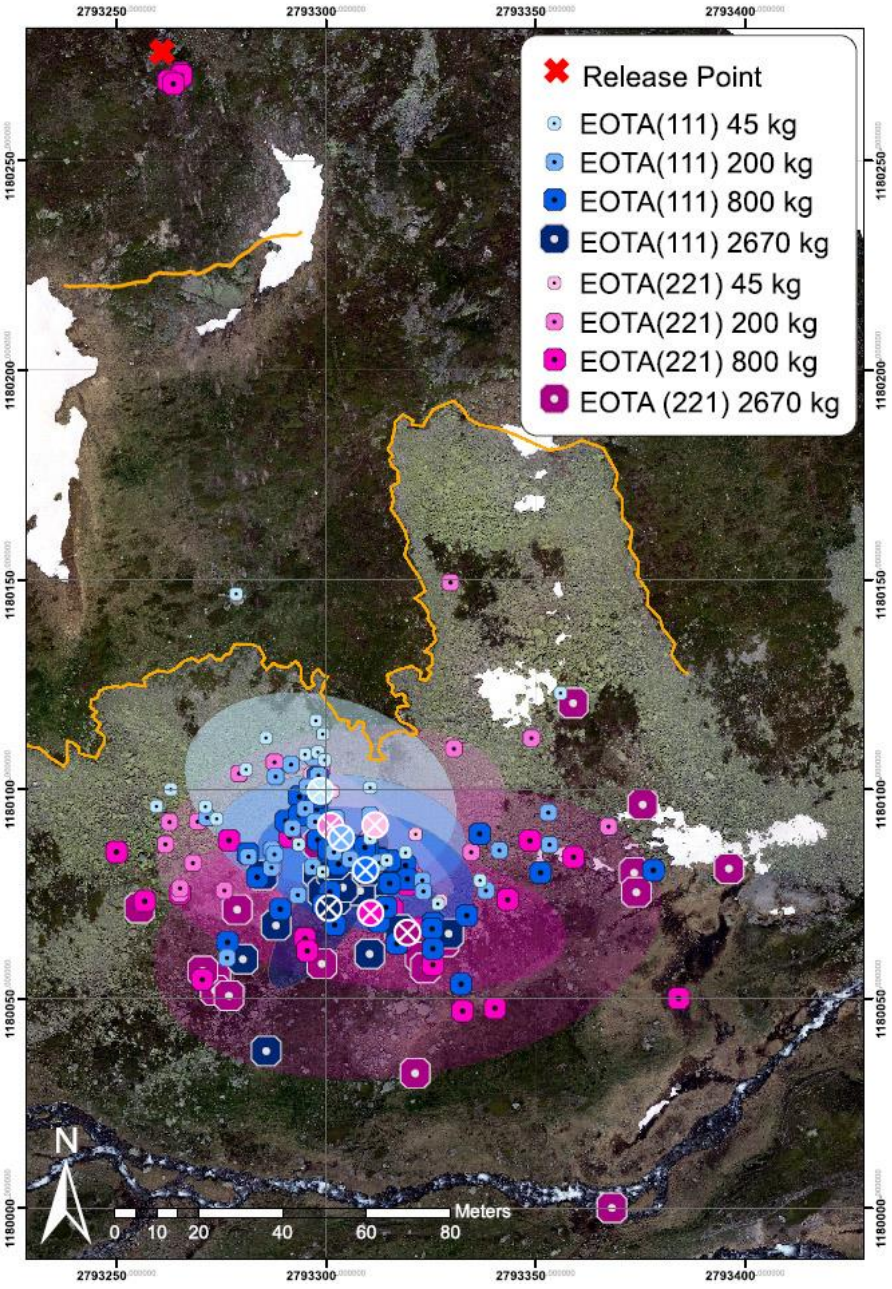
Geohazards 2022-5

The dangers of rolling boulders

PUBLISHED ON *July 31, 2022*

Field work in lonely and spectacular places is a privilege. Though it can be great, boredom sometimes sets in, which is hard for the lone geologist. Today, I guess a cell phone would help, especially in high places where the signal is good. That means of communication and entertainment only emerged in the 1980s and did not reach wild places until well into the 90s. Pre-cellnet boredom could be relieved by what remains a dark secret: lone geologists once rolled large boulders down mountains and valley sides, shouting 'Below!' as a warning to others. Their excuse to themselves for this unique thrill (bounding boulders reach speeds of up to 40 m s^{-1}) was vaguely scientific: sooner or later a precarious rock would fall anyway. This week it emerged that Andrin Caviezel of the Institute for Snow and Avalanche Research in Davos, Switzerland, an Alpine geoscientist, rolls boulders for a living (Caviezel, A. 2022. The gravity of rockfalls. Where I work, *Nature*, v. **607**, p. 838; DOI: 10.1038/d41586-022-02044-9). He finds that '…flinging giant objects down a mountain is still super fun'. The serious part of his job attempts to model how rockfalls actually move downslope, as an aid to risk assessment (Caviezel, A. and 23 others 2021. The relevance of rock shape over mass – implications for rockfall hazard assessments. *Nature Communications*, v. **12**, article 5546; DOI: 10.1038/s41467-021-25794-y)

Caviezel's team (@teamcaviezel) don't use actual rocks but garishly painted, symmetrical blocks of reinforced concrete weighing up to 3 tonnes, which are more durable than most outcropping rock and can be re-used. A Super Puma helicopter shifts a block to the top of a slope, from which it is levered over the edge (watch video). The team deploys two types of block, one equant and resembling a giant garnet crystal, the other wheel-shaped with facets. The first represents boulders of rock types with uniform properties throughout, such as granite. The wheel type mimics boulders formed from rocks that are bedded or foliated, which are usually plate-like or spindly.



Vertical aerial photograph of a uniform, south-facing slope in the Swiss Alps used to roll concrete 'boulders'. The red X marks the release point; the blue symbols show the points of rest of equant 'boulders, the sizes of which are shown in the inset, the wheel-shaped ones are magenta. Coloured circles with crosses show the mean rest position of each category (the lighter the colour the smaller the set of 'boulders'). The coloured ellipses indicate the standard deviation for each category. (Credit: Caviezel et al., Fig 2)

Unlike other gravity-driven hazards, such as avalanches and mudflows, the directions that rockfalls may follow by are impossible to predict. Rather than hugging the surface, boulders interact with it, bouncing and being deflected, and they spin rapidly. To follow each experiment's trajectory a block contains a motion sensor, measuring speed and acceleration, and a gyroscope that shows rotation, wobbling and motion direction, while filming records jump heights – up to 11 m in the experiments. Despite the similarity of the blocks, the same release point for each roll and a uniform mountainside

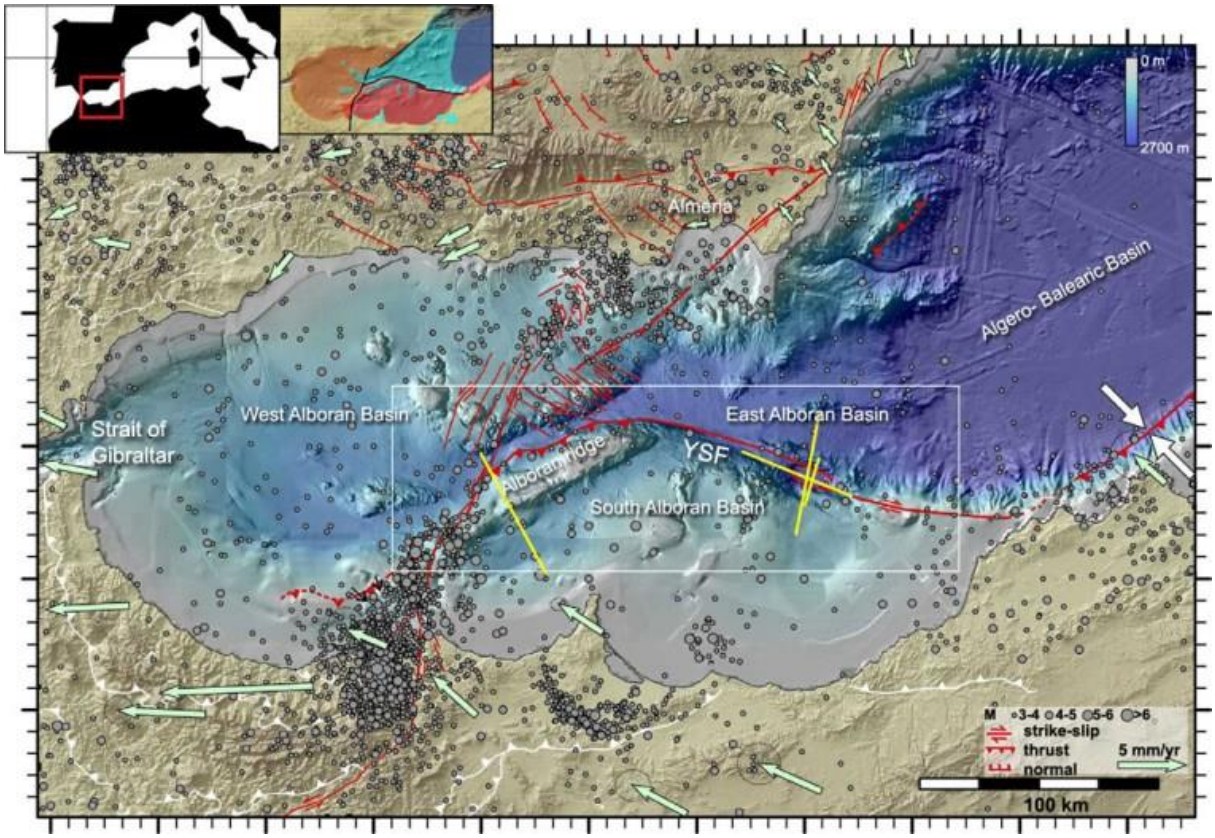
slope, with one cliff line, the final resting places are widely spread. That hazard zone of rockfalls is distinctly wider than that of snow avalanches; observing a boulder once it starts to move gives a potential victim little means of knowing a safe place to shelter.

The most important conclusion from the experiments is that the widest spread of tumbling 'boulders' is shown by the wheel-shaped ones. So, slopes made from bedded or foliated sedimentary and metamorphic rocks may pose wider hazards from rockfalls than do those underpinned by uniform rocks. However, plate-like or spindly boulders are more stable at rest than are equant ones. Yet boulders rarely fall as a result of being pushed (except in avalanches). On moderate slopes they are undermined by erosion, and on steep slopes or cliffs winter ice wedges open joints allowing blocks to fall during a thaw.

Sun, sand and sangria on the Mediterranean Costas – and tsunamis?

PUBLISHED ON *September 2, 2022*

You can easily spot a tourist returning from a few summer weeks on the coast of the western Mediterranean, especially during 2022's record-breaking heat wave and wildfires: sunburnt and with a smoky aroma that expensive après-sun lotion can't mask. Judging from the seismic records, they may have felt the odd minor earthquake too, perhaps putting it down to drink, lack of sleep and an overdose of trance music. Data from the last 100 years show that southern Spain and north-west Africa have a generally uniform distribution of seismic events, mostly less than Magnitude 5. Yet there is a distinct submarine zone running NNE to SSW from Almeria to the coast of western Algeria. It crosses the Alboran Basin, and reveals significantly more events greater than M 5. Most earthquakes in the region occurred at depths less than 30 km mainly in the crust. Five geophysicists from Spain and another two from Algeria and Italy have analysed the known seismicity of the region in the light of its tectonics and lithospheric structure (Gómez de la Peña, L., *et al.* 2022. Evidence for a developing plate boundary in the western Mediterranean. *Nature Communications*, v. **13**, article 4786; DOI: 10.1038/s41467-022-31895-z).



Topography of the Alboran Basin beneath the western Mediterranean. The colours grey through blue to purple indicate increasing depth of seawater. Grey circles indicate historic earthquakes, the smallest being M 3 to 4, the largest greater than M 6. Green arrows show plate motions in the area measured using GPS. Active faults are marked in red (see key for types of motion). (Credit: based on Fig 1 of Gómez de la Peña et al.)

The West Alboran Basin is underlain by thinner continental crust (orange on the inset to the map) than beneath southern Spain and western Algeria. Normal crust underpins the Southern Alboran Basin. To the east are the deeper East Alboran and Algero-Balearic Basins, the floor of the latter being true oceanic crust and that of the former created in a now extinct island arc. Running ENE to WSW across the Alboran Basin are two ridges on the sea floor. Tectonic motions determined using the Global Positioning System reveal that the African plate is moving slowly westwards at up to 1 cm yr^{-1}, about 2 to 3 times faster than the European plate. This reflected by the dextral strike-slip along the active ~E-W Yusuf Fault (YSF). This bends southwards to roughly parallel the Alboran Ridge, and becomes a large thrust fault that shows up on ship borne seismic reflection sections. The reflection seismic survey also shows that the shallow crust beneath the Alboran Ridge is being buckled under compression above the thrust. The thrust extends to the base of the African continental crust, which is beginning to override the arc crust of the East Alboran basin. Effectively, this system of major faults seems to have become a plate boundary between Africa and Europe in the last 5 million years and has taken up about 25 km of convergence between the two plates. An estimated 16 km of this has taken place across the Alboran Ridge Thrust which has detached the overriding African crust from the mantle beneath.

The authors estimate an 8.5 to 10 km depth beneath the Alboran fault system at which the overriding crust changes from ductile to brittle deformation – the threshold for strains being taken

up by earthquakes. By comparison with other areas of seismic activity, they reckon that there is a distinct chance of much larger earthquakes (up to M 8) in the geologically near future. A great earthquake in this region, where the Mediterranean narrows towards the Strait of Gibraltar, may generate a devastating tsunami. An extension of the Africa-Europe plate boundary into the Atlantic is believed to have generated a major earthquake that launched a tsunami to destroy Lisbon and batter the Atlantic coasts of Portugal, Spain and NW Africa on 1st November 1755. The situation of the active plate boundary in the Alboran Basin may well present a similar, if not worse, risk of devastation.

Flash: Huge rockslide imminent in Swiss village of Brienz

PUBLISHED ON *May 15, 2023*

The rockslide above Brienz in eastern Switzerland marked by a white surface bare of vegetation. Credit CHRISTOPH NÄNNI, TIEFBAUAMT GR, SWITZERLAND via the BBC

On 9 May 2023 the authorities of the Albula/Alvra municipality in the Swiss canton of Graubünden informed people living in the small village of Brienz that they must evacuate the area by 18 May as the threat of rock falls from the mountain beneath which they live had triggered a red alert. By 13 May all 130 dwellings had been abandoned.

The danger is posed by an estimated 5 million tons of rock associated with a developing landslide that is now estimated to be moving at around 32 m per year. The village itself had long been creeping down slope at a few centimetres each year, but recently its church spire had begun to tilt

and buildings became riven by cracks. Seemingly, engineering attempts to mitigate the hazards have been unsuccessful, and large boulders have already tumbled into the vicinity of Brienz.

Being situated beneath a crumbling scree slope devoid of vegetation that had been developing since the last glaciation, the geological risk to the village comes as no surprise to its population and local authority. The local geology has a thick limestone resting on the thinly bedded Flysch – a metamorphosed sequence of fine-grained turbidites – from which groundwater escapes very slowly, thereby becoming lubricated. A curved (listric) failure zone has developed beneath the exposed mountainside, hence the danger. Acceleration on the listric surface began about 20 years ago.

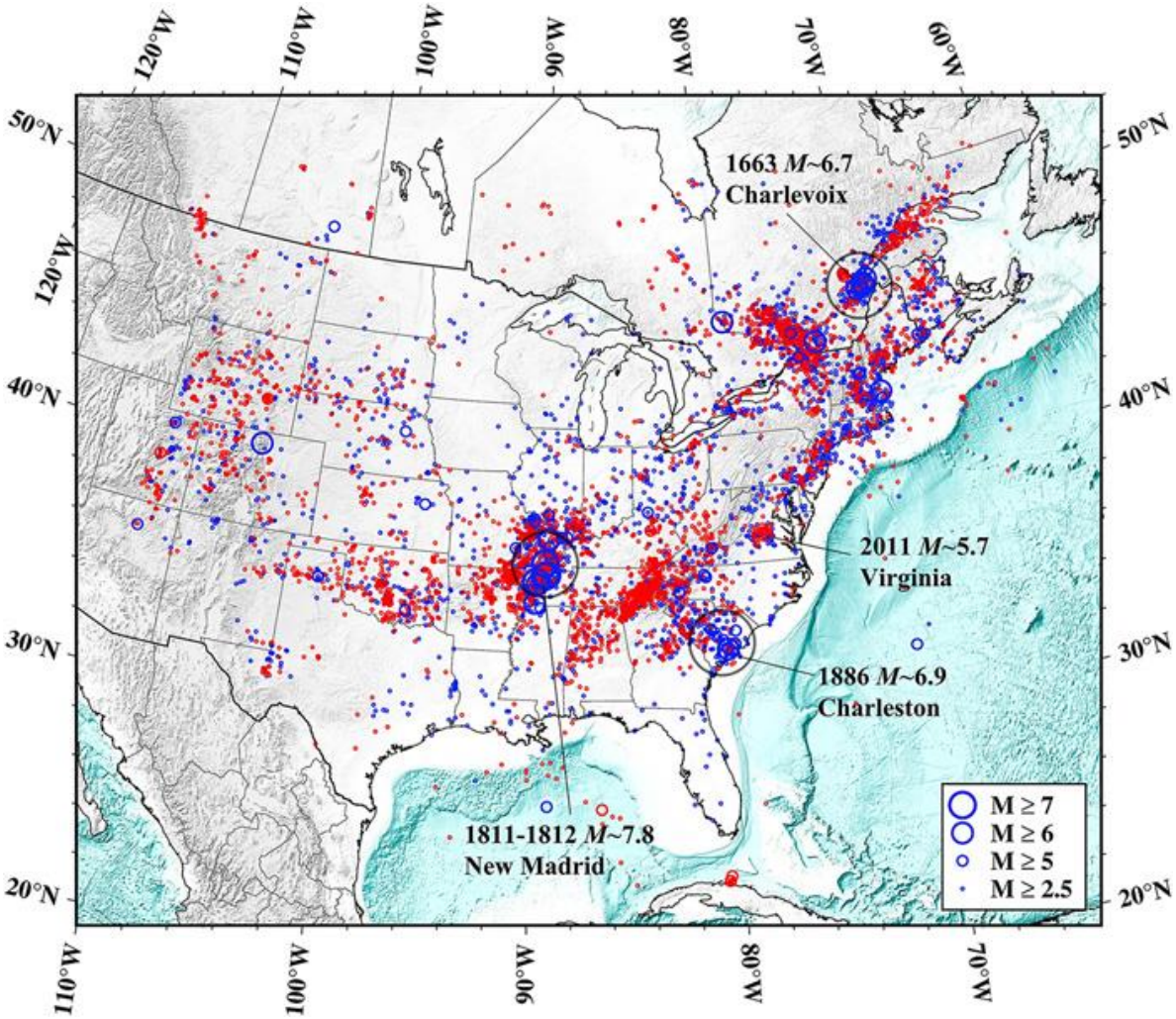
At least the people of Brienz have been moved to safety, unlike 144 school children and adults in the mining village of Aberfan in South Wales. On 21 October 1966 they were crushed to death by coal-mining waste that suddenly flowed from waste tips on the steep valley side above the village. In that case no warning was given by the National Coal Board authorities who allowed the tipping witout a thought for its geological consequences.

See also: Petley, D. 2023. The very large incipient rockslide at Brienz in Switzerland. *The Landslide Blog* (10 May 2023)

Aftershocks of ancient earthquakes

PUBLISHED ON *November 23, 2023*

Any major earthquake is likely to be followed by aftershocks. Survivors of seismic devastation live in dread of them for weeks, even months. In reality the fault responsible for the initial event continues to move for longer than that. Commonly, aftershock activity dies down in magnitude and frequency over time, sometimes after a few weeks and in other cases much later to reach 'normal background seismicity' for the associated tectonic setting. Near a major plate boundary, such as the San Andreas Fault system in coastal California or the mid-Atlantic Ridge in Iceland, there is a continual risk of damaging seismic events, but the area around each major event becomes less risky a few tens of years afterwards. For instance, the Loma Prieta area on the San Andreas became quiescent sixteen years after the October 1989 Magnitude 6.9 earthquake that wrought havoc in San Francisco – and interrupted a Major League baseball match in the city. The December 1954, Magnitude 7.3 Dixie Valley earthquake in the active extensional zone of Nevada had a longer period of instability: 48 years. There is no fixed period for the aftermath, seismicity 'stops when it stops'.



Earthquakes of greater than Magnitude 2.5 in eastern North America (see key to magnitudes at lower right). Those shown in blue date from 1568 to 1979, those in red between 1980 and 2016. (Credit: Chen & Liu, Fig 1)

Sometimes devastating earthquakes take place in what seem to be the least likely places: in tectonically 'stable' continental plate interiors. A Magnitude 7.9 earthquake in Sichuan Province, central China on 12 May 2008 left 86 thousand dead or missing, 374 thousand injured and 4.2 million homeless. It occurred in a region whose ancient fault systems had had little if any historic activity. One of the best studied records of seismic events in the middle of a continent is in the Mississippi River valley at the Missouri-Kentucky border, USA, near the town of New Madrid. This experienced three major earthquakes in 1811 and 1812 at Magnitudes estimated from 7.0 to 7.4. Seismicity there has continued ever since. Others that occurred long ago in the 'stable' North American continental crust were in South Carolina (1886) and southern Quebec, Canada (1663). They and the subsequent, lesser earthquakes that define clusters up to 250 km around them have been studied using spatial statistics (Chen, Y. & Liu, M. 2023. Long-Lived Aftershocks in the New Madrid seismic Zone and the Rest of Stable North America. *Journal of Geophysics Research: Solid Earth*, v. **128**; DOI: 10.1029/2023JB026482). Yuxuan Chen and Mian Lui of Wuhan University, China and the University of Missouri, USA considered the dates of historic events, their estimated magnitudes and their proximity to other events in each cluster. The closer two events are the greater the chance that the later one is an aftershock of the first, although the relationship may also

indicate a long-lived deformation process responsible for both. The authors suggest that this 'nearest-neighbour' approach may reveal that up to 65% of earthquakes in the New Madrid zone between 1980 and 2016 are aftershocks of the 1811-1812 major earthquake cluster, and a significant number of modern events in South Carolina could similarly relate to the 1886 Charleston earthquake. On the other hand, small modern earthquakes in Quebec are more likely to be part of the regional seismic background than to have any relationship to the large 17th century event.

Earthquakes are manifestations of deep-seated processes, most usually the build-up and release of strain in the lithosphere. If such processes persist they can result in long-lived earthquake swarms. So both delayed aftershocks and a high background of seismicity can contribute to the mapped clusters of historic events: a blend of relics of the past and modern deformation. They are yet to be detected in earthquake records associated with tectonic plate boundaries. A long history of movements within continents suggests that it is possible that long-delayed aftershocks may masquerade as foreshocks that presage greater events that are pending. Chen and Liu's nearest-neighbour approach may therefore distinguish false alarms from real risk of major seismic motions.

See also: Some of today's earthquakes may be aftershocks from quakes in the 1800s. *Eureka|Alert*, 13 November 2023

Using lasers to map landslide risk

PUBLISHED ON *December 9, 2023*

As radar stands for **ra**dio **d**etection **a**nd **r**anging, so lidar signifies **li**ght **d**etection **a**nd **r**anging. In one respect the two are related: they are both *active* means of remote sensing and illuminate the surface, rather than passively monitoring solar radiation reflected from the surface or thermal radiation emitted by it. The theory and practice of imaging radar that beams microwaves at a surface and analyses the returning radiation are fiendishly complex. For a start microwave beams are directed at an angle towards the surface. Lidar is far simpler being based on an aircraft -mounted laser that sends pulses vertically downwards and records the time taken for them to be reflected from the surface back to the aircraft. The method measures the distance from aircraft to the ground surface and thus its topographic elevation. Lidar transmits about 100 thousand pulses per, so the resulting digital elevation model has remarkably good spatial resolution (down to 25 cm) and can measure surface elevation to the nearest centimetre. The technique is becoming popular: the whole of England and much of the nations of Scotland, Wales and Northern Ireland now have lidar coverage with 1 metre resolution.

The first thing the laser pulses encounter is the vegetation canopy, from which some are reflected back to the instrument. Others penetrate gaps in the canopy, to be reflected by the ground surface, so they take slightly longer to return. If the penetrating pulses are digitally separated from those reflected by vegetation, they directly map the elevation of the solid ground surface or the *terrain*. These data produce a digital terrain model (DTM) whereas the more quickly returning pulses map the height and structure of the ground cover, if there is any. Both products are useful, the first to map topographic and geological features, the details of which are hidden to conventional remote sensing, the second to assess vegetation. The great advantage of a DTM is that image processing

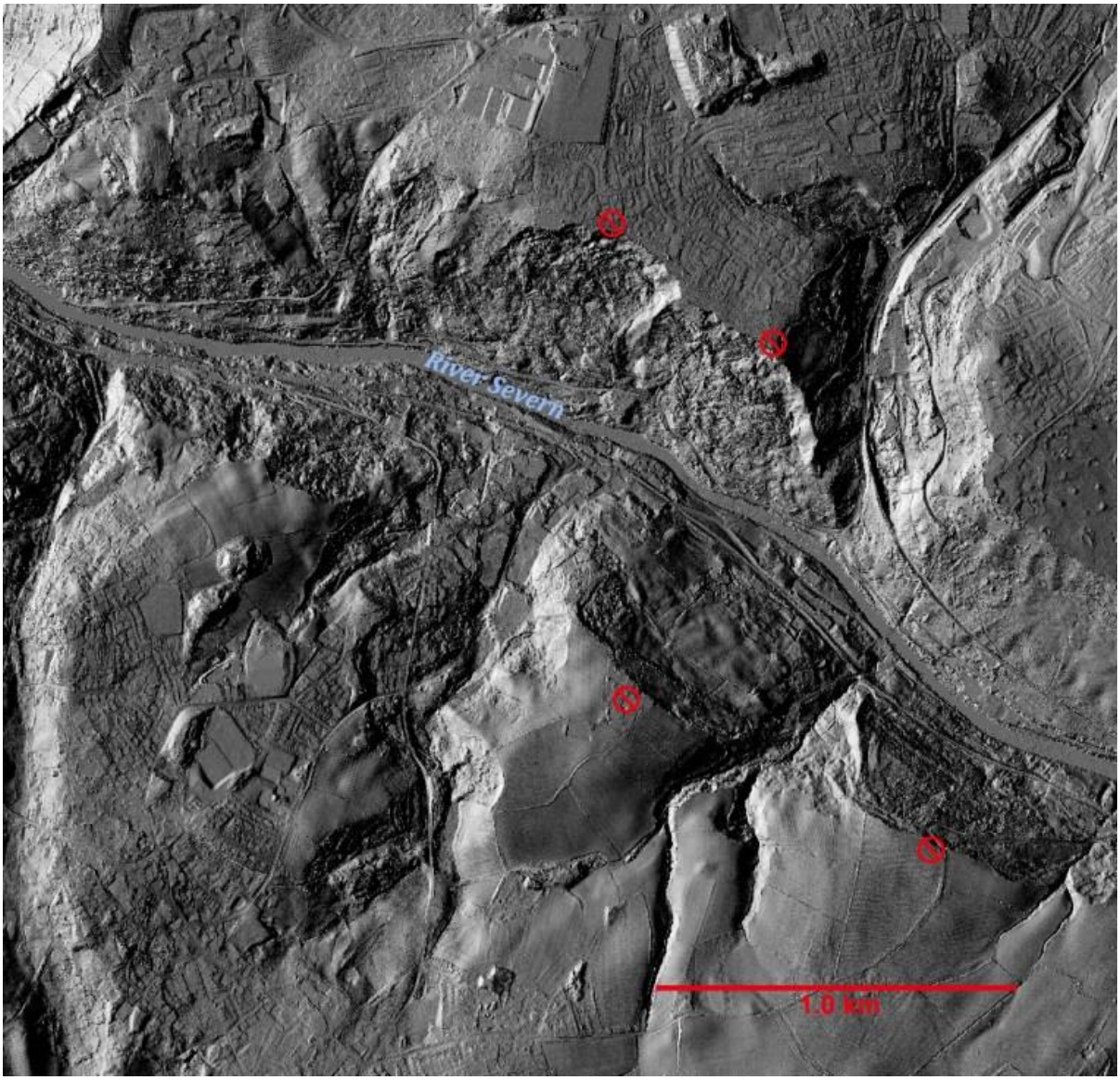
software can simulate illumination and shading of the terrain from different directions and angles to improve interpretation. Aerial photography has but a single direction and angle of solar illumination, depending on the time of day, the season and the area's latitude. Stereoscopic viewing of overlapping photographic images does yield topographic elevation, and photogrammetric analysis produces a digital elevation model, but its usefulness is often compromised by ground cover in vegetated terrain and by shadows. Also its vertical resolution is rarely better than 1 m. Another factor that limits terrain analysis using aerial photographs and digital images from satellites is the 'patchwork-quilt' appearance of farmed land that results from sharp boundaries between fields that contain different crops, bare ploughed soil and grassland. Together with spatial variation of natural vegetation, both 'camouflage' physical features of the landscape.


A Cliff collapse in July 2023 at Seatown, Dorset England

In the field, areas of what is known as 'mass wasting', such as landslides, landslips, rockfalls, debris flows and solifluction, show topographic features that are characteristic of the processes involved. They can be mapped by careful geological surveys. But are overlooked, being masked by vegetation cover such as woodland or because slower downslope movement of soil has smoothed out their original landforms. Potentially devastating mass wasting is encouraged by increased moisture content of soils and rocks that lie beneath steep slopes. Moisture provides lubrication that gravitational forces can exploit to result in sudden disruption of slopes and the movement of huge masses of Earth materials. Large areas of upland Britain show evidence of having experienced such mass wasting in the past. Some continue to move, such as that in the Derbyshire Peak District on the slopes of Mam Tor, as do cases on rugged parts of Britain's coast where underlying rocks are weak and coastal erosion is intense (see image above).

It is thought that many of the mass-wasting features in Britain were initiated at the start of the Holocene. Prior to that, during the Younger Dryas cooling event, near-surface Earth materials were gripped solid by permafrost. Sudden warming at about 11.7 ka ago melted deeply frozen ground to create ideal conditions for mass wasting. In the last eleven thousand years the surface has come to a more or less stable gravitational balance. Yet heavy, sustained rainfall may reactivate some of the structures or trigger new ones. The likelihood of increased annual rainfall as the climate warms will

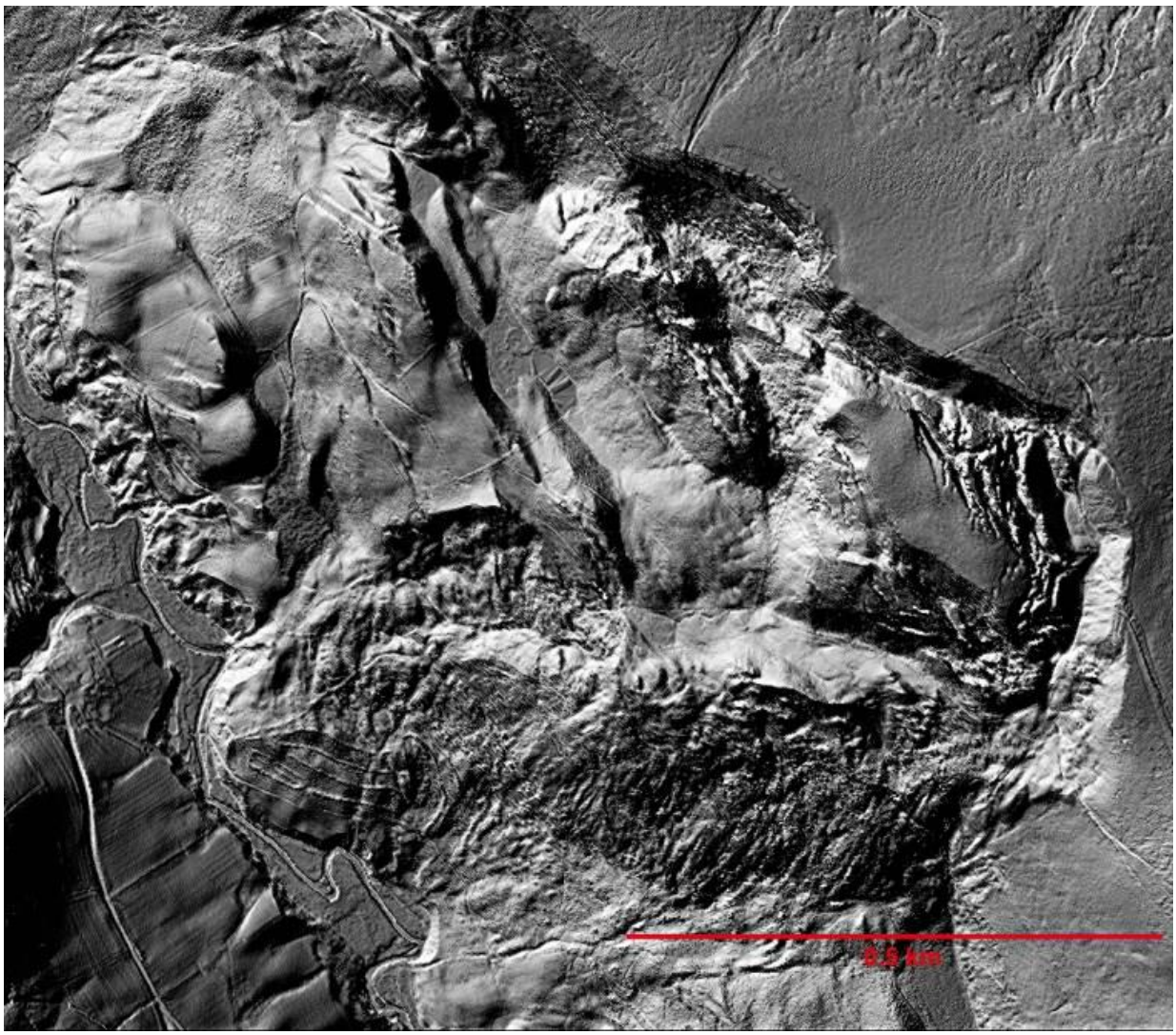
undoubtedly increase the risk of more and larger instances of mass wasting. Indeed such an acceleration is happening now.



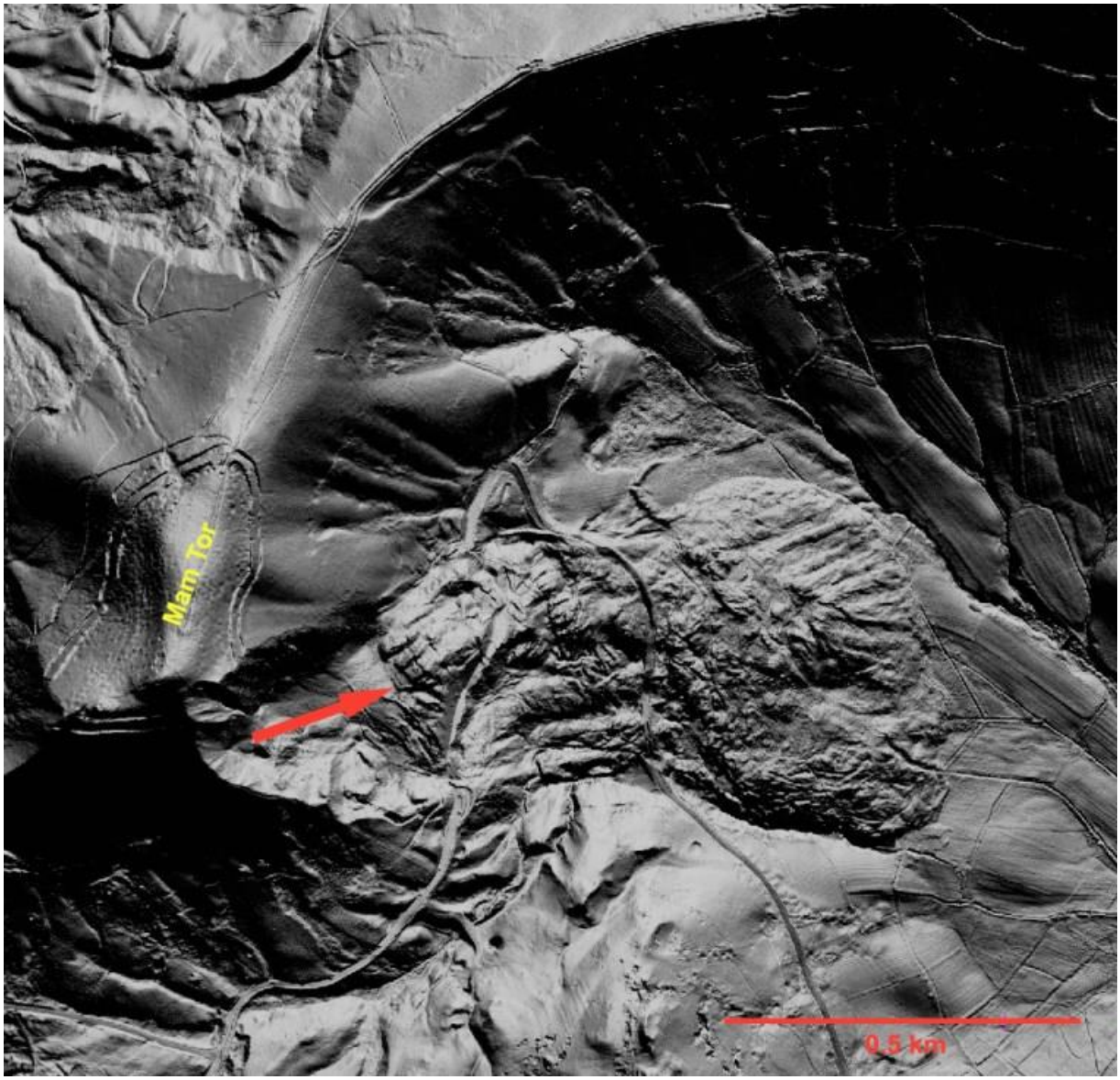
Lidar DTM illuminated from the west for the Severn Gorge near Ironbridge, Telford, Shropshire, UK. Lips of four major landslides shown by 'No Entry' signs. Initiated at the beginning of the Holocene, they continue to be active to this day, the southernmost slide having obliterated a tile factory and workers' dwellings at Jackfield in 1952

The most risky places are those with a history of landslides etc. So detailed mapping of such risk-prone ground is clearly needed. The UK has a large number of sites where mass wasting has been recorded, and below are lidar images of three of the most spectacular. Undoubtedly, there are other areas where no recent movements have been recorded, but which may 'go off' under changed climatic conditions. One of the best documented risky areas is in the English West Midlands within the new city of Telford. It follows the flanks of the River Severn as it passes through the Ironbridge Gorge that was cut by subglacial meltwater after the last glacial maximum. This area is also

recognised as having been the birthplace of the Industrial Revolution. In 1714 Abraham Darby pioneered the use of coke in iron smelting and mass production of cast iron at Coalbrookdale a few kilometres to the east. The Severn also powered numerous forges and other heavy industries in the 18th and 19th centuries. Industrial activity and townships in the Gorge have been plagued by large-scale mass wasting throughout subsequent history and no doubt long before. An excellent illustrated guide to the area has been produced by the Shropshire Geological Society (Rayner, C. *et al*. 2007. A Geological Trail through the landslides of Ironbridge Gorge, *Proceedings of the Shropshire Geological Society*, v. **12**, p. 39-52; ISSN 1750-8568)



Lidar DTM illuminated from the NW for the Alport Valley in the Peak District of North Derbyshire, UK. This includes the largest landslide complex in England, known as Alport Castles from the huge displaced sandstone blocks in the area of mass wasting.



An active landslide near Castleton, Derbyshire, UK. Note the defences of an Iron Age hillfort on Mam Tor that have been cut as the head of the landslide retreated westwards, as have medieval field walls. The relics of a major road that has been repeatedly disrupted and then destroyed following decades of maintenance can also be seen in the debris flow: it was abandoned in the 1970s.

Earthquakes and flooding in the Ganges Basin

PUBLISHED ON *June 28, 2024*

Floods pose a huge threat to the large populations of West Bengal, India and the state of Bangladesh, particularly in the highly fertile fluvio-deltaic plains of the Ganges and Brahmaputra. The two river systems drain 2 million km^2 of the Eastern Himalaya of annual monsoon rains and snow melt, the first flowing west to east and the latter from east to west at the apex of the low-lying Bengal Basin. The 400 million people subsisting in the 105 thousand km^2 onshore basin make it the world's most populous delta plain with one of the highest population densities, averaging 1,100 per square kilometre in 2019. The risk of catastrophic flooding is generally ascribed to unusually high

monsoonal precipitation and snow melt, combined with storm surges from the Bay of Bengal that funnels tropical cyclones. But either can bring inundation. Another factor has recently been proposed as an addition to flood hazard: earthquakes near the basin (Chamberlain, E.L and 12 others 2024. Cascading hazards of a major Bengal basin earthquake and abrupt avulsion of the Ganges River. *Nature Communications*, v. **15**, online article 4975; DOI: 10.1038/s41467-024-47786-4). It seems they can completely and suddenly change the flow networks in such a complex system of major channels.

Using remotely sensed data Elizabeth Chamberlain, currently at Wageningen University in the Netherlands, and colleagues from Bangladesh, the US, Germany and Austria have detected an immense abandoned channel in the Ganges River. They reckon that it resulted from a sudden change in the river's course. Such avulsions in the sluggish lower parts of a river system are generally caused by the flow becoming elevated above the flood plain by levees. When they burst free the channel may be abandoned. This one is 1.0 to 1.7 km wide and may have been the main Ganges channel at the time of avulsion. The main channel now flows about 45 km north of the abandoned relic. The event must have been sudden and irreversible as the relic channel contains a much thinner layer of fine mud deposited by stagnant water than in other abandoned channels that became ox-bow lakes. That implies rapid uplift and complete drainage from the channel. Throughout the Bengal Basin the immense high-water discharge and heavy sediment load seems generally to have infilled most abandoned channels, so this one is an anomaly.

Sand dykes along fractures in river alluvium of the Bengal Basin. (Credit: Chamberlain et al. Figs 3c and 3d)

Fieldwork near the old channel reveals fracturing of earlier riverbed sediments some of which are filled by intrusions of sand in the form of dykes up to 40 cm wide. Sand dykes are produced by

liquefaction of sandy alluvium by seismic waves to slurry that can be injected into fractures pulled apart by seismic movements. The channel is now about 3 m below the level of the floodplain, suggesting subsidence since the avulsion event. Optically stimulated luminescence dating of sediment grains from the uppermost channel sands yielded ages averaging around 2.5 ka, marking the time when the sudden event took place. The authors consider that it marked a major reorganisation of the Ganges River system, involving catastrophic flooding. The nearest seismically active area is about 180 to 300 km to the east and northeast. Seismic modelling suggests that for liquefaction and fracturing to have affected the area of the abandoned channel the earthquake must have been of magnitude 7.5–8.0, possibly in the subduction zone that roughly follows the Bangladesh-Myanmar border. It may have had similar, yet to be demonstrated, effects throughout the eastern Bengal Basin.

There are no historic records of more recent massive earthquake-induced flooding of the Bengal Basin. However, global warming and growing human intervention in the Ganges-Brahmaputra river systems, such as large-scale dredging and industrialisation could make such events more likely. Other basins close to seismically active fault systems, such as the Yangtze and Yellow River basins of China, also face such risks.

A 9-day seismic reverberation set off by a giant tsunami in a Greenland fjord

PUBLISHED ON *September 13, 2024*

In September 2023 the global network of seismic recorders detected a sequence of low-strength earth movements. It resembled the reverberation of a church bell albeit one that lasted for 9 days. rising and falling in strength every 90 seconds. For months this strange event on seismograms baffled geophysicists. All they could tell was that the signals did not show signs of having been generated by earthquakes; they were too regular. It was, however, possible to triangulate the position of the source of each individual event. There turned out to be only a single location for the seismic ‘campanology’ – at about 73° N on the eastern coast of Greenland, in Dickson Fjord and isolated branch of the enormous Kong Oscar Fjord system. Greenland is not noted for volcanic activity, ruling out the rumblings of a magma chamber that sometimes presages major eruptions. Whatever the cause, there were no human witnesses at the time. The only real clue lay at the start of the signal: the very long-period (VLP) signal was preceded by a sharp, high energy signal that could be matched with some kind of landslide.

View of a side glacier on Dickson Fjord, East Greenland where the tsunami occurred. Left – August 2023; right – 19 September 2023. The rocky peak at top centre on the left fell onto the glacier below to generate a rock-ice slide into the fjord. (Credit: Søren Rysgaard/Danish Army)

On 16 September 2023 the military base for the famous Sirius Dog Sled Patrol on Ella Island was smashed by a tsunami – fortunately it had been closed for the coming winter. When the Danish Navy patrolled Dickson Fjord some days later they found clear signs that the shores opposite the site of a recent colossal rock and ice slide (see images) had been scoured to a height of 200 m. For 5 km either side shoreline scouring averaged 60 m. The initial tsunami was gigantic, yet the fjord was able to contain its worst effects because the outlet to the rest of the system was at right angles to its trend. Some energy obviously was released to reach Ella Island near the mouth of the system to destroy the Danish Army post. The bizarre seismic signal was probably a result of the displaced water sloshing around in the fjord to dissipate the enormous energy released by the collapse of a mountain peak and a substantial amount of a valley glacier. Such behaviour is known as a seiche. Topographic analysis of Dickson Fjord enabled the researchers to calculate its resonant frequency: at 11 millihertz it matched that of the fluctuating seismic signal. (Svennevig, K. and 67 others 2024. A rockslide-generated tsunami in a Greenland fjord rang Earth for 9 days. *Science*, v. **385**, p. 1196-1205; DOI: 10.1126/science.adm9247).

Valley glaciers in Greenland bolster their rocky flanks against collapse. With climatic warming being much faster there than for the rest of the world, its almost innumerable valley glaciers are shrinking. Yet they have been eroding the crust for tens of thousand years. The fjords that they occupied at the height of the last glacial maximum have very steep sides. Likewise, the remaining glaciers have carved U-shaped valleys. So when the glaciers retreat their exposed flanks become gravitationally unstable. Despite the fact that much of Greenland is underpinned by very hard crystalline rocks, that presents a major hazard for water craft. East Greenland's spectacular scenery draws many tourist

cruisers and Innuit fishing boats each summer. Moreover, removal of the ice load allows elastic strain that had built up in the upper crust to be released along joint systems that further weaken resistance to collapse.

A great deal of publicity has been given to the rapid melting of the huge ice sheet that covers most of Greenland. That is currently the biggest contributor to sea-level rise: a few millimetres per year. The Dickson Fjord event highlights the potential deadly threat of deglaciation, although the extremely complex nature of most of its fjord systems may prevent regional tsunamis from escaping their damping effect. Bu there are increasing dangers from the largest, more open fjords, such as Scoresby Sund, which conceivably might blurt catastrophic tsunamis towards Iceland, Svalbard and the west coast of Norway. Even small ones could wreak havoc on wildlife, such as seal and walrus nurseries.

See also: Carrillo-Ponce, A. *et* al. 2024. The 16 September 2023 Greenland Megatsunami: Analysis and Modeling of the Source and a Week-Long, Monochromatic Seismic Signal. *The Seismic Record*, v. **4**, p. 172-183; DOI: 10.1785/0320240013; Le Page, M. 2024. Greenland landslide caused freak wave that shook Earth for nine days. *New Scientist* 12 September 2024

A major breakthrough in carbon capture and storage?

PUBLISHED ON *November 20, 2024*

Carbon capture and storage is in the news most weeks and is increasingly on the agenda for some governments. But plans to implement the CCS approach to reducing and stopping global warming increasingly draws scorn from scientists and environmental campaigners. There is a simple reason for their suspicion. State engagement, in the UK and other rich countries, involves major petroleum companies that developed the oil and gas fields responsible for unsustainably massive injection of CO_2 into the atmosphere. Because they have 'trousered' stupendous profits they are a tempting source for the financial costs of pumping CO_2 into porous sedimentary rocks that once contained hydrocarbon reserves. Not only that, they have conducted such sequestration over decades to drive out whatever petroleum fluids remaining in previously tapped sedimentary strata. For that second reason, many oil companies are eager and willing to comply with governmental plans, thereby seeming to be environmentally 'friendly'. It also tallies with their ambitions to continue making profits from fossil-fuel extraction. But isn't that simply a means of replacing the sequestered greenhouse gas with more of it generated by burning the recovered oil and natural gas; i.e. 'kicking the can down the road'? Being a gas – technically a 'free phase' – buried CO_2 also risks leaking back to the atmosphere through fractures in the reservoir rock. Indeed, some potential sites for its sequestration have been deliberately made more gas-permeable by 'fracking' as a means of increasing the yield of petroleum-rich rock. Finally, a litre of injected gas can drive out pretty much the same volume of oil. So this approach to CCS may yield a greater potential for greenhouse warming than would the sequestered carbon dioxide itself.

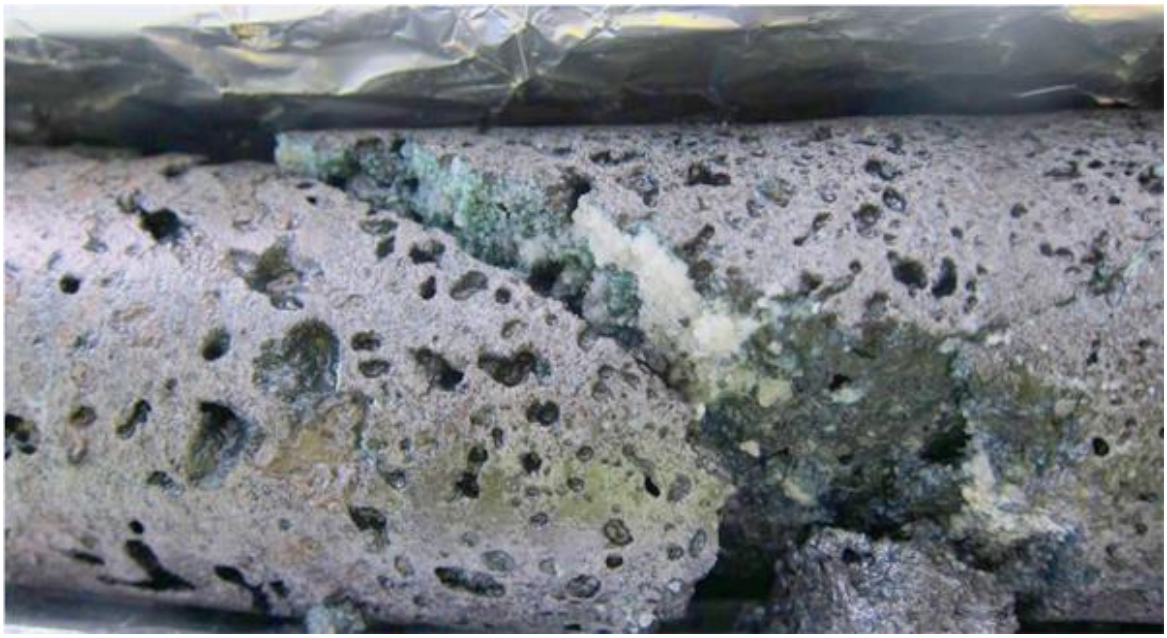


Image of calcite (white) and chlorite (cyan) formed in porous basalt due to CO_2-charged water-rock interaction at the CarbFix site in Iceland. (Credit: Sandra Ósk Snæbjörnsdóttir)

Another, less widely publicised approach is to geochemically bind CO_2 into solid carbonates, such as calcite ($CaCO_3$), dolomite ($CaMgCO_3$), or magnesite ($MgCO_3$). Once formed such crystalline solids are unlikely to break down to their component parts at the surface, under water or buried. One way of doing this is by the chemical weathering of rocks that contain calcium- and magnesium-rich minerals, such as feldspar ($CaAl_2Si_2O_8$), olivine ($[Fe,Mg]_2SiO_4$) and pyroxene ($[Fe,Mg]CaSi_2O_6$) . Mafic and ultramafic rocks, such as basalt and peridotite are commonly composed of such minerals. One approach involves pumping the gas into a Icelandic borehole that passes through basalt and letting natural reactions do the trick. They give off heat and proceed quickly, very like those involved in the setting of concrete. In two experimental field trials 95% of injected CO_2 was absorbed within 18 months. Believe it or not, ants can do the trick with crushed basalt and so too can plant roots. There have been recent experiments aimed at finding accelerants for such subsurface weathering (Wang, J. *et al*. 2024. CO_2 capture, geological storage, and mineralization using biobased biodegradable chelating agents and seawater. *Science Advances*, v. **10**, article eadq0515; DOI: 10.1126/sciadv.adq0515). In some respects the approach is akin to fracking. The aim is to connect isolated natural pores to allow fluids to permeate rock more easily, and to release metal ions to combine with injected CO_2.

Chelating agents are biomolecules that are able to dissolve metal ions; some are used to remove toxic metals, such as lead, mercury and cadmium, from the bodies of people suffering from their effects. Naturally occurring ones extract metal ions from minerals and rocks and are agents of chemical weathering; probably used by the aforesaid ants and root systems. Wang and colleagues, based at Tohoku University in Japan, chose a chelating agent GLDA (tetrasodium glutamate diacetate – $C_9H_9NNa_4O_8$) derived from plants, which is non-toxic, cheap and biodegradable. They injected CO_2 and seawater containing dissolved GDLA into basaltic rock samples. The GDLA increases the rock's porosity and permeability by breaking down its minerals so that Ca and Mg ions entered solution and were thereby able to combine with the gas to form carbonate minerals. Within five days porosity was increased by 16% and the rocks permeability increased by 26 times. Using electron

microscopy the authors were able to show fine particles of carbonate growing in the connected pores. In fact these carbonate aggregates become coated with silica released by the induced mineral-weathering reactions. Calculations based on the previously mentioned field experiment in Iceland suggest that up to 20 billion tonnes of CO_2 could be stored in 1.3 km^3 of basalt treated in this way: about 1/25000 of the active rift system in Iceland (3.3 x 10^4 km^2 covered by 1 km of basalt lava). In 2023 fossil fuel use emitted an estimated 36.6 bllion tons of CO_2 into the atmosphere.

So, why do such means of efficiently reducing the greenhouse effect not receive wide publicity by governments or the Intergovernmental Panel on Climate Change? Answers on a yellow PostIt™ please . . .

The prospect of climate chaos following major volcano eruptions

PUBLISHED ON *November 18, 2024*

It hardly needs saying that volcanoes present a major hazard to people living in close proximity. The inhabitants of the Roman cities of Herculaneum and Pompeii in the shadow of Vesuvius were snuffed out by an incandescent pyroclastic during the 79 CE eruption of the volcano. Since December 2023 long-lasting eruptions from the Sundhnúksgígar crater row on the Reykjanes Penisula of Iceland have driven the inhabitants of nearby Grindavík from their homes, but no injuries or fatalities have been reported. Far worse was the 1815 eruption of Tambora on Sumbawa, Indonesia, when at least 71,000 people perished. But that event had much wider consequences, which lasted into 1817 at least. As well as an ash cloud the huge plume from Tambora injected 28 million tons of sulfur dioxide into the stratosphere. In the form of sulfuric acid aerosols, this reflected so much solar energy back into space that the Northern Hemisphere cooled by 1° C, making 1816 ‘the year without a summer’. Crop failures in Europe and North America doubled grain prices, leading to widespread social unrest and economic depression. That year also saw unusual weather in India culminate in a cholera outbreak, which spread to unleash the 1817 global pandemic. Tambora is implicated in a global death toll in the tens of millions. Thanks to the record of sulfur in Greenland ice cores it has proved possible to link past volcanic action to historic famines and epidemics, such as the Plague of Justinian in 541 CE. If they emit large amounts of sulfur gases volcanic eruptions can result in sudden global climatic downturns.

The ash plume towering above Pinatubo volcano in the Philippines on 12 June 1991, which rose to 40 km (Credit: Karin Jackson U.S. Air Force)

With this in mind Markus Stoffel, Christophe Corona and Scott St. George of the University of Geneva, Switzerland, CNRS, Grenoble France and global insurance brokers WTW, London, respectively, have published a Comment in *Nature* warning of this kind of global hazard (Stoffel, M., Corona, C. & St. George, S. 2024. The next massive volcano eruption will cause climate chaos — we are unprepared. *Nature* v. **635**, p. 286-289; DOI: 10.1038/d41586-024-03680-z). The crux of their argument is that there has been nothing approaching the scale of Tambora for the last two centuries. The 1991 eruption of Pinatubo fed the stratosphere with just over a quarter of Tambora's complement of SO_2, and decreased global temperatures by around 0.6°C during 1991-2. Should one so-called Decade Volcanoes – those located in densely populated areas, such as Vesuvius – erupt within the next five years actuaries at Lloyd's of London estimate economic impacts of US$ 3 trillion

in the first year and US$1.5 trillion over the following years. But that is based on just the local risk of ash falls, lava and pyroclastic flows, mud slides and lateral collapse, not global climatic effects. So, a Tambora-sized or larger event is not countenanced by the world's most famous insurance underwriter: probably because its economic impact is incalculable. Yet the chances of such a repeat certainly are conceivable. A 60 ka record of sulfate in the Greenland ice cores allows the probability of eruptions on the scale of Tambora to be estimated. The data suggest that there is a one-in-six chance that one will occur somewhere during the 21st century, but not necessarily at a site judged by volcanologists to be precarious . Nobody expected the eruption from the Pacific Ocean floor of the Hunga Tonga-Hunga Ha'apai volcano on January 15, 2022: the largest in the last 30 years.

The authors insist that climate-changing eruptions now need to be viewed in the context of anthropogenic global warming. Superficially, it might seem that a few volcanic winters and years without a summer could be a welcome, albeit short-term, solution. However, Stoffel, Corona and St. George suggest that the interaction of a volcano-induced global cooling with climatic processes would probably be very complex. Global warming heats the lower atmosphere and cools the stratosphere. Such steady changes will affect the height to which explosive volcanic plumes may reach. Atmospheric circulation patterns are changing dramatically as the weather of 2024 seems to show. The same may be said for ocean currents that are changing as sea-surface temperatures increase. Superimposing volcano-induced cooling of the sea surface adds an element of chaos to what is already worrying. What if a volcanic winter coincided with an el Niño event? The Intergovernmental Panel on Climate Change that projects climate changes is 'flying blind' as regards volcanic cooling. Another issue is that our knowledge of the effects in 1815 of Tambora concerned a very different world from ours: a global population then that was eight times smaller than now; very different patterns of agriculture and habitation; a world with industrial production on a tiny proportion of the continental surface. Stoffel, Corona and St. George urge the IPCC to shed light on this major blind spot. Climate modellers need to explore the truly worst-case scenarios since a massive volcanic eruption is bound to happen one day. Unlike global warming from greenhouse-gas emission, there is absolutely nothing that can be done to avert another Tambora.

Human interventions in geological processes

PUBLISHED ON *August 29, 2025*

During the Industrial Revolution not only did the emission of greenhouse gases by burning fossil fuels start to increase exponentially, but so too did the movement of rock and sediment to get at those fuels and other commodities demanded by industrial capital. In the 21st century about 57 billion tons of geological materials are deliberately moved each year. Global population followed the same trend, resulting in increasing expansion of agriculture to produce food. Stripped of its natural cover on every continent soil began to erode at exponential rates too. The magnitude of human intervention in natural geological cycles has become stupendous, soil erosion now shifting on a global scale about 75 billion tons of sediment, more than three times the estimated natural rate of surface erosion. Industrial capital together with society as a whole also creates and dumps rapidly growing amounts of solid waste of non-geological provenance. The Geological Society of America's journal *Geology* recently published two research papers that document how capital is transforming the Earth.

Dust Bowl conditions on the Minnesota prairies during the 1930s.

One of the studies is based on sediment records in the catchment of a tributary of the upper Mississippi River. The area is surrounded by prairie given over mainly to wheat production since the mid 19th century. The deep soil of the once seemingly limitless grassland developed by the prairie ecosystem is ideal for cereal production. In the first third of the 20th century the area experienced a burst of erosion of the fertile soil that resulted from the replacement of the deep root systems of prairie grasses by shallow rooted wheat. The soil had formed from the glacial till deposited by the Laurentide ice sheet than blanketed North America as far south as New York and Chicago. Having moved debris across almost 2000 km of low ground, the till is dominated by clay- and silt-sized particles. Once exposed its sediments moved easily in the wind. Minnesota was badly affected by the 'Dust Bowl' conditions of the 1930s, to the extent that whole towns were buried by up to 4.5 metres of aeolian sediment. For the first time the magnitude of soil erosion compared with natural rates has been assessed precisely by dating layers of alluvium deposited in river terraces of one of the Mississippi's tributaries (Penprase, S.B. *et al*. 2025. Plow versus Ice Age: Erosion rate variability from glacial–interglacial climate change is an order of magnitude lower than agricultural erosion in the Upper Mississippi River Valley, USA. *Geology*, v. **53**, p. 535-539; DOI: 10.1130/G52585.1).

Shanti Penprase of the University of Minnesota and her colleagues were able to date the last time sediment layers at different depths in terraces were exposed to sunlight and cosmic rays, by analysing optically stimulated luminescence (OSL) and cosmogenic ^{10}Be content of quartz grains from the alluvium. The data span the period since the Last Glacial Maximum 20 thousand years ago during which the ecosystem evolved from bare tundra through re-vegetation to pre-settlement prairie. They show that post-glacial natural erosion had proceeded at around 0.05 mm yr^{-1} from a maximum of 0.07 when the Laurentide Ice Sheet was at its maximum extent. Other studies have revealed that after the area was largely given over to cereal production in the 19th century erosion rates leapt to as high as 3.5 mm yr^{-1} with a median rate of 0.6 mm yr^{-1}, 10 to 12 times that of post-glacial times. It was the plough and single-crop farming introduced by non-indigenous settlers that accelerated erosion. Surprisingly, advances in prairie agriculture since the Dust Bowl have not resulted in any decrease in soil erosion rates, although wind erosion is now insignificant. The US

Department of Agriculture considers the loss of one millimetre per year to be ‘tolerable’: 14 times higher than the highest natural rate in glacial times.

The other paper has a different focus: how human activities may form solid rock. The world over, a convenient means of disposing of unwanted material in coastal areas is simply to dump waste in the sea. That has been happening for centuries, but as for all other forms of anthropogenic waste disposal the volumes have increased at an exponential rate. The coast of County Durham in Britain began to experience marine waste disposal when deep mines were driven into Carboniferous Coal Measures hidden by the barren Permian strata that rest unconformably upon them. Many mines extended eastwards beneath the North Sea, so it was convenient to dump 1.5 million tons of waste rock annually at the seaside. The 1971 gangster film *Get Carter* starring Michael Caine includes a sequence showing ‘spoil’ pouring onto the beach below Blackhall colliery, burying the corpse of Carter’s rival. The nightmarish, 20 km stretch of grossly polluted beach between Sunderland and Hartlepool also provided a backdrop for *Alien 3*. Historically, tidal and wave action concentrated the low-density coal in the waste at the high-water mark, to create a free resource for locals in the form of ‘sea coal’ as portrayed in Tom Scott Robson’s 1966 documentary *Low Water*. Closure of the entire Duham coalfield in the 1980s and ‘90s halted this pollution and the coast is somewhat restored – at a coast of around £10 million.

‘Anthropoclastic’ conglomerate formed from iron-smelting slag dumped on the West Cumbrian coast. It incorporates artefacts as young as the 1980s, showing that it was lithified rapidly. Credit: Owen et al, Supplementary Figure 2

On the West Cumbrian coast of Britain another industry dumped millions of tons of waste into the sea. In the case it was semi-molten 'slag' from iron-smelting blast furnaces poured continuously for 130 years until steel-making ended in the 1980s. Coastal erosion has broken up and spread an estimated 27 million cubic metres of slag along a 2 km stretch of beach. Astonishingly this debris has turned into a stratum of anthropogenic conglomerate sufficiently well-bonded to resist storms (Owen, A., MacDonald, J.M. & Brown, D.J 2025. Evidence for a rapid anthropoclastic rock cycle. *Geology*, v. **53**, p. 581–586; DOI: 10.1130/G52895.1). The conglomerate is said by the authors to be a product of 'anthropoclastic' processes. Its cementation involves minerals such as goethite, calcite and brucite. Because the conglomerate contains car tyres, metal trouser zips, aluminium ring-pulls from beer cans and even coins lithification has been extremely rapid. One ring-pull has a design that was not used in cans until 1989, so lithification continued in the last 35 years.

Furnace slag 'floats' on top of smelted iron and incorporates quartz, clays and other mineral grains in iron ore into anhydrous calcium- and magnesium-rich aluminosilicates. This purification is achieved deliberately by including limestone as a fluxing agent in the furnace feed. The high temperature reactions are similar to those that produce aluminosilicates when cement is manufactured. Like them, slag breaks down in the presence of water to recrystallis in hydrated form to bond the conglomerate. This is much the same manner as concrete 'sets' over a few days and weeks to bind together aggregate. There is vastly more 'anthropoclastic' rock in concrete buildings and other modern infrastructure. Another example is tarmac that coats millions of kilometres of highway.

See also: Howell, E. 2025. Modern farming has carved away earth faster than during the ice age. *Science*, v. **388**

Ancient mining pollutants in river sediments reveal details of early British economic history

PUBLISHED ON *September 22, 2025*

People have been mining in Britain since Neolithic farmers opened the famous Grimes Graves in Norfolk – a large area dotted with over 400 pits up to to 13 metres deep. The target was a layer of high quality black flint in a Cretaceous limestone known as The Chalk. Later Bronze Age people in Wales and Cornwall drove mine shafts deeper underground to extract copper and tin ores to make the alloy bronze. The Iron Age added iron ore to the avid search for sources of metals. The production and even export of metals and ores eventually attracted the interest of Rome. Roman invasion in 43 CE during the reign of Claudius annexed most of England and Wales to create the Province of Britannia. This lasted until the complete withdrawal of Roman forces around 410 CE. Roman imperialism and civilisation depended partly on lead for plumbing and silver coinage to pay its legionaries. Consequently, an important aspect in Rome's four-century hegemony was mining, especially for lead ore, as far north as the North Pennines. This littered the surface in mining areas with toxic waste. Silver occurs in lead ore in varying proportions. In the Bronze Age early metallurgists extracted silver from smelted, liquid lead by a process known as cupellation. The molten Pb-Ag alloy is heated in air to a much higher temperature than its melting point, when lead reacts with oxygen to form a solid oxide (PbO) and silver remains molten.

Mine waste in the North Pennine orefield of England. Credit: North Pennines National Landscape

Until recently, historians believed that the fall of the Western Empire brought economic collapse to Britain. Yet archaeologists have revealed that what was originally called the "Dark Ages" (now Early Medieval Period) had a thriving culture among both the remaining Britons and Anglo Saxon immigrants. A means of tracking economic activity is to measure the amount of pollutants from mining waste at successive levels in the alluvium of rivers that flow through orefields. Among the best known in Britain is the North Pennine Orefield of North Yorkshire and County Durham through which substantial rivers flow eastwards, such as the River Ure that flows through the heavily mined valley of Wensleydale. A first attempt at such geochemical archaeology has been made by a British team led by Christopher Loveluck of Nottingham University (Loveluck, C.P. and 10 others 2025. Aldborough and the metals economy of northern England, c. AD 345–1700: a new post-Roman narrative. *Antiquity: FirstView*, online article; DOI: 10.15184/aqy.2025.10175). Aldborough in North Yorkshire – sited on the Romano-British town of *Isurium Brigantum* – lies in the Vale of York, a large alluvial plain. The River Ure has deposited sands, silts and muds in the area since the end of the last Ice Age, 11 thousand years ago.

Loveluck *et al.* extracted a 6 m core from the alluvium on the outskirts of Aldborough, using radiocarbon and optically-stimulated luminescence of quartz grains to calibrate depth to age in the sediments. The base of the core is Mesolithic in age (~6400 years ago) and extends upwards to modern times, apparently in an unbroken sequence. Samples were taken for geochemical analysis every 2 cm through the upper 1.12 m of the core, which spans the Roman occupation (43 to 410 CE), the early medieval (420 to 1066 CE), medieval (1066 to 1540 CE), post-medieval (1540 to 1750 CE) and modern times (1750 CE to present). Each sample was analysed for 56 elements using mass spectrometry; lead, silver, copper, zinc, iron and arsenic being the elements of most interest in this context. Other data gleaned from the sediment are those of pollen, useful in establishing climate

and ecological changes. Unfortunately, the metal data begin in 345 CE, three centuries after the Roman invasion, by which time occupation and acculturation were well established. The authors assume that Romans began the mining in the North Pennines. They say nothing about the pre-mining levels of pollution from the upstream orefield nor mining conducted by the Iron Age Brigantes. For this kind of survey, it is absolutely essential that a baseline is established for the pollution levels under purely natural conditions. The team could have analysed sediment from the Mesolithic when purely natural weathering, erosion and transport could safely be assumed, but they seem not to have done that.

The team has emphasised that their data suggest that mining for lead continued and even increased through the 'Dark Ages' rather than declining, in an economic 'slump' once the Romans left, as previous historians have suggested. Lead pollution continued at roughly the same levels as during the Roman occupation through the Early Medieval Period and then rose to up to three times higher after the late 14th century. The data for silver are different. The Ag data from Aldborough show a large 'spike' in 427 to 427 CE. Interestingly this is *after* the Roman withdrawal. Its level in alluvium then 'flatlines' at low abundances until the beginning of the 14th century when again there is a series of 'booms'. This seems to me to mark sudden spells of coining, after the Romans left perhaps first to ensure a money economy remained possible, and then as a means of funding wars with the French in the 14th century. The authors also found changing iron abundances, which roughly double from low Roman levels to an Early Medieval peak and then fall in the 11th century: a result perhaps of local iron smelting. The overall patterns for zinc and copper differ substantially from those of lead, as does that for arsenic which roughly follows the trend for iron. That might indicate that local iron production was based on pyrite (FeS_2) which can contain arsenic at moderate concentrations: pyrite is a common mineral in the ore bodies of the North Pennines' The paper by Loveluck *et al.* is worth reading as a first attempt to correlate stratigraphic geochemistry data with episodes in British and, indeed, wider European history. But I think it has several serious flaws, beyond the absence of any pre-Roman geochemical baseline, as noted above. No data are presented for barium (Ba) and fluorine (F) derived from the gangue minerals baryte ($BaSO_4$) and fluorite (CaF_2), which outweigh lead and zinc sulfides in North Pennine ore bodies, yet had no use value until the Industrial Revolution. They would have made up a substantial proportion of mine spoil heaps – useful ores would have been picked out before disposal of gangue – whose erosion, comminution and transport would make contributions to downstream deposition of alluvium consistent with the pace of mining. That is: Ba and F data would be far better guides to industrial activity. There is a further difficulty with such surveys in northern Britain. The whole of the upland areas were subjected to repeated glaciation, which would have gathered exposed ore and gangue and dumped it in till, especially in the numerous moraines exposed in valleys such as Wensleydale. Such sources may yield sediment in periods of naturally high erosion during floods. Finally, the movement of sediment downstream is obviously not immediate, especially when waste is disposed in large dumps near mines Therefore phases of active mining may not contribute increased toxic waste far downstream until decades or even centuries later. These factors could easily have been clarified by a baseline study from earlier archaeological periods when mining was unlikely, into which the Aldborough alluvium core penetrates