of muds, many bound up with flocculation. Confidently discussing the true environmental conditions of mudstone deposition is often thwarted by their ease of weathering and disturbance by small animals that exploit often high contents of organic debris in mud. Even the fissility of shales is a mystery in the field. Now and again, muds do reveal surprises, such as ripples and cross lamination, that surely reflect current action. Only experimentation can throw light on Sorby’s great challenge (Schieber, J. *et al*. 2007. Accretion of mudstone beds from migrating floccule ripples. *Science*, v. **318**, p. 1760-1763; DOI: 10.1126/science.1147001). Schieber and colleagues from MIT and Indiana University used experimental flumes to investigate what happens to clay floccules, seeding the materials with fine hematite grains to show up any bedforms clearly. The muds used were from 5 to 63 μm in size, which produced floccules between 0.1 to 1.0 mm. Again and again the experiments produced migrating ripples, some like tiny barchan dunes made of clay floccules. The surprise lay in the flow speeds at which they began to form: between 10 to 30 cm s^{-1}, much the same as those needed to produce sand ripples. Floccules were preserved in the experiments, but since they are made of clay minerals, compaction tends to destroy floccule outlines when mudstones form.

No doubt some fine-grained sedimentary rocks reflect low-energy environments, but without more careful examination of their small-scale features muds formed by energies as high as those involved in producing sandstones will go unnoticed. Since mudstones are the most common sedimentary rocks in the geological record, some big surprises are in store.

See also: MacQuaker, J.H.S. & Bohacs, K.M. 2007. On the accumulation of mud. *Science*, v. **318**, p. 1734-1735; DOI: 10.1126/science.1151980.

Epoch, Age, Zone or Nonsense

The International Commission on Stratigraphy lists 37 Series/Epochs and 85 Stages/Ages in the latest version of the International Stratigraphic Chart for the 11 Systems/Periods of the Phanerozoic. A great battle against ICS's attempt to extinguish the Quaternary, the only enduring Era originated by Giovanni Arduino (1714-1795) and Johann Gotlob Lehmann (1719-1767), now seems to have ended in a compromise (Kerr, R.A. 2008. A time war over the period we live in. *Science*, v. **319**, p. 402-403). While that vigorous struggle has apparently petered out, the Stratigraphic Commission of the Geological Society of London has launched another by proposing a new Epoch – the Anthropocene. This follow a suggestion by Nobel laureate and chemist Paul Crutzen that the Holocene Epoch ended once humanity made a significant impact on the Earth system (Zalasiewicz, J. and 20 others 2008. Are we now living in the Anthropocene? *GSA Today*, v.**18(ii)**, p. 4-8).

The device intended by the ICS to mark boundaries between Periods, Epochs and Ages in the Phanerozoic is a symbolic Global Standard Section and Point (GSSP), combining an absolute age definition and a type section. A growing number of boundaries are marked by a physical 'golden' spike (not necessarily made of gold) including a plaque engraved with the Period or Age names, welded into the agreed boundary itself. There is good reason for this seemingly odd behaviour; geologists need to have agreed nomenclature and locations so that their discourse can be internationally sensible. It is also a deeply exciting, even exalting moment when any geologist puts her/his finger on a boundary of global significance: and how supremely triumphant actually to wield the hammer that drives the spike home. So much so, that there have been monumental squabbles, some not far short of diplomatic 'incidents', about exactly where GSSPs should be placed.

But the whole bureaucratic process has its awkwardly humorous side. There is a proposal that the GSSP for the Pleistocene/Holocene boundary be located in a Greenland ice core. Is that to be in the hole left by the NGRIP core drill at the centre of Greenland, at the depth at which evidence for the warming at the end of the Younger Dryas (11.5 ka) occurs? Or should it be in the core itself – a GSSP in a fridge? Either way, it is going to be difficult to put a finger on that particular boundary Moreover, global warming and the attendant social disruption might remove both. The proposed Anthropocene might have an even stranger GSSP. For a start, when did it begin? An anthropogenic human signature appears clearly in the NGRIP core around 8 ka bp, and at a variety of levels in pollen records, but the GSL's Stratigraphic Commission wants it to start at the beginning of the Industrial Revolution. Sadly, that is a profoundly diachronous, economic boundary. To make it Eurocentric, as Crutzen suggested, would be a bit non-PC.

Let's face it, the Holocene is just an interglacial, similar to a great many since 2.4 Ma ago. It is noted only for the brief period in which humanity became separated into two groups: a very small one owning the means of production; the other, initially diverse, being forced to work for the first in order to survive. The Industrial Revolution marked a social simplification into two opposed *classes*, as clearly defined by Marx, and the increased dominance of human affairs by an inhuman entity called *capital*. The working through of the contradictions bound up in class society and in capital itself has been largely responsible for the huge environmental changes drawn on by Zalasiewicz *et al*. It seems our somewhat po-faced authors forget the great many more scholars of human affairs than there are geologists: historians and political economists. Already there are plenty of anthropocentric equivalents of GSSPs in London itself, in the form of its celebrated blue plaques. Historians and political economists might well agree that the rise to dominance of capital – and hence the emergence of rapid environmental change during the uniquely short-lived Anthropocene – began outside the Banqueting Hall on Whitehall at 2.04 pm on Tuesday 30 January 1649 with the separation of the head of the divinely righteous monarch, Charles I, from his body. Ladies and Gentlemen of the SC of the GSL, that is where you place your 'golden' spike. However, geology might yet have its say, any time now (and geologists cannot really foretell): a super-volcanic eruption; a comet strike or a cosmic gamma-ray burst. So you had better be quick, if your aim is posterity.

Where do ocean-floor sediments go? (*March 2008*)

It used to be widely thought that sediments on the ocean floor and those at active continental margins or ahead of volcanic arcs were scraped off subducting lithosphere and simply added to continental growth. If that didn't happen, then perhaps continents could be recycled by a combination of erosion and tectonics? Geochemists know better now, for a variety of compositional anomalies in volcanic rocks do suggest a measure of recycling of subducted lithosphere, and it is becoming clear that part of the oddity has a sedimentary source. "Which one?" is the question?

Hafnium and neodymium isotopes have become popular tracers of whether basaltic magmas formed from pristine mantle, that depleted by previously sourcing magma or some kind of mixture with recycled materials. Catherine Chauvel and colleagues from the University of Grenoble have pondered on the sizeable amount of Hf and Nd isotopic data that has emerged from a couple of decades of mass spectrometry of ocean-island and mid-ocean-ridge basalts, and a variety of sediments (Chauvel, C. *et al*. 2007. Role of recycled oceanic basalt and sediment in generating the Hf-Nd mantle array. *Nature Geoscience*, v. **1**, p. 64-67; DOI: 10.1038/ngeo.2007.51). By modelling how various reasonable mixtures of isotopes of the two elements might fit the simple Hf-Nd relationship for the source mantle of all oceanic basalts they discovered that it couldn't be derived from just the crystalline oceanic lithosphere, but must involve a substantial contribution from subducted sediments. Moreover, they seem to have demonstrated that much of the mantle involved in producing ocean-island, hot-spot basalts is a product of this recycling – both oceanic crust and its sedimentary cover get down to the levels where the mantle involved in hot-spot melting originates. Although there is a good probability of separation of sediment and crystalline components of subducted slabs according to density, it seems from the modelling that some sediment does get down to profound levels.

See also: Plank, T. & van Keken, P.E. 2008. The ups and downs of sediment. *Nature Geoscience*, v. **1**, p. 17-18; DOI: 10.1038/ngeo.2007.68. See especially their astonishing figure giving a graphic notion of the forms mantle convection might take.

Geologists may now synchronise their watches? (*May 2008*)

Calibrating the stratigraphic column to absolute time depends, of course, on radiometrically dating geochemically suitable rocks or minerals. Yet there is a range of available methods based on decay of unstable isotopes, such as ^{14}C, ^{40}K, ^{87}Rb, ^{147}Sm, uranium and thorium. All depend on a variety of assumptions, of which that of a constant, well-established half-life is common to all. If all were perfect, several methods applied to the same materials should give the same results. The trouble is, each parent isotope favours different minerals and different compositions of igneous rocks, so that discrepancies in the dates assigned by different methods to the same stratigraphic unit may either be due to disturbance of one isotopic system relative to the other or to the half-life of one (or both) parent isotope being inaccurate. Currently, the two most widely used and best-regarded methods are U-Pb and Ar-Ar, the latter depending on ^{40}K being converted to ^{40}Ar by neutron bombardment. The first often uses zircons, the second various potassium minerals such as alkali feldspar. Both minerals are magmatic in origin and so the same igneous rock may sometimes be dated by either method or both. It is becoming increasingly clear that the two approaches do not give the same age, which is worrisome at the detailed level permitted by the high precision of each of the methods.

A means of checking the timing parameters for radiometric dating is to compare its results with absolute age determined by a non-radiometric method. The best-calibrated and most widely achievable method that does not rely on radioactive decay is based on the astronomical pacing of climate, with its 100, 41, 23 and 19 ka cycles. Analysis of cyclicity in repetitive sedimentary sequences reveals patterns of frequencies that match the astronomical signals. So, within such a sequence it is possible to chart time differences to within a few thousand years, and sometimes much less. If there are igneous rocks interlayered with the cyclical sediments it should be possible to check their radiometric age differences against the difference determined independently. A Miocene sequence in Morocco has many intercalations of igneous tephras, and therefore provides a crucial test for radiometric approaches (Kuiper, K.F. *et al*. 2008. Synchronizing rock clocks of Earth history. *Science*, v. **320**, p. 500-504; DOI: 10.1126/science.1154339). The team from the University of Utrecht, the Free University of Amsterdam in the Netherlands, and the University of California, dated sanidine (K-feldspar) from the tephras using the Ar-Ar method. This involved using a standard age determined for sanidines from a similar rock type at Fish Canyon in Colorado USA. By turning the approach on its head, i.e. by using astronomically calibrated ages for the samples, they recalculated the age of the Fish Canyon standard. It seems to be 0.65% older than previously thought (from rather dodgy U-Pb dating of zircons in the Fish Canyon Tuff).

All Ar-Ar ages involve the Fish Canyon standard. So, an underestimate of its age would imply revision of quite a lot of geological events dated by Ar-Ar, especially those that happened abruptly, such as mass extinctions, impacts and magnetic reversals. Using the new standard age puts the K/T boundary event back to 66 Ma from 65.5 Ma. The formerly 251.0 Ma mass extinction at the end of the Permian becomes 252.5 Ma, which coincides better with the outpouring of the Siberian Traps. Similarly, the once 200 Ma end-Triassic extinction, but now possibly 201.6 Ma, links better to the Central Atlantic Magmatic Province outpourings. Quite a stir may be on the horizon, if Kuiper and colleagues' recalibration is confirmed by similar independent measures.

That radiocarbon dates need to be used with caution is well known, as the amount of ^{14}C produced by cosmic ray bombardment of atmospheric nitrogen varies markedly over time. Again, the 'work-around' involves using non-radiometric ages to calibrate the fluctuating relationship between radiocarbon ages and real time. The data of choice are those from tree-ring analysis, but ice cores also preserve ages with a 1-year precision from their annual layering. The Younger Dryas cold period that interrupted the global deglaciation began when atmospheric ^{14}C production was high. It was also a tremendously important event in the progress of human migration and perhaps even genetics – population crashes in hard times can have a 'bottleneck' effect on evolution. A multinational team has addressed the interrelations between radiocarbon dating, ice-core climate proxy records and tree-ring analysis for this crucial episode (Muscheler, R. *et al*. 2008. Tree rings and ice cores reveal calibration uncertainties during the Younger Dryas. *Nature Geoscience*, v. **1**, p. 263-267; DOI: 10.1038/ngeo128). They combined measures of varying ^{14}C in tree rings and ^{10}Be in ice cores, both of which are cosmogenic. Rather than resolving the issue, they discovered that the best marine record of the carbon-cycle during the YD, in the Cariaco basin off Venezuela, has a bias caused by anomalous concentration of ^{14}C in shallow seawater as the YD began. Their study open the possibility of resolving such changes in the marine C-cycle.

See also: Kerr, R.A. 2008. Two geological clocks finally keeping the same time. *Science*, v. **320**, p.434-435; DOI: 10.1126/science.320.5875.434.

The banding in BIFs (*November 2008*)

Banded ironstones from Hamersley, Western Australia. (Credit: Wikipedia)

Banded iron formations, or BIFs, from the late Archaean and early Proterozoic are made of interlayered accumulations of iron oxides (and occasionally sulfides) and chert, and are the world's most important iron ores. The BIFs of the Hammersley Range in Western Australia produce 26 % of the western world's iron ore, and are hundreds of metres thick. The banding extends down to the scale of a few micrometres, and in some cases seems to record cyclic events. It has been claimed that sun-spot, tidal, Milankovich and other natural cycles can be discerned. Few dispute that the iron oxides formed by oxidation of dissolved iron(II) ions through the influence of micro-organisms in shallow seawater. A popular candidate is photosynthetic blue-green bacteria, which produce oxygen. Abundant reduced iron dissolved in Archaean seawater would have consumed the oxygen to become insoluble iron (III) oxides, delaying the development of an oxygen-bearing environment until about 2.2 Ga. There are other possibilities, such as anoxygenic photosynthesising bacteria, known as photoferrotrophs, that could have achieved the Fe(II) to Fe(III) oxidation directly, without the need for free oxygen.

The puzzle is the on-off mechanism needed to produce the banding itself. That may have been resolved by experimental work under simulated Archaean conditions (Posth, N.R. *et al*. 2008. Alternating Si and Fe deposition caused by temperature fluctuations in Precambrian oceans. *Nature Geoscience*, v. **1**, p. 703-708; DOI: 10.1038/ngeo306). The authors based their experiments on primitive, but living photoferrotrophs in conditions that chemically mimic likely Archaean seawater. They discovered that the critical factor in this form of biogenic precipitation of iron is sea-surface temperature: the microbes reproduce fastest to maximise iron-oxide formation at 20-25ºC. Temperatures above or below this range shut down productivity. However, temperatures above 25ºC favour silica remaining in solution, so the alternation of Fe- and Si-rich bands favours cooler sea temperatures for the latter. As well as providing a means of producing the enigmatic BIF banding, the experiments help resolve the controversy over prevailing sea-surface temperatures in the Archaean, which have been suggested by some to be as high as 85ºC. At least for the late Archaean, ocean temperatures seem to have been much the same as at present.

Holding it together (*November 2008*)

It is always exciting to come across direct and tangible evidence for a concept conceived in the 18th century Scottish Enlightenment, taken up by James Hutton and immortalised by Charles Lyell as "the present is the key to the past". The most common are ripple marks, sun cracks and raindrop impressions, usually in sandstones. If you are exceptionally lucky you may find a hominin footprint. Because relatively high-energy currents move sands, every tide on a beach or in an estuary seems likely to obliterate the previous low tide's sedimentary structures: it is easy to think that only a 'one in a billion' chance preserves them. In fact they are a lot more common than common sense might suggest. That is because photoautotropic bacteria can coat sediment surfaces quite quickly to form biofilms or microbial mats, given the right conditions. They knit the grains together, thereby armouring the structures against erosion to some extent. The October 2008 issue of *GSA Today* begins with a useful summary of the influence of biofilms in preserving intricate signs of sedimentary processes (Noffke, N. 2008. Turbulent lifestyle: microbial mats on Earth's sandy beaches – today and 3 billion years ago. *GSA Today*, v. **18** October issue, p. 4-9; DOI: 10.1130/GSATG7A.1). Equally important, the author shows how close examination of even Archaean littoral sedimentary structures reveals clear signs of the microbial mats themselves. These are convincing evidence for ancient life, even in the absence of tangible fossil cells (the oldest undisputed fossils date back only about 2 Ga).

The Palaeozoic record of sea-level change (*November 2008*)

Variations in global sea level shift the positions where different sedimentary facies are deposited, and also change some aspects of oceanic chemistry. Consequently changing sea levels have long been of interest to petroleum explorationists, because reservoir- and source rocks will be laid down in different areas as the sea inundates stable continental areas or withdraws from them. Plots of changing sea level can be derived indirectly from seismic sections that reveal on- and off-lapping stratal sequences with detail added from the stratigraphy of such sequences determined in the field or from well logs, and considerable detail is available globally for the Mesozoic and Cenozoic Eras. The Palaeozoic Era is not so well known, and information has been acquired piecemeal but not correlated to time. So, a semiquantitative compilation will be welcomed in many quarters (Haq, B.U. & Schutter, S.R. 2008. A chronology of Paleozoic sea-level changes. *Science*, v. **322**, p. 64-68; DOI: 10.1126/science.1161648).

The outcome reveals a steady rise, with short term ups and downs, from about the same as modern levels to around 220 m higher through the Cambrian and Ordovician, dropping in late Ordovician times by about 80 m, perhaps due to glaciation at that time. Through the Silurian and Devonian global sea-level stood around 180 m higher than now, with only broad fluctuation, then to fall gradually through the Carboniferous to reach modern levels around 320 Ma. The Devonian to mid-Carboniferous decline marks the onset of the longest glaciation in Earth's history, which lasted until the late Permian. The broad shifts have superimposed short-term eustatic fluctuations, resolved into 172 separable events that vary in amplitude from a few tens of metres to around 125 m. Parts of the record show short-term fluctuations that may correspond to the ~400 ka cycle bound up with Earth's orbital eccentricity. Yet there is insufficient evidence outside the Carboniferous-Permian glacial epoch to suppose that 400 ka shifts in sea level had a glacial origin