How does glacial erosion control tectonics in mountain belts?

Dr Matt Fox, UCL. Feb 2021

During periods of intense precipitation, erosion rates increase across the landscape and mountain belts become narrower as mass is removed from the crust. Faults respond to that change as well. In effect, the accretionary flux, the material that is being added into the orogen through subduction and shortening, is balanced by the erosional flux that is being removed by erosion.

When looking at glaciers today, the Aletsch glacier in Switzerland for example, there are big features that are doing a lot of the glacial erosion. And when we look at areas of past glaciation in Norway, one can see the role that glaciers have played in shaping the landscape and eroding material. Faults in the accretionary wedges should be sensitive to this mass redistribution, and may control the tectonics in mountain ranges in some way.

This has been shown nicely in the St Elias Range in SW Alaska where the Pacific plate is subducting below the Alaskan margin. In a cross section through that range was based on a combination of seismic sections and as study measuring erosion rates back through time and reconstructing sediment flux, concluded that before the onset of the N hemisphere glaciation about 2 Ma ago, the mountain range was in a critically tapered wedge which was quite wide and the material removed by erosion was spread over a large distance. Then following glaciation, there was a rapid removal of material and the orogen became much narrower. This is a nice example of where glacial erosion has controlled the style of deformation within a tectonic orogenic wedge, because faults responded to changes in stress regime from the redistributed mass, and this changes the width of the orogen.

One can estimate the degree of glacial erosion by looking at landscapes using a method called thermo-chronometry. In Yosemite Valley, Matt is looking at estimating how much of the topography is generated by glaciers, and how much topography developed before glaciation. A lot of this work was done in the 1930s by Mathes, who reconstructed what he thought the landscape looked like through time, suggesting an early phase of low relief topography across the Sierra Nevada and across Yosemite Valley, followed by a phase of fluvial incision and finally intense glacial erosion that produced the dramatic landscape seen today. But modern quantitative methods applied to glacial landscapes allow an estimate of how much material has been removed, by taking information that is preserved in the upper parts of the landscape, then projecting that information across the glacial valleys to reconstruct the pre-incision landscape, e.g. in the Ribbon Creek valley.

This is done by developing a mathematical model for how rivers look under a steady state condition, and how rivers of different sizes have different elevation changes i.e. projecting the shape of the low-relief landscape out across the glaciated landscape, ‘filling in’ the eroded material and comparing it with the actual landscape today. These reconstructions can be used in landscape evolution models, ice sheet reconstruction models and tectonic models, to explore glacial erosion in much more detail. But in essence, it is analogous to what Mathes did in the 1930s, although in a much greater scale.

In the Alps, famous for the deep glaciated valleys which can be 'filled in' with the same sort of equations described above, effectively converting a glacial landscape into a fluvial landscape, i.e. a modern landscape with deep valleys draining into the Po Plain area and into Lake Como, also around Geneva and Zurich, but which extend as low areas right into the central parts of the orogen. Whereas in a fluvial reconstructed landscape, these deep valleys do not occur deep into the landscape, which has deep implications for the types of ice sheets that can be supported on topography, the climatic reconstructions that can be inferred from these ice extent models, and for the mass distributions across the landscape.

So, can we actually measure glacial erosion? In Fiordland in N Zealand, with its dramatic glacial landscape of deep U-shaped valleys that penetrate deep into the orogen, up to 2km of relief is seen. Did these valleys form immediately after the onset of glaciation or did they form over a long period of repeated glaciations?

The method used to investigate these questions is called low temperature thermo-chronometry, a radioactive dating technique which relies on the decay of U & Th and the formation of He. Hence if one knows the amount of U & Th that is in individual crystals of apatite, one can estimate how quickly He is being produced. But as He is a very small atom (No 2 in the periodic table) its diameter is not truly compatible in a crystal lattice and it can escape this unnatural embrace over time. Consequently, at very high temperatures, the rate at which He can escape from a lattice is high and any He produced is lost immediately. But as the crystal cools, on the approach to the Earth's surface from depth, the rate of diffusion decreases and will approach zero at temperatures below about 70C, where there is no escape at all and the He remains in the crystal lattice and a radiometric clock is generated. In other words, how much time has elapsed since the host rock has cooled below 70C. From an idea of the heat flux at the surface, one can estimate the geothermal gradient and hence relate these temperatures to depths within the Earth.

In Washington State, a heat transfer model gave an estimate of how deep one would have to go to find a 70C isotherm and for a 110C isotherm; that is, if one can estimate the time it would have taken those rocks to travel from depths of 2-5km to the surface, one can also measure how quickly the surface has eroded down to expose these rocks from depth.

Apatite crystals which are about 70 microns in diameter or more are collected with tweezers under high magnification from a large rock sample. They are then placed in tiny platinum envelopes which are heated by laser to about 600C, sort of mini-furnace which releases all the He that was trapped in the apatite into a vacuum, and which is measured by a mass spectrometer. Then the crystals are dissolved in acid and the U & Th is measured in a different mass spectrometer to give a thermometric age.

In Fiordland in N Zealand, the thermometric He ages can be plotted on the X axis against the elevation of the sample on the Y axis. The ages in areas where glaciation occurred are very young, at about 2.5 Ma, hence rocks from 2-3 km have been brought to the surface over a very short period of time, providing evidence that erosion is very fast in such locations.
In a compilation of apatite ages across several mountain belts published in 2013, it was shown that there had been an acceleration of erosion rates over the last 2 Ma, i.e. at the onset of glaciation in the N hemisphere.

But somewhat perversely, in places which have been glaciated for a very long time, e.g. the Antarctic Peninsula, there is evidence that the erosion rate is slow. Glaciers in this region have persisted for about 30 Ma, despite a transient looking landscape with big glacial cirques which one might expect would have been eaten away back into the low relief surface. So why is the landscape so well preserved there?

In Fiordland the sample density for this type of analysis is high, from the lowest and highest parts of the landscape, but in Antarctica it is not possible to sample the bedrock under 2 km thickness of ice. Instead, the glaciers themselves provide the samples by collecting sand from the toe of the big glaciers, sourced from the catchment area beneath the ice. Regarding the age distribution below the surface using a thermal model with predicted ages at the surface, there is a large range of predicted ages across the landscape from 20 Ma in the lowest part, to 100 Ma at the highest. So, based on where the glaciers are bringing in material from the landscape, we would expect to see different patterns in the detrital samples. In 2017, Matt collected samples from these fiords from a US ice strengthened research vessel up to the deepest part of the landscape accessible by the ship. Owing to the fact that many of these fiords have never been accessed by ship before, this was a very slow process due to collecting detailed bathymetry first, but then using a box-shaped seabed sample of about 0.5m3. After selecting apatite crystals - a very labour-intensive process – the conclusion reached was that glacial erosion on the Antarctic Peninsula is very slow.

Despite this modern data, there is still no clear model for how glacial erosion controls tectonic mountain belts.

<u>Discussion and remarks</u>

Glacial erosion can be very localised but also complex over a given glaciated area with erosion at the peaks as well as at the base of glaciers, so the total mass removed by a glacier is much greater than the volume of a U-shaped valley alone.

Is it correct that the depth of lowering in the topography has in many cases been reduced by kilometres in quite short time periods? It follows that a great deal of material must have been moved out of an orogen and put somewhere else! Correct. Quite a lot of work has been done in estimating the source-to-sink problem in the Alps, with material accumulating in the Rhine and Rhone valleys, perhaps up to two km depth over the past 2 Ma, from the peaks as well as valley bottoms.

There was a great deal of alteration in the southern Alps from the Messinian event (during which the Mediterranean Sea went into a cycle of partly or nearly complete desiccation in the Miocene epoch, from 5.96 to 5.33 Ma), so did this lowering of the base level of erosion have any measurable impact?

The Messinian event had been part of Matt's original research work but it appears to have been too short a duration to have much impact, as the 'nick' points would not have travelled very into the Alps; which explains why the topography in the S Alps is much younger than the Messinian. Some of the adjacent bedrock/sediment interface has been dated and it all seems to be younger than about 2 Ma.

How do rates of erosion compare from the glaciated regions to those in the tropics? There has been a lot of research comparing the erosion rates in the Alaskan St Alias range with Taiwan and other tropical areas, where the depths of erosion in the latter have been estimated at tens of kms, due to deep weathering and frequent seasonal typhoons. So high rates of erosion are possible without glaciers. N Zealand appears to have oscillated from a glacial to a fluvial landscape in the interglacial periods, with fast rates of uplift since, so the landscape appears to be changing back to purely fluvial now.

Given that the rates of glacial erosion in Antarctica appear to be much lower than say the Alps, is this because super cold ice has a much lower ductility, and hence it does not flow as easily? It is probably more about the ice in Antarctica and Patagonia being frozen to the bedrock, with very little sliding at the interface. In temperate glaciers there is a lot of melting with meltwater penetrating down crevasses and lubricating the base.

Is the high uplift in the Taiwan, E Timor and Papua New Guinea area related to the high tectonic spreading rates in the western Pacific? Perhaps, but the very narrow width of the orogen coupled with very high rainfall is also a factor which will also cause massive rates of erosion. By contrast, while the N-S width of the Himalaya is vast, much of the high plateau is arid and so there is little erosion by water.

How you compare the erosion rate during a glacial period with the rate during an interglacial period, say in the Alps? This is still a very open research question but it is clear that the interglacial periods have resulted in high rates of fluvial incision through an inner gorge which opens upwards into more open pastures, with high rates of erosion on the rocky hillsides. But there is also deposition in the deep U-shaped valleys and especially in the over-deepened locations today. However, if ice grew back into these locations, one might expect very slow rates of erosion in areas which had high rates during fluvial conditions. There is not much actual glacial erosion during glacial periods but very rapid erosion during the interglacial periods.

The timescales for this sort of oscillation could be millions of years, but in Britain the glacial – interglacial periods are very short, with about 5 in the last 500,000 years, and in Snowdonia for example, the U-shaped valleys are believed to have formed in a very short interval, say a few hundred thousand years. They could have formed very early in the ice age but as the cirques subsequently filled with sediment, this may have largely protected them in later glacial periods. It is also likely that the initial phase of an ice age would have had a high rate of erosion, with a corresponding high degree of sediment transport and deposition, but is not easy to distinguish one phase of glacial deposition from another.

The meeting closed with traditional toasts to the Queen and to the Society.

John Bennett