# Hunting monsters

## The search for earthquake ruptures in the Himalayas

Disaster struck in the summer of 1255. The people of Kathmandu valley had been enjoying the sunny June day when, suddenly, there was a deep rumbling noise and the birds took to the skies. The ground began to shake violently, temples tumbled to the ground, confusion reigned, and dust filled the air. Within minutes, more than 30,000 people had perished, killed by the collapsing buildings, and amongst them was none other than the king himself: King Abhaya Malla.

The 1255 earthquake is the oldest in Nepal's recorded history, but many earthquakes – both before and since – have shaken this region of the planet. Nepal sits astride the largest continental collision zone in the world, making it particularly vulnerable. As the Indian subcontinent moves northwards at nearly five centimetres per year, it collides with Asia, pushing up the Himalayas and forming the Tibetan Plateau. Whilst much of the resulting deformation occurs further to the north, two of the five centimetres per year are taken up along the edge of the Himalayas, where the Indian crust is thrust under Asia. It is here, on what is called the Main Frontal Thrust, that many of the deadliest Himalayan earthquakes have taken place.

During the nineteenth and twentieth centuries major Himalayan earthquakes occurred in 1803, 1833, 1897, 1905, 1934 and 1950 – and yet, until recently, none of these events were thought to have ruptured the surface. Many scientists assumed that these events had occurred on 'blind' thrusts within the crust: the earthquakes hid at depth, leaving no traces behind at the Earth's surface. If this were the case, scientists worried, that meant there was still strain to be released and even larger earthquakes could occur in the future. Furthermore, if an earthquake breaks the surface and the resulting scarp is buried by sediment, then the sediments just above and below the top of the scarp can be dated to bracket the age of the earthquake – but without surface ruptures, the timing of historical earthquakes can be hard to determine. In essence, the situation was, and to some extent still is, poorly understood. How often do earthquakes occur in the Himalayas? How big do we expect the next earthquake to be? Do these plate boundary megathrusts generate large earthquakes every few hundred years or giant earthquakes every few thousand years?

Some recent research, published last December in *Nature Geoscience* (Sapkota et al., 2012), has begun to address these problems. The team of scientists, from France, Singapore and Nepal, set out on a hunt for some of the elusive surface ruptures. Using satellite images and aerial photographs taken by helicopter, they honed in on a portion of the Main Frontal Thrust between the city of Bardibas and the eastern border of Nepal. They also chose this area for fieldwork because it lay within the zone of the most intense shaking during the 1934 Bihar–Nepal earthquake. Here they found

Helicopter view of the Sir River alluvial terraces and cumulate escarpment along the Main Frontal Thrust in eastern Nepal. The 1255 and 1934 earthquake scarp follow the sharp contact between the deeply incised Siwalik sandstone folds in the background and inset terraces in the foreground. The rivercut cliff and 43-m-long trench in which the surface breaks of the past earthquakes have been discovered are visible to the right of the river course. (Credit: Laurent Bollinger)

evidence of recent faulting at a site where the Sir River cuts across part of the thrust. They mapped the heights of river terraces, dug a 43-metre-long trench across the fault, and collected charcoal samples for radiocarbon dating. Reassuringly, their dates were consistent with an earthquake occurring here in the first half of the twentieth century.

In retrospect, they suggest, it's perhaps unsurprising that that 1934 rupture was never found at the time. The area was densely forested and sparsely populated: only two roads crossed the Main Frontal Thrust and malaria was endemic. After the earthquake, people were, understandably, more concerned about the damage on the Ganges plain (where sediments had amplified the shaking) than by the need to search for a rupture. Furthermore, in many places the fault scarp would have been rapidly obliterated by the monsoon rains.

But the 1934 rupture wasn't all. The team's trench investigations also revealed evidence of an older earthquake on the same portion of the fault. According to their logging and dating it was this event that was responsible for the death of King Abhaya Malla in 1255. The result is interesting: it implies that rather than one giant earthquake occurring every few thousand years, this portion of the Main Frontal Thrust has seen two slightly smaller earthquakes separated by an interval of just a few hundred years. "The discovery of two great earthquake ruptures, separated by 679 years, is unique in the Himalayas", explained Dr Bollinger, one of the authors on the recent paper, "although we are far from determining a mean recurrence interval or discussing the validity of a characteristic earthquake model with these two earthquake records, it is still nice information. It helps reduce the uncertainties we had on the great Himalayan earthquake sources in seismic hazard assessment studies."

Seismic hazard assessment is vital in this region of the world. One seventh of the entire global population lives on the Indo–Gangetic plain – the fertile strip of land that abuts the Himalayas. Since the great earthquake in 1905 the population has increased tenfold. The capital cities of Bangladesh, Bhutan, India, Nepal and Pakistan are all vulnerable. Today, more than 50 million people are at direct risk from the next great Himalayan earthquake: never has such a densely populated part of the world been in such danger.

This is why more research is urgently needed. "I am almost certain more surface ruptures are preserved along strike [in the] Himalayas", says Dr Bollinger. "It's currently what motivates us to persevere in the direction we've taken these last five years."

The hunt for other Himalayan monsters is definitely on.

*Tim Middleton*

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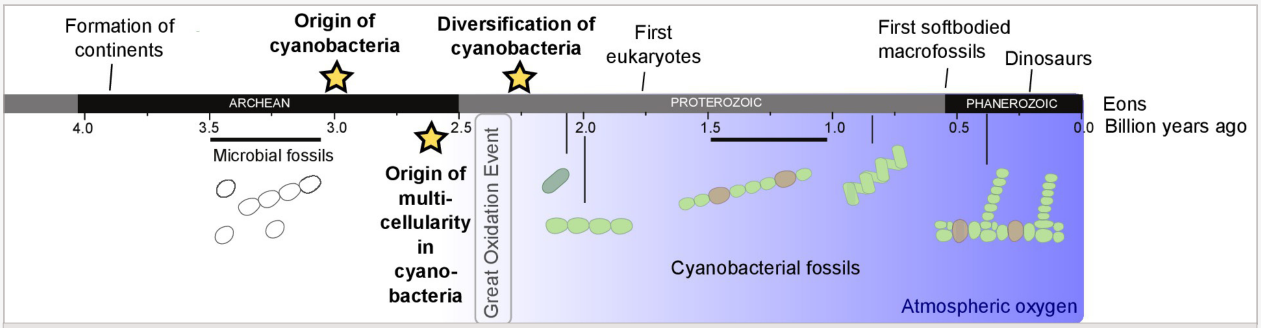
# Understanding the role of cyanobacteria in the Great Oxidation Event

One of the most significant events in Earth's history has been the oxygenation of its atmosphere 2.45–2.32 billion years ago (Bya). This accumulation of molecular oxygen in the Earth's atmosphere was so significant that it is now commonly referred to as the Great Oxidation Event (GOE). The long-reaching effects of the GOE were literally world-changing, altering not just the composition of the atmosphere and hydrosphere but, through various redox reactions, the continents and climate also. However, and perhaps from an anthropocentric viewpoint, the most important effect would be upon the biosphere; the GOE paved the way for the evolution of aerobic (oxygen respiring) organisms, including ourselves.

Through various geochemical proxies, the effects of the GOE can be easily traced, but whether or not this event represents either a




Timeline of the evolution of Earth. Continents formed ~3.8 Bya, after temperatures had cooled and meteorite bombardment had stopped. In ~3.46 billion year old rocks (Australia) first evidence for life is found. Around 2.45–2.32 Bya, oxygen accumulated in the atmosphere during the Great Oxidation Event (GOE) produced by cyanobacterial oxygenic photosynthesis. The oldest cyanobacterial fossils can be found in the Gunflint Chert (1.88-2.0 Bya). The first eukaryotes evolve around 1.6-1.8 Bya. By applying phylogenetic methods to living taxa and combining results with fossil estimates, the origin of multicellularity in cyanobacteria could be determined. The results support theories which suggest an origin of cyanobacteria in the Archean Eon and an evolution of multicellularity before the GOE. (Credit Schirrmeister et al., 2013) sharp increase in oxygen production or a reduction in oxygen sinks still remains to be discerned. With so much ambiguity over the dynamics of the GOE, it may be surprising to discover that there is a long-standing consensus on how the oxygen was actually produced: photosynthetic organisms called cyanobacteria (blue-green algae).

Cyanobacteria represent one of the most morphologically diverse groups of prokaryotic organisms (bacteria and archaea). They are classically separated into their various biological groups by their morphology; some groups are unicellular, others are multicellular and then there are those that can produce differentiation between cells. However, genetic studies show that this morphological grouping is not representative of actual biological relationships between cyanobacteria and that morphological characteristics such as multicellularity evolved independently in several lineages.

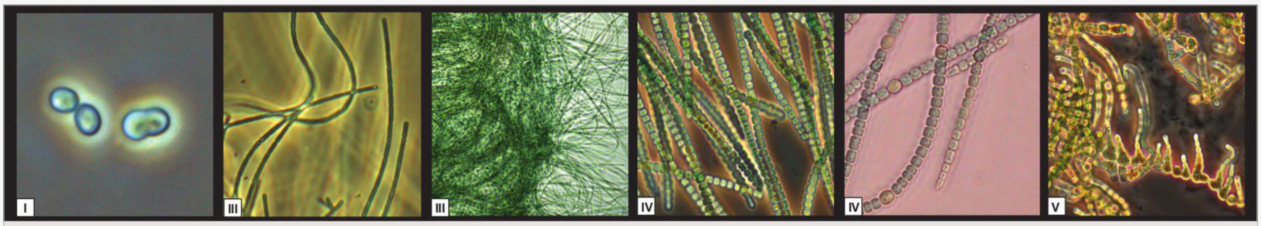
Fortunately, relative to other prokaryotes, cyanobacteria have a well-studied fossil record. This has led to the realisation that much of the diversity in modern forms existed early on in the evolutionary history of the group; they have in fact changed very little in basic form over billions of years. This is best exemplified in the 2 Bya Gunflint Chert, where the first unequivocal evidence of cyanobacteria can be found. Single-celled (coccoidal) and multicellular (filamentous) forms are both present and show very little superficial variance from their modern counterparts. Prior to this, potential evidence for cyanobacterial existence is found in the form of trace-fossils, so called stromatolites. These are large sedimentary structures, formed by the interaction of photosynthetic bacterial mats (commonly, but not always, cyanobacteria) and sediment. The bacterial mats snare and concrete sediments around them, forming a consolidated calcareous structure. The photosynthetic bacteria then propagate through to the top surface and the cycle repeats eventually forming large columns. Stromatolites have been observed as long ago as ~3.45 Bya, persisting through to the modern day, suggesting that photosynthetic organisms were present at this time, even if not necessarily cyanobacteria.

Although cyanobacteria are fairly well accepted as the main source of oxygen for the GOE, their role in the event remains unclear. Were they indirect contributors, having existed fairly unchanged for billions of years, when at 2.45 Bya tectonic events caused the cessation of oxygen sinks? Or were they the driving force behind the GOE representing a biological revolution in cyanobacterial forms? Without discovery of any direct fossil evidence older than the 2 Bya Gunflint Chert this may seem an impossible question to ask, yet a team from the University of Zurich, led by Dr Bettina Schirrmeister, conducted a phylogenetic analysis of living and fossil cyanobacteria in the hope of providing an answer.

Phylogenetic analyses are statistical methods for testing relationships between any group of individuals based on their shared characteristics and the number of differences from one individual to the next. This provides not only a quantifiable hypothesis of relationships between organisms, but a hypothetical evolutionary 'pathway of least resistance' through which each organism evolved. Even though a hypothetical family tree, including all of its relationships and evolutionary branches, is produced, unless each branch has a temporal association, it is useless in answering the questions as to the relation of cyanobacteria to the GOE. This is where the fossil record of the cyanobacteria can be used. If you are able to assign a fossil to any particular group, then you can assign a minimum age of origin for that group. However, bearing in mind that the fossil record of cyanobacteria only exists from around 2 Bya, how could they estimate times of evolution for those groups beyond this point?

This is where genetic studies of extant cyanobacteria come into play: by determining the number of differences between cyanobacterial genomes and dividing this by the observed mutation rates in modern specimens, the point where different species diverged can be estimated. These divergence times can then be incorporated into our temporally constrained evolutionary tree. The study showed that all extant lineages of cyanobacteria existed from before the GOE in the Archaean Eon, a result that was repeated in all permutations of the analysis. This was not particularly surprising given the diversity of fossils already present in the 2 Bya Gunflint Chert and the rarity of fossil yielding localities. However, there were some significant coincidences between the GOE and hypothesised cyanobacterial divergence events. The evolution of multicellularity was resolved at, or just before, the onset of the GOE, with the emergence of the majority of the modern lineages shortly after the accumulation of atmospheric oxygen.

What this shows is that the cause of the GOE, at least in part, was not the ascendance of any particular group of cyanobacteria, but a revolution of form in multiple lineages. Multicellularity would have enabled an increase in motility and produced favourable metabolic economies of scale, both obvious advantages. As a respiratory by-product, oxygen would most likely have been toxic to much of the biota. Increased oxygen levels would likely have created an evolutionary pressure on the cyanobacteria, and in response, driving their evolutionary radiation into the diversity of forms we see today.




The morphologies of cyanobacteria (unicellular and multicellular taxa). Classically cyanobacteria have been grouped into five 'sections' according to their morphology, with sections I and II describing unicellular taxa and section III–V comprising multicellular species. However, molecular data have shown that none of these sections are representative of true biological diversity because multicellularity has evolved independently in many different groups. (Credit: Schirrmeister et al., 2011).

However, in identifying this concurrence, many more questions regarding the evolution of multicellularity are raised: why did it occur when it did? Was it the sole driving force behind the GOE? The one thing we do know is that this association exists and it paved the way for the evolution of the planet as we now know it.

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# Piecing together the puzzle of past climates

## Melting of the West Antarctic Ice Sheet and sea-level rise

Climate change – a buzzword for the media industry. They may choose to argue against it, or embrace it with visions of soaring or plunging temperatures, catastrophic flooding and disastrous hurricanes. It all makes for a terrific screenplay (remember *The Day After Tomorrow*?) but the truth, inevitably, is a little less dramatic.

While we don't yet fully understand how the world's complex climate system operates one thing is clear: current data series for rates of change are short – some of them 50 years or less – and if we are to predict how climate might change in the future with any degree of accuracy, then we need to better comprehend how it did in the past. Results of studies, such as that conducted by a multi-organisation team and led by the British Antarctic Survey's Claus-Dieter Hillenbrand (published in *Geology*), are vital additional pieces for the jigsaw of our understanding.

### The West Antarctic Ice Sheet

The cryosphere plays a crucial role in the climate system through its close coupling with both the atmosphere and the hydrosphere. Numerous recent studies from the International Panel on Climate Change (IPCC) and others have shown that not only is Arctic summer ice cover shrinking rapidly but that land-based ice sheets in both the northern and southern hemispheres are melting at an increasingly high rate. Indeed, another large-scale international study, led by Professor Andrew Shepherd of the University of Leeds, concluded that the ice sheets of Greenland and West Antarctica lost an average of approximately 298 Gt of ice annually over the period 2000–2011, compared to just 100 Gt/year between 1992–2000.

But is the rate observed in West Antarctica unprecedented, and if it is, how do we know?

Dr Hillenbrand and his team used sediment cores taken from the sea bed to identify the historic extent of the Western Antarctic Ice Sheet (WAIS). Evaluating the sediment structure of the cores revealed a depositional setting typical of the ice sheet edge and radiocarbon dating the calcareous microfossils within them enabled them to determine its maximum extent during the last glaciation. And the findings? The results, which covered a 10,000 year period roughly since the end of the last glacial maximum, revealed that the WAIS has retreated by up to 110 km.

RV Polarstern in Pine Island Bay, Antarctica. (Credit: Claus-Dieter Hillenbrand)

So what does this mean, and how does it compare with modern rates of retreat? According to Dr Hillenbrand 110 km or so "is just 3.5 times the distance it has retreated within the last 20 years." Which means that the recent rate of melt (since 1992) is, as he says, "exceptional (but not necessarily unprecedented) during the last ten millennia."

### Why does the melting of the Ice Sheet matter?

Though we don't fully understand all the interactions and feedbacks which the cryosphere has with the climate system as a whole, the Antarctic ice sheet, along with those of Greenland and elsewhere, is crucial to the climate system. The United States Geological Survey estimates that in total land ice covers around 10% of the Earth's surface and holds around 69% of its freshwater.

At present the WAIS is estimated to contribute an increase of around 0.15–0.3 mm per year to global sea level – but, as Dr Hillenbrand

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points out, the loss of the glaciers which flow into the Amundsen Sea alone would raise sea levels by around 1.5 metres. If the rate of melting identified here is representative of rates elsewhere then this is potentially catastrophic news for some areas of the world – not just island nations but those with extensive, densely-inhabited low-lying coastal plains. In Bangladesh, for example, the UN Development Programme estimates that a sea level rise of one metre would inundate an area of approximately 25,000 km$^2$, devastating the agriculture in coastal Bangladesh and increasing the potential for damaging storm surges.

There are, of course, other deleterious impacts. A sudden influx of cold, low-salinity water can affect the ocean's thermohaline circulation, driven by differences in temperature, density and salinity. An influx of cold water from the Greenland Ice Sheet, for example, might disrupt the Gulf Stream. This would cause climatic cooling in northern and western Europe – though the timescales for this are unlikely to be immediate.

## Another piece in the jigsaw

The BAS-led study may seem a small one, with its focus on a single part of the ice sheet, but its findings do more than just demonstrate an extremely high rate of recent melting. By providing data on past rates, it provides crucial information that feeds into predictive climate models. Dr Hillenbrand states that "If the models provide a reconstruction that is consistent with the real data about past ice-sheet behaviour we can be confident about the reliability of their results and then we can trust their predictions of future sea-level rise and respond accordingly."

Comparing the exceptional recent rate of WAIS melting with the longer-term retreat identified by the study certainly gives cause for concern – but it also gives hope. With such information coming on stream, the accuracy of climate modelling can be improved and we may begin to equip ourselves with the tools to better understand, and possibly combat, climate change.

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# Interview with soil-scientist Jorge Mataix-Solera

*Jorge Mataix-Solera (Environmental Soil Science Group, Miguel Hernández University of Elche, Spain) talks to us about his research into the effects of forest fires on soil properties and the importance of working with natural processes in forest fire management.*

### Could you tell us a little about yourself and your field of research?

I studied the modifications in soil properties as a consequence of forest fires during my PhD, and this continues to be my main research area. I often work in collaboration with research teams from around the world, in this and other lines of research, such as developing soil quality indices and the use of treated wastewaters for irrigation. Currently our research is especially focussed on soil water repellency and aggregate stability in fire-affected areas and in the post-fire management practices used to avoid soil degradation.

### What are the oldest soils in the Mediterranean Basin, and how does their response to fire compare with that of other soil types?

In Mediterranean areas there are a wide diversity of soil types, one of the oldest are *terra rossa*, a reddish clayey to silty-clay material, which covers limestones or dolomites. The red colour is due to the iron oxides accumulated from the long-term weathering of the parent material. In contrast with other soils of the region, *terra rossa* has a very low susceptibility to becoming water repellent after burning. The factors that seem to control this behaviour are the relatively low ratio soil organic matter/clay content compared to other forest soils in the region, and the high presence of kaolinite (due to the high stability of this mineral in Mediterranean soils). These very old soils have accumulated kaolinite through the dissolution of the rock over time, whereas other less stable minerals have been weathered away.

Our results suggest that the probability of finding water repellency in forest areas affected by fire with *terra rossa* is lower than in areas with other soil types. This means a forest with *terra rossa* is able to better regulate the absorption of water into the soil after a fire. For example, there is no increase in runoff rate as a consequence of water repellency, thus promoting the restoration of vegetation and preservation of the soil after a fire.

### How do forest fires influence soil properties and what are their hydrological implications?

The changes in soil properties as a consequence of forest fires depend on factors such as fire intensity (a function of fuel type, quantity, degree of moisture, and weather patterns), soil type and its conditions at the moment of fire spread (e.g. soil moisture). All of this will control how severe the effect of the fire is on the soil properties. For example, fire usually induces water repellency in soils. This corresponds to a reduction in infiltration rates, increased runoff and erosion in fire-affected soils. The strength of these effects depends on the temperatures reached in the soil and the soil type, with some having a very low susceptibility to developing this

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Jorge Mataix-Solera in Breacon Beacons, Wales, in 2012. (Credit: Jorge Mataix-Solera)

property. Another example of complex behaviour is soil aggregate stability (the resilience of the soil's structure in response to external mechanical forces) and many authors consider soil aggregation to be a parameter reflecting soil health, as it depends on chemical, physical and biological factors. The response of aggregate stability to forest fires is complex, since it depends on how fire has affected organic matter content, soil microbiology, water repellency and soil mineralogy. There are many different patterns of response to fires and for this reason it is important to know how fire affects different types of soil, and to develop specific protocols of assessment in fire-affected areas.

### How must we manage fire-affected areas to avoid post-fire soil degradation?

In the months after a fire, and before vegetation begins the recovery of the soil surface, the soil must be considered as a very fragile system that can be degraded if we do not take care with the post-fire management practices. Actions involving the use of heavy machinery for the extraction of burned wood can be very harmful to the soil and vegetation that is sprouting and germinating.

In some burned areas it may be necessary to protect the soil against possible erosion by applying straw mulch to the soil surface. This has been very effective, but in some areas, weeks after the fire, scorched pine litter starts to fall and covers the ground to create a magnificent natural mulch. Where the soil and vegetation have been severely affected, reforestation could be unsuccessful, so we can apply an organic substrate, such as composted sewage sludge, which acts as an injection of nutrients and organic matter to improve soil properties.

Restoration of vegetation cover can also be carried out, but it is important to use non-aggressive strategies and avoid the use of a sole species, such as pines, that in a few years can lead to increased risk of a new fire. These decisions must be made after careful evaluation of the affected area and bearing in mind that, where possible, the best reforestation is the natural one, which in many cases occurs since fire is a natural process in the Mediterranean. The problem is not the fire but the alteration of the fire regimes (frequency and intensity).

### How can we improve forest management to prevent catastrophic wildfires?

In Spain and other northern Mediterranean countries, the abandonment of farming activities and poor forest management has led to the development of large high-risk areas in the last five decades. Combining this with a few days of extreme weather risk and lower investment in fire prevention and fire fighting, we have an explosive cocktail. Big forest fires like those in the Valencia region last summer (more than 40,000 hectares affected after only two fires) have high environmental, socio-economic impacts, and what is worst, the loss of human lives. We need changes in forest policy and economic investment to carry out important prevention plans, by reducing the biomass in strategic high risk areas, using low intensity prescribed fires, and herbivores to maintain the land.

We must not be obsessed with the idea of trying to eradicate fire from the environment, as it is part of the natural environmental dynamics. Instead, we must use small fires as an ally that can help us, if well managed, to prevent major ones (the real problem). We must understand that all areas of forest in Mediterranean-type conditions eventually burn. We can only decide how we want them to burn in order to avoid the occurrence of catastrophic, high intensity fires.

### With a greater frequency of forest fires being a possible consequence of climate change, how do you anticipate this will affect soils and ecosystems within the Mediterranean?

It is known that Mediterranean is a fire-dependent system, and that an increase in the recurrence of fires (higher frequency) causes soil and ecosystem degradation. Plant species are adapted to this perturbation but each one has its fire regime, and out of this regime (a change in frequency and intensity) its behaviour will be modified. The soil as a part of the environment will be affected, and for example it is expected that there would be a loss in the soil organic carbon – a significant change as most soil properties are related to organic matter quantity and quality. In summary a loss of soil quality and a degradation of the ecosystem could be expected with a higher frequency of forest fires.

### You have developed an extensive teaching resource using your photographs in the field – how do you think resources like these can best be used to communicate science to the public?

Teaching in geoscience today is easier than it was decades ago. Lots of tools can be used to support the lectures in the classrooms, such as innovative teaching web pages, portfolios, social networks pages, etc. – all of this can help teachers to explain geodynamic processes to their students, but also to communicate science to the public in general. A picture with a very short description can get the public interested in understanding and learning what forces and factors control the landforms. When you know how a landscape has been formed, it becomes more valuable to you.

*Email interview conducted by Sara Mynott*
*EGU Communications Officer*