Geomorphology

Tectonics and climate, and the rate of mountain erosion (January 2004)

It is rare for one issue of a “journal of record”, such as *Nature* to contain three papers on closely related topics, especially when they are geoscientific, but its 11 December issue of 2003 did. All were about the way in which mountains erode, and attempted to measure the rates involved in three different settings. Insofar as it is possible in Earth science, they try a reductionist approach in terms of the climatic and tectonic forces that are involved in denudation. Getting useful timings is not as easy as it might seem with measuring fission tracks and the amount of radiogenic helium generated by decay of uranium and thorium isotopes in grains of apatite. The principle lies in estimating when unroofed rocks rose and cooled below the temperatures at which apatite loses noble gases and the tracks in it formed by alpha particle emission heal up. In an exposed section subjected to erosion and isostatic uplift the higher rocks should record older ages than those lower down, the difference representing the pace of erosion and uplift. There is, as yet, no way that periods less that 500 thousand years can be resolved by either method, and in terms of recent climate that can cover several glacial-interglacial cycles.

The simplest of the case studies was in the Cascade mountains of the NW USA, where there has been minimal tectonic activity, but a great deal of rain over the last few million years. The crust has risen as material was stripped off the mountains. The average rates of erosion on time scales of millions to tens of million years closely follow the modern variation in precipitation over the area (Reiners, P.W. 2003. *Coupled spatial variations in precipitation and long-term erosion rates across the Washington Cascades*. *Nature*, v. 426, p. 645-647; DOI: 10.1038/nature02111). As a result, western parts of the range where rainfall is far higher than in the eastern rain shadow could be expected to be rising as much as three times faster, if a balance between erosion and isostatic uplift has been achieved. Since erosional power is expressed by rainfall and surface gradient, the fact that average erosion rates do not correlate well with topographic relief suggests that precipitation has outweighed the effects of slope steepness.

The opposite seems to hold in the Himalaya of central Nepal, which show the most gross variations in precipitation, due to monsoonal conditions (Burbank, D.W. and 7 others 2003. *Decoupling of erosion and precipitation in the Himalayas*. *Nature*, v. 426, p. 652-655; DOI: 10.1038/nature02187), yet long-term erosion rates do not vary very much, except between the topographically distinct Lesser and Greater Himalaya ranges. The Himalaya are altogether more geologically and tectonically complex than the NW USA, so finding such little variation is as interesting as it seems currently inexplicable. The lack of correlation in the Greater Himalaya between precipitation (a five-fold decrease from south to north across the range) and erosion rates (more or less constant and high) suggests that tectonic uplift is the main driving force. Much the same findings from the area immediately to the east in the Nepalese Himalaya, though using a mica Ar-Ar thermochronology method that spans a longer period, have been interpreted very differently (Wobus, C.W. *et al*. 2003. *Has focused denudation sustained active thrusting at the Himalayan topographic front?* *Geology*, v. 31, p. 861-864; DOI: 10.1130/G19730.1). Wobus and his colleagues from MIT suggest that rapid
rise of the Greater Himalaya (~10 km in the last 10 Ma) was induced by isostatic uplift driven by erosion, even maintaining movement on the huge bounding thrusts to the orogenic belt.

Altogether more complicated is the erosion of Taiwan, which is seismically active, has a complex tectonic history that affected rocks of very different strengths in different areas and is subject to a highly variable maritime climate (Dadson, S.J. and 11 others 2003. Links between erosion, runoff variability and seismicity in the Taiwan orogen. Nature, v. 426, p. 648-651; DOI: 10.1038/nature02150). They detect changing patterns of erosion as deformation has migrated. Attempts at correlation between modern erosion rates and various factors came up with only two of significance, with recent seismicity and typhoons. Each triggers landslips that instantaneously add debris to flowing rivers. Precipitation rates, river discharge, slopes and stream power showed little link with erosion rates. Of the four papers, only one (Wobus et al.) is able to relate differences in the erosive power of streams to the contrasting erosion rates of the Greater and Lesser Himalaya.

Such a hodge-podge of seemingly conflicting findings, based on studies that use supposedly revolutionising techniques, must worry agencies who have been induced to part with large funds to support fission-track and (U-Th/He) dating facilities supposedly to advance geomorphological studies. Peter Molnar, who with Phillip England first reviewed the complex interplay between erosion, tectonics and uplift, and their counter-intuitive outcomes, made the following pithy comment, “The differences among these papers call attention to the inadequacy of current theory, without which one gropes for a way to plot data”. Plainly, there has been over-excitement about techniques in the hope of empirically deriving theories, which has resulted in half-cocked research, and some gullibility among funding bodies.


Australian surface not so old (March 2004)

One of the most widely quoted bits of geological information that appear in non-specialist literature is that the oldest land surface on Earth is that of interior Australia. Vast tracts are Precambrian capped by horizontal Permian glaciogenic rocks in places, but for the most part by relics of lateritic palaeosols that give it is famous red appearance. The oldest outlying platform sediments are 1100 Ma old, so the actual surface does date back at least as far, but has it been exposed at the surface for that long? Dating the present surface has not been easy. New methods involving the creation of unstable isotopes by cosmic-ray bombardment offer a solution (see Measuring erosion rates, February 2002), combined with apatite fission-track dating (Belton, D.X. et al. 2004. Quantitative resolution of the debate over antiquity of the central Australian landscape: implications for the tectonic and geomorphic stability of cratonic interiors. Earth and Planetary Science Letters, v. 219, p. 21-34; DOI: 10.1016/S0012-821X(03)00705-2). The results suggest that Australian landscape antiquity is a myth. Erosion rates since the Cambrian varied over most of the Red Centre from 0.4 to 4.0 metres per million years, and reached as high as 17 m per Ma on occasion. They suggest a common or garden history, comparable with those of most continental interiors. Again and again it has been buried by sediments, albeit on a flat surface, and equally it has been exhumed several times by erosion. Only at the outset of the Cenozoic did much of it sit unchanged for long, which enabled its red surface to develop. The present
surface is covered with what is termed regolith by Australians, but much of that is reworked material from the Palaeocene laterites that sits in a network of shallow drainage systems, including huge ephemeral lakes. It might seem that recourse to Hutton’s “the present is the key to the past” should long ago have staved off the myth of the gnarled old place of which Australians have become inordinately proud.

**River incision and anticlines (April 2004)**

In many areas of active deformation, landforms that suggest that uplift and river down-cutting keep pace are very common. Stream courses cross zones of uplift, rather than being diverted or ponded up to form lakes. Traditionally, geomorphologists have described such drainages as “antecedent”, i.e. rivers that were present before uplift began. They can be seen on all scales up to examples such as the Indus and Brahmaputra rivers that carve their way across the actively rising Himalaya. The most common are anticlines through which streams flow in canyons perpendicular to the fold axes. A curious and common feature is that the canyons are not haphazard, but often cut the fold where its amplitude is greatest and its axis plunges away from the site of incision. The stupendous rates at which crustal rocks are eroded and transported away in the courses of the Indus and Brahmaputra, and in lesser drainages on the flanks of major extensional orogens, such as the Red Sea, clearly removes load from the crust. Consequently there is an isostatic component to the uplift involved in the two cases at a grand scale. Peter Molnar and Phillip England suggested an erosional role in large-scale uplift over a decade ago. Intervening ridges rise higher than they would if erosion was slower or non-existent. In major rift systems, the highest peaks are often within the escarpments rather than at the lip of uplift, sometimes more than 500 m higher. Bearing this well-known process in mind, Guy Simpson of ETH Zurich, has sought evidence that it functions on much smaller scales (Simpson, G. 2004. *Role of river incision in enhancing deformation*. *Geology*, v. 32, p. 341-344; DOI: 10.1130/G20190.2). That comes from the surprising symmetry of doubly plunging anticlines that are cut by rivers at their highest point. His modelling suggests that the phenomenon can occur when the crust deforms plastically, allowing isostatic response to erosion on even minor scales during compression. When deformation is by brittle means, any uplift of rigid crust is flexural and has long wavelengths, so that rivers bear no relation to local structures.

**Caves and snoticles (May 2004)**

If ever there was “received wisdom” in the geosciences the most pervasive is the notion that the weak acid formed when carbon dioxide dissolves in rainwater is the cause of carbonate solution. Anyone hearing it in the spiel from a cave guide, while admiring caverns as big as cathedrals, is not surprisingly awe-struck by such an innocuous sculpting agent. Many speleologists have long wondered if there might be other mechanisms, and the discovery of bacterial films that generate strong sulphuric acid provides a good candidate. They can take the form of floppy, stalactite-like masses, that have become fondly known as “snoticles”. However, their role in cave formation had not been substantiated until April 2004.

Microbial geochemists at the University of Texas carefully studied the geochemical balances in a cave system in Wyoming where such bacteria are abundant (Summers Engel, A. *et al.*
2004. Microbial contributions to Cave formation: New insights into sulfuric acid speleogenesis. Geology, v. 32, p. 369-372; DOI: 10.1130/G20288.1. The bacteria are members of two groups that live in aerated conditions and use the oxidation of sulphide ions (from hydrogen sulphide) as a source of metabolic energy. Oxidation results in sulphuric acid, which rapidly dissociates in water to generate abundant hydrogen ions (the source of acidity and low pH) and sulphate ions. So, to thrive the bacteria need a continuous source of hydrogen sulphide, of which more later. The study by Annette Summers Engels and two colleagues shows that hydrogen sulphide is efficiently consumed by the bacteria, so that little if any enters the cave’s atmosphere. Interestingly, water flowing through the cave isn’t particularly acid either, yet the bacteria generate a great deal of sulphuric acid. It is rapidly neutralised by reaction with calcium carbonate near the colonial mats, to increase the flux of calcium and sulphate ions into solution. The effect extends to limestone pebbles on the beds of the cave streams, so the bacteria encourage solution beneath water as well as near snoticles hanging from the roof. That suggests that they can live below the water table, where many caves are thought to have formed in the past, being left as open caverns as the water table fell as bulk permeability increased with solution.

The studied cave does experience a constant flux of hydrogen sulphide, but where does that come from? There are other groups of bacteria that generate sulphide from dissolved sulphate ions, but under highly reducing conditions. They are the source of the “sour gas” that is a constant danger in oil production in some petroleum fields, consumed gleefully in dissolved form at a great many spas and generated in our own guts. These sulphate-sulphide reducing bacteria get their energy from dead organic matter, that many sediments deposited under reducing conditions contain in substantial volumes. Interestingly, connectivity between oxygen-rich and oxygen-starved groundwater might create a recycling of sulphur that involves both bacterial groups. Many limestones contain strata that are rich in organic remains and metal sulphides, in which conditions become reducing. Equally, interbedded, black shales might play a role.

Climate and mountain relief (July/August 2004)

The greater the rainfall, the more effective streams become as agents of erosion. So, “common sense” suggests that very wet mountain areas should be eroded more quickly and develop a more profound relief than those that are drier. With the advent of detailed digital elevation models that cover the world, it is easy to calculate slope angles and relief over huge areas, and match them with rainfall records. Geomorphologists from the Universities of Montana and California have done this for the wettest and most rugged area in the
world, the Annapurna area of the Himalaya (Gabet, E.J. et al. 2004. Climatic controls on hillslope angle and relief in the Himalayas. Geology, v. 32, p. 629-632; DOI: 10.1130/G20641.1). The main agent of erosion there, as streams cut downwards, is by landslides. The region also shows a profound gradient in annual rainfall from about 1000 mm in the High Himalaya to 4500 at the front of the range, where the monsoon rains hit hardest. “Common sense” is wrong, for the slopes decrease from an average of 35º to 25º as rainfall increases. The authors believe this is due to the influence of deeper weathering in more humid parts that reduces the strength of slope materials so that they must stabilise at lower angles than those in dry areas; i.e. to become more muted. Their other finding is that relief (elevation difference in small segments of an area) and slope angle have a strong positive correlation, so that relief itself is inversely related to rainfall. They are able to comment interestingly on various ideas about mountain evolution. Their main conclusion is that in any particular area, a transition from dry to wet conditions lowers mountain ridges faster than valley incision can shift the debris, whereas during drying, ridges are barely lowered, while streams cut unhindered into bedrock, thereby sharpening up the landscape.

Formation of gorges in tectonically quiet areas (July/August 2004)

The flanks of the North Atlantic probably became tectonically inactive in Mesozoic times, yet rivers large and small have cut large gorges, often through highly resistant bedrock. But they also have developed broad valleys over millions of years, and it is into them that the gorges are incised. Slow upward flexing caused by sediment loading on the continental shelves, a general lowering of sea level since Antarctica first formed a permanent ice cap, and isostatic response to gradual denudation help explain the full extent and shape of the rivers drainage basins. Yet the gorges are young, and must have developed rapidly. Old ideas focussed on W.M. Davis’ theories of landscape evolution, particularly rejuvenation associated with changing base levels of erosion, but with no quantitative backing. The development of means of dating eroded surfaces using the decay of short-lived radioactive isotopes produced by cosmic-ray bombardment now offers an opportunity to test hypotheses rigorously and come up with others. Quite a few published works on cosmogenic dating applied to landform development seem to add little to geomorphological knowledge, so it is a relief to find one that does (Reusser, L.J. et al. 2004. Rapid late Pleistocene incision of Atlantic passive-margin river gorges. Science, v. 305, p. 499-502; DOI: 10.1126/science.1097780).

The authors, from the Universities of Vermont and Maryland, the USGS and the Lawrence Livermore National Laboratory, focus on impressive gorges in the lower reaches of the Susquehanna and Potomac Rivers as they drain the eastern US into the Atlantic, and a series of higher surfaces which they cut into to leave as rocky straths. The oldest ages occur on the highest of these straths, as expected, and age decreases on successively lower ones to the rocky flood plain of the modern rivers just above their current channels. The highest levels are between 85 and 97 ka, the most prominent strath formed between 30 and 33 ka, succeeded by one at 19 ka and the lowest level seems to have formed between 13 and 14 ka. Interpreting the periods of intense erosion that cut each level must involve late Pleistocene climate change, sea-level shifts, and the bulging effect due to the North American ice sheet which reached its maximum extent in the northernmost part of the Susquehanna basin.
It seems that during the early part of the last glacial episode, incision was slow, although probably faster than during the Holocene. But around 30 to 33 ka ago it accelerated rapidly to half a metre every thousand years, some 1 to 2 orders of magnitude greater than at present. This was at a time when ice loading was only half that at the glacial maximum around 20 ka, so it seems likely to have been initiated more by increased storminess and torrents, and indeed correlates with an abrupt increase in sea-salt content in the Greenland ice cap brought in by winds at that time. Lasting through the glacial maximum, increased frequency of flooding combined with more rapid sea-level fall, also beginning at around 32 ka, were probably the main driving forces for gorge incision. This still leaves a puzzle. Both drainage basins had been in existence since well before the cycles of glacial and interglacial periods began on the flanks of the North Atlantic around 2.5 Ma ago. Similar periods of accelerated incision must have been repeated, at least during the last 6 or 7 glaciations which were the most extensive. Did earlier topographic features exert any control over later ones, and do any relics of them remain?

**Black Sea flooding put to test (September 2004)**

In 1997, William Ryan and Walter Pitman of the US Lamont-Doherty Earth Observatory captured a much wider audience than is normally the case for geoscientists, when they announced evidence from the Black Sea that seemed to confirm legends of the Flood in the Old Testament and the Epic of Gilgamesh (Ryan, W.B.F. et al. 1997. *An abrupt drowning of the Black Sea shelf*. *Marine Geology*, v. **138**, p. 119–12; DOI: [10.1016/s0025-3227(97)00007-8](https://doi.org/10.1016/s0025-3227(97)00007-8)). They claimed that in early Holocene times, the Black Sea was a freshwater lake some 150 m below present sea level. At the time, global sea level was below the threshold of the floor of the Bosporus, thereby isolating the Black Sea from the world’s oceans. Yet sea level was rising inexorably as continental ice sheets melted back. Around 8000 years ago, sea water flooded through the Bosporus to fill the Black Sea to its present level. Evidence takes the form of submerged beaches and even possible townships (mounds similar to the tells in Turkey and Mesopotamia formed during long-term occupation by Neolithic to Bronze Age cultures). Other features on the floor of the Black Sea are zones of large sand waves and signs of incision, ascribed by Ryan and Pitman to massive currents when flow began through the Bosporus.

The way in which such flooding might have take progressed is testable using hydraulic modelling, although the topographic parameters are complex (Siddall, M. et al. 2004. *Testing the physical oceanographic implications of the suggested sudden Black Sea infill 8400 years ago*. *Paleoceanography*, v. **19**, p. 1-11; DOI :10.1029/2003PA000903). The work of Siddall and colleagues suggests a flow rate of 60 thousand m$^3$ s$^{-1}$, about that of a river as powerful as the Brahmaputra (see *Catastrophic erosion in Tibet* below). That would have taken around 30 years to fill the Black Sea to its present level; far longer than the Biblical 40 days and nights, but quick enough to force sudden, large-scale migration and to live on in legend. The model fits with the seabed sand waves and channelling, and being based only on known topography and post-glacial sea level rise, rather than the myths, it carries weight scientifically. However, little is known about the way in which young sediments in the Black Sea basin formed, and proper documentation awaits their coring.

Catastrophic erosion in Tibet (September 2004)

The world’s most awesome natural spectacle is probably the Brahmaputra River in full spate. Unlike most large rivers, it is constrained for most of its course within a deep, narrow gorge that has to take the snow melt from a huge catchment on the northern flank of the High Himalaya, brought partly by the Tibetan Tsangpo River. Each spate hurtles onto the plains of Bangladesh, loaded with debris, at a rate of around 70 thousand cubic metres per second. Although that is but a third of the flood discharge of the Amazon, for much of the Brahmaputra’s course it must pass through a gorge only a few hundred metres wide in places. This gives not inconsiderable erosive power, indeed probably the highest anywhere. Not surprisingly, little is known about the Tsangpo-Brahmaputra valley, because of its inhospitable character.

With the recent release of ~90m resolution elevation data from the Shuttle Radar Topography Mission, it is now possible to analyse the whole catchment’s morphology in detail, without needing to follow the individual rivers. Parts of the lower Tsangpo have remarkably high gradients, including a 100 km stretch with a fall of more than 2 km, through a gorge with almost 7 km of relief on either flank that cuts N-S across the axis of the Eastern Syntaxis of the High Himalaya. The gorge lies downstream of a west to east stretch with lower gradients, falling around 1 km in 300 km, which suggests some dramatic incision begins at the junction of the two sections. US and Chinese geomorphologists visited the area and discovered that high on the flanks of the upper Tsangpo are terraces of lacustrine sediments, at about 3100 and 3500 m (200 and 600 m higher than the river) (Montgomery, D.R. et al. 2004. Evidence for Holocene megafloods down the Tsangpo River gorge, southeastern Tibet. *Quaternary Research*, v. 62, p.201-207; DOI: [10.1016/j.yqres.2004.06.008](https://doi.org/10.1016/j.yqres.2004.06.008)). Charcoal in the sediments gives radiocarbon ages between 1200 to 1600 BP and 8800 to 9800 BP for the lower and higher terrace levels, so the lakes formed during the Holocene. The terraces stop at a zone of thick glacial moraine, cut by the Tsangpo, which suggests that both formed in lakes behind two ice dams. Using SRTM data allows the volume of water ponded in both ice-dammed lakes to be estimated. The older and higher level indicates about 830 km³, and the lower some 80 km³. Breaching of the dams would have caused the largest recorded erosive events in recent Earth history, and explains the gorge below. Each flood discharge would have been between 1 and 5 million cubic metres per second, equivalent 3 to 15 times the maximum flood discharge of the Amazon.