Geohazards (2020)

The dilemma of Rwanda's Lake Kivu (January 2020)

In 1986 the small, roughly circular Lake Nyos in the Cameroon highlands silently released a massive cloud of carbon dioxide. Being a dense gas it hugged the ground and flowed down valleys for up to 25 km. 1700 local people perished by suffocation, together with their livestock (See Geohazards 2000). Having a recent volcanic origin, the lake is fed by springs in its bed that contain dissolved CO_2 emitted from the residual magma chamber below. At 200 m deep the bottom water is sufficiently pressurised to retain the dissolved gas so that signs of the potential hazard remain hidden until such a limnic eruption occurs. Far larger, with a surface area of 2700 km^2, Lake Kivu bordered by Rwanda and The Democratic Republic of Congo, is even deeper (up to 470 m). It too lies within a volcanically active zone, in this case the western arm of the East African Rift System. Being one of the most nutrient-rich bodies of fresh water on Earth, its biological productivity is extremely high, so as well as bottom water enriched in dissolved CO_2 – a staggering 256 km^3 – methane (CH_4) is also present in very large amounts (~65 km^3). This comes partly from anaerobic decay of dead organisms and from microbial reduction of the magmatic CO_2 passing through its bottom sediments. Sulfate-reducing bacteria also generate toxic hydrogen sulfide (H_2S) in the anoxic bottom waters – Lake Nyos contains less dissolved salts and did not emit H_2S.

So Kivu presents a far greater hazard than the volcanic lakes of Cameroon and an emission of a dense gas mixture might fill the rift valley in the area to a depth of about a hundred metres. Being highly fertile the valley around the lake has a high population (2 to 3 million), so the death toll from a limnic eruption could be huge. A further hazard stems from tsunamis generated by such gas bursts. Once bubbles form at depth the bulk density of water drops, so large masses of water surge to the surface rather than the gas itself; a phenomenon known to happen in the periodic eruptions of Lake Nyos. What might trigger such an event in Lake Kivu? The East African Rift System is seismically active, but recent earthquakes did not result in limnic eruptions. Subaqueous volcanic eruption is the most likely to set one off. A surface lava flow from the nearby Mount Nyiragongo entered the lake at the town of Goma in 2002 but, fortunately, did not reach the threatening deeper part of Kivu. Sediment samples from the lake reveal periodic transport of land vegetation to its deeper parts, roughly every thousand years. The sediments with plant fossils also contain abundant remains of aquatic animals, suggesting both tsunamis accompanied by toxic emissions.

Mitigating the hazard of limnic eruptions at Lake Nyos was made possible in 2002 by linking its bottom waters to the surface by plastic piping. After initial pumping, the release of bubbles at shallower depths and the resulting fall in bulk water density set off something akin to a large soda siphon, slowly relieving the deeper layers of their load of dissolved CO_2. This resulted in 50 m high fountains of what was effectively soda 'pop'. In 2009 this was repeated on a far larger scale on Lake Kivu, the operation being paid for by separation and sale of methane. Yet even this attempt at mitigation has its risks: first of destabilising what may be a fragile equilibrium to trigger a limnic eruption; second by lifting nutrient-rich bottom water that would encourage algal blooms at the lake surface and potential deoxygenation. The current issue of the *Journal of African Earth Sciences* includes a detailed review of the issues surrounding such dual-purpose hazard mitigation (Hirslund, F. & Morkel, P. 2020. Managing the dangers in Lake Kivu – How and why. *Journal of African Earth*

Sciences, v. **161**, Article 103672; DOI: 10.1016/j.jafrearsci.2019.103672). By 2015 the Rwandan KivuWatt Methane Project had a capacity for 25 MW of electrical power generation.

KIVUWATT's methane extraction rig on Lake Kivu. (Credit: Contour Global)

Running at full capacity, degassing the depths of Lake Kivu would provide the economic benefit of low-cost electricity for Rwanda and the DRC, at a maximum generating capacity of 300 mW using the most efficient power plant, as well as removing the risk of a catastrophic gas release. Yet the release of CO_2 from the lake and from methane burning would increase atmospheric greenhouse warming significantly, albeit less than if the methane was simply released, for CH_4 has 25 times the potential for trapping outgoing heat. Hence the dilemma. Either way, there remains the risk of turning Kivu's surface water into an anoxic algal 'broth' with devastating effects on its fishery potential. Burial of the dead phytoplankton, however, might generate more methane by bacterial decay; a possible source of renewable biofuel that 'recycles' the atmospheric CO_2 consumed by algal photosynthesis. The geohazards, according to Hirslund and Morkel, are really the ultimate driver for development of Lake Kivu's fossil fuel potential, now that they are better understood as a real and present danger to millions of people. The authors calculate that a catastrophic gas release may be on the cards in the late 21st century. Yet there are other resource issues bound up with the health of the lake's surface waters. Preserving the layered structure of the lake water to some extent is also important. Until the rates of natural infiltration of volcanic CO_2 and biogenic production of methane are known, a minimum rate of gas extraction to make the lake safe is impossible to calculate. Perhaps matching those rates with gas removal should govern future operation. The total methane content of Lake Kivu is just 1.5 times the annual production from the UK sector of the North Sea. It is sufficient for power generation at 300

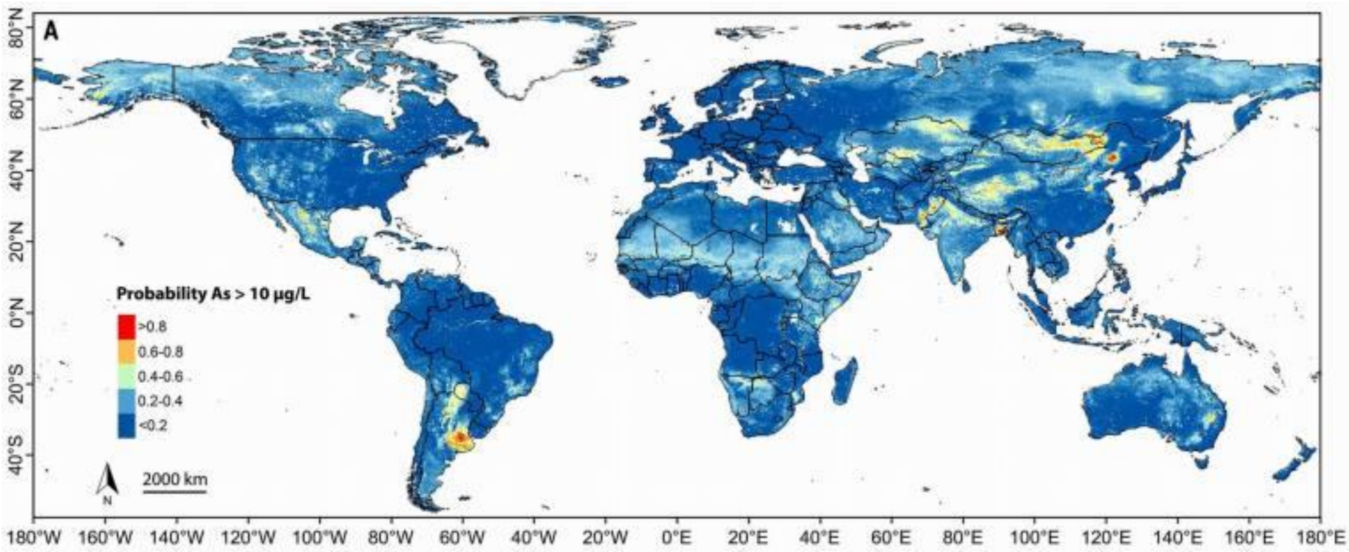
MW, at most, for 50 years, which would roughly double Rwanda's current installed generation capacity – mainly from hydropower. Although Kivu is shared equally between Rwanda and the DRC even half of the short term power potential would be a significant benefit to Rwanda's ~11 million people, though considerably less to the ~81 million living in the DRC; if access was equitable.

Arsenic hazard on a global scale (May 2020)

I have been following the harrowing story of how arsenic gets into domestic water supplies for 20 years (see: Earth-logs *Geohazards* for 2002; 2003; 2004; 2005; 2006; 2008; 2009; 2011; 2013; 2017). In my opinion, it is the greatest natural hazard in terms of the numbers at risk of poisoning. In 2006 I wrote about the emergence in Bangladesh of arsenic poisoning on a huge scale during the mid 1990s for a now defunct Open University distance learning course (*S250 Science in Context*). If people depend for drinking water on groundwater from tube wells driven into alluvium they would not know of the risk, unless the water is rigorously analysed for levels of As greater than 10 micrograms per litre ($\mu g\ l^{-1}$), the WHO recommended maximum. The sad fact is that the affected population were advised to switch from surface water supplies, which carry a high risk of biological infection, to well water. That is because during downward percolation from the surface oxidation destroys bacteria and viruses as well as parasites. Opportunities provided by a massive UN-funded drilling programme and local well digging made the choice seemingly obvious. Most people came to prefer well water as gastro-intestinal infections and child mortality fell rapidly.

Arsenic adds no taste, which is why it was once the 'poison of choice'. How it gets into groundwater is difficult to judge, unless wells are downflow of areas riddled with metal mines. Years of research uncovered an unsuspected mechanism. The most common colorant of mineral grains, and thus sedimentary rocks, is brownish iron hydroxide (goethite), and that is able to adsorb a range of dissolved elements, including arsenic. One would think, therefore, that groundwater should be made safe by such a natural 'filtering' process: indeed goethite can be used in decontamination. The problem is that iron hydroxide, which contains Fe-3, is only stable in water with a high capacity for oxidation. Under reducing conditions it breaks down to soluble Fe-2 and water, thereby releasing to solution any other element that it has adsorbed. In alluvium, beds containing organic matter are prone to this 'reductive dissolution' of goethite. If weathering upstream has released even seemingly insignificant amounts of arsenic during the build up of alluvium, there is a potential life-threatening problem as arsenic builds up in the goethite coating of sedimentary grains to become 'locked in', with the potential to be released in high concentrations if subsurface chemical conditions change. The colour of the alluvial sediments penetrated by wells is a clue. If they are reddish brown, groundwater is safe, if they are greyish and goethite-free then, 'beware'. But it is rare to examine 'cuttings' from a drill site aimed at groundwater, unlike those aimed at ores or oil

Since the tragedy of Bangladesh, which resulted after 5 years or so in obvious signs of arsenicosis – dark wart-line keratoses on hands and feet or black blotches on facial and torso skin – several alluvial basins in large river systems have had their well water tested. But by no means all such basins have been screened in this way, and there are many less-obvious signs of arsenic poisoning. After long exposure to the lower range of dangerous arsenic levels a variety of cancers develop in known areas of arsenic risk. There are also high levels of endemic respiratory problems, cardiovascular disease, reduced intellectual development in children and even diabetes. Geochemical monitoring of all populated and farmed river systems is a huge task that is far beyond the resources of many countries through which they run. One approach to 'screening' for hazard or safety is to use geological, hydrological, soil, climate and topographic data. Those from known arsenic-prone basins and those where its levels are shown to be consistently below the 10 μg l^{-1} danger threshold help to develop a predictive model (Podgorski, J. & Berg, M. 2020. Global threat of arsenic in groundwater. *Science*, v. **368**, p. 845-850; DOI: 10.1126/science.aba1510).



Modelled global probability of arsenic concentration in groundwater exceeding 10 μg l-1. Click to display a larger map in a separate browser tab. (credit: Podgorski & Berg; Fig 2A, with enhanced colour)

Rather than trying to model the full range of arsenic concentrations, Joel Podgorski and Michael Berg of the Swiss Federal Institute of Aquatic Science and Technology focussed on assessing probabilities that arsenic in well water exceeds the WHO recommended maximum safe level of 10 μg l^{-1}. Their global map highlights areas of concern for environmental health. Thankfully, huge (blue) areas are suggested to present low risk, the pale, yellow, orange and red patches signifying areas of increasing concern. No populated continent is hazard-free. What is very clear is that Asia presents the greatest worries. Most of the Asian 'hot zones' are spatially close to large mountain ranges and plateaus. In the case of the Indus and Ganges-Brahmaputra plains the sources for excessive arsenic in groundwater implicated by previous geochemical investigations lie in the Himalaya. The factor common to all major hot spots seems to be rapid transport of huge amounts of sediment released by weathering from areas of high topographic relief, rather than local large-scale mining operations. There are hazardous areas related to historic and active mining, such as the Andes of Bolivia, Peru and Chile and the western USA, but they are tiny by comparison with the dominance of natural arsenic mobilisation.

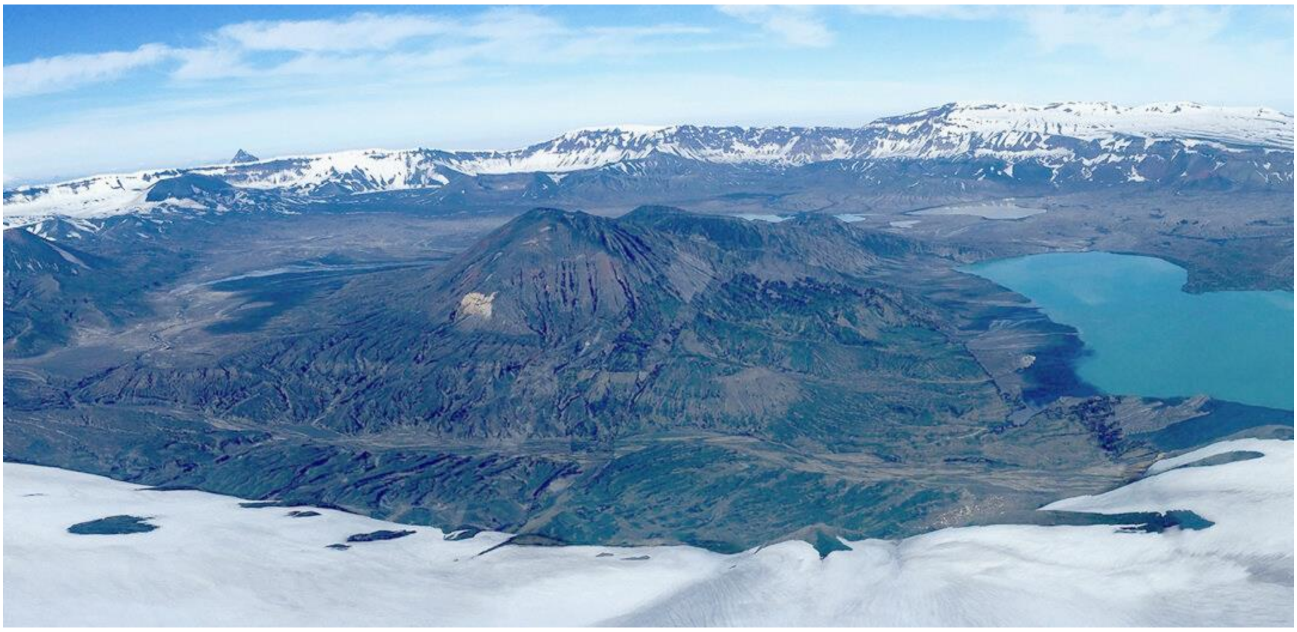
Despite the WHO recommended maximum of 10 μg l^{-1} of arsenic, many countries base their policy on levels that are five times higher, largely because of the difficulty of analysing for the lower concentration without expensive analytical facilities. Field analyses are often done using simple semi-quantitative tests based on paper impregnated with reagents that show a colour range for different concentrations, which are unreliable for those lower than 100 μg l^{-1}. Thankfully, despite the many risky areas, most of them have population densities less than 1 per km^2.

If you are interested in the geological details of the arsenic problems of Bangladesh, the course text that I produced for the Open University (Drury, S. 2006. *Water and well-being: arsenic in Bangladesh*. The Open University: Milton Keynes, UK. ISBN 0-7492-1435-X), the course itself (S250 Science in Context) was withdrawn some years ago. It may be possible to arrange a PDF through me for private use.

See also: Zheng, Y. 2020. Global solutions to a silent poison. *Science*, v. **368**, p. 818-819; DOI: 10.1126/science.abb9746

Turmoil in Roman Republic followed Alaskan volcanic eruption (July 2020)

That activities in the global political-economic system are now dramatically forcing change in natural systems is clear to all but the most obdurate. In turn, those changes increase the likelihood of a negative rebound on humanity from the natural world. In the first case, data from ice cores suggests that an anthropogenic influence on climate may have started with the spread of farming in Neolithic times. Metal pollution of soils had an even earlier start, first locally in Neanderthal hearths whose remains meet the present-day standards for contaminated soil, and more extensively once Bronze Age smelting of copper began. Global spread of anomalously high metal concentrations in atmospheric dusts shows up as 'spikes' in lead within Greenland ice cores during the period from 1100 BCE to 800 CE. This would have resulted mainly from 'booms and busts' in silver extraction from lead ores and the smelting of lead itself. In turn, that may reflect vagaries in the world economy of those times



The Okmok caldera on the Aleutian island of Umnak (Credit: Desert Research Institute, Reno, Nevada USA)

Precise dating by counting annual ice layers reveals connections of Pb peaks and troughs with major historic events, beginning with the spread of Phoenician mining and then by

Carthaginians and Romans, especially in the Iberian Peninsula. Lead reaches a sustained peak during the acme of the Roman Republic from 400 to 125 BC to collapse during widespread internal conflict during the Crisis of the Republic. That was resolved by the accession of Octavian/Augustus as Emperor in 31 BCE and his establishment of Pax Romana across an expanded empire. Lead levels rose to the highest of Classical Antiquity during the 1st and early 2nd centuries CE. Collapse following the devastating Antonine smallpox pandemic (165 to 193 CE) saw the ice-core records' reflecting stagnation of coinage activity at low levels for some 400 years, during which the Empire contracted and changed focus from Rome to Constantinople. Only during the Early Medieval period did levels rise slowly to the previous peak.

Earth-logs has previously summarised how natural events, mainly volcanic eruptions, had a profound influence in prehistory. The gigantic eruption of Toba in Sumatra (~73 ka ago) may have had a major influence on modern-humans migrating from Africa to Eurasia. The beginning of the end for Roman hegemony in the Eastern Mediterranean was the Plague of Justinian (541–549 CE), during which between 25 to 50 million people died of bubonic plague across the Eastern Empire. This dreadful event followed the onset of famine from Ireland to China, which was preceded by signs of climatic cooling from tree-ring records, and also with a peak of volcanogenic sulfate ions in the Greenland and Antarctic ice caps around 534 CE. Regional weakening of the populace by cold winters and food shortages, also preceded the Black Death of the mid-14th century. In the case of the Plague of Justinian, it seems massive volcanism resulted in global cooling over a protracted period, although the actual volcanoes have yet to be tracked down. Cooling marked the start of a century of further economic turmoil reflected by lead levels in ice cores (see above). Its historical context is the Early Medieval equivalent of world war between the Eastern Roman Empire, the Sassanid Empire of Persia and, eventually, the dramatic appearance on the scene of Islam and the Arabian, Syrian and Iraqi forces that it inspired (see: Holland, T. 2013. *In the Shadow of the Sword: The battle for Global Empire and the End of the Ancient World*. Abacus, London)

An equally instructive case of massive volcanism underlying social, political and economic turmoil has emerged from the geochemical records in five Greenlandic ice cores and one from the Siberian island of Severnaya Zemlya (McConnell, J.R. and 19 others 2020. Extreme climate after massive eruption of Alaska's Okmok volcano in 43 BCE and effects on the late Roman Republic and Ptolemaic Kingdom. *Proceedings of the National Academy of Sciences, recent article (*22 June 2020); *DOI:* 10.1073/pnas.2002722117). In this case the focus was on ice layers in all six cores that contain sulfate spikes and, more importantly, abundant volcanic dust, specifically shards of igneous glass. Using layer counting, all six show major volcanism in the years 45 to 43 BCE. The Ides (15th) of March 44 BCE famously marked the assassination of Julius Caesar, two years after the Roman Republic's Senate appointed him Dictator, following four years of civil war. This was in the later stages of the period of economic decline signified by the fall in ice-core levels of Pb (see above). The Roman commentator Servius reported "…after Caesar had been killed in the Senate on the day before, the sun's light failed from the sixth hour until nightfall." Other sources report similar daytime dimming, and unusually cold weather and famine in 43 and 42 BCE.

As well as pinning down the date and duration of the volcanic dust layers precisely (to the nearest month using laser scanning of the ice cores' opacity), Joseph McConnell and the team members from the US, UK, Switzerland, Germany and Denmark also chemically analysed the minute glass shards from one of the Greenlandic ice cores. This has enabled them to identify a single volcano from 6 possible candidates for the eruption responsible for the cold snap: Okmok, an active, 8 km wide caldera in the Aleutian Islands of Alaska. Previous data suggest that its last major eruption was 2050 years ago and blasted out between 10 to 100 km^3 of debris, including ash. Okmok is an appropriate candidate for a natural contributor to profound historic change in the Roman hegemony. The authors also use their ice-core data to model Okmok's potential for climate change: it had a global reach in terms of temperature and precipitation anomalies. Historians may yet find further correlations of Okmok with events in other polities that kept annual records, such as China.

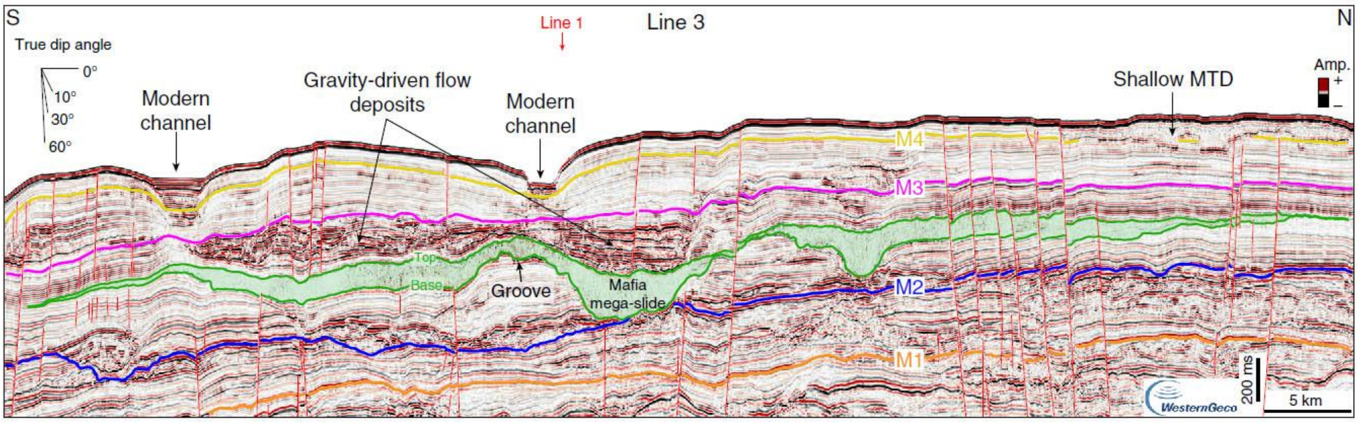
See also: Eruption of Alaska's Okmok volcano linked to period of extreme cold in ancient Rome (*Science Daily*, 22 June 2020); Kornei, K. 2020. Ancient Rome was teetering. Then a volcano erupted 6,000 miles away. (*New York Times*, 22 June 2020)

Submarine landslides and formation of the East African Rift System (July 2020)

East Africa is traversed from the Afar Depression in the north to Malawi in southern Africa by several great depressions bounded by active normal fault systems: grabens in the old terminology. They are regions of active crustal extension and thinning decorated by chains of active volcanoes. The last 50 years has witnessed more than 3400 major earthquakes (magnitude 4 to 7); unsurprising for the Earth's largest active continental rift system. In Afar, the East African Rift system links to two others that have extended sufficiently to create oceanic crust: the Red Sea and the Gulf of Aden rifts. Afar is the site of the best documented tectonic triple junction. In Ethiopia, the rifting began after the whole of the Horn of Africa and Yemen had been smothered by continental flood basalts 30 Ma ago, during the Oligocene Epoch. The East African rifts are repositories for younger sediments that contain a continuous record of hominid evolution from about 5 Ma ago. This is no coincidence, for adjacent bulging of the continental crust resulted both from its unloading by thinning along the rifts and the buoyancy conferred by high heat flow in the mantle beneath. The uplifted areas have risen as high as 4 kilometres elevation (in Ethiopia), and present some of the world's most spectacular land forms. This N-S barrier disrupted earlier climatic patterns that had much of tropical Africa blanketed by dense woodland and resulted in a strongly seasonal climate during the last few million years and the development of open savannah land. Put simply, open grassland with widely spaced trees was no place for diminutive forest apes to scamper on all-fours. Being able to leg-it nimbly on two gave the apes that developed such a gait a decisive evolutionary advantage: the rest, as they say, is human evolutionary history.

The East African Rift System (Credit: P.C. Neupane, M.Sc thesis 2011; Fig. 1)

The extension and rapid uplift along the rift flanks to this day pose severe risk of landslides. Indeed, some are so large as to resemble fault blocks in their own right. Vast amounts of the upper crust have been stripped off by rapid erosion driven by the uplift. The debris has not only ended-up on the rift floors as sedimentary fill but far more has made its way eastward to be deposited on the Indian Ocean continental shelf. Until recently, piecing together the history of rifting and uplift has been restricted to the rifts themselves and their adjacent flanks. Such terrains have extremely complex and usually discontinuous geological sequences, so signs of the onset of extensional tectonics and uplift may differ from region to region. Agreement is limited to some time between 25 and 17 Ma. The whole tectonic process may, in fact, have begun at different times along the length of the rift. A clearer picture should emerge from studies of the post-30 Ma sedimentary pile along the Indian Ocean continent shelf. A sure-fire way of getting the needed data is from offshore areas that are prospective for oil and natural gas. Such is the case off the Tanzanian coastline at the southern limit of the rift system.



Seismic reflection profile parallel to the Tanzanian coastline with the Mafia mega-slide highlighted in green (Credit: Maselli et al. 2020; Fig. 5) Click to view full resolution

The Tanzania Petroleum Development Corporation and Shell have conducted seismic reflection surveys and drilled some test wells to the SE of Zanzibar Island, an area of major deposition from the eastward flowing Ruaha–Rufiji and Rovuma Rivers. Vittorio Maselli of Dalhousie University in Halifax Nova Scotia and colleagues from the UK, Italy and the Netherlands analysed a wealth of data from these surveys, to discover one of the biggest landslides on Earth (Maselli, V. and 10 others 2020. Large-scale mass wasting in the western Indian Ocean constrains onset of East African rifting. *Nature Communications*, v. **11**, article 3456; DOI: 10.1038/s41467-020-17267-5). The Mafia mega-slide is represented in seismic profiles by a sedimentary unit, up to 300 m thick. It has a highly irregular base that cuts across strata in late-Oligocene to early-Miocene (25-23 Ma) sediments. It covers an area of more than 11,600 km^2 and has a volume of at least 2500 km^3. The unit's upper surface is also irregular, suggesting that the unit's thickness varies considerably. Younger sediments are draped across the irregular top of the slide body. In other, parallel sections the deposit is absent. Unlike the clearly bedded nature of sediments above and below it, the seismic response of the slide deposit is featureless, except for zones of chaotic stratification that reveal slump-folds. Nor is this the only sign of major submarine slides: there are others of lesser extent that predate the base of the Pliocene (5.3 Ma).

A mass movement of this magnitude would have generated a tsunami larger than that which possibly wiped out Mesolithic habitation on the east coast of Britain 8200 years ago due to the even larger Storegga Slide at the edge of the Norwegian continental shelf. The Mafia slide event would have flooded wide tracts of the East African coast. Its estimated age, between 22.9 to 19.8 Ma, is roughly coeval with the initiation of volcanism in the Tanzanian segment of the East African Rift and the onset of rifting and uplift of its flanks. It was probably launched by a major earthquake (>7 on the Richter scale). Such is the pace of current deposition and the thickness of sedimentary build-up since the Pliocene, there is a danger of future slides, albeit of lesser magnitude: the system continues to be seismically active, with recently recorded quakes offshore of Tanzania.

'Mud, mud, glorious mud' (August 2020)

Earth is a water world, which is one reason why we are here. But when it comes to sedimentary rocks, mud is Number 1. Earth's oceans and seas hide vast amounts of mud that have accumulated on their floors since Pangaea began to split apart about 200 Ma ago during the Early Jurassic. Half the sedimentary record on the continents since 4 billion years ago is made of mudstones. They are the ultimate products of the weathering of crystalline igneous rocks, whose main minerals – feldspars, pyroxenes, amphiboles, olivines and micas, with the exception of quartz – are all prone to breakdown by the action of the weakly acidic properties of rainwater and the CO_2 dissolved in it. Aside from more resistant quartz grains, the main solid products of weathering are clay minerals (hydrated aluminosilicates) and iron oxides and hydroxides. Except for silicon, aluminium and ferric iron, most metals end up in solution and ultimately the oceans. As well as being a natural product of weathering, mud is today generated by several large industries, and humans have been dabbling in natural muds since the invention of pottery some 25 thousand years ago. On 21 August 2020 the journal *Science* devoted 18 pages to a Special Issue on mud, with seven reviews (Malakoff, D. 2020. Mud. *Science*, v. **369**, p. 894-895; DOI: 10.1126/science.369.6506.894).

Mud carnival in Brazil (Credit: africanews.com)

The rate at which mud accumulates as sediment depends on the rate at which erosion takes place, as well as on weathering. Once arable farming had spread widely, deforestation and tilling the soil sparked an increase in soil erosion and therefore in the transportation and deposition of muddy sediment. The spurt becomes noticeable in the sedimentary record of river deltas, such as that of the Nile, about 5000 years ago. But human influences have also had negative effects, particularly through dams. Harnessing stream flow to power mills and forges generally required dams and leats. During medieval times water power exploded in Europe and has since spread exponentially through every continent except Antarctica, with a similar growth in the capacity of reservoirs. As well as damming drainage these efforts also capture mud and other sediments. A study of drainage basins in north-east USA, along which mill dams quickly spread following European colonisation in the 17th century, revealed their major effects on valley geomorphology and hydrology (see: Watermills and meanders; March 2008). Up to 5 metres of sediment build-up changed stream flow to an extent that this now almost vanished industry has stoked-up the chances of major flooding downstream and a host of other environmental changes. The authors of the study are acknowledged in one Mud article (Voosen, P. 2020. A muddy legacy. *Science*, v. **369**, p. 898-901; DOI: 10.1126/science.369.6506.898) because they have since demonstrated that the effects in Pennsylania are reversible if the 'legacy' sediment is removed. The same cannot be expected for truly vast reservoirs once they eventually fill with muds to become useless. While big dams continue to function, alluvium downstream is being starved of fresh mud that over millennia made it highly and continuously productive for arable farming, as in the case of Egypt, the lower Colorado River delta and the lower Yangtze flood plain below China's Three Gorges Dam.

Mud poses extreme risk when set in motion. Unlike sand, clay deposits saturated with water are thixotropic – when static they appear solid and stable but as soon as they begin to move *en masse* they behave as a viscous fluid. Once mudflows slow they solidify again, burying and trapping whatever and whomever they have carried off. This is a major threat from the storage of industrially created muds in tailings ponds, exemplified by a disaster at a Brazilian mine in 2019, first at the site itself and then as the mud entered a river system and eventually reached the sea. Warren Cornwall explains how these failures happen and may be prevented (Cornwall, W. 2020. A dam big problem. *Science*, v. **369**, p. 906-909; DOI: 10.1126/science.369.6506.906). Another article in the Mud special issue considers waste from aluminium plants (Service, R.F. 2020. Red alert. *Science*, v. **369**, p. 910-911; DOI: 10.1126/science.369.6506.910). The main ore for aluminium is bauxite, which is the product of extreme chemical weathering in the tropics. The metal is smelted from aluminium hydroxides formed when silica is leached out of clay minerals, but this has to be separated from clay minerals and iron oxides that form a high proportion of commercial bauxites, and which are disposed of in tailings dams. The retaining dam of such a waste pond in Hungary gave way in 2010, the thixotropic red clay burying a town downstream to kill 10 people. This mud was highly alkaline and inflicted severe burns on 150 survivors. Service also points out a more positive aspect of clay-rich mud: it can absorb CO_2 bubbled through it to form various, non-toxic carbonates and help draw down the greenhouse gas.

Muddy sediments are chemically complex, partly because their very low permeability hinders oxygenated water from entering them: they maintain highly reducing conditions. Because of this, oxidising bacteria are excluded, so that much of the organic matter deposited in the muds remains as carbonaceous particles. They store carbon extracted from the atmosphere by surface plankton whose remains sink to the ocean floor. Consequently, many mudrocks are potential source rocks for petroleum. Although they do not support oxygen-demanding animals, they are colonised by bacteria of many different kinds. Some – methanogens – break down organic molecules to produce methane. The metabolism of others depends on sulfate ions in the trapped water, which they reduce to sulfide ions and thus hydrogen sulfide gas: most muds stink. Some of the H_2S reacts with metal ions, to precipitate sulfide minerals, the most common being pyrite (FeS_2). In fact a significant proportion of the world's copper, zinc and lead resources reside in sulfide-rich mudstones:

essential to the economies of Zambia and the Democratic Republic of Congo. But there are some strange features of mud-loving bacteria that are only just emerging. The latest is the discovery of bacteria that build chains up to 5 cm long that conduct electricity (Pennisi, E. 2020. The mud is electric. *Science*, v. **369**, p. 902-905; DOI: 10.1126/science.369.6506.902). The bacterial ‘nanowires’ sprout from minute pyrite grains, and transfer electrons released by oxidation of organic compounds, effectively to catalyse sulfide-producing reduction reactions. **NB** Oxygen is not necessary for oxidation as its chemistry involves the loss of electrons, while reduction involves a gain of electrons, expressed by the acronym OILRIG (**o**xidation **i**s **l**oss, **r**eduction **i**s **g**ain). It seems such electrical bacteria are part of a hitherto unsuspected chemical ecosystem that helps hold the mud together as well as participating in a host of geochemical cycles. They may spur an entirely new field of nano-technology, extending, bizarrely, to an ability to generate electricity from moisture in the air.

Anthropocene more an Event than an Epoch (September 2020)

The Vattenfall lignite mine in Germany; the Anthropocene personified

The issue of whether or not to assign the time span during which human activities have been significantly affecting the planet and its interwoven Earth Systems has been dragging on since the term ‘Anthropocene’ was first proposed more than two decades ago. A suggestion that may resolve matters, both amicably and with a degree of scientific sense, has emerged in a short letter to the major scientific journal *Nature*, written by six eminent scientists (Bauer, A.M. *et al*. 2021. Anthropocene: event or epoch? *Nature*, v. **597**, p. 332; DOI: 10.1038/d41586-021-02448-z). The full text is below

> “*The concept of the Anthropocene has inspired more than two decades of constructive scholarship and public discussion. Yet much of this work seems to us incompatible with the proposal to define the Anthropocene as an epoch or series in the geological timescale, with a precise start date and stratigraphic boundary*

in the mid-twentieth century. As geologists, archaeologists, environmental scientists and geographers, we have another approach to suggest: recognize the Anthropocene as an ongoing geological event.

The problems with demarcating the Anthropocene as a globally synchronous change in human–environment relations, occurring in 1950 or otherwise, have long been evident (P. J. Crutzen and E. F. Stoermer IGBP Newsletter 41, 17–18; 2000). As an ongoing geological event, it would be analogous to other major transformative events, such as the Great Oxidation Event (starting around 2.4 billion years ago) or the Great Ordovician Biodiversification Event (around 500 million years ago).

Unlike formally defined epochs or series, geological events can encompass spatial and temporal heterogeneity and the diverse processes — environmental and now social — that interact to produce global environmental changes. Defining the Anthropocene in this way would, in our view, better engage with how the term has been used and criticized across the scholarly world."

AUTHORS: ***Andrew M. Bauer****, Stanford University, Stanford, California, USA;* ***Matthew Edgeworth****, University of Leicester, Leicester, UK;* ***Lucy E. Edwards****, Florence Bascom Geoscience Center, Reston, Virginia, USA;* ***Erle C. Ellis****, University of Maryland, Baltimore County, Maryland, USA ;* ***Philip Gibbard****, Scott Polar Research Institute, University of Cambridge, Cambridge, UK;* ***Dorothy J. Merritts****, Franklin and Marshall College, Lancaster, Pennsylvania, USA*.

I have been grousing about the attempt to assign Epoch/Series status to the Anthropocene for quite a while (you can follow the development of my personal opinions by entering 'Anthropocene' in the **Search Earth-logs** box). In general I believe that the proposal being debated is scientifically absurd, and a mere justification for getting a political banner to wave. What the six authors of this letter propose seems eminently sensible. I hope it is accepted by International Commission on Stratigraphy as a solution to the increasingly sterile discussions that continue to wash to and fro in our community. Then perhaps the focus can be on action rather than propaganda.

As things have stood since 21 May 2019, a proposal to accept the Anthropocene as a formal chrono-stratigraphic unit defined by a GSSP at its base around the middle of the 20th century is before the ICS and the International Union of Geological Sciences (IUGS) for ratification. It was accepted by 88% of the 34-strong Anthropocene Working Group of the ICS Subcommission on Quaternary Stratigraphy. But that proposal has yet to be ratified by either the ICS or IUGS. Interestingly, one of the main Anthropocene proponents was recently replaced as chair of the Working Group.

A Bronze Age catastrophe: the destruction of Sodom and Gomorrah? (October 2020)

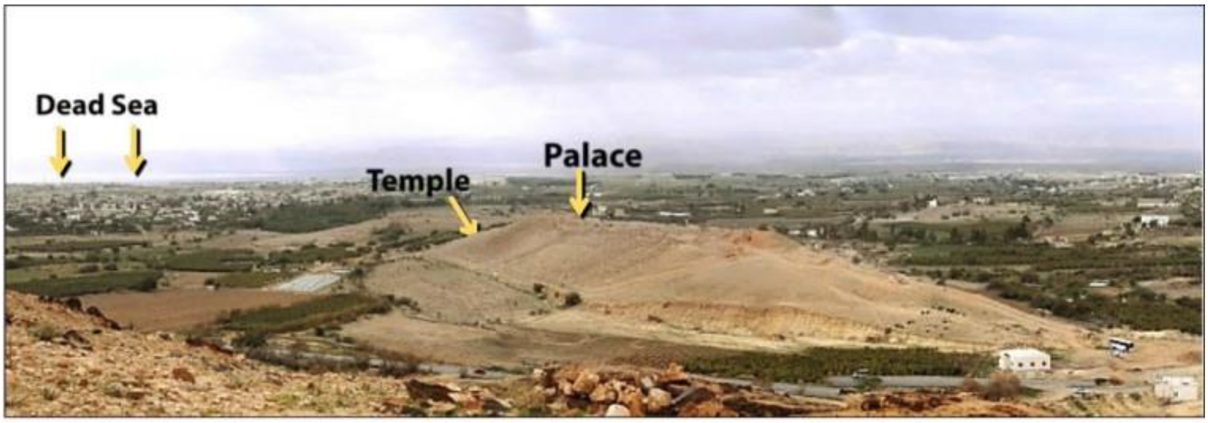
> "…*The sun was risen upon the earth when Lot entered into Zoar. Then the Lord rained upon Sodom and Gomorrah brimstone and fire from the Lord out of heaven. And overthrew those cities, and all the plain, and all the inhabitants of the cities, and that which grew upon the ground. But his wife looked back from behind him, and she became a pillar of salt* …"

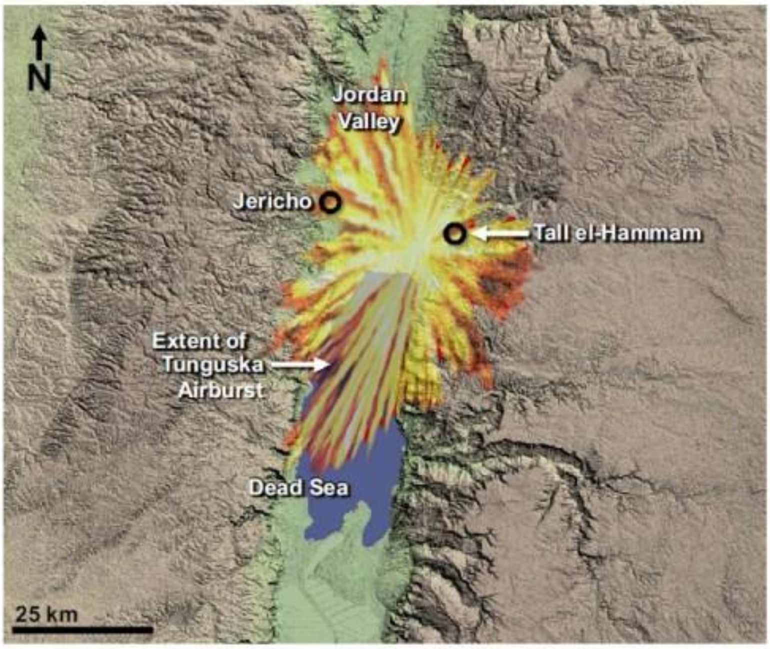
This is the second catastrophe recorded in the Old Testament of the King James Bible (Genesis 19:23-26), after the Noachian Flood (Genesis 7 and 8). The Flood is now regarded by many geoscientists to be a passed-down and mythologised account of the rapid filling of the Black Sea when the Bosporus was breached around 7600 years ago, as global see level rose in the early Neolithic. Eleven Chapters and a great many begotten people later comes the dramatic punishment of the 'sinners' of Sodom and Gomorrah. The two legendary settlements are now considered to have been in the Lower Jordan Valley near the Dead Sea. Being on the major strike-slip fault that defines the Jordan Rift, related to the long-active spreading of the Red Sea, the most obvious rationalisation of the myth is a major earthquake. The sedimentary sequence contains sulfide-rich clays and silts, as well as thick salt beds. Major seismicity would have liquidised saturated sediments full of supersaturated salt water and the release of large volumes of hydrogen sulfide gas. There are also remains of early settlements in the form of large mounds known locally as 'talls'. The largest and archaeologically most productive of these is Tall el Hammam in Jordan, whose excavation has proceeded since 2005. It lies just to the north of the Dead Sea on the eastern flank of the Jordan valley, 15 km from Jericho on the occupied West Bank.

The Tall el Hammam mound is formed from layers of debris, mainly of mud bricks, dwellings being built again and again on the remains of earlier ones. It seems to have been continuously occupied for three millennia after 6650 ka ago (4700 BCE) at the core of a presumably grain-based city state with upwards of 10 thousand inhabitants. The site was destroyed around 3600 Ka (1650 BCE). The catastrophic earthquake hypothesis can be neither confirmed nor refuted, but the destruction toppled structures with walls up to 4 m thick.. Whatever the event, 15 years of excavation have revealed that it was one of extremely high energy. There is evidence for pulverisation of mud bricks and at some dwellings they were apparently blown off-site: a possibility in a large magnitude earthquake. Unusually, however, mud bricks and clay used in pottery and roofing had been partially melted during the final destruction. Various analyses suggest temperatures were as high as 2000 °C.

A detailed summary of results from the Tall el Hammam site has just appeared (Bunch T.E., and 20 others 2021. A Tunguska sized airburst destroyed Tall el-Hammam a Middle Bronze Age city in the Jordan Valley near the Dead Sea. *Nature Scientific Reports*, v. **11**, article 18632; DOI: 10.1038/s41598-021-97778-3). As the title indicates, it comes to an astonishing conclusion, which rests on a large range of archaeological and geochemical data that go well beyond the earlier discovery of the tall's destruction at very high temperatures. Radiocarbon dates of 26 samples from the destruction layer reveal that it happened in 1661±21 BCE – the mid- to late Bronze Age, as also suggested by the styles of a variety of artefacts. The most revealing data have emerged from the debris that caps the archaeological section, particularly fine-grained materials in it. There are mineral grains indicating that sand-sized grains were melted, some to form spherules or droplets of glass.

Even highly refractory minerals such as zircon and chromite were melted. Mixed in with the resulting glasses are tiny nuggets of metals, including platinum-group metals.





Top – oblique aerial view of the mound at Tal el Hammam looking to the south-west; Bottom – the Lower Jordan Valley and Bronze age talls superimposed by the extent of the area devastated by the 1908 Tunguska air-burst. (credit: Bunch et al. 2021, Figs 1b and 52)

As well as high temperatures the event involved intense mechanical shock that produced tell-tale lamellae in quartz grains, familiar from sites of known extraterrestrial impacts. One specimen shows a micro-crater produced by a grain of carbonaceous material, which is now made up of ~ 1 μm diamond-like carbon (diamondoids) crystals. There is abundant evidence of directionality in the form of linear distributions of ceramic shards and carbonised cereal grains that seem to have been consistently transported in a SW to NE direction: a kind of high-speed 'blow-over'. In the debris are also fragments of pulverised bone, most too small to assign to species. But among them are two highly damaged human skulls and isolated and charred human limb- and pelvic bones. Forensic analysis suggests at least two individuals were decapitated, dismembered and incinerated during the catastrophe. Isolated scatters of recognisable human bones indicate at least 10 people who suffered a similar death. Finally the destruction layer is marked by an unusually high concentration of salt, some of which has been melted.

Such a range of evidence is difficult to reconcile by hypotheses citing warfare, accidental burning, tornadoes or earthquakes. However, the diversity of phenomena associated with the destruction of Tall el Hammam has been compared with data from nuclear explosion sites, suggesting the huge power of the event. The authors turned to evidence linked to the air-burst detonation of a cosmic body over Tunguska, Siberia in 1908 which had a power estimated at between 12- to 23 megatonnes of TNT equivalent. Such an event seems to fit the fate of Tall el Hammam. The Tunguska event devastated an area of 2200 km^2. The tall and another at Jericho lies within such an area. Perhaps not coincidentally, the destruction of Jericho was also in the mid- to late Bronze Age sometime between 1686 and 1626 BCE: i.e. statistically coeval with that of Tall el Hammam.

Archaeologists working in the Lower Jordan Valley have examined 15 other talls and more than a hundred lesser inhabited sites and have concluded that all of them were abandoned at the end of the Middle Bronze Age. The whole area is devoid of evidence for agricultural settlements for the following three to six centuries, although there are traces of pastoralist activity. The high amount of salt in the Tall el Hammam debris, if spread over the whole area would have rendered its soils infertile until it was eventually flushed out by rainfall and runoff. If, indeed, the event matches the biblical account of Sodom and Gomorrah, then Lot and his remaining companions would have found it difficult to survive without invading the lands of other people who had escaped, much as recorded later in Genesis. Of more concern is what will become of Ted Bunch and his 20 US colleagues? Will they be charged with blasphemy?

See also: Tunguska-Sized Impact Destroyed Jordan Valley City 3,670 Years Ago, *SciNews,* 29 September 2021; Did an impact affect hunter gatherers at the start of the Younger Dryas? *Earth-logs*, 3 July 2020*.*

Wide criticism of Sodom airburst hypothesis emerges (October 2020)

A follower of Earth-logs has brought to my attention a wide range of concerns regarding the veracity of the paper by Bunch *et al* in *Nature Scientific Reports*, which Earth-logs covered on 8 October 2021. The reactions are summarised by the Retraction Watch website (Criticism engulfs paper claiming an asteroid destroyed Biblical Sodom and Gomorrah *Retraction Watch* 1 October 2021). It seems that the Chief Editor of *Scientific Reports* is considering the issues that have been raised. Anyone who has downloaded and read the paper by Bunch *et al* will have noted the very large amount of data that it cites. It is alleged that there are flaws in the evidence, and that some of the figures may have been falsified. Some of the authors also contributed to the 'airburst' hypothesis for onset of the Younger Dryas, covered in Earth-pages several times, which uses similar data. The same group has also suggested an impact cause of the destruction around 12 ka ago of a Mesolithic tell at Abu Hureyra in Syria, again based on similar data.

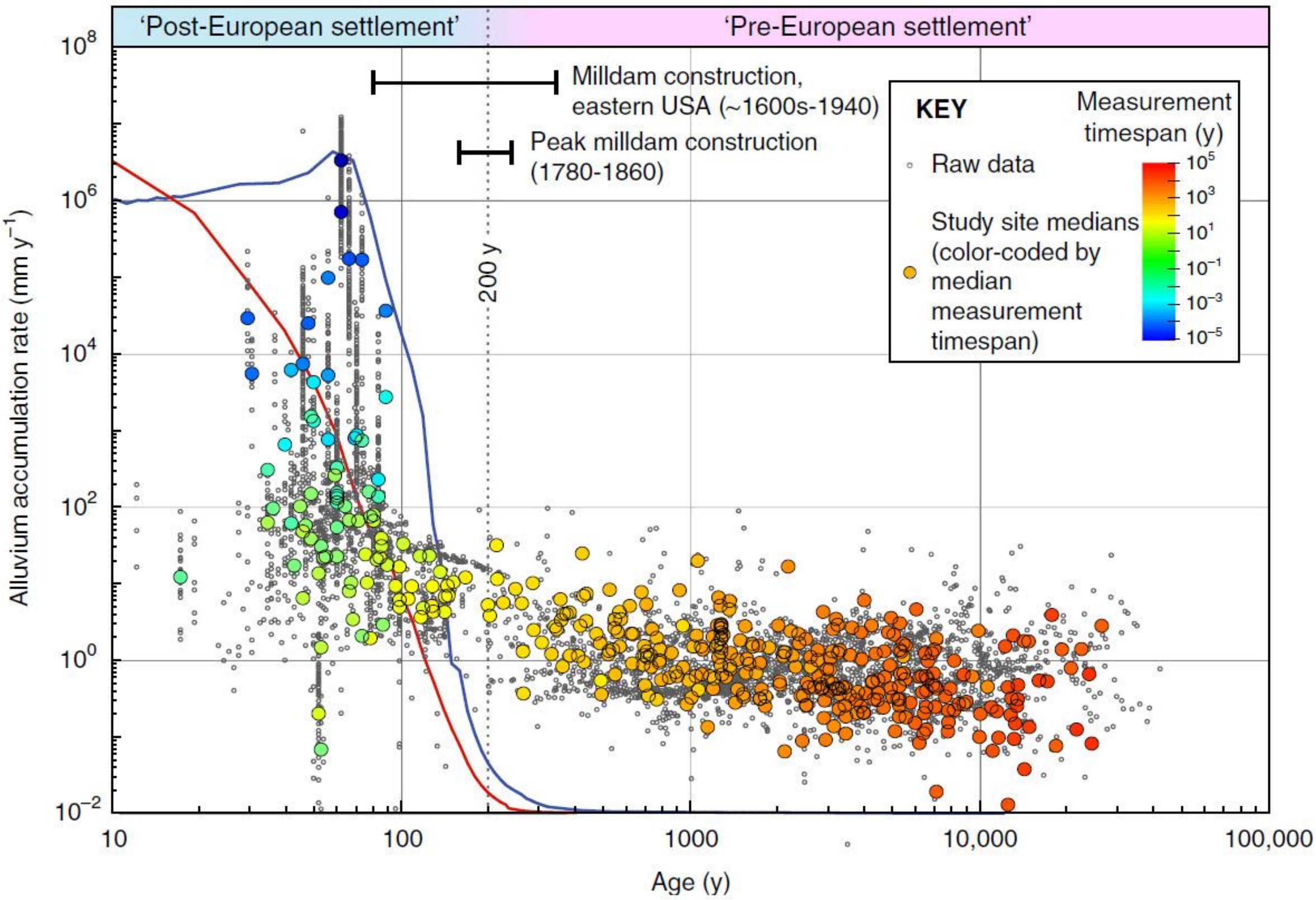
See also: Tall el-Hammam: an airburst of gullibility

Human impact on surface geological processes (November 2020)

I last wrote about sedimentation during the 'Anthropocene' a year ago (See: Sedimentary deposits of the 'Anthropocene', November 2019). Human impact in that context is staggeringly huge: annually we shift 57 billion tonnes of rock and soil, equivalent to six times the mass of the UKs largest mountain, Ben Nevis. All the world's rivers combined move about 35 billion tonnes less. I don't particularly care for erecting a new Epoch in the Stratigraphic Column, and even less about when the 'Anthropocene' is supposed to have started. The proposal continues to be debated 12 years after it was first suggested to the IUGS International Commission on Stratigraphy. I suppose I am a bit 'old fashioned', but the proposals is for a stratigraphic entity that is vastly shorter than the smallest globally significant subdivision of geological time (an Age) and the duration of most of the recorded mass extinctions, which are signified by horizontal lines in the Column. By way of illustration, the thick, extensive bed of Carboniferous sandstone on which I live is one of many deposited in the early part of the Namurian Age (between 328 and 318 Ma). Nonetheless, anthropogenic sediments of, say, the last 200 years are definitely substantial. A measure of just how substantial is provided by a paper published online this week (Kemp, S.B. *et al*. 2020. The human impact on North American erosion, sediment transfer, and storage in a geologic context. *Nature Communications*, v. **11**, article 6012; DOI: 10.1038/s41467-020-19744-3).

'Badlands' formed by accelerated soil erosion.

Anthropogenic erosion, sediment transfer and deposition in North America kicked off with its colonisation by European immigrants since the early 16th century. First Americans were hunter-gatherers and subsistence farmers and left virtually no traces in the landscape, other than their artefacts and, in the case of farmers, their dwellings. Kemp and colleagues have focussed on late-Pleistocene alluvial sediment, accumulation of which seems to have been pretty stable for 40 ka. Since colonisation began the rate has increased to, at present, ten times that previously stable rate, mainly during the last 200 years of accelerated spread of farmland. This is dominated by outcomes of two agricultural practices – ploughing and deforestation. Breaking of the complex and ancient prairie soils, formerly held together by deep, dense mats of grass root systems, made even flat surfaces highly prone to soil erosion, demonstrated by the 'dust bowl' conditions of the Great Depression during the 1930s. In more rugged relief, deforestation made slopes more likely to fail through landslides and other mass movements. Damming of streams and rivers for irrigation or, its opposite, to drain wetlands resulted in alterations to the channels themselves and their flow regimes. Consequently, older alluvium succumbed to bank erosion. Increased deposition behind an explosion of mill dams and changed flow regimes in the reaches of streams below them had effects disproportionate to the size of the dams (see: Watermills and meanders, March 2008). Stream flow beforehand was slower and flooding more balanced than it has been over the last few hundred years. Increased flooding, the building of ever larger flood defences and an increase in flood magnitude, duration and extent when defences were breached form a vicious circle that quickly transformed the lower reaches of the largest American river basins.



North American rates of alluvium deposition since 40 Ka ago – the time axis is logarithmic. (Credit: Kemp et al., 2020; Fig. 2)

All this deserves documentation and quantification, which Kemp *et al*. have attempted at 400 alluvial study sites across the continent, measuring >4700 rates of sediment accumulation at various times during the past 40 thousand years. Such deposition serves roughly as a proxy for erosion rate, but that is a function of multiple factors, such as run-off of rain- and snow-melt water, anthropogenic changes to drainage courses and to slope stability. The scale of post-settlement sedimentation is not the same across the whole continent. In some areas, such as southern California, the rate over the last 200 years is lower than the estimated natural, pre-settlement rate: this example may be due to increased capture of surface water for irrigation of a semi-arid area so that erosion and transport were retarded. In others it seems to be unchanged, probably for a whole variety of reason. The highest rates are in the main areas of rain-fed agriculture of the mid-west of the US and western Canada.

In a nutshell, during the last century the North American capitalism shifted as much sediment as would be moved naturally in between 700 to 3000 years. No such investigation has been attempted in other parts of the world that have histories of intense agriculture going back several thousand years, such as the plains of China, northern India and Mesopotamia, the lower Nile valley, the great plateau of the Ethiopian Highlands, and Europe. This is a global problem and despite its continent-wide scope the study by Kemp *et al*. barely scratches the surface. Despite earnest endeavours to reduce soil erosion in the US and a few other areas, it does seem as if the damage has been done and is irreversible.

Doggerland and the Storegga tsunami (December 2020)

Britain is only an island when sea level stands high; i.e. during interglacial conditions. Since the last ice age global sea level have risen by about 130 m as the great northern ice sheets slowly melted. That Britain could oscillate between being part of Europe and a large archipelago as a result of major climatic cycles dates back only to between 450 and 240 ka ago. Previously it was a permanent part of what is now Europe, as befits its geological identity, joined to it by a low ridge buttressed by Chalk across the Dover Strait/Pas de Calais. All that remains of that are the white cliffs on either side. The drainage of what became the Thames, Seine and Rhine passed to the Atlantic in a much larger rive system that flowed down the axis of the Channel. Each time an ice age ended the ridge acted as a dam for glacial meltwater to form a large lake in what is now the southern North Sea. While continuous glaciers across the northern North Sea persisted the lake remained, but erosion during interglacials steadily wore down the ridge. About 450 ka ago it was low enough for this pro-glacial lake to spill across it in a catastrophic flood that began the separation. Several repeats occurred until the ridge was finally breached (See: When Britain first left Europe; September 2007). Yet sufficient remained that the link reappeared when sea level fell. What remains at present is a system of shallows and sandbanks, the largest of which is the Dogger Bank roughly halfway between Newcastle and Denmark. Consequently the swamps and river systems that immediately followed the last ice age have become known collectively as Doggerland.

Dredging of the southern North Sea for sand and gravel frequently brings both the bones of land mammals and the tools of Stone Age hunters to light – one fossil was a skull fragment of a Neanderthal. At the end of the Younger Dryas (~11.7 ka) Doggerland was populated and became a route for Mesolithic hunter-gatherers to cross from Europe to Britain and become transient and then permanent inhabitants. Melting of the northern ice sheets was slow and so was the pace of sea-level rise. A continuous passage across Dogger Land remained even as it shrank. Only when the sea surface reached about 20 m below its current level was the land corridor breached bay what is now the Dover Strait, although low islands, including the Dogger Bank, littered the growing seaway. A new study examines the fate of Doggerland and its people during its final stage (Walker, J. *et al*. 2020. A great wave: the Storegga tsunami and the end of Doggerland? *Antiquity*, v. **94**, p. 1409-1425; DOI: 10.15184/aqy.2020.49).

The shrinkage of Doggerland since 16,000 BCE (Credit: Europe's Lost Frontiers Project, University of Bradford)

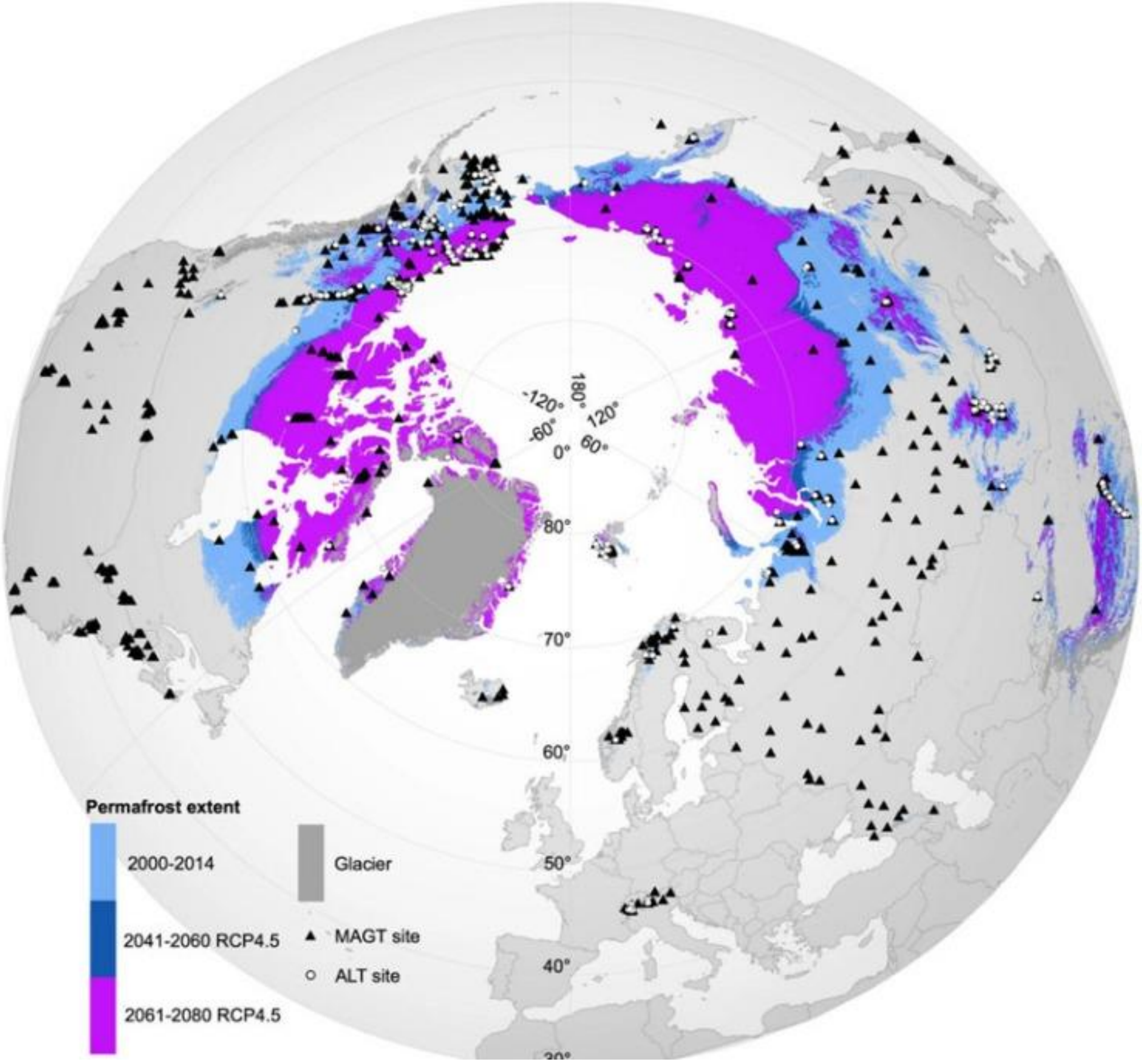
James Walker and colleagues at the University of Bradford, UK, and co-workers from the universities of Tartu, Estonia, Wales Trinity Saint David and St Andrews, UK, focus on one devastating event during Doggerland's slow shrinkage and inundation. This took place around 8.2 ka ago, during the collapse of a section of the Norwegian continental edge. Known as the Storegga Slides (storegga means great edge in Norse), three submarine debris flows shifted 3500 km^3 of sediment to blanket 80 thousand km^2 of the Norwegian Sea floor, reaching more than half way to Iceland. Tsunami deposits related to these events occur along the coast western Norway, on the Shetlands and the shoreline of eastern Scotland. They lie between 3 and 20 m above modern sea level, but allowing for the lower sea level at the time the 'run-up' probably reached as high as 35 m: more than the maximum of both the 26 December 2004 Indian Ocean tsunami and that in NW Japan on 11 March 2011. Two Mesolithic archaeological sites definitely lie beneath the tsunami deposit, one close to the source of the slid, another near Inverness, Scotland. At the time part of the Dogger Bank still lay above the sea, as did a wide coastal plain and offshore islands along England's east coast. This catastrophic event was a little later than a sudden cooling event in the Northern Hemisphere. Any Mesolithic people living on what was left of Doggerland would not have survived. But quite possibly they may already have left as the climate cooled substantially

A seabed drilling programme financed by the EU targeted what lies beneath more recent sediments on the Dogger Bank and off the embayment known as The Wash of Eastern England. Some of the cores contain tsunamis deposits, one having been analysed in detail in a separate paper (Gaffney, V. and 24 others 2020. Multi-Proxy Characterisation of the Storegga Tsunami and Its Impact on the Early Holocene Landscapes of the Southern North Sea. *Geosciences*, v. **10**, online; DOI: 10.3390/geosciences10070270). The tsunami washed across an estuarine mudflat into an area of meadowland with oak and hazel woodland, which may have absorbed much of its energy. Environmental DNA analysis suggests that this relic of Doggerland was roamed by bear, wild boar and ruminants. The authors also found evidence that the tsunamis had been guided by pre-existing topography, such as the river channel of what is now the River Great Ouse. Yet they found no evidence of human occupation. Together with other researchers, the University of Bradford's Lost Frontiers Project have produced sufficient detail about Doggerland to contemplate looking for Mesolithic sites in the excavations for offshore wind farms.

See also: Addley, E. 2020. Study finds indications of life on Doggerland after devastating tsunamis. (*The Guardian*, 1 December 2020); Europe's Lost Frontiers website

Thawing permafrost, release of carbon and the role of iron (December 2020)

Global warming is clearly happening. The crucial question is 'How bad can it get?' Most pundits focus on the capacity of the globalised economy to cut carbon emissions – mainly CO_2 from fossil fuel burning and methane emissions by commercial livestock herds. Can they be reduced in time to reverse the increase in global mean surface temperature that has already taken place and those that lie ahead? Every now and then there is mention of the importance of natural means of drawing down greenhouse gases: plant more trees; preserve and encourage wetlands and their accumulation of peat and so on. For several months of the Northern Hemisphere summer the planet's largest bogs actively sequester carbon in the form of dead vegetation. For the rest of the year they are frozen stiff. Muskeg and tundra form a band across the alluvial plains of great rivers that drain North America and Eurasia towards the Arctic Ocean. The seasonal bogs lie above sediments deposited in earlier river basins and swamps that have remained permanently frozen since the last glacial period. Such permafrost begins at just a few metres below the surface at high latitudes down to as much as a kilometre, becoming deeper, thinner and more patchy until it disappears south of about 60°N except in mountainous areas. Permafrost is melting relentlessly, sometimes with spectacular results broadly known as thermokarst that involves surface collapse, mudslides and erosion by summer meltwater.



Projected shrinkage of permanently frozen ground around the Arctic Ocean over the next 60 years

Permafrost is a good preserver of organic material, as shown by the almost perfect remains of mammoths and other animals that have been found where rivers have eroded their frozen banks. The latest spectacular find is a mummified wolf pup unearthed by a gold prospector from 57 ka-old permafrost in the Yukon, Canada. She was probably buried when a wolf den collapsed. Thawing exposes buried carbonaceous material to processes that release CO_2, as does the drying-out of peat in more temperate climes. It has long been known that the vast reserves of carbon preserved in frozen ground and in gas hydrate in sea-floor sediments present an immense danger of accelerated greenhouse conditions should permafrost thaw quickly and deep seawater heats up; the first is certainly starting to happen in boreal North America and Eurasia. Research into Arctic soils had suggested that there is a potential mitigating factor. Iron-3 oxides and hydroxides, the colorants of soils that overlie permafrost, have chemical properties that allow them to trap carbon, in much the same way that they trap arsenic by adsorption on the surface of their molecular structure (see: Screening for arsenic contamination, September 2008).

Thawing permafrost in Siberia and associated collapse structures

But, as in the case of arsenic, mineralogical trapping of carbon and its protection from oxidation to CO_2 can be thwarted by bacterial action (Patzner, M.S. and 10 others 2020. [Iron mineral dissolution releases iron and associated organic carbon during permafrost thaw](). *Nature Communications*, v. **11**, article 6329; DOI: 10.1038/s41467-020-20102-6). Monique Patzner of the University of Tuebingen, Germany, and her colleagues from Germany, Denmark, the UK and the US have studied peaty soils overlying permafrost in Sweden that occurs north of the Arctic Circle. Their mineralogical and biological findings came from cores driven through the different layers above deep permafrost. In the layer immediately above permanently frozen ground the binding of carbon to iron-3 minerals certainly does occur. However, at higher levels that show evidence of longer periods of thawing there is an increase of reduced iron-2 dissolved in the soil water along with more dissolved organic carbon – i.e. carbon prone to oxidation to carbon dioxide. Also, biogenic methane – a more powerful greenhouse gas – increases in the more waterlogged upper sediments. Among the active bacteria are varieties whose metabolism involves the reduction of insoluble iron in ferric oxyhdroxide minerals to the soluble ferrous form (iron-2). As in the case of arsenic contamination of groundwater, the adsorbed contents of iron oxyhydroxides are being released as a result of powerful reducing conditions.

Applying their results to the entire permafrost inventory at high northern latitudes, the team predicts a worrying scenario. Initial thawing can indeed lock-in up to tens of billion tonnes of carbon once preserved in permafrost, yet this amounts to only a fifth of the carbon present in the surface-to-permafrost layer of thawing, at best. In itself, the trapped carbon is equivalent to between 2 to 5 times the annual anthropogenic release of carbon by burning fossil fuels. Nevertheless, it is destined by reductive dissolution of its host minerals to be emitted eventually, if thawing continues. This adds to the even vaster potential releases of greenhouse gases in the form of biogenic methane from waterlogged ground.

However, there is some evidence to the contrary. During the deglaciation between 15 to 8 thousand years ago – except for the thousand years of the Younger Dryas cold episode – land-surface temperatures rose far more rapidly than happening at present. A study of carbon isotopes in air trapped as bubbles in Antarctic ice suggests that methane emissions from organic carbon exposed to bacterial action by thawing permafrost were much lower than claimed by Patzner *et al*. for present-day, slower thawing – **see:** Old carbon reservoirs unlikely to cause massive greenhouse gas release, study finds. *Science Daily*, 20 February 2020 – as were those released by breakdown of submarine gas hydrates.