Palaeoclimatology 2023

Is erosion paced by Milankovich cycles?

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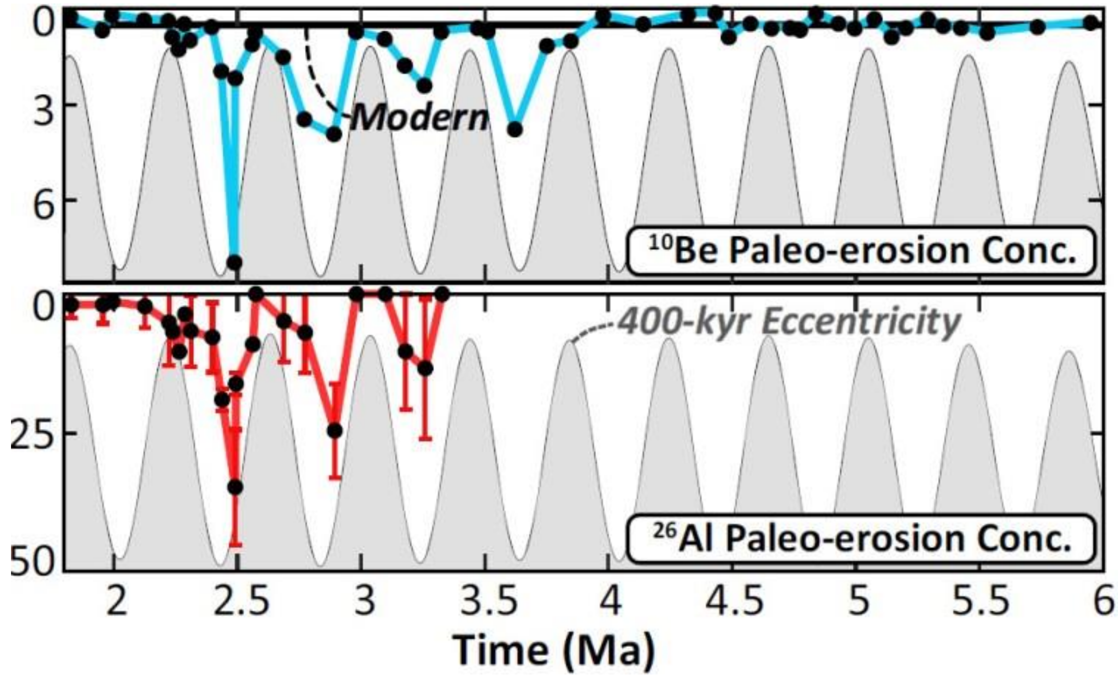
Both physical and chemical weathering reflects climatic controls. Erosion is effectively climate in continuous action on the Earth's solid surface through water, air and bodies of ice moving under the influence of gravity. These two major processes on the land surface are immensely complicated. Being the surface part of the rock cycle, they interact with biological processes in the continents' web of climate-controlled ecosystems. It is self-evident that climate exerts a powerful influence on all terrestrial landforms. But at any place on the Earth's surface climate changes on a whole spectrum of rates and time scales as reflected by palaeoclimatology. With little room for doubt, so too do weathering and erosion. Yet other forces are at play in the development of landforms. 'Wearing-down' of elevated areas removes part of the load that the lithosphere bears, so that the surface rises in deeply eroded terrains. Solids removed as sediments depress the lithosphere where they are deposited in great sedimentary basins. In both cases the lithosphere rises and falls to maintain isostatic balance. On the grandest of scales, plate tectonics operates continuously as well. Its lateral motions force up mountain belts and volcanic chains, and drag apart the lithosphere, events that in themselves change climate at regional levels. Tectonics thereby creates 'blips' in long term global climate change. So evidence for links between landform evolution and palaeoclimate is notoriously difficult to pin down, let alone analyse.

The evidence for climate change over the last few million years is astonishingly detailed; so much so that it is possible to detect major global events that took as little as a few decades, such as the Younger Dryas, especially using data from ice cores. The record from ocean-floor sediments is good for changes over hundreds to thousands of years. The triumph of palaeoclimatology is that the last 2.5 Ma of Earth's history has been proved to have been largely paced by variations in the Earth's orbit and in the angle of tilt and wobbles of its rotational axis: a topic that Earth-logs has tracked since the start of the 21st century. The record also hints at processes influencing global climate that stem from various processes in the Earth system itself, at irregular but roughly millennial scales. The same cannot be said for the geological record of erosion, for a variety of reasons, foremost being that erosion and sediment transport are rarely continuous in any one place and it is more difficult to date the sedimentary products of erosion than ice cores and laminations in ocean-floor sediments. Nonetheless, a team from the US, Germany, the Netherlands , France and Argentina have tackled this thorny issue on the eastern side of the Andes in Argentina (Fisher, G.B. and 11 others 2023. Milankovitch-paced erosion in the southern Central Andes. *Nature Communications*, v. **14**, 424-439; DOI: 10.1038/s41467-023-36022-0.

Burch Fisher (University of Texas at Austin, USA) and colleagues studied sediments derived from a catchment that drains the Puna Plateau that together with the Altiplano forms the axis of the Central Andes. In the late 19th century the upper reaches of the Rio Iruya were rerouted, which has resulted in its cutting a 100 m deep canyon through Pliocene to Early Pleistocene (6.0 to 1.8 Ma) sediments. The section includes six volcanic ash beds (dated precisely using the zircon U-Pb method) and records nine palaeomagnetic reversals, which together helped to calibrate more closely spaced dating. Their detailed survey used the decay of radioactive isotopes of beryllium and aluminium

(^{10}Be and ^{26}Al) in quartz grains that form in the mineral when exposed at the surface to cosmic-ray bombardment. Such cosmogenic radionuclide dating thus records the last time different sediment levels were at the surface, presumably when the sediment was buried, and thus the variation in the rate of sediment supply from erosion of the Rio Iruya catchment since 6 Ma ago.



Measured concentrations (low to high values downwards) of cosmogenic 10Be (turquoise) and 26Al (red) in samples from the Rio Iruya sediment sequence. The higher the value, the longer the layer had resided at the surface; i.e. the slower the erosion rate. (Credit: Fisher et al. Fig 4)

The data from ^{10}Be suggest that erosion rates were consistently high from 6 to 4 Ma, but four times during the later Pliocene and the earliest Pleistocene they slowed dramatically. Each of these episodes occupies downturns in solar warming forced by the 400 ka cycle of orbital eccentricity. The ^{26}Al record confirms this trend. The most likely reason for the slowing of erosion is long-term reductions in rainfall, which Fisher *et al* have modelled based on Milankovich cycles. However the modelled fluctuations are subtle, suggesting that in the Central Andes at least erosion rates were highly sensitive to climatic fluctuations. Yet the last 400 ka cycle in the record shows no apparent correlation with climate change. Despite that, astronomical forcing while early Pleistocene oscillations between cooling and warming ramped up does seem to have affected erosion rates based on the cosmogenic dating. The authors attribute this loss of the 400 ka pattern to a kind of swamping effect of dramatically increased erosion rates as the regional climate became more erratic. Whether or not data of this kind will emerge for the more climatically drastic 100 ka cyclicity of the last million years remains to be seen … Anyone who has walked over terrains covered in glacial tills and glaciofluvial gravel beds nearer to the former Late Pleistocene ice sheets can judge the difficulty of such a task.

Sudden climate change: a warning from 8 millennia ago

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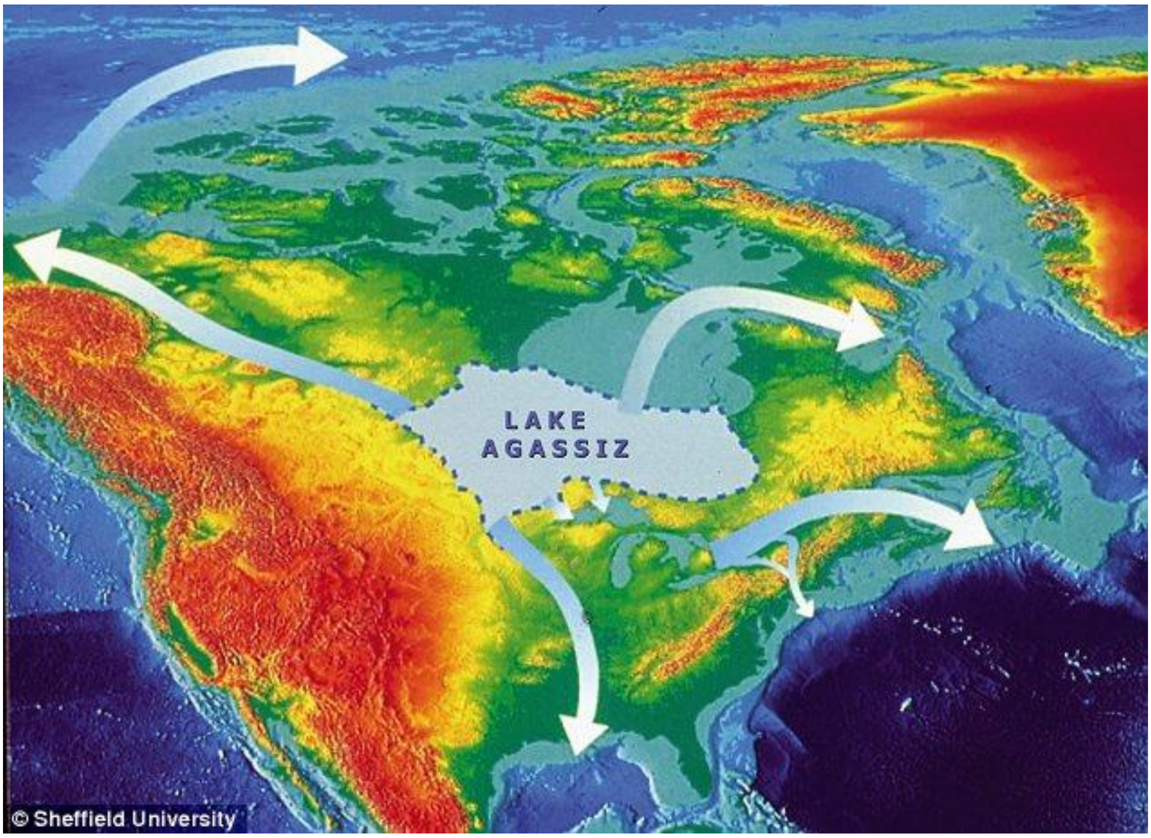
Mesolithic hunter-gatherers in Britain must have had a very hard time around 8.2 thousand years age. The whole area around the North Atlantic experienced sudden climatic cooling of around 3.3°C together with drought that lasted about 70 years. To make things worse shortly afterwards, coasts around the North were devastated by a tsunami generated by a submarine landslide off western Norway. That event exceeded the maximum coast 'run up' of both the 26 December 2004 Indian Ocean tsunami and that in NW Japan on 11 March 2011. Doggerland, then in the central North Sea was devastated by a catastrophic event of a few days duration. It littered the seabed with the bones of its megafauna and even Mesolithic tools recovered by trawlers from its surviving relic the shallow Dogger Bank. It seems the tsunami arrived just as climate was warming back to 'normal' Holocene conditions: for many foragers, surely, a last straw.



Colour coded topographic elevation of North America showing the maximum extent of Lake Agassiz and four possible routes for its drainage: north-west to the Arctic Ocean via the Mackenzie River; south to the Gulf of Mexico via the Mississippi valley; east to the North Atlantic via the Great Lakes and St Laurence River; north to the North Atlantic via Hudson Bay. (Credit: ©Sheffield University)

The cooling episode has been attributed to perturbation of the Atlantic Meridional Overturning Circulation (AMOC) as a result of meltwater discharge during the deglaciation of the Laurentide Ice Sheet (see: Just when you think it's going to turn out alright… November 2009).The event may have unfolded in a similar fashion to the trigger for the Younger Dryas and the succession of warming-cooling episodes known as Dansgaard-Oeschger events that interrupted the otherwise relentless global cooling towards the last glacial maximum (see: Review of thermohaline circulation; February 2002). The physics that set off such climatic 'hiccups' is that freshening of surface seawater reduces its density, so that it cannot sink to be replaced by denser saline water 'dragged' northwards from warmer latitudes. That currently takes the form of the Gulf Stream with its warming influence, particularly in the eastern North Atlantic and even beyond Norway's North Cape, responsible for much warmer winters than at similar latitudes on the western side. The culprit had long been suggested to be the drainage of a huge lake dammed by the ice sheet that covered most of eastern Canada during late stages of deglaciation. Seemingly the best candidate was Lake Agassiz trapped by the early Holocene ice front in Manitoba – the largest proglacial lake known anywhere.

The present landforms of central Canada show evidence for several outflow directions at different times, Including to the northwest to reach the Arctic Ocean at the onset of the Younger Dryas. Until recently there was little detailed evidence for the flow volume and timing of its drainage around 8 to 9 ka. Providing the details in the context of the short-lived event around 8.2 ka requires accurate data over a mere 200 years able to reveal a change in sea level to a precision of better than a few tens of centimetre. Any site on the shores of the North Atlantic would do, provided it satisfies these criteria. Geographers from universities in York, Leeds, Sheffield and Oxford, UK selected the small estuary of the River Ythan in NE Scotland. There, a continuous sand unit just above fine-grained intertidal tidal muds marks the knife-sharp time datum of the Storegga tsunami (Rush, G. *et al*. 2023. The magnitude and source of meltwater forcing of the 8.2 ka climate event constrained by relative sea-level data from eastern Scotland. *Quaternary Science Advances*, v. **12**, article 100119; DOI: 10.1016/j.qsa.2023.100119).

Cores of the intertidal sediments from beneath the present Ythan salt marsh contain plant remains that yielded precise radiocarbon dates at several stratigraphic levels from which to derive an age-depth model for the age range of interest. The buried sediments are also rich in marine microfossils (foraminifera and diatoms) that thrive in estuaries at a variety of depths. These enabled fluctuations in relative sea level during the build-up of the intertidal sediments to be constrained at unprecedented resolution and precision for a three thousand year period from 9.5 to 6.5 ka. The authors show that there were two episodes of rapid sea-level rise over that time: between 8.53 and 8.37 ka (~2.4 m at 13 mm yr^{-1}) and 8.37 to 8.24 ka (~ 0.6 m at 4 mm yr^{-1}) – these would have been *global* increases in sea level.

Despite its vast size, it turns out that Lake Agassiz would have been unable to result in sea-level rises of that magnitude so quickly merely through outflow. Rush *et al*. suggest that the huge and rapid addition of fresh water to the North Atlantic involved flow of lake water towards Hudson Bay, *beneath* the ice sheet, causing it to collapse and melt, followed by completion of Lake Agassiz's emptying in the second stage. It took a long drawn-out 'freshening' of the North Atlantic surface water ultimately to shut down the Atlantic Meridional Overturning Circulation, thereby depriving high latitudes of its east-side warming effect by the Gulf Stream.

Sea level has been rising since the early 20th century mainly through the melting of Greenland's ice cap together with a substantial amount of thermal expansion while global climate has been warming. Between 1901 and 2018 the rise has amounted to 15 to 25 cm at a rate of 1 to 2 mm yr^{-1}. The AMOC is possibly weaker now than at any time during the last millennium (Zhu, C. *et al.* 2023. Likely accelerated weakening of Atlantic overturning circulation emerges in optimal salinity fingerprint. *Nature Communications*, v. **14**, article 1245; DOI: 10.1038/s41467-023-36288-4). Yet increases in freshening of the northernmost parts of the North Atlantic are now being added to by annual increases in the melting of polar sea ice, which is salt-free. The AMOC may be approaching a tipping point, because warming is accelerating over Greenland at around 1.5°C each year: faster than most of the rest of the world. In 2021 it rained for the first time ever recorded at the ice cap's summit (3.2 km above sea level). A 'perturbation' of the AMOC would add chaos to the dominantly linear view of global warming taken by climatologists. That could launch frigidity and drought at mid northern latitudes as it did eight millennia ago: the opposite of what is currently feared.

See also: Unlocking Ancient Climate Secrets – Melting Ice Likely Triggered Climate Change Over 8,000 Years Ago. *Scitechdaily* 16 September 2023.

Repeated climate and ecological stress during the run-up to the K-Pg extinction

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The Cretaceous-Palaeogene mass extinction is no longer an event that polarises geologists' views between a slow volcanic driver (The Deccan large igneous province) and a near instantaneous asteroid impact (Chicxulub). There is now a broad consensus that both processes were involved in weakening the Late Cretaceous biosphere and snuffing out much of it around 66 Ma ago. Yet is still no closure as regards the details. From a palaeontologist's standpoint the die-off varied dramatically between major groups of animals. For instance, the non-avian dinosaurs disappeared completely while those that evolved to modern birds did not. Crocodiles came through it largely unscathed unlike aquatic dinosaurs. In the seas those animals that lived in the water column, such as ammonites, were far more affected than were denizens of the seafloor. But much the same final devastation was visited on every continent and ocean. However, lesser and more restricted extinctions occurred before the Chicxulub impact.

Scientists from Norway, Canada, the US, Italy, the UK and Sweden have now thrown light on the possibility that climate change during the last half-million years of the Cretaceous may have been eroding biodiversity and disrupting ecosystems (Callegaro, S. *et al*. 2023. Recurring volcanic winters during the latest Cretaceous: Sulfur and fluorine budgets of Deccan Traps lavas. *Science Advances*, v. **9**, article eadg8284; DOI: 10.1126/sciadv.adg8284). Almost inevitably, they turned to the record of Deccan volcanism that overlapped the K-Pg event, specifically the likely composition of the gases that the magmas may have belched into the atmosphere. Instead of choosing the usual suspect carbon dioxide and its greenhouse effect, their focus was on sulfur and fluorine dissolved in pyroxene grains from 15 basalts erupted in the 10 Formations of the Deccan flood-basalt sequence. From these analyses they were able to estimate the amounts of the two elements in the magma erupted in each of these 10 phases.

Exposed section through a small part of the Deccan Traps in the Western Ghats of Maharashtra, India. (Credit: Gerta Keller, Princeton University)

The accompanying image of a famous section through the Deccan Traps SE of Mumbai clearly shows that 15 sampled flows could reveal only a fraction of the magmas' variability: there are 12 flows in the foreground alone. The mountain beyond shows that the pale-coloured sequence is underlain by many more flows, and the full Deccan sequence is about 3.5 km thick. Clearly, flood-basalt volcanism is in no way continuous, but builds up from repeated lava flows that can be as much as 50 m thick. Each of them is capped by a red, clay-rich soil or bole – from the Greek word bolos (***βόλος***) meaning 'clod of earth'. Weathering of basalt would have taken a few centuries to form each bole. Individual Deccan flows extend over enormous areas: one can be traced for 1500 km. At the end of volcanism the pile extended over roughly 1.5 million km^2 to reach a volume of half a million km^3.

Fluorine is a particularly toxic gas with horrific effects on organisms that ingest it. In the form of hydrofluoric acid (HF) – routinely used to dissolve rock – it penetrates tissue very rapidly to react with calcium in the blood to form calcium fluoride. This causes very severe pain, bone damage and other symptoms of skeletal fluorosis. The 1783-4 eruption of the Laki volcanic fissure in Iceland emitted an estimated 8,000 t of HF gas that wiped out more than half the domestic animals as a result of their eating contaminated grass. The famine that followed the eruption killed 20 to 25% of Iceland's people: exhumed human skeletons buried in the aftermath show the distinctive signs of endemic skeletal fluorosis. This small flood-basalt event had global repercussions, as the Wikipedia entry for Laki documents. Volcanic sulfur emissions in the form of SO_2 gas react with water vapour to form sulphuric acid aerosols in a reflective haze. If this takes place in the stratosphere as a result of powerful eruptions, as was the case with the 1991 Pinatubo eruption in the Philippines, the high-altitude haze lingers and spreads. This results in reduced solar warming: a so-called 'volcanic winter'. In the Pinatubo aftermath global temperatures fell by about 0.5°C during 1991-3. Unsurprisingly, volcanic sulfur emissions also result in acid rainfall. Moreover, inhaling the sulphur-rich haze at low altitudes causes victims to choke as their respiratory tissues swell: an estimated 23,000 people in Britain died in this way when the 1783-4 Laki eruption haze spread southwards Sara Calegaro and colleagues found that the fluorine and sulfur contents of Deccan magmas fluctuated significantly during the eruptive phases. They suggest that fluorine emissions were far above those from Laki, perhaps leading to regional fluorine toxicity around the site of the Deccan flood volcanism but not extinctions. Global cooling due to sulphuric acid aerosols in the stratosphere is suggested to have happened repeatedly, albeit briefly, as eruption waxed and waned during each phase. Magmas rich in volatiles would have been more likely to erupt explosively to inject SO_2 to stratospheric altitudes (above 10 to 20 km). The authors do not attempt to model when such cooling episodes may have occurred: data from only 15 levels in the Deccan Traps do not have the time-resolution to achieve that. They do, however, show that this large igneous province definitely had the potential to generate 'volcanic winters' and toxic episodes. Time and time again ecosystems globally and regionally would have experienced severe stress, the most important perhaps being disruption of the terrestrial and marine food chains.