Geomorphology

How patterned ground forms (*January 2003*)

Patterned ground in northern Alaska (Credit: Feuillet & Certini, 2014; Fig.1)

Visiting flat areas of permanently frozen ground brings you face to face with truly bizarre patterns at the ground surface. Some are perfect hexagons of stones around finer soils, others doughnut-like circles and then a perplexing range of other features that look for all the world as though they were built by humans. Undoubtedly, they result from the forces at work when the top soil layer freezes and thaws annually, together with soil creep down extremely shallow slopes, repeated over millennia. However, exactly how the patterned ground develops has eluded geomorphologists for more than a century. Rejecting the reductionist approach that any landform's evolution can be deduced from basic principles of physics seems to be the key (Kessler, M.A. & Werner, B.T. 2003. Self-organization of sorted patterned ground. *Science*, v. **299**, p. 380-383;). Kessler and Werner of the University of California modelled the two likely processes of ice lensing that sorts stones and finer soil, and the transport of individual stones along the lines of accumulated stones as freezing fines expand, building in elements of spatial and time scales plus other parameters such as surface slope. Their model is self-organising, and proceeds to mimic many of the intricacies of patterned ground, even the most labyrinthine. It might seem a little heavy handed to crunch numbers to help explain what are really quite minor features. But having demonstrated the power of non-linear modelling here, the authors open up a novel approach to landscape evolution of every scale and antiquity.

Catastrophic floods and denudation (April *2003*)

Working out the rate at which landscapes evolve depends on some means of dating surfaces formed at different stages in the cutting down of topography. Modern studies rely to a large extent on the build up of isotopes, such as ^{10}Be, that form in minerals no more than a metre or so beneath the Earth's surface when they are exposed to cosmic ray bombardment. If such transmuted nuclides stay in place, for instance on a relic surface or a series of alluvial terraces, cosmogenic isotope analysis dates the formation of that surface. No matter how precise such surface dating can be, and currently there is a slop of around 20% either side of an age, there is a limit to the number of suitable surfaces. So, the continual degradation of landscape can only be sampled at a few isolated times. At best, an average denudation rate over long periods is all that geomorphologists can hope for. The same goes for analysis of the range of times during which grains in sediment were exposed to cosmic rays, before they were eroded, transported and finally protected from bombardment when they were buried in alluvium, which is another approach to timing erosion. Average rates of erosion are useful in assessing some aspects of landscape development, but they are not much good for judging how it took place. Standing in some awesome scenery easily gives the impression that it must have evolved by some continuous, steady process, and there is a long tradition dating back to James Hutton that views surface processes in that way. Changes in rates have been seen as responses to "rejuvenation", either by falls in the base-level of erosion or tectonic uplift to add gravitational potential to a region that makes flowing water more energetic.

Another approach is to look at the actual transfer of mass, either carried by rivers during different seasons or in the volumes of sediments that were deposited by recognisable individual events, such as a flood. In large river basins that have a low average gradient it is well-accepted that occasional floods don't have much effect on sediment movement in the long term, but most of the sediment moved in such basins is alluvium already supplied by earlier processes. In mountainous areas rivers carry material directly from bedrock and the regolith that lies on it. Anyone who has witnessed flash floods in a normally crystal clear mountain river knows their awesome power. They become mud torrents studded with boulders that even fly through the air; they are debris flows rather than streams in the normally accepted sense. Such flows are episodic, but frequently annual, and exert a major influence over denuding the landscape. Yet over millennia, they too should maintain a consistent down wearing. In the Appalachian mountains of the eastern USA denudation rates seem to average out between 2.5 to 5 centimetres per thousand years. However, four catastrophic Appalachian storms in the late 20th century, related to hurricanes, had an astonishing effect on erosion there (Eaton, L.S. *et al*. 2003. Role of debris flows in long-term landscape denudation in the central Appalachians of Virginia. *Geology*, v. **31**, p. 339-342; doi: 10.1130/0091-7613(2003)031<0339:RODFIL>2.0.CO;2). Carbon-14 dating of ancient mass-flow deposits formed in Virginia by comparable storms indicates recurrences in particular drainage basins around every 2500 to 3500 years. During that time the average rate of erosion would have denuded the surface by a measurable amount (5 to 10 cm), yet the recent storms removed between 47 to 63% of that expected during periods measured in millennia. The Appalachians are well vegetated, and therefore well protected from the effects of extreme floods compared with the surfaces of really big mountains such as the Himalaya and rugged areas in arid regions. The obvious question is, "Are average denudation rates, no matter how precise, very relevant to the way landscapes actually develop?" It is an important one, because weathering of debris from mountains is regarded by many geochemists as a means of taking carbon dioxide from the atmosphere – silicate weathering that involves CO_2 dissolved in rainwater locks atmospheric carbon in bicarbonate ions that carbonate-secreting creatures in the sea can sequester to deep storage when they die. If about half the erosion of mountains is in widely separated catastrophes, which shift and then dump debris in a matter of days, then it is possible that the sums based on equating rates of weathering with those of erosion are not entirely valid. Weathering of continental silicates is one means of forcing global cooling by reducing the greenhouse effect, and understandably mountain rivers teem with researchers sampling the water and sediment load, especially in the Himalaya. If the bulk of debris shed to plains, such as those of the Indus, Ganges and Brahmaputra, never had time to be weathered at high altitude because it moved in catastrophic pulses, then maybe the sampling should be done somewhere else. Processes in the vast alluvial tracts far below high mountains are slower and more constant wit time, so maybe looking at groundwater that moves through them might add to the current research..

Cosmogenic nuclides and tropical erosion (July 2003)

In the highlands of central Sri Lanka the sediment suspended in rivers suggest rates of soil loss from agricultural land of the order of up to 7000 tonnes per km^2 each year. However, it is difficult to judge how much would be eroded under natural conditions, compared with the probable loss as a result of deforestation and human activities, particularly from very rugged landscapes where seasonal rainfall is high.. Radionuclides produced by cosmic-ray bombardment of minerals exposed to them, such as ^{10}Be and ^{26}Al, accumulate in soil that is being eroded at a rate that is inversely proportional to the rate of erosion. The nuclides form in the top 0.6 m of soil, which is the depth within which cosmic rays are normally absorbed. So erosion rates that can be calculated from the cosmogenic nuclides in minerals, such as quartz, in river sediments apply to the times taken to remove that depth of soil. Essentially, the rates that are measured represent the long-term erosion within a catchment basin. Swiss and Sri Lankan geoscientists have applied the technique to rivers in central Sri Lanka, whose catchments have different vegetation cover and land usage (Hewawasam, T. *et al*. 2003. Increase of human over natural erosion rates in tropical highlands constrained by cosmogenic nuclides. *Geology*, v. **31**, p. 597-600; DOI: 10.1130/0091-7613(2003)031<0597:IOHONE>2.0.CO;2), such as forest reserves, rice terraces, tea plantations, areas of slash and burn agriculture, and various levels of degraded land. The unmodified forest catchments give the lowest long-term erosion rates of 5-11 mm per 100 ka (13-30 tonnes per km^2 per year) as expected, but this is about a quarter of the rate of erosion measured by the same method throughout the highland region. That probably reflects the antiquity of erosion induced by agriculture, yet current rates measured from sediments being carried by rivers suggests that soil erosion is now between 10 and 100 times faster than would occur under natural conditions.

Wildfires and uplift chronology (*December 2003*)

The "next big thing" in geomorphological studies has been said to be precisely dating crustal exhumation during erosion and uplift. Fission tracks produced in some minerals by particles emitted by radioactive isotopes within them are preserved only when temperature is below that at which annealing can take place. That temperature varies from mineral to mineral. By counting the tracks it is possible to estimate the time since the containing mineral cooled below its annealing temperature during its rise to the surface. Analysing surface samples from different topographic elevations in an area can therefore build up a history of uplift, those lowest in the section being the last to pass through the temperature, and vice versa. Similarly, radiogenic gases only accumulate in a mineral once it cools below a temperature at which the molecular structure blocks diffusion of the gas from the mineral. One example is radiogenic argon produced by decay of ^{40}K. Ages of potassium minerals, such as micas and feldspars, determined by the Ar-Ar technique relate to the time when the containing samples rose through the blocking temperature. There are numerous problems with fission track dating, although most users assume that the ages that they get are real. For Ar-Ar "thermochronology" the blocking temperatures are above 150ºC, which is also problematic, because for a normal continental geothermal gradient of 30ºC km^{-1} a sample would have to rise 5 km to reach the surface before yielding an age relevant to uplift and erosion history. Unless a study area has much higher geothermal heat flow, or has undergone enormous rapid uplift, most ages obtained by such studies are much older than the event of interest. In the case of helium, the blocking temperatures are lower, about 70ºC in the case of apatite. So dating the accumulation of helium produced by decay of uranium and thorium in apatite offers a tool that seems near-ideal for studying rapid exhumation of the order of a couple of kilometres, and that seems likely for many mountain belts and continental margins.

It is the apatite U-Th/He dating method that has spurred a flurry of new studies, now that mass spectrometry is capable of precisely measuring the tiny amounts of helium in single apatite grains. But that has its drawbacks too. On that is pretty obvious is the effect of heating of the surface in recent times. Sara Mitchell and Peter Reiners of the universities of Washington and Yale studied the effects of biomass burning on the method (Mitchell, S.G & Reiners, P.W. 2003. Influence of wildfires on apatite and zircon (U-Th)/He ages. *Geology*, v. **31**, p. 1025-1028) because modelling suggests that fires can reset apatite ages. They found that resetting and scrambling of ages does indeed occur, down to depths of 3 cm in surface samples. That casts doubt on this dating not only on detrital apatites found in soils and sediment, but also in rocks, unless the exposed surfaces are ground away before separating mineral grains. Fires are not the only means of heating rock surfaces, and high temperatures are experienced daily by many rocks due simply to solar heating at low latitudes. This affects depths down to as much as 30 cm, especially in rocks with a dark surface. It is possible to fry eggs on exposed rock in some parts of the world, though they are not very appetizing.