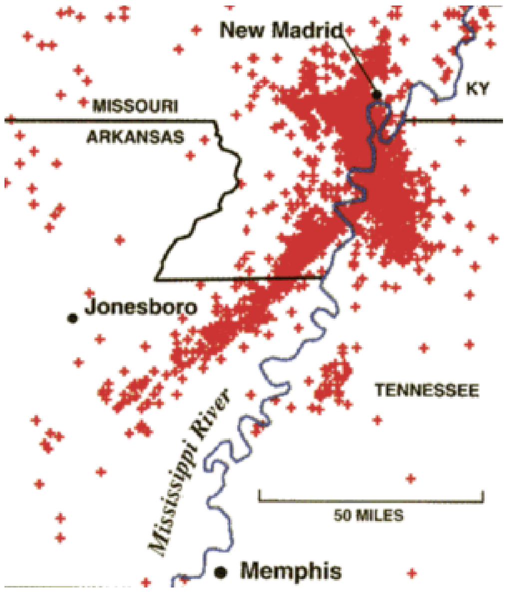
# *Geohazards*

**Within-plate earthquakes (*January 2012*)**

Almost all devastating earthquakes within living memory, together with the tsunamis that ensued from some of them, have occurred where tectonic plates meet and move past one another either horizontally through strike-slip motion or vertically as a result of subduction. This link between real events and the central theory of global dynamics gives an impression of inherent predictability about *where* damaging and deadly earthquakes might happen, if not the more useful matter of *when* the lithosphere might rupture. Such confidence is potentially highly dangerous: the most deadly earthquake in recorded history killed at least 800 thousand people in China's Shanxi Province in 1556 when according to a description written shortly afterwards,

> '… *various misfortunes took place… In some places, the ground suddenly rose up and formed new hills, or it sank abruptly and became new valleys. In other areas, a stream burst out in an instant, or the ground broke and new gullies appeared…*'.

Shanxi is far from any plate boundary. A study of Chinese historic records covering the last two millennia (Liu, M. *et al*. 2011. 2000 years of migrating earthquakes in North China: How earthquakes in midcontinents differ from those at plate boundaries. *Lithosphere*, v. **3**, p. 128-132; DOI: 10.1130/L129.1) shows a pattern to the position of large intraplate events. Rather than occurring along lines as do those at plate boundaries, earthquakes 'hopped' from place to place without affecting the same areas twice. Liu and colleagues consider this almost random pattern to result from reactivation of interlinked faults through broad-scale and gradual tectonic loading of the crust by far off plate movements. After a short period of reactivation one fault locks so that energy build-up is eventually released by another in the plexus of crustal weaknesses.




Recent earthquakes in the US mid-west around New Madrid Missouri.

The best studied site of such intraplate seismicity lies midway along the Mississippi valley, between St Louis and Memphis, USA. In 1811 and 1812 four Magnitude 7 to 8 earthquakes struck, the most affected place being the small township of New Madrid on the banks of the great river where mud and sand spouted from numerous sediment volcanoes. No-one died there but tremors were felt over a million square kilometers, bells ringing spontaneously as far away as Boston and Toronto (see *Mid-continent earthquakes: warnings or memories?* January 2010). It is now known that this section of the Mississippi basin lies above a graben that affects the ancient basement beneath the alluvial sediments, one of whose faults was reactivated, perhaps in an analogous way to the hypothesis about Chinese seismicity. A coauthor in Liu *et al*. (2011), Seth Stein of Northwestern University, Illinois, believes stress redistribution through a Mid-western fault network was responsible and other events are likely at some uncertain time in the future on this and other areas underpinned by ancient fault complexes. Indeed sporadic 'quakes up to Magnitude 7 have affected the eastern US and Canada and the Atlantic seaboard since European settlement. But since the largest of the New Madrid quartet of earthquakes, populations have grown across the likely areas of tenuous risk and future ones could have extremely serious consequences for which it is difficult to plan by virtue of unpredictability of both place and timing: in some respects a more worrying prospect than is the case where major events are inevitable – sometime – as along the San Andreas Fault. There are few, if any, major conurbations worldwide that could be considered seismically safe if the theory of networked stress redistribution through otherwise inert parts of continental crust is borne out.

In some respects the theory is a small-scale version of the suggested mechanical linkage through all major plate boundaries that has been suggested by some to account for the clustering in time of great earthquakes – around and above Magnitude 8 – around the globe. Since 2000 great earthquakes have occurred on subduction zones beneath Sumatra, the Himalaya, the Andes, Central America, Alaska, New Guinea, the mid-Pacific, Japan and the Kurile islands, on the strike-slip system that cuts New Zealand and in the intraplate setting of the 2008 Sichuan earthquake in China. Almost all plate boundaries link up globally, but although it seems likely that stress is redistributed along boundaries, especially between adjacent segments, as documented for the great Anatolian fault system of Turkey and the Indonesian subduction zone, a mechanism that transmits stress beyond individual plates seems unlikely.

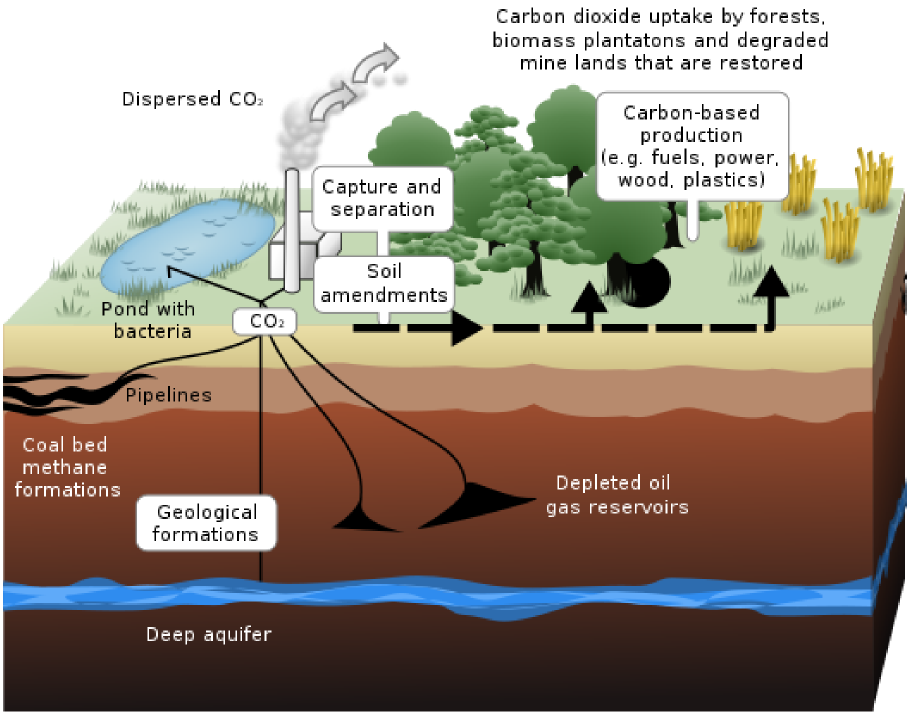
**Related articles:** Scientists find rift between New Mexico and Colorado geologically active and capable of generating quakes (theextinctionprotocol.wordpress.com); Quake Update : Pacific shakes are 'not linked'[ (environmentaleducationuk.wordpress.com); Jabr, F. 2012. Quake escape. *New Scientist*, v. **213** (2847), p. 34-37.

### Possible snags and boons for CO2 disposal (*April 2012*)

Not many people would like to visit a waste heap at an asbestos mine. That is not because waste heaps are generally boring but all forms of asbestos are carcinogens when inhaled. Encountering pits in the tailings that emit puffs of warm air would cause health and safety alarm bells to ring. Yet that is exactly what has attracted researchers to the huge asbestos mining complex at Thetford in Quebec, Canada: the air leaving the vents can be extremely depleted in carbon dioxide (Pronost, J. and 10 others 2012. $CO_2$-depleted warm air venting from chrysotile milling waste (Thetford Mines, Canada): Evidence for in-situ carbon capture and storage. *Geology*, v. **40**, p. 275-278;). More precisely, the depletion – down to less than 10 parts per million (ppm) compared with normal atmospheric levels of 385 ppm – occurs in winter, when the puffing pits emit warm air far above the frigid air temperatures encountered in winter Quebec.

Asbestos mine tailings at Thetford in Quebec, Canada

The chrysotile must be reacting with groundwater and $CO_2$, and is therefore a potential means of using near-surface natural materials for carbon capture and storage (CCS). The end product is an innocuous carbonate – $Mg_5(OH)_2(CO_3)_4 \cdot 4H_2O$ – and dissolved silica. Quite a find, it might seem, as the reaction is exothermic too: CCS plus geothermal energy plus safe decomposition of a major environmental hazard. In fact any magnesium-rich silicates are likely to undergo the same carbonation reaction, especially if ground-up to increase the net surface area exposed to moist air.




Scheme for carbon sequestration and storage (Credit: LeJean Hardin and Jamie Payne)

The parent asbestos rock at Thetford is a metamorphic derivative from mantle ultramafic rocks in an ophiolite, and the asbestos insulation business, both for extremely hazardous blue (crocidolite) and less dangerous white (chrysotile) asbestos has been hugely profitable since the 19th century. Consequently, wherever there are altered ophiolites, generally in collision-zone orogenic belts, asbestos has been exposed either naturally or through mining and processing. There are many related cancer 'hot spots' in populous mining areas of Canada, India, the Alps and southern Africa, and in dry climates even natural exposures pose considerable risk. Could these blighted areas take on a new role in lessening the chance of global warming? About 30 billion tonnes of $CO_2$ are emitted by burning fossil fuels each year. To keep pace, at the current atmospheric concentration of $CO_2$, some 75 trillion tonnes of air would have to react annually with about 100 billion tonnes of magnesian silicate, making this form of CCS the largest industry on the planet.

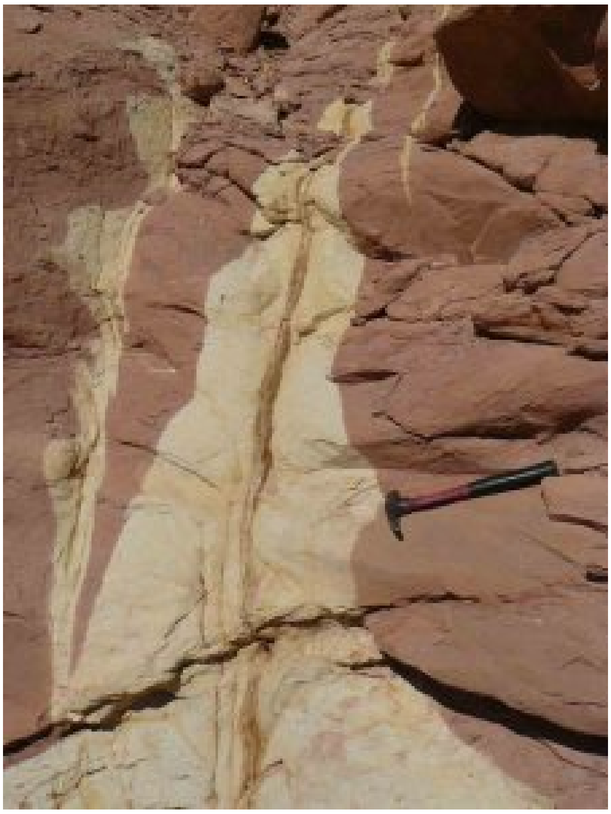
Another factor tempering somewhat forced optimism for CCS as a way of having our fossil fuel cake and eating it is that direct injection of greenhouse gases into deep storage may have an unforeseen down-side. Deep drilling and injection of fluids may trigger earthquakes. The alarm raised by small yet disturbing seismicity accompanying sites for shale-gas development by 'fracking' (see *Fracking check list* November 2011) has died down to some extent following detailed analysis of small earthquakes around drilling sites. It turns out that they are triggered not by the drilling itself but the subsurface disposal of the large amounts of fluids that have to be passed through the oil shales to make the tight rock permeable to gas (Kerr, R.A. 2012 Learning how to NOT make earthquakes. *Science, v.* **23** *p.* 1436-1437; DOI: 10.1126/science.335.6075.1436). Safe subsurface disposal requires injection wells penetrating 1 to 3 km below the surface, often below the cover of sedimentary strata and into crystalline basement. Such hard rocks store elastic strain induced by burial and tectonics, and release it when lubricated by fluids, especially if they contain dormant faults. Once impermeable rock can thus be hydrofractured in the same manner as 'fracked' gas-prone shales and old, often unsuspected faults reactivate: a catastrophic prospect for injected $CO_2$. In sedimentary sequences, drilling CCS wells into porous rocks capped by impermeable ones – the scenario for 'safe' gas storage – could also induce 'fracking' of the sealing rocks and thereby causing leakage.

**Related articles:** Marshall, M. 2012. Fracking could foil carbon capture plans. *New Scientist* (31 March 2012); Bill Chameides: Carbon Capture and Storage: A Fresh Look at Storage and Other Issues (huffingtonpost.com)

### Carbon capture and storage: an analogy of some pitfalls (*June 2012*)

Of all the 'geoengineering' approaches that may offer some relief from global warming pumping $CO_2$ into deep sedimentary rocks, through carbon capture and storage (CCS) is one that most directly intervenes in the natural carbon cycle by adding an anthropogenic route to the movement of $CO_2$. It is difficult if not impossible for natural processes to 'pump' gases downwards except when they are dissolved in water. Such natural sequestration is most often through the conversion of $CO_2$ to solid carbonates or carbohydrates that are simply buried on the ocean floor. Artificially producing carbonate or organic matter on a sufficient scale to send meaningful amounts of anthropogenic carbon dioxide to long-term rock storage is pretty much beyond current technology, but gas sequestration seems feasible, if costly. The main issues concern making sure geological traps are 'tight' enough to prevent sufficient leakage to render the exercise useless, and to understand the geochemical effects of large amounts of buried gas that would inevitably move around to some extent.

The geochemistry is interesting, as reactions of $CO_2$ with rock and subsurface water are inevitable. The most obvious is that solution in water releases hydrogen ions to create weakly acidic fluids: on the one hand that might be a route for precipitation of carbonate and more secure carbon storage, through reaction with minerals (see *Possible snags and boons for CO2 disposal* in Geohazards November 2012). However, another possibility is increasing solution of minerals, such as those cementing the host rock, which might eventually cause a trap to leak. A counterpart of pH change is the release of electrons, whose acceptance in chemical reactions creates reducing conditions. The most common minerals to be affected by reducing reactions are the iron oxides, hydroxides and sulfates that often coat sand-sized grains in sedimentary rocks, or occur as accessory minerals in igneous and metamorphic rocks. Iron in such minerals is in the Fe-3 valence state (*ferric* iron from which an electron has been lost through oxidation) which makes them among the least soluble common materials, provided conditions remain oxidising. Flooding sedimentary rocks with $CO_2$ inevitably produces a commensurate flow of electrons that readily interact with Fe-3. The oxidised product Fe-2 (*ferrous* iron) is soluble in water, and so reduction breaks down iron-rich grain coatings. Much the same happens with less abundant manganese oxides and hydroxides. One important concern is that iron hydroxide (FeO.OH or goethite) has a molecular structure so open that it becomes a kind of geochemical sponge. Goethite may lock up a large range of otherwise soluble ions, including those of arsenic and some toxic metals. Should goethite be dissolved by reduction that toxic load moves into solution and can migrate.



Bleached zone with carbonate-oxide core in Jurassic Entrada Sandstone, Green River, Utah. (Credit: Max Wigley)

Except where carbonated deep groundwater leaks to the surface in springs – the famous Perrier brand of mineral water is an example – it is difficult to judge what is happing to gases and fluids at depth. But their long-past activity can leave signatures in sedimentary rocks exhumed to the surface. Most continental sandstones, formed either through river or wind action, are strongly coloured by iron minerals simply because of strongly oxidising conditions at the Earth's surface for the past two billion years or more. Should reducing fluids move through the pre spaces, the iron is dissolved and leached away to leave streaks and patches of bleached sandstone in otherwise red rocks. In a few cases an altogether more pervasive bleaching of hundreds of metres of rock marks the site of massive fluid-leakage zones. Terrestrial Mesozoic sedimentary sequences in the Green River area of Utah, USA exhibit spectacular examples, easily amenable to field and lab study (Wigley, M. *et al*. 2012. Fluid-mineral reactions and trace metal mobilization in an exhumed natural $CO_2$ reservoir, Green River, Utah. *Geology*, v. **40**, p. 555-558; DOI: 10.1130/g32946.1). There the bleaching rises up through the otherwise brown and yellow sandstones, cutting across the bedding. In the bleached zone, secondary calcite fills pore spaces. At the contact with unbleached sandstone there are layers of carbonate and metal oxides, enriched in cobalt, copper, zinc, nickel, lead, tin, molybdenum and chromium: not ores but clear signs confirming the general model of reductive dissolution of iron minerals and movement of metal-rich fluid. Carbon isotopes from the junction are richer in $^{13}C$ than could be explained by the gas phase having been methane, and confirm naturally $CO_2$-rich fluids.

So, Green River provides a natural analogue for a carbon capture and storage system, albeit one that leaked so profusely it would be a latter day disaster zone. In that sense the site will help in deciding where not to construct CCS facilities.

**Carbon capture and storage: dissolving it (*September 2012*)**

Tucking away vast amounts of atmospheric carbon dioxide, or at least that emitted by fossil-fuel power stations, is a widely suggested and well supported approach to slowing down global warming. It has two main downsides: if successful it helps maintain the dominance of fossil fuels and vast amounts of buried greenhouse gas might simply leak out some time. Ideally, the storage part of CCS would involve $CO_2$ being taken up by an inert solid. Carbonates may be stable enough but arranging the chemical reactions to make them seems difficult, the most widely considered being by encouraging weathering of ultramafic rocks to form magnesium carbonates as a by-product: huge areas would have be coated with finely-ground peridotite. A less satisfactory approach would to dissolve the gas in water held at great depths in sedimentary aquifers, but if that water doesn't move and doesn't get warmed it might do the trick.

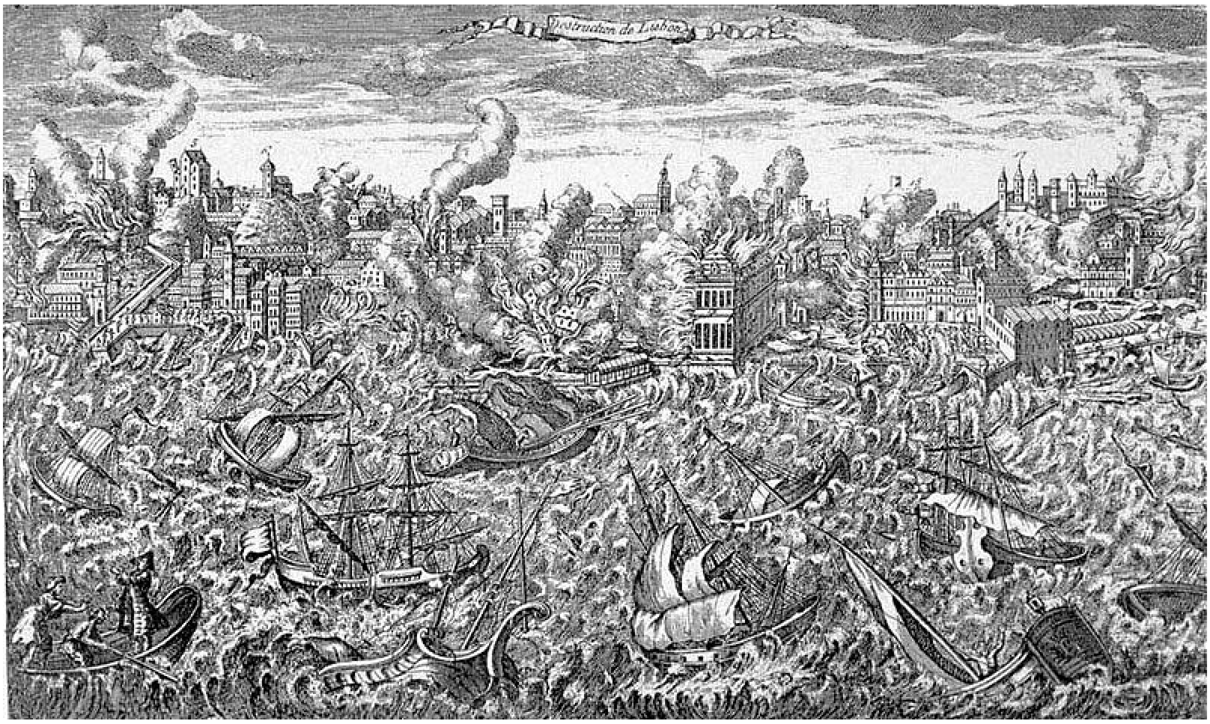
Unsurprisingly, a lot of funds are available to research CCS and ideas are pouring forth, a recent, sober assessment focussing on the solubility option (Steele-MacInnis, M. *et al*. 2013. Volumetrics of $CO_2$ storage in deep saline formations. *Environmental Science and Technology*, v. 47, p. 79-86; DOI**:** 10.1021/es301598t). The team from Virginia Tech and the US Department of Energy conclude that solution in brines trapped in deep aquifers may help, although solution is an equilibrium between gas and dissolved $CO_2$, so that a gas layer in the aquifer is always likely to be present, even at high pressures. The only way of avoiding that is if the dissolved gas reacted with carbonate in the aquifer so that calcium and hydrogen-carbonate ($HCO_3^-$) ions entered solution. That 'enhanced' solution is not so easy since, although it mimics the calcite-weathering effect by acid rain that naturally takes $CO_2$ from the atmosphere, calcite dissolves very sluggishly. But solution adds to the density of already dense brine so that it is less likely to leak upwards into more shallow aquifers. Their preferred technology is to liquefy the gas under pressure and pump that to deep aquifers where eventually the supercritical $CO_2$ liquid will dissolve. The problem is this: while experiment and theory suggest the approach will work, nobody knows how long $CO_2$ solution in brine will take. There needs to be a sizeable pilot study…

## Landslides and multiple dangers (*October 2012*)

August, 1989 landslide in Guerrero, Mexico

Just as modern humans were establishing a permanent foothold in Britain and engaging in the transition to settled farming and livestock husbandry disaster struck some of the most attractive Mesolithic real estate. Around 8 000 years ago the east coast of Scotland, from the Shetland Isles to the Firth of Forth, was struck by a tsunami as big as that affecting the north eastern island of Honshu in the Japan archipelago in 2011. It washed over low lying islands of Shetland and Orkney and roiled up the great inlets or firths of eastern mainland Scotland to leave thick sand deposits containing carcases of whales and other large sea mammals. At that time, Britain was joined to the rest of Europe by marshy lowlands linking East Anglia and the Netherlands dubbed 'Doggerland' at the southern end of a huge gulf that became the North Sea. Final sea level rise removed that initial gateway to Britain, so we cannot judge what damage the tsunami wrought, but tools and animal bones dredged from the area show that it was full of game and people. A disaster, but not one linked to seismicity. The driving force has been recognised in a series of submarine scars off the west coast of Norway that witness massive slides of sediment on the sea bed area known as Storegga. Similar scars around the Hawaiian Islands and those making up the Azores and Canaries in the mid Atlantic bear witness to many large slippage events, on the sea bed and from the islands themselves. Recognising signs of past tsunami damage in coastal areas worldwide reveals plenty of cases triggered by landslides rather than earthquakes.

The March 2011 Sendai tsunami and those which ravaged lands around the Indian Ocean in late 2004 formed because of vertical movements on major faults that dropped or shoved up the oceanic crust itself. Yet any sudden change in the shape of the sea floor will displace all the ocean water above, the difference from seismic tsunamis lies in the energy source: instead of tectonic plate forces, gravitational potential energy is released by slumps and slides. That may happen because of erosion producing unstable steep slopes, build up of sedimentary piles, large outpourings of lavas or slopes being destabilised by minor earthquakes or release of gases from the sediments themselves. The Mesolithic submarine slide at Storegga may have been set in motion by massive release of methane from gas-hydrate deposits, and such is the extent of scarring of the sea floor there that it must have happened before and may do so again.




Copper engraving showing the 1755 Lisbon tsunami overwhelming ships in the harbour.

Realisation of the potential for tsunamis to be triggered by submarine and coastal landslides has spurred bathymetric studies in a number of likely areas, including the Gorringe Bank that lies on the Atlantic floor just west of the Iberian Peninsula. It is tectonic in origin but has a thick veneer of sediment brought by Iberian river systems. On its northern flank is a 35 km long scar of a slip that moved 80 $km^3$ of sediment (Lo Iacono, C. And 11 others 2012. Large, deepwater slope failures: implications for landslide generated tsunamis. *Geology*, v. **40**, p. 931-934; DOI: 10.1130/G33446.1). The Spanish-British-Italian group estimate that the slip would have generated a 15 m tsunami most likely to have affected the Iberian coast south of Lisbon. Conditions for slides of si,ilar magnitude still exist on the Gorringe Bank. One unstable system ripe for collapse lies far out in the Atlantic on the south-east coast of the island of Picos in the Azores (Hildenbrand, A. *et al*. 2012. Large-scale active slump on the southeast flank of Picos Island, Azores. *Geology*, v. **40**, p. 939-942; DOI: 10.1130/G33303.1). This is in a coastal area where repeated volcanism has piled up lavas on the flanks of the island's main volcanic edifice. Failure has already started, with a number of prominent arcuate scars having developed. The Picos slide moves very slowly sideways but vertical displacements ar estimated at up to a centimetre a year. The volume of the slowly moving mass is an order of magnitude less that the fossil slide on the Gorringe Bank. Yet should it fail entirely, the slopes involved, the absence of water's slowing effect and the height of the mass might ensure comparable energy is delivered to the Atlantic Ocean, though the likely trajectory of tsunamis would be parallel to the coast of Africa rather than directly towards it.

Landslides of all kinds, though hazardous, have long been thought to be less of a risk to life globally than the more spectacular seismic and volcanic hazards, but there are few data to support that view. In an attempt to assess the annual risk properly, David Petley of Durham University, UK 'mined' world-wide landslide records for the seven years since 2004 (Petley, D. 2012. Global patterns of loss of life from landslides. *Geology*, v. **40**, p. 927-930; DOI: 10.1130/G33217.1). There were more than 2600 recorded slope-failures that killed people and caused a total of more than 32 thousand fatalities: ten time more than previous vague estimates. This is a minimum because many landslides occur in very remote areas, especially in the mountainous regions of China and the Himalaya. The number of fatalities accompanying each event shows distinct signs, on a country-by-country basis, of a relationship with population density. Several international agencies are emerging that aim at means of measuring disaster risk, one being the Integrated Global Observing Strategy for Geohazards (IGOS).

**Related article:** Landslide fatalities are greater than previously thought (sciencedaily.com)

**Una parodia della giustizia? (*October 2012*)**

Damage caused by the L' Aquila earthquake of 6 April 2009. (Credit: Reuters)

Lying above a destructive plate margin, albeit a small one, Italy is prone to earthquakes. Seismometers detect a great many of low magnitude that no one notices and that do no obvious damage to buildings. From 2006 to autumn 2008 the Abruzzo region on the eastern flank of the Appenine mountains of central Italy experienced a background of one low-magnitude tremor every day (Papadopoulos, G.A. *et al*. 2010. Strong foreshock signal preceding the L'Aquila (Italy) earthquake (Mw 6.3) of 6 April 2009. *Natural Hazards and Earth System Sciences*, v. **10**, p. 19-24). In the following 6 months the rate more than doubled but the epicentres continued to be almost randomly situated. Things changed dramatically in the 10 days following 27 March 2009: the pace increased to twenty times the normal 'background' and epicentres clustered directly beneath the regional capital L' Aquila (population 73 thousand) close to a known fault line. At 3.32 am on 6 April 2009 the Paganica fault failed less than 10 km below L' Aquila, directing most of the Magnitude 6.3 energy at the town. This was the deadliest earthquake in Italy for three decades; 308 people died 1500 were injured and 40 thousand found themselves homeless. Silvio Berlusconi, not a man to flinch from controversy, commented on German TV about the homeless, 'Of course, their current lodgings are a bit temporary. But they should see it like a weekend of camping'.

Former Italian President Silvio Berlusconi

L' Aquila has a dismal history of seismic damage, having been devastated 7 times since the 14th century. Having grown on a foundation of lake-bed sediments, notorious for amplifying ground movements, the city was clearly in a high-risk status in much the same manner as Mexico City. Shaken several times before and built with no regard to seismicity, much of L' Aquila's centuries-old building stock was incapable of resisting the event of 6 April 2009: up to 11 thousand building were damaged, some collapsing completely.

Not only was the earthquake preceded by an increasing pace of foreshocks, but many local people reported strange 'earth lights' during the months beforehand (Fidani, C. The earthquake lights (EQL) of the 6 April 2009 Aquila earthquake, in Central Italy. *Natural Hazards and Earth System Sciences*, v. **10**, p. 967-978; DOI: 10.5194/nhess-10-967-2010). In fact, so many sightings were made that plans have been outlined for a CCTV monitoring network in rural areas.

So, this disaster was not short of signs that all was not well in Abruzzo, in a seismic sense: historical precedent; poor urban siting; foreshocks and oddities that have come to be associated with impending energy release. But was this litany sufficient to predict the place, date, and magnitude of what was coming? Plate tectonics, local structural geology and worldwide seismicity allow geophysicists to assess risk from earthquakes in the same way as hydrologists can outline flood-prone areas: literally on flood plains. Yet there are few if any records of a devastating earthquake having been predicted anywhere with sufficient accuracy to allow evacuation and mitigation of death and injury. That is despite the fact that teams of seismologists in the western US, Japan, Italy and several other well-off countries continually monitor seismic events even with a power many orders of magnitude less than those which kill or injure. Such bodies are faced with a dreadful choice in the face of evidence like that summarised above: warn tens of thousands to evacuate, organise such an exodus in a few days and prepare accommodation for them, or advise that similar seismic escalations rarely lead to massive damage with an estimate of the probability of risk. Both choices are guesswork for there are no rigorous equations that spell 'doom' or 'all clear' from such data. Earthquakes are not rainstorms or hurricanes, as 250 thousand dead people on the shores of the Indian Ocean bear grim witness.

Despite broad knowledge of the deep uncertainty associated with earthquakes and volcanic eruptions – no longer privy to specialist scientists these days, even in the least developed parts of the world – the Italian authorities saw fit to prosecute six earth scientists and a public official for multiple manslaughter.  Because they provided "inaccurate, incomplete and contradictory" information about what might have been the aftermath of tremors felt ahead of 6 April 2009 earthquake, a regional court sentenced all of them to six years in prison – two years more than even the prosecution demanded – and they are to pay the equivalent of £6.7 million in compensation. This was not a jury verdict, but the decision of a single judge, Marco Billi. No scientist, even one poring over data from the Large Hadron Collider in search of the Higgs boson, would every claim that what they report is perfectly accurate, complete and incontrovertible. The L'Aquila Seven never said they were certain that no earthquake would ensue, and the city's people were well aware of what risk they faced in much the same way that Neapolitans living on the slopes of Vesuvius know that one day they may be incinerated.

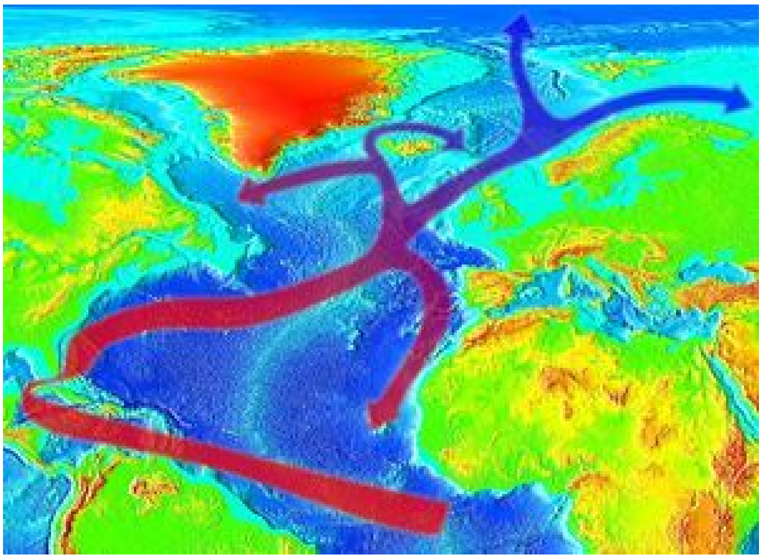
This is a travesty of justice so bizarre that one must look to the famous adage of Roman Law: *qui bono*? Certainly not the victims and their mourners, and definitely not science because any sensible Italian geophysicist will in future simply play dumb. There is already a huge world wide outcry, not just from outraged scientists.

**Added 25 October 2012**: The 12 October issue of *Science* carried a lengthy summary of proceedings early in the trial (Cartlidge, E. 2012. Aftershocks in the courtroom. *Science*, v. **338**, p. 185-188). Read *Nature*'s editorial on the L' Aquila verdict here and further comment.

**Short fuse on clathrate bomb? (*October 2012*)**

Gas hydrate (methane clathrate) block embedded in seabed

The biggest tsunami to affect inhabitants of Britain, mentioned in the earlier post *Landslides and multiple dangers*, emanated from the Storegga Slide in the northern North Sea west of Norway. That submarine debris flow was probably launched by gas hydrates beneath the sea bed breaking down to release methane thereby destabilising soft sediments on the continental slope. Similar slides were implicated in breaking Europe-America communications in the 20th century, such as the Grand Banks Slide of 1929 that severed submarine cables up to 600 km from the source of the slide. Even now, much Internet traffic is carried across oceans along optic-fibre cables, breakages disrupting and slowing services. A more mysterious facet of clathrate breakdown is its possible implication in unexplained and sudden losses of ships. When gas escapes to the surface, the net density of seawater decreases, the more so as the proportion of bubbles increases. Ship design and cargo loading rests on an assumed water density range from fresh to salt water and for different temperatures at high and low latitudes.



Gulf stream map

The Atlantic seaboard of the USA hosts some of the best-studied accumulations of clathrates in the top 100-300 m of seabed sediments. Since their discovery these 'cage complexes' of mainly methane and carbon dioxide trapped within molecules of water ice have been studied in detail. Importantly, the temperatures at which they form and the range over which they remain stable depend on pressure and therefore depth below the sea surface. At atmospheric pressure solid methane hydrate is unstable at any likely temperature and requires -20°C to form at a pressure equivalent to 200 m water depth. Yet is stable at temperatures up to 10°C 500 m down and 20°C at a depth of 2 km. Modern sea water cools to around 0°C at depths greater than 1.5 km, so gas hydrates can form virtually anywhere that there is a source of methane or $CO_2$ in seafloor sediment. In the sediments temperature increases sharply with depth beneath the seabed due to geothermal heat flow thereby limiting the clathrate stability zone to the top few hundred metres.

Two factors may lead to clathrate instability: falling sea level and sea-floor pressure or rising sea-floor temperature. Many gas-hydrate deposits, especially on the continental shelf and continental edge are likely to be close to their stability limits, hence the worries about destabilisation should global warming penetrate through the water column. The western North Atlantic is an area of especial concern because the Gulf Stream flows northward from the Caribbean to pass close to the US seaboard off the Carolinas: that massive flow of tropical warm water has been increasing during the last 5 thousand years so that its thermal effects are shifting westwards.

Geophysicists Benjamin Phrampus and Matthew Hornbach of the Southern Methodist University in Dallas, Texas have used thermal modelling to predict that gas-hydrate instability is imminent across 10 thousand square kilometres of the Caroline Rise (Phrampus, B.J. & Hornbach, M.J. 2012. Recent changes to the Gulf Stream causing widespread gas hydrate destabilization. *Nature*, v. **490**, p. 527-530; DOI: 10.1038/nature11528). As a test they analysed two seismic reflection profiles across the Carolina Rise, seeking anomalies known as bottom-simulating reflectors that signify free gas in the sediments. These are expected at the base of the gas-hydrate zone and their presence helps assess sediment temperature. At depths less than 1 km the base of the gas-hydrates modelled from the present temperature profile through the overlying seawater lies significantly above the base's signature on seismic lines. The deeper levels probably formed under cooler conditions than now – probably eight degrees cooler – and may be unstable. If that is correct, the Caroline Rise area seems set to release around 2.5 Gt of methane to add to atmospheric greenhouse warming. The Storegga Slide also lies close to the northern track of the Gulf-Stream – North Atlantic Drift…

**Related articles:** Gulf Stream Shift Linked to Methane Gas Escaping from Seabeds (*Scientific American*); Seismic signs of escaping methane under the sea (nature); Scientists uncover diversion of Gulf Stream path in late 2011; Warmer waters flowed to shelfbreak south of New England (sciencedaily.com)

**Batter your planet (*November 2012*)**

Depiction of the asteroid impact 65 Ma ago that caused the K-T mass extinction

Just in time for the festive season I have been sent the URL for an on-line impact simulator written by a team from Imperial College London and the University of Arizona (Collins, G.S. *et al*. 2005. Earth Impact Effects Program: A Web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth. *Meteoritics and Planetary Science*, *v.* **40**, p. 817–840), with a web presence designed at Purdue University, Indiana. ImpactEarth  has been around for two years and has a scientifically pleasing level of precision, thanks to the authors, Gareth Collins, Jay Melosh and Robert Marcus.

The fact that the target shown by the accompanying animation and other graphics seems to be the Washington-New York megalopolis may be a cause for some concern for US readers, especially the Department of Homeland Security, National Security Agency and CIA. They can rest easy, however, as this seems to be a matter of artistic license: the choice of parameters allows for ocean strikes and targets of sedimentary or crystalline rocks. Others are impactor diameter and density, impact angle and speed, plus distance from ground zero. An element of whimsy allows the casual user to choose inbound humpback whales, school buses and the Empire State Building as well as more astronomically likely scenarios.

There are a number of missing parameters such as direction relative to Earth's rotation, latitude and the likely affect of an ice-cap strike, and no mention in the results of the electromagnetic burst from atmospheric compression on entry – the Diesel effect. However, the thermal effects on bystanders, buildings and vegetation at the 'viewpoint' personalise the experience to some extent. It is the detail about crater dimensions and evolution, lithospheric melting and what might happen to the Earth's axial tilt and day length that the wealth of computations produce surprises. It is not easy to destroy our planet: using a body with a density of 3000 kg $m^{-3}$ and the diameter of Asia causes no significant melting or changes in axial tilt at speeds less than 12 km $s^{-1}$, but does change the length of the day by up to 113 hours. This is because the power of impacts and therefore the work done by them is proportional to the square of the speed. Mind you, nothing is left standing as the seismic effect has a Richter Magnitude of more than 15! Yet, curiously, no atmospheric or thermal radiation effects are noted.

Have fun.