Methane hydrates – natural gas held in clathrate solids that resemble water ice – that occur in sea-floor sediments are on the one hand a potential energy resource and on the other pose great risks. There are between $10^{15}$ to $10^{17}$ m$^3$ buried beneath the ocean floors and an unknown amount in Arctic soils and lakes. The temperature that confers stability on these peculiar solids depends on pressure. At pressures lower than those at a water depth of around 250m they are unstable. Clathrate crystals form from natural gas and water in sediments at 0°C at that depth and at progressively higher temperatures at deeper levels beneath the seafloor, until geothermal heat flow at a depth of around 2.5 km results in temperatures above about 20°C when they cannot form; there is a depth-temperature window in which gas hydrates may be found in seafloor sediments, which depends on the temperature of deep water. Little is known about the stability of gas hydrates. In some areas there is a steady release of methane that bubbles to the surface, whereas in others they can be detected by seismic surveys in huge volumes that appear to be stable with no release.

One area rich in gas hydrates occurs at the continental edge off the Norwegian coast (the Storegga in Norwegian). Periodically sediments at the Storegga fail in massive sub-sea landslides which have resulted in tsunamis in the North Sea. The last such tsunami occurred around 6100 BCE after a slide displaced 3500 km$^3$ of debris, devastating the east coast of Scotland. Either an earthquake triggered the slide or it was due to destabilizing of the clathrates. Either way huge amounts of methane would have been released. At the end of the Palaeocene Epoch (55 Ma) a global carbon-isotope anomaly coincides with evidence for very rapid climatic warming, which suggests that vast amounts of methane – a far more
powerful greenhouse gas than CO₂ – were released from submarine gas hydrates. In recent years the loss without trace of several large ships may have resulted from a lowering in the density of surface water by gas bubbles that caused the vessels to founder. One country that plans to exploit gas hydrates off its Pacific coast is Japan, and recent surveys indicate a large basin underlain by highly disturbed sediments which contain clathrates on the flank of the basin (Bangs, N.L. et al. 2010. Massive methane release triggered by seafloor erosion offshore southwestern Japan. Geology, v. 38, p. 1019-1022; DOI: 10.1130/G31491.1). It appears that bottom currents eroded the seafloor to destabilize the clathrates that then ‘erupted’ ripping through the sediments to release around 1.5 x 10¹¹ m³ of methane. Clearly, drilling into gas hydrate deposits is going to be a risky business; drilling will reduce the pressure so that gas is released and it is not known whether or not this might trigger a form of chain reaction. In the longer term, warming of deep water as a result of climate change could place much larger areas of clathrate-rich seafloor in a knife edge.

A possible earthquake prediction tool? (March 2011)

Every time seismic disaster strikes, as it did in Christchurch, New Zealand on 22 February killing at least 160 people and destroying a third of the city’s buildings, people long for some means to be forewarned of pending earthquakes early enough to escape collapsing buildings. Many approaches have been suggested over the years, such as changing water levels in wells, increased emission of radon and even the behaviour of animals in advance of major events. Ideally, seismic early warning tools should be generally applicable, easily implemented and possible to telemeter immediately to local and national authorities. Probably the best place to seek such a method is in the field of seismology itself, and one candidate recently emerged (Bouchon, M. et al. 2011. Extended nucleation of the 1999 M₉. 7.6 Izmit earthquake. Science, v. 331, p. 877-880; DOI: 10.1126/science.1197341).

Radar interferogram showing the movement along the North Anatolian Fault during the 16 August 2009 Izmit earthquake. Each sequence of colours (lower left) represents 28 mm of movement (Credit: Wikimedia)

This examines foreshocks of the tragic events at around midnight 16 August 2009 in NW Turkey that ripped along 150 km of the North Anatolian Fault to kill around 17 000 people. The seismological records of the Izmit earthquake are not good quality, but Michel Bouchon
and his French and Turkish colleagues, experts on the event, were able mine the ‘blurred’ data using new techniques. What they found was a sequence of 18 small earthquakes up to 45 minutes before the main one, each of which showed remarkably similar seismogram traces. From them they were able to show that most of the foreshocks arose from the same place on the fault and involved the same kind of deformation; by slippage in a patch or nucleus only about a few hundred metres wide at 15 km depth on the main fault. At each successive foreshock the rate of slip can be shown to have speeded up, and in the final 2 minutes before the main earthquake the localised acceleration was at its fastest. Also the low-frequency ‘rumble’ associated with each shock steadily got more powerful. These features define a similar shape for each seismogram record in the foreshock sequence.

The Izmit data tally well with a theoretical scenario for the initiation of movement along a fault. As tectonic stress builds up it begins to be dissipated by slow creep that can focus on a small part of the fault. Since this weakens that patch, subsequent creep is likely to favour the same place which becomes a nucleus for later events. If the stress loading is large enough to presage an eventual rip along a greater section of the fault such a major event will probably propagate sideways from the nucleus weakened by creep. Given sensitive seismometers suitably placed along threatening faults zones linked by telemetry to a central unit, as might seem sensible anyway, automated analysis of foreshock records with the signature of spatially restricted creep that begin to show an accelerating sequence might give the 5 to 10 minutes of warning that are the minimum to reduce fatalities in major earthquakes. However, analysis of better data from some other earthquakes does not reveal the same features, but it is early days and similar patterns may emerge from yet others: fault systems behave in a range of ways depending on their tectonic settings. The other issue is the cost of installations and facilities and their maintenance over long periods – how could somewhere like Haiti find the resources. And sadly, some earthquakes, like that beneath Christchurch occur on faults that show no sign at the surface.

The Sendai great earthquake in hindsight (May 2011)

Media coverage of the disasters following the magnitude 9.0 earthquake of 11 March 2011 that devastated the north-eastern coast of Honshu, Japan around the city of Sendai is now (early May) fitful and dominated by the aftermath of the tsunamis’ effect on the Fukushima Daiichi nuclear power station. For those who escaped the tsunamis the experience is irredeemably seared on their memory. Unlike the great waves that killed 10 times more people around the Indian Ocean on 26 December 2004, it will also be unforgettable for those of us far from the event who witnessed the lengthy, high-definition footage captured during the black-water torrents that swept all before them far inland. But that is no longer ‘news’...

Only 6 to 7 weeks later lessons are being learned that probably should have been anticipated long before. Japan has the world’s best disaster preparedness systems. They are centred on civil engineering that was proven to resist great earthquakes by that of 11 March; the terrifying tremors resulted in far fewer casualties than would have been the case anywhere else under such conditions. The tragedy lay with the magnitude of the tsunamis – as high as 30 m in some areas - that reached the coast within an hour of the seismic event. As well as the devastation and loss of life along the coast and up fertile low-lying valleys, waves of this size swept over defences of the coastal Fukushima Daiichi nuclear power plant.
cutting off emergency power supplies: the world’s largest tsunami barriers proved inadequate to the task and near-meltdown ensued.

Despite the densest network of seismometers anywhere and in-place earthquake early-warning and risk-assessment systems, the events were not forecast and the only warning was that of the earthquake itself which alerted a well-versed population to the imminence of tsunamis to follow. Public education and preparedness proved to be the major life saver, except of course for those tragically killed or lost without trace. So what went wrong?

The risk assessment and warning systems produced results that bore little relation to the actual seismic shaking; the warning was for the immediate vicinity of Sendai city to experience the highest intensities (5-6), most of the rest of Honshu, including Tokyo, having expected intensities in the 2-4 range. For Fukushima Daiichi a maximum magnitude of 7.2 in its vicinity was predicted to have less than 10% chance of occurring over the next 50 years. In reality seismometers across the whole eastern part of the Honshu north of Tokyo recorded intensities between 5-7, demonstrated graphically by numerous CCT recordings in shops and offices. The emerging opinion is that the theory and historic data used for risk and warning systems are flawed or inadequate. For instance the earthquake ripped along 400 km of the Japan Trench subduction zone rather than being a point source – a lesson also from the Sumatra earthquake of 26 December 2004, when ocean-floor thrusting extended 1200 km northwards to the Andaman Islands. Great earthquakes are far too infrequent for sufficient modern-style seismic data to have been collected for previous cases in the 20th century, but it seems clear since 2004 that: (1) stresses accumulate to unexpectedly high values where opposed plates are coupled or stuck together; (2) the ‘point-source’ model for earthquakes, which the use of seismic focuses and epicentres pinpointed by the world-wide
seismic network encourages, is far from reality, the more so for the biggest stress accumulations; (3) existing approaches will fail for events with magnitudes greater than 8.0.

Part of the problem is the sparse record of great earthquakes and the likelihood that, if they do have cyclicity, it may be of the order of hundreds to thousands of years. Historical sources record a large earthquake and tsunamis affecting Sendai district in 869 CE (Common Era), confirmed recently by geologists having located a typical tsunami deposit extending 3-4 km up the Sendai Plain, compared with more than 5 km in March 2011. The survey team claimed at the time that their discovery might indicate far higher risk now in the area than modelled ‘officially’. Sadly, evaluating the prediction was incomplete when disaster did strike. Geoscientists can map faults, infer the length of their activity and work out the mechanisms whereby they fail, but apart from historical data – often sketchy – pinpointing and quantifying past events is beyond us. Looking at more widespread secondary effects, tsunami deposits in particular that often contain dateable organic debris, seems a fruitful way forward for coastal areas likely to bear the brunt of both shaking and huge inundations and the powerful ebbing of their flood waters. That is a topic in its infancy, but likely now to burgeon.

Ominously, because great earthquakes are so rare along any plate boundary, for seven greater than magnitude 8 to occur worldwide in a matter of 6 years (Sumatra, 2004, 9.1, 2005, 8.8, and three with magnitude >7 in 2010; Kuril Islands, 2006, 8.3, 2007, 8.1; Sichuan, 2008, 8.0; Chile, 2010, 8.8; Japan, 2011, 9.0) raises the questions, do they occur in time clusters, and if so, why? Although the numbers are small enough to strain statistics, comparing the last six years with the previous century or so of seismometer recordings shows that great earthquakes have never occurred so frequently. Is there a domino effect so that, say, energy from the Sumatran earthquake of late 2004 has somehow been transmitted throughout the interconnected subduction-zone system to destabilise other highly stressed areas? It is widely acknowledged that in one subduction system there is evidence of clustering, and this may extend to the two great earthquakes (2006 and 2007) in the Kuril Islands on the same boundary as the Sendai event, and two off Sumatra (2004 and 2005) with three more with magnitude >7 in 2010 on what previously had been regarded as a relatively quiescent subduction zone. Analysing all recorded seismic events greater than magnitude 5 to improve the statistics suggests that clustering does not extend to global scales, yet great earthquakes buck other trends shown by lesser ones. Their motions both vertical and lateral could conceivably cause widespread destabilisation, yet worryingly the only test of the idea is the occurrence of yet more in the next few years.


Search on for past tsunamis (*July 2011*)

Spurred by the horrific scenes and death toll wrought by tsunamis following the 26 December 2004 Sumatran and 11 March 2011 Sendai giant earthquakes, environmental geologists are beginning to look for signs that can reveal past tsunamis in order to evaluate
risk from region to region. Before the 11 March disaster Japanese scientists had in fact traced signs of a tsunami in 869 CE and showed that it had reached almost as far inland as that which followed the Sendai earthquake. There are a number of geological features that mark the wake of a tsunami: dislodgment of huge boulders on rocky shores; signs of powerful scouring of sallow marine sediments as water recedes from the land; chaotic sediments made up of a jumble of clasts; sediments associated with high-energy flow interleaved with those that mark long periods of low energy deposition; marine faunas unexpectedly found in otherwise terrestrial sediments.

Shortly after the 2004 Indian Ocean tsunamis Indian and Japanese scientists visited the Andaman Islands, which were at the northern end of the megathrust deformation, to seek onshore signs of previous catastrophes (Malik, J.N. et al. 2011. Geologic evidence for two pre-2004 earthquakes during recent centuries near Port Blair, South Andaman Island, India. Geology, v. 39, p. 559-562; DOI: 10.1130/G31707.1). They discovered a layer of ripped-up lumps of mud set in a sandy matrix dumped on a low-energy black mud, the sandy unit showing inclined stratification that dips inland. All the evidence pointed to deposition by a
tsunami. An earlier event reveals swamping of older non-marine sediments by the black mud unit that contains brackish-marine diatoms; a probable result of sudden subsidence linked to an earthquake affecting the Andamans in much the same way as did that of December 2004. The mud had also been intruded by a body of structureless sand, probably resulting from liquefaction as a result of the seismicity. Dating the events using radiocarbon methods proved difficult. Although dating of the earlier event suggested an event around 1670 CE, carbon from the later one gave much older ages, suggesting that the tsunami had ripped up older sediments and redeposited them. However it may be correlated with the major Arakan earthquake of 2 April 1762 close to the coast of Myanmar.

Evidence of this kind can easily be overlooked, and rather less research centres on recent coastal-zone sediments than on sedimentary rocks of the distant past. Areas where such signs of neotectonics have been sought assiduously are those surrounding coastal nuclear installations, but largely to check for evidence of recent faulting that may indicate potential seismic threat but not tsunamis. Clearly it was that kind of threat that decisively put the Japanese Fukushima Daiichi nuclear power station out of action and almost resulted in complete melt-down in March 2011, and severely set back construction of an advanced fast-breeder reactor on the eastern coat of India at Kalpakkam, near Chennai in 2004.

**Seafloor mud cores and the seismic record (October 2011)**

The most important factors in attempting to assess risk from earthquakes are their frequency and the time-dependence of seismic magnitude. Historical records, although they go back more than a millennium, do not offer sufficient statistical rigor for which tens or hundreds of thousand years are needed. So the geological record is the only source of information and for most environments it is incomplete, because of erosion episodes, ambiguity of possible signs of earthquakes and difficulty in precise dating; indeed some sequences are extremely difficult to date at all with the resolution and consistency that analysis requires. One set of records that offer precise, continuous timing is that from ocean-floor sediment cores in which oxygen isotope variations related to the intricacies of climate change can be widely correlated with one another and with the records preserved in polar ice cores. For the past 50 ka they can be dated using radiocarbon methods on foraminifera shells. The main difficulty lies in finding earthquake signatures in quite monotonous muds, but one kind of feature may prove crucial; evidence of sudden fracturing of otherwise gloopy ooze (Sakagusch, A. et al. 2011. Episodic seafloor mud brecciation due to great subduction zone earthquakes. Geology, v.39, p. 919-922; DOI: 10.1130/G32043.1).

The Japanese-US team scrutinised cores from the Integrated Ocean Drilling Program (IODP) that were drilled 5 years ago through the shallow sea floor above the subduction zone associated with the Nankai Trough to the SE of southern Japan. Young, upper sediments were targeted close to one of the long-lived faults associated with the formation of an accretionary wedge by the scraping action of subduction. Rather than examining the cores visually the team used X-ray tomography similar to that involved in CT scans, which produce precise 3-D images of internal structure. This showed up repeated examples of sediment disturbance in the form of angular pieces of clay set in a homogeneous mud matrix separated by undisturbed sections containing laminations. The repetitions are on a scale of centimetres to tens of centimetres and were dated using a combination of $^{14}$C and $^{210}$Pb dating ($^{210}$Pb forms as a stage in the decay sequence of $^{238}$U and decays with a half-life of
about 22 years, so is useful for recent events). The youngest mud breccia gave a $^{210}$Pb age of AD 1950±20, and probably formed during the 1944 Tonankai event, a great earthquake with Magnitude 8.2. Two other near-surface breccias gave $^{14}$C ages of 3512±34 and 10626±45 years before present. These too probably represent earlier great earthquakes as it can be shown that mud fracturing and brecciation by ground shaking needs accelerations of around 1G, induced by earthquakes with magnitudes greater than about 7.0. So, not all earthquakes in a particular segment of crust would show up in seafloor cores, most inducing turbidity flow of surface sediment, but knowing the frequency of the most damaging events, both by onshore seismicity and tsunamis, could be useful in risk analysis. In its favour, the method requires cores that penetrate only about 10 m, so hundreds could be systematically collected using simple piston coring rigs where a weighted tube is dropped onto the sea floor from a small craft.

**Fracking check list** *(November 2011)*

Britain is on the cusp of a shale-gas boom (see *Britain to be comprehensively fracked?* above) and it is as well to be prepared for some potential consequences. In extensively fracked parts of the US – the states of New York, Pennsylvania, Texas and Colorado – there are reports of water taps emitting roaring flames after dissolved methane in groundwater ignites. This is largely due to common-place supply of household water from unprocessed groundwater, which are rare in Britain. But there are other hazards (Mooney, C. 2011. *The truth about fracking*. *Scientific American*, v. 305 (5), p. 80-85; DOI: 10.1038/scientificamerican1111-80) that have enraged Americans in affected areas, which are just as likely to occur in Britain. In fact the nature of shale-gas exploitation by horizontal drilling beneath large areas poses larger threats in densely populated areas, as the people of Blackpool have witnessed in the form of small earthquakes that the local shale-gas entrepreneur Cuadrilla admit as side effects of their exploratory operations.

Chris Mooney succinctly explains the processes involved in fracking shale reservoirs; basically huge volumes of water laced with a cocktail of hazardous chemicals and sand being blasted into shales at high pressure to fracture the rock hydraulically and create pathways for natural gas to leak to the wells. One risk is that this water has to be recovered and stored in surface ponds for re-use. About 75% returns to the surface and also carries whatever has been dissolved from the shales, which can be extremely hazardous. By definition a shale containing hydrocarbons creates strongly reducing conditions, which in turn can induce several elements to enter solution as well as easily dissolved salts; for instance divalent iron (Fe$^{2+}$) is highly soluble, whereas more oxidised Fe$^{3+}$ is not, so waters having passed through gas-rich shales will be iron-rich. But that is by no means the worst possibility; one of the most common iron minerals in sedimentary rocks is goethite (FeOOH), which adsorbs many otherwise soluble elements and compounds. In reducing conditions goethite can break down to release its adsorbed elements, among which is commonly arsenic. The blazing faucet hazard results from hydrocarbon gases leaking through imperfectly sealed well casings to enter shallow groundwater, where the gases can also create reducing conditions and release toxic elements and compounds into otherwise pure groundwater by dissolution of ubiquitous goethite, as in the infamous arsenic crisis of Bangladesh and adjoining West Bengal in India where natural reducing conditions do the damage.
Aftermath of the 1906 gas explosion at Courrières coal mine, northern France; the largest mining disaster in Europe with 1099 fatalities.

What is not mentioned in the Scientific American article is the common association of hydrogen sulfide gas with petroleum, produced from abundant sulfate ions in formation water by bacteria that reduce sulfate to sulfide in the metabolism. This ‘sour gas’, as it is known in the oil industry, is a stealthy killer: at high concentrations it loses its rotten-eggs smell and in the early days of the petroleum industry killed more oil workers than did any other occupational hazard. Visit the spa towns of Harrogate in Yorkshire and Strathpeffer in northern Scotland and sample their waters for examples of what Carboniferous and Devonian gas-rich shales produce quite naturally: noxious stuff of questionable efficacy. The environmental effects of such natural seepage from gas-rich rocks tell a cautionary tale as regards fracking. The highly reducing cocktail of hydrocarbon and sulfide gases in rising, mineral-rich formation water kills the mycorrhizal symbionts that are essential to plant root systems for nutrient uptake die and so too do trees. The onshore Solway Basin of Carboniferous age in NW England illustrates both points, having many chalybeate springs as the sulfide- and iron-rich waters are euphemistically known. There is also a strange phenomenon in many of the deep valleys cut by glacial melt waters as land rose following the last glacial maximum. Once trees reach a certain height – and correspondingly deep root systems – they die, to litter the valley woodland with large dead-heads. Also leaves on smaller trees turn to their autumnal colours earlier than on higher ground. Both seem to be due to minor gas seepages from thick shale sequences in the depths of the sedimentary basin. Indeed, both are botanical indicators to the hydrocarbon explorationist.

To recap, a common size of a fracking operation using several horizontal wells driven from a single wellhead is a zone 4 km in diameter entering gas-rich shales at up to 2 km depth. Each well can generate fractures a hundred metres or more in the shales and surrounding rocks,
as they have to for commercial production. In Britain, most of the sites underlain by shales with gas potential are low-lying agricultural- or urban land. The producing rock in the Blackpool area is the Middle Carboniferous Bowland Shale that lies beneath the Coal Measures of what was formerly the Lancashire coalfield, now a patchwork of expanding urban centres. On 23 May 1984 an explosion occurred in Abbystead, Lancashire at an installation designed to pump winter flood water between the rivers Lune and Wyre through a tunnel beneath the Lower to Middle Carboniferous Bowland Fells. The Abbystead Disaster coincided with an inaugural demonstration of the pumping station to visitors, of whom 16 were killed and 22 injured. Methane had escaped from Carboniferous shales to build up in the flood-balancing tunnel soon after its construction. Methane build-ups were by far the worst hazard throughout the history of British coal mining, thousands dying and being maimed as a result of explosions. One of the largest death tolls in British coal-mining history was 344 miners at Hulton Colliery in Westhoughton, Lancashire in 1910 after a methane explosion; the methane may well have escaped from the underlying Bowland Shales.

Related articles: Fracking was ‘probable’ cause of Lancashire tremors(independent.co.uk). Can we really manage all the risks if we allow fracking in the hope of a gas bonanza? (independent.co.uk)

South Asian arsenic update (November 2011)

That groundwater in West Bengal, India was polluted with arsenic to such levels that symptoms of poisoning had become endemic was reported by Depankar Chakrabarti in 1983, leading to his being branded a ‘panic monger’ by the Indian authorities. The news broke internationally in 1993 as the now infamous tragedy in neighbouring Bangladesh emerged. Means of mitigating the effects – lesions or keratoses and skin discoloration, and later increases in incidence of several forms of cancer – and ideas of how the pollution had occurred had to await proper geochemical analyses of well waters and logging of the mainly alluvial sediments from which water was being withdrawn; another 8 years went by. Reports of arsenicosis began to emerge from other areas of alluvial sediments in SE Asia, revealing by far the worst mass poisoning in history and the likelihood that the lives of millions would be blighted by what Bangladeshis dubbed ‘the Black Rain’ from the resemblance of the characteristic skin lesions to drops of black water.

Thanks principally to the work of water engineer Peter Ravenscroft with other geochemists, the source of arsenic in groundwater was narrowed down to the effect of reducing conditions in grey, carbonaceous sandstones and peats on the mineral goethite, an iron oxy-hydroxide that forms the main colorant in oxidised sediments and whose loose structure normally encourages the mopping-up by surface adsorption of a wide spectrum of dissolved ions, including those of arsenic. Goethite readily breaks down under reducing conditions, and when that happens all the adsorbed material is released into solution. The upper parts of the alluvial and deltaic sediments in the lower reaches of the Ganges and Brahmaputra rivers contain abundant organic remains picked up when vegetation burgeoned during the Holocene, which mixed with goethite-coated sand grains derived from erosion in the Himalayan stretches of the rivers. Purely natural sedimentary and hydrogeological processes created the dreadful plight of villagers. The terrible irony was that before the 1980s there were no signs of arsenicosis, yet mortality, especially of under-fives, was very high due to
water-borne pathogens in surface water supplies. Indian and Bangladeshi authorities and UN agencies waged a campaign to sink shallow wells for drinking water rather than relying on river and pond supplies. At first rural people resisted the change since they regarded water from wells as the ‘Devil’s water’, but as infant mortality began to fall, the resistance turned to rapid construction nationwide of wells, both public and private. A few years later came the ‘Black Rain’.

In the attempts to mitigate the arsenicosis plague, filters containing adsorptive materials, including goethite, were installed on pumps. However, the geochemists showed that in the deeper wells there were consistently low concentrations of arsenic in sediments that were brown-coloured due to prevailing oxidising conditions and the presence of goethite. Although arsenic was present in the sediments it was safely locked in the goethite coatings of sand grains. Steadily major public supplies were transferred to deep, high-yield wells. Alluvial and deltaic deposits are generally highly permeable, so it was feared that as the deeper wells were pumped arsenic-rich water from the reduced shallow sediments would replace the safe groundwater. Thankfully, it seems that is not likely to be a problem (Radloff, K.A. and 12 others 2011. Arsenic migration to deep groundwater in Bangladesh influenced by adsorption and water demand. Nature Geoscience, v. 4, p. 793-798; DOI: 10.1038/ngeo1283). The study injected As-bearing groundwater into a deep aquifer and monitored its arsenic concentration over time, once in place. Within a day, the concentration of dissolved arsenic fell by 70% and by 5 days had fallen below recommended maximum levels for drinking water; a dramatic demonstration of the clean-up power of even minute films of goethite in sediments, for that seems the only explanation for the fall. The US-Bangladeshi team verified this by testing samples of the deeper sediments from drill cuttings. They mixed highly contaminated groundwater with the cuttings, to find that arsenic sorption over about a week was extremely high (~40mg kg⁻¹).

Rather than just publishing their reassuring findings, the team input them to hydrogeological models of the Bengal Basin, varying hypothetical pumping rates to assess the changes in deep-groundwater chemistry over time due to downward migration of the highly polluted near-surface waters. Sure enough, the As-rich waters would end up in the
deep aquifer eventually to overwhelm the sorptive capacity of its goethite content; arsenic would once again enter well supplies. However, if deep extraction was limited to drinking water by limiting pumping for irrigation to intermediate depths, safe limits could be sustained theoretically for a thousand years or more, except in some areas especially prone downward intrusion of polluted shallow groundwater. (Use of highly contaminated shallow groundwater for irrigation would simply transfer the problem to crops.) Clearly, monitoring is obligatory, but one hopes this important study does resolve the horrifying plight faced by so many people in catchments fed by Himalayan waters.