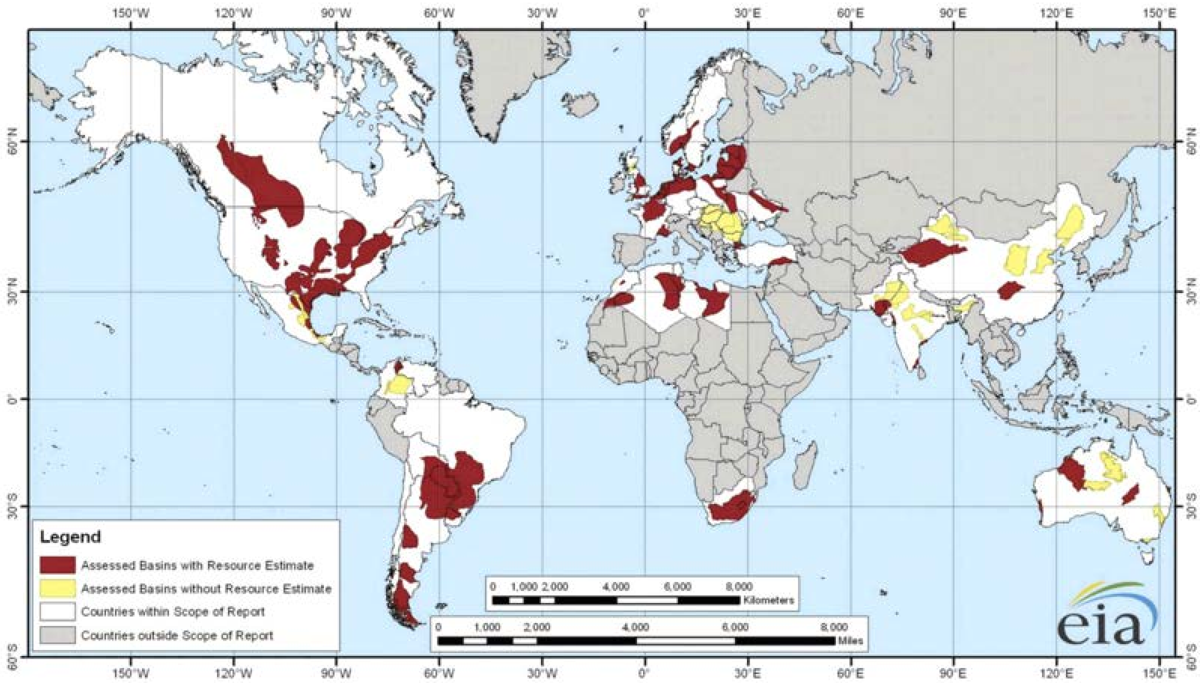
Geohazards

Fracking and earthquakes (*July 2013*)

Review of Fracking Issues (in Physical Resources 2013) briefly commented on a major academic study of the impact of shale gas exploitation on groundwater. The 12 July 2013 issue of *Science* follows this up with a similarly extensive treatment of how underground disposal of fracking fluids might influence seismicity in new gas fields (Ellsworth, W.J. 2013. [Injection-induced earthquakes](). *Science*, v. **341**, DOI: 10.1126/science.1225942) plus a separate paper on the same topic (van der Elst, N.J. *et al*. 2013. [Enhanced remote earthquake triggering at fluid-injection sites in the Midwestern United States](). *Science*, v. **341**, p.164-167; DOI: 10.1126/science.1238948).



Major shale gas basins

It was alarm caused by two minor earthquakes (<3 local magnitude) that alerted communities on the Fylde peninsula and in the seaside town of Blackpool to worrisome issues connected with Cuadrilla Resources' drilling of exploratory fracking wells. These events were put down to the actual hydraulic fracturing taking place at depth. Such low-magnitude seismic events pose little hazard other than nuisance. The two reports in *Science* look at longer-term implications associated with regional shale-gas development. All acknowledge that the fluids used for hydraulic fracturing need careful disposal because of their toxic hazards. The common practice in the 'mature' shale-gas fields in the US is eventually to dispose of the fluids by injecting them into deep aquifers, hopefully ensuring limited leakage into shallow groundwater used for domestic purposes.

The studies, such as that by William Ellsworth, of connection between deep waste-water injection and seismicity are somewhat less reassuring. From 1967 to 2001 (i.e. before fracking began) the central US experienced a steady stream of earthquakes with magnitudes greater than 3.0, which can be put down to the natural background of seismicity in the stable lithosphere of mid North America. In the last 12 years activity at this energy level increased significantly, notably in areas underlain by targets for shale-gas fracking such as the Marcellus Shale of the north-eastern US. The increase coincides closely with the history of shale-gas development in the US. The largest such event (5.6 local magnitude) destroyed 14 homes in Oklahoma near to such a waste-injection site. Raising the fluid pressure weakens faults in the vicinity thereby triggering them to fail, even if their tectonic activity ceased millions of years ago: many retain large elastic strains dependent on rock strength.

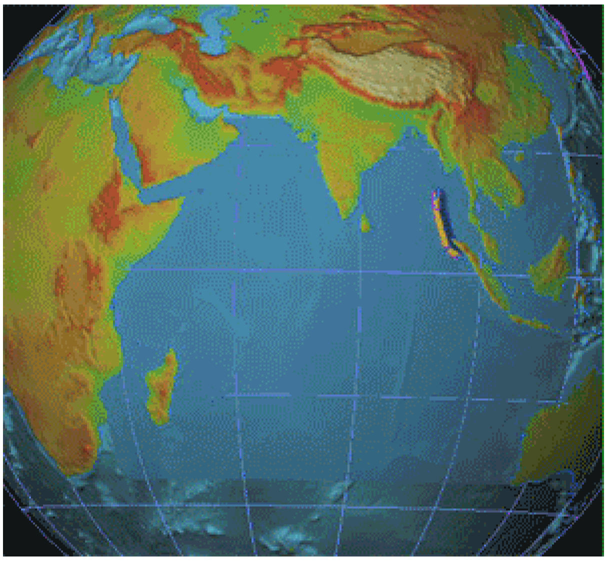
Apart from the mid-continent New Madrid seismic zone (see *Mid-continent earthquakes: warnings or memories?* Geohazards 2010) associated with a major fault system running parallel to the Mississippi River, much of the central US is geologically simple with vast areas of flat-bedded sediments with few large faults. The same cannot be said for British geology which is riven with major faults formed during the Caledonian and Variscan orogenies, some of which in southern Britain were re-activated by tectonics associated with the Alpine events far off in southern Europe. Detailed geological maps show surface-breaking faults everywhere, whereas deep coal mining records and onshore seismic reflection surveys reveal many more at depth. A greater population density living on more 'fragile' geology may expect considerably more risk from industrially induced earthquakes, should Britain's recently announced 'dash' for shale gas materialise to the extent that its sponsors hope for.

Nicholas van der Elst and colleagues' paper indicates further cause for alarm as regards the distant effects of large earthquakes on seismicity in areas of fracking. In the 10 days following the 11 March 2011 Magnitude 9.0 Sendai earthquake a swarm of low-energy events took place around waste injection wells in central Texas, to be followed 6 months later by a larger one (4.5 local magnitude). Similar patterns of injection-related seismicity followed other distant great earthquakes between 2010 and 2012. Other major events seem not to have triggered local responses. The authors claim that the pattern of earth movements produced by such global triggering might be an indicator of whether or not fluid injection has brought affected fault systems to a critical state. That may be so, but it seems little comfort to know that one's home, business or community is potentially to be shattered by intrinsically avoidable seismic risk.

Assessing submarine great-earthquake statistics fails (*July 2013*)

Geologists who study turbidites assume that the distinctive graded beds from which they are constructed and a range of other textures represent flows of slurry down unstable steep slopes when submarine sediment deposits are displaced. Such turbidity currents were famously recorded by the severing of 12 transatlantic telecommunication cables off Newfoundland in 1929. This happened soon after an earthquake triggered 100 km hr^{-1} flows down the continental slope, which swept some 600 km eastwards.

Sea beds at destructive margins provide the right conditions for repeated turbidity currents and it is reasonable to suppose that patterns should emerge from the resulting turbidite beds that in some way record the seismic history of the area. British and Indonesian geoscientists set out to test that hypothesis at the now infamous plate margin off Sumatra that hosted the great Acheh Earthquake and tsunamis of 26 December 2004 to kill 250 thousand people around the rim of the Indian Ocean (Sumner, E.J. *et al*. 2013. Can turbidites be used to reconstruct a paleoearthquake record for the central Sumatra margin? *Geology*, v. **41**, p.763-766; DOI: 10.1130/G34298.1)



Animation of Indonesian tsunami of 26 December 2004 (click to view)

Cores through turbidite sequences along a 500 km stretch of the margin formed the basis for this important attempt to test the possibility of recording long-term seismic statistics. To avoid false signals from turbidity currents stirred up by storms, floods and slope failure from rapid sediment build-up 17 sites were cored in deep water away from major terrestrial sediment supplies, which only flows triggered by major earthquakes would be likely to reach. To calibrate core depth to time involved a variety of radiometric and stratigraphic methods

Late Cretaceous turbidites on the Basque coast of France

Disappointingly, few of the sites on the submarine slopes recorded turbidites that match events during the 150-year period of seismic records in the area, none being correlatable with the 2004 and 2005 great earthquakes. Indeed very little correlation of distinctive textures from site to site emerged from the study. Some sites on slopes revealed no turbidites at all from the last 150 years, whereas turbidites in others that could be accurately dated occurred when there were no large earthquakes. Only cores from the deep submarine trench consistently preserved near-surface turbidites that might record the 2004 and 2005 great earthquakes.

These are surprising as well as depressing results, but perhaps further coring will discover what kind of bathymetric features might yield useful and consistent seismic records from sediments.

Yet another risk of arsenic exposure

The most widely feared risk of poisoning through natural causes, which grossly disfigures and kills through a range of cancers, is from chronic exposure to arsenic in drinking water. Tragically, the risk is highest from what has traditionally been considered safest source, groundwater. That was the gruesome lesson of a massive transfer in Bangladesh from drinking surface water containing organic pathogens to reliance on well waters. The greatest mass poisoning in history was eventually traced to shallow aquifers in the Ganges-Brahmaputra plains that were rich in organic matter. Their reducing chemistry broke down iron hydroxide coatings on sedimentary grains. Since these minerals are among the most accommodating adsorbers of ions from the environment, including a variety of arsenic-bearing ions, their dissolution releases potential poisons from otherwise safe storage. In Bangladesh and neighbouring West Bengal in India it was found that deeper aquifers have oxidising chemistry and so the iron minerals not only hold ionic pollutants fast by adsorption but help to extract them from groundwater. Deep wells together with various kinds of treatment of shallow groundwater, some using the very iron minerals whose breakdown caused the pollution, are helping to mitigate the perilous situation for people of South Asia.

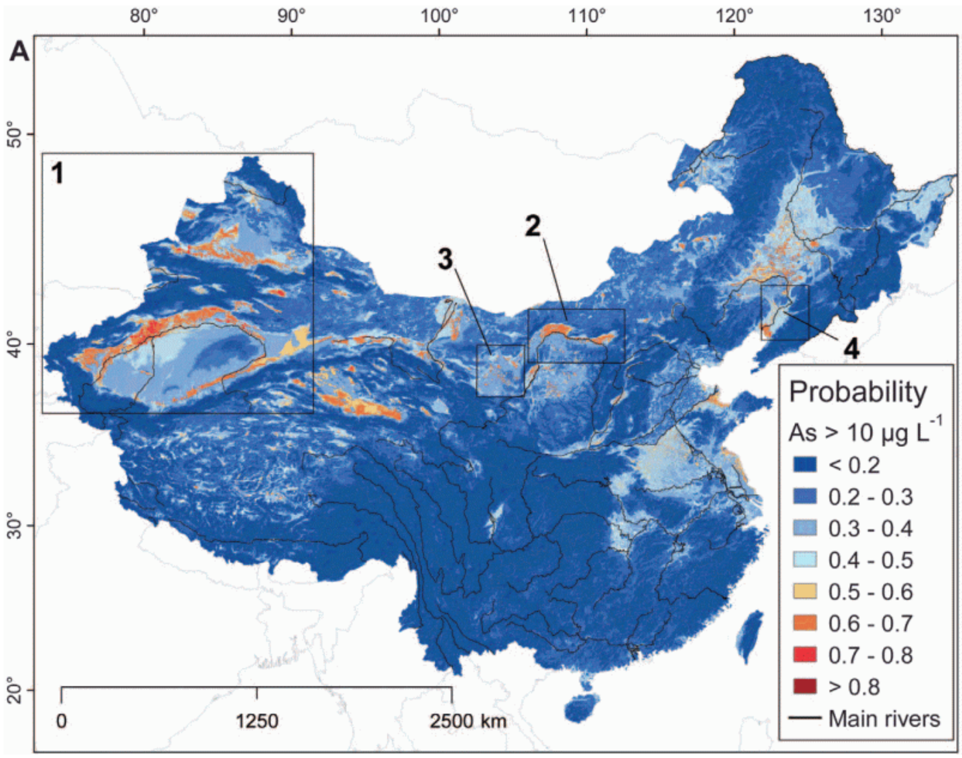
Much the same kind of arsenic pollution has subsequently been revealed in groundwaters of lowland Vietnam and Cambodia. Yet the turn there to deep groundwater has revealed a new twist. That too is yielding increasingly high arsenic concentrations, but for a different reason (Erban, L.E. *et al*. 2013. Release of arsenic to deep groundwater in the Mekong Delta, Vietnam, linked to pumping-induced land subsidence. *Proceedings of the National Academy of Science*, v. **110**, p. 13751-13756; DOI: 10.1073/pnas.1300503110). Scientists from Stanford University, California analysed waters from around 900 wells in the Lower Mekong Delta and found several tracts with arsenic contents well above levels deemed safe by the WHO. Some, as could be anticipated from South Asian studies, were from shallow wells along the present course of the Mekong. However, in the delta area to the southwest of Ho Chi Minh City (formerly Saigon) is a large cluster from wells 150 to 450 m deep, totally unlike the situation in other areas of thick Pliocene to Recent river sedimentation.

Comparing the distribution of affected wells with precise estimates of the subsidence rates of the land surface from orbital interferometric radar surveys shows a close correlation of arsenic contamination with rates of subsidence. This suggests that groundwater pumping from deep aquifers is causing compaction at depth, in much the same way as in the environs of Venice. But is this somehow drawing in arsenic polluted water from higher levels? It seems not. So the pollution seems most likely to be an effect of pumping itself. The authors suggest that most of the subsidence is due to compaction of clay-rich sediments rather than the sandy aquifers, well known by engineers to resist compression. They explain the increasing arsenic concentrations by the introduction into the aquifers of water expelled from the clays, either containing arsenic ions in solution or carrying organic compounds that create the reducing conditions to break down iron hydroxide grain coatings and release ions adsorbed on their surfaces.

This presents another grim prospect for South Asian people forced to make the choice between drinking polluted surface water and enteric disease and increasingly exploited deep groundwaters that seem to be safe as well as in very high volumes. Let's hope that arsenic monitoring can be maintained in the Ganges-Brahmaputra plains in the long term.

Estimating arsenic risks in China (*September 2013*)

Two weeks after my summary of the previous article, another important paper has emerged about modelling risk of arsenic contamination across the People's Republic of China (Rodriguez-Lado, L. *et al*. 2013. [Groundwater arsenic contamination throughout China](). *Science*, v. **341**, p. 866-868; DOI: 10.1126/science.1237484). Scientists based in the Swiss Federal Institute of Aquatic Science and technology and the China Medical University follow up the results of geochemical testing of groundwater from almost 450 thousand wells in 12% of China's counties; part of a nationwide aim to test millions of wells. That is a programme likely to last for decades, and their work seeks to develop a predictive model that might better focus such an enormous effort and help in other large regions where well sampling is not so advanced.



Estimated probability of arsenic in Chinese groundwater above the WHO acceptable maximum concentration (Credit:Rodriguez-Lado, et al. 2013)

As well as the well-known release of ions containing arsenic through the dissolution of iron oxy-hydroxides in aquifers that exhibit reducing conditions, aridity that causes surface evaporation can create alkaline conditions in groundwater that also desorbs arsenic from similar minerals. The early results from China suggested 16 environmental factors available in digital map form, mainly geological, topographic and hydrogeochemical, that possibly encourage contamination; a clear indication of the sheer complexity of the problem. Using GIS techniques these possible proxies were narrowed down to 8 that show significant correlation with arsenic levels above the WHO suggested maximum tolerable concentration of 10 parts per billion by volume. Geology – Holocene sediments are the most likely sources; the texture of soils and their salinity; the potential wetness of soils predicted from topography, and the density of surface streams carrying arsenic correlate positively with high well-water contamination. Conversely, topographic slope, distance from streams and gravity (a measure of depth of sedimentary basins) show a negative correlation. These parameters form the basis for the predictive model and more than 2500 new arsenic measurements in areas at risk were used to validate the results of the analysis.

The results graphically highlight possible high risk areas, mainly in the northern Chinese provinces, which are partly confirmed by the validation. Using estimated variations in population density across the country the team discovered that as many as 19.6 million people may be affected by consumption of arsenic contaminated water. In fact if groundwater is used for irrigation, arsenic may also be ingested with locally grown food. It seems that the vast majority of Chinese people live outside the areas of risk, so that mitigating risk is likely to be more manageable that it is in Bangladesh and West Bengal where this particular geohazard was first discovered.

As well as being an important input to environmental health management in the PRC the approach is appropriate for other large areas where direct water monitoring is less organised, such as Mongolia, Kazakhstan and Kyrgyzstan in central Asia, and in the arid regions of South America.

Related article: New risk model sheds light on arsenic risk in China's groundwater (phys.org)

How the great Tohoku-Sendai earthquake and tsunami happened (*December 2013*)

The great Tohoku earthquake (moment magnitude 9.0) of 11 March 2011 beneath the Pacific Ocean east of Honshu resulted in the devastating tsunami that tore many kilometres inland along its northern coast line and affected the entire Pacific Basin (see NOAA animation of the tsunami's propagation) . The area and indeed Japan itself have yet to recover from the devastation almost 3 years later. Over 18 thousand people died, witnessed by hundreds of millions of television viewers. The Fukashima Daiichi nuclear reactor had a catastrophic meltdown and release of radioactive materials that, along with the urban destruction by the tsunami, displaced a third of a million people, many of whom are yet to be properly housed.

The seismic trigger happened at a plate boundary where lithosphere of the Western Pacific is being subducted beneath Japan. Subduction zone seismicity extends from shallow depths to as deep as 700 km beneath the surface. The destructive nature of the Tohoku eathquake stemmed from its occurrence at a shallow depth (~20-30 km) that allowed the motion to shove crustal material eastwards, up and over the sea floor, causing the sea floor to bulge upwards by tens of metres in a matter of seconds. It was that surface-breaking megathrust that displaced Pacific Ocean water and launched the huge tsunami waves. Geophysicists were caught by surprise as regards the magnitude of the event, having long considered that part of the Pacific 'ring of fire' to be incapable of generating seismic energies above a magnitude of 8.0; 32 times less energetic than that reached in reality. The area to watch was believed to be the southwestern coastline of Japan, affected by subduction beneath the Sagami and Suguma Troughs. The reason for this attempt at anticipation in what is one of the world's most risky places for seismicity is that theory suggested that subduction slip was greatest at depth and becomes smaller at shallower levels.

Railway locomotive thrown aside by the 11 March 2011 Tsunami in Japan

Clearly, a major scientific effort had to be undertaken to explain such a disastrous misconception. Part of this involved drilling into the seabed above the 11 March 2011 epicentre. The extracted rock cores revealed a major surprise (Chester, F.M. and 14 others. 2013. Structure and composition of the plate-boundary slip for the 2011 Tohoku-Oki earthquake. *Science*, v. **342**, p. 1208-1211; DOI: 10.1126/science.1243719): the fault zone was a layer of clayey rock less than 5 m thick with a rupture zone for the Tohoku earthquake estimated at only a few centimetres across. Experiments revealed that hardly any heat had been generated by such a huge earthquake (Fulton, P.M. and 9 others 2013. Low coseismic friction on the Tohoku-Oki Fault determined from temperature measurements. *Science*, v. **342**, p. 1214-1217; DOI: 10.1126/science.1243641). Friction had been extremely low, probably because the clay was so impermeable that water pressure in it was able to build up and not diffuse away (Ujie, K. and 9 others 2013. Low coseismic shear stress on the Tohoku-Oki Megathrust determined from laboratory experiments. *Science*, v. **342**, p. 1211-12145; DOI: 10.1126/science.1243485). The thrust fault was lubricated, but fortunately one that was localised: unlike the strike-slip fault that drove the Indian Ocean tsunamis of 2005 which was able to propagate for over 1000 km.

While there is cause for some satisfaction among seismologists for a technical explanation, how the findings can be applied to better prediction of tsunami-prone subduction zones is not very clear. It does seem that the Tohoku-Oki Fault has developed, probably over millions of years, in particularly clay-rich sea-floor sediments. Such a phenomenal amount of slippage would be less likely in coarser shallow sediments that would probably generate much more friction. Putting the findings into practice will involve greater investment in and speeding up oceanographic studies of submarine trench systems.

Related article: Slippery Clay Explains Mystery of Tohoku-Oki Earthquake and Tsunami (guardianlv.com)