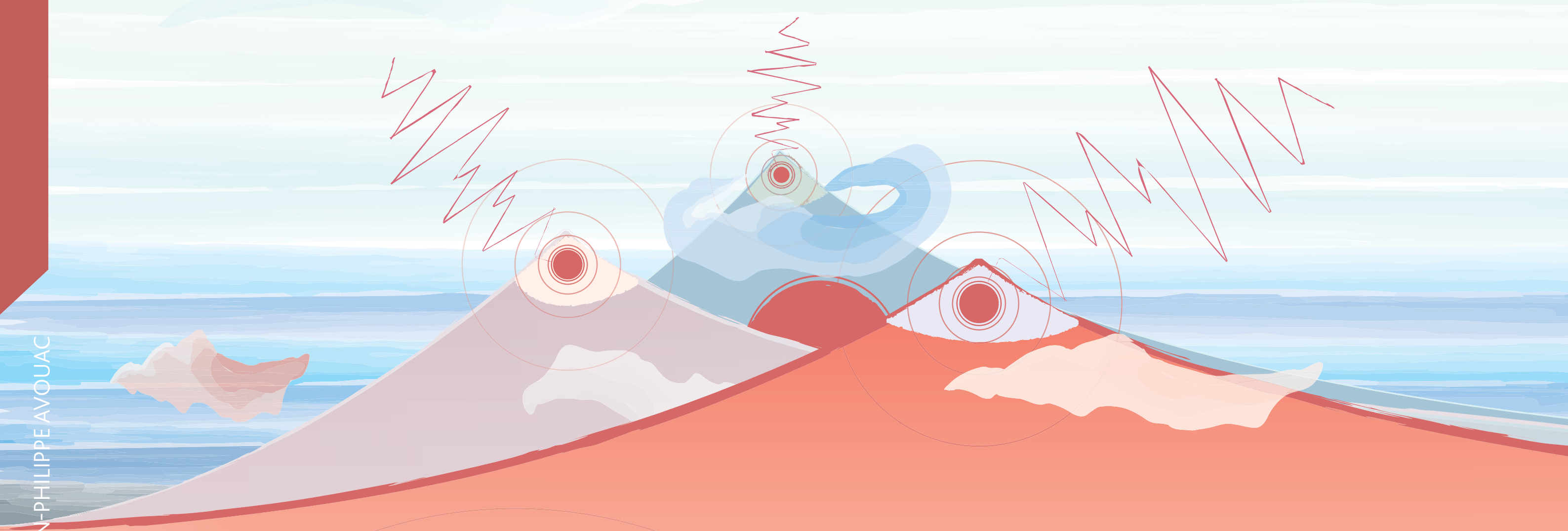

DR JEAN-PHILIPPE AVOUAC

Earthquakes and mountains

Dr Jean-Philippe Avouac's research in the seismic hotbed of the Himalaya is elucidating the key factors behind the size and frequency of earthquakes and their role in mountain formation

To begin, what are the main objectives of the research project?

The main objective is to better understand the physics of earthquakes: how they nucleate, the factors determining how big they can grow and how frequently they occur. A secondary objective is to understand how mountain ranges develop, because earthquakes are one of the processes involved in mountain building.

Why did you focus your research on this particular geographical area?

To study the earthquake cycle, it is best to focus on very active areas because the signals associated with seismo-tectonic activity are easier to measure there than in quieter areas.

Large earthquakes tend to cluster along plate boundaries, but the major faults associated with most plate boundaries are under the sea and are therefore difficult to monitor. Among the plate boundaries running onshore, the Himalaya is one of the largest and most active.

The Himalaya has produced magnitude 8 earthquakes in the past, so we would like to be able to make quantitative predictions for future events, particularly along the 800 km stretch of the central Himalaya that has not produced any large earthquakes for more than four centuries.

How will the results assist with estimating the impact of earthquakes?

My hope is that we will be able to develop physical models that can be used to assess both the wide range of possible earthquake scenarios and the probability of occurrence along particular fault systems. This could help to mitigate earthquake damage, as it should provide more realistic estimates of the possible level of ground shaking used in formulating building codes.

What have been your key findings from the research so far?

Based on our early geological investigations, we have demonstrated that there is essentially one major fault that emerges at the front of the Himalaya in Central Nepal. This is where the large Himalayan earthquakes occur repeatedly over geological time, resulting in the upthrust of the range over the Indian Piedmont.

We have found that the shallow portion of the fault has remained completely locked over the last 20 years, whilst the deeper fault portion slips steadily. Thus stress is building up on the shallow portion and will need to be released by transient slip events (ie. earthquakes). This indicates that the long central segment of the Himalaya, which has remained so quiet over the last century, will probably experience large earthquakes in the future.

One of the GPS stations which are continuously recording ground displacements in the Nepal Himalaya.

© JOHN GALTEZKA

How does the research project form part of Caltech Tectonics Observatory and what is the significance of this observatory?

This research on the Himalaya is one of the projects led by the Tectonics Observatory, which was created eight years ago at Caltech with support from the Gordon and Betty Moore Foundation. Creation of the Tectonics Observatory has allowed very significant resources to be focused on this research. The human resources include faculty, staff and students with a diverse range of expertise spanning geology, geophysics and geochemistry. Financial resources have enabled a first rate network of Global Positioning System (GPS) stations to be built and operated, which has provided unique key data for our research.

How do your interests in mountain formation link into this research and what do you think are the impacts of your results on our knowledge of mountain formation and the link to earthquakes?

Our geodetic measurements have helped quantify the role of both seismic and aseismic deformation processes in mountain building. The research has provided a detailed and well-constrained picture of how deformation is currently taking place across the Nepal Himalaya. By extrapolating our model of deformation and erosion back in time, we can explain the overall topography, cooling history and structure of the Himalayan mountain range over the last 15 million years.

What have been the key challenges in conducting the research?

One challenge has been to deploy and operate the monitoring systems – seismic and GPS networks – in Himalayan conditions. In this regard, I would like to acknowledge the important role of my collaborators at the California Institute of Technology, the Analysis and Monitoring Department of the Environment (DASE) at the CEA in France, and the Nepalese Department of Mines and Geology.

The other key challenge has been obtaining funding to operate experiments for the kind of duration that is needed for this research. The resources provided by the Tectonics Observatory at Caltech have therefore been critical.

Seismicity and strain in the Himalaya

An earthquake in the Himalaya could have major implications on the local population. The **California Institute of Technology** is monitoring and modelling strain to enable more precise earthquake hazard assessment

DR JEAN-PHILIPPE AVOUAC, Professor of Geology at California Institute of Technology (Caltech), is leading a research project of the Tectonics Observatory at Caltech, partially funded by the National Science Foundation, which is investigating seismicity in the Himalaya. He explains the importance of this research: "Our studies provide information to help assess seismic hazard along the Himalayan front, which is a major societal concern. In 1934, one of the last major earthquakes in the Himalaya destroyed most of Kathmandu at a time when the population was only a small fraction of what it is today". If a similar magnitude 8 earthquake was to occur again there or elsewhere in the Himalaya, the death toll could be dramatic given the high density of the population now living in the intramontane basins (such as the Kathmandu or Kashmir basins for example), in the Himalayan foothills, and in the plains of Northern India. This is a significant concern, as the magnitude 7.6 earthquake of 2005 in Kashmir, a moderate earthquake by Himalayan standard, killed about 85,000 people.

Specifically, Avouac's team aims to determine the pattern of locking on the Main Himalayan Thrust fault (MHT), assessing the relationship between interseismic strain buildup and seismicity. This will enable them to analyse the relationship between seismicity and strain rates, and to determine the physical laws that govern how seismic ruptures nucleate, grow and arrest. From this they will develop models of the seismic cycle in the Himalaya that will yield the range of possible earthquake scenarios and their probability of occurrence.

To achieve this goal, researchers on the project are analysing the spatial pattern and temporal evolution of geodetic strain and seismicity using data from a Continuous GPS (CGPS) network, which has been deployed as part of a collaboration between the Department of Mines and Geology of Nepal, the Analysis and Monitoring Department of the Environment (DASE) at the CEA in France, and the Tectonics Observatory at Caltech. The project also utilises data from the National Seismic Network of Nepal.

THE HIMALAYAN MEGATHRUST

Studies of deformed terraces, ancient river beds which were dated to a few thousand years to ten thousands years old in the Sub-Himalaya of central Nepal, have revealed that shortening across the Nepal Himalaya is mainly absorbed by localised thrusting along a major fault, the MHT. This fault has had long periods of stress accumulation and sudden episodes of slip which are probably the cause of large earthquakes.

Geodetic Measurements collected over the last few decades, have shown that relative displacements between the Northern India and the Himalaya range have been small, showing that the shallow portion of the MHT has remained locked. Actually these datasets show that the fault is locked over a width of 100-150 km that extends from the front of the Himalayan foothills to beneath the high Himalayan peaks.

Background seismicity releases only a very small fraction – less than 1 per cent – of the interseismic geodetic strain. Consequently, in the interseismic period, some 'deficit of slip' accumulates, which ultimately needs to be transferred to slip on the locked fault zone. The frequency and location of large earthquakes in the Himalaya depend critically on where and how fast any deficit of slip accumulates in this interseismic period.

This deficit of slip must be balanced by transient slip. The MHT is therefore considered to be the fault which produces the major Himalayan earthquakes. Magnitude 7.6-8.2 events are known to have occurred from historical accounts at various locations along the Himalayan arc, but paleoseismic investigations suggest that even larger events may have happened in the past, with magnitude possibly larger than 8.5. It takes centuries of interseismic strain to accumulate a deficit of slip commensurable with the amount of slip that occurs during large earthquakes, typically 5-10 m. The MHT is thus the equivalent of a subduction Megathrust running on land, with a similar potential to produce destructive earthquakes.

STRESS BEFORE EARTHQUAKE

Local seismic monitoring in the Kathmandu area has revealed clustered microseismic activity, which is driven by stress accumulation near the downdip edge of the locked fault zone. However, the pattern of geodetic strain and the distribution of seismicity show lateral variations, revealing a heterogeneous spatial pattern of stress buildup, which could influence large earthquake ruptures.

The creep rate on the MHT, which drives interseismic shortening, could also vary with time. It is important to assess how the locking of the MHT varies both in space and time, as it might give a clue regarding the physical laws governing fault slip, and also because

SPATIO-TEMPORAL VARIATIONS OF SEISMICITY AND COUPLING IN THE HIMALAYA

OBJECTIVES

The main aims of this project are to:

- Determine the pattern of locking on the Main Himalayan Thrust fault (MHT)
- Assess the relationship between interseismic strain build up and seismicity
- Determine the cause of temporal changes of strain
- Analyse the relationship between seismicity and strain rates and derive implications for earthquake nucleation

PARTNERS

Department of Mines and Geology, Kathmandu, Nepal

Département Analyse et Surveillance de l'Environnement, **CEA**, France

FUNDING

Gordon and Betty Moore Foundation
National Science Foundation - contract no. 0838495

CONTACT

Dr Jean-Philippe Avouac
Project leader

California Institute of Technology
Division of Geological and Planetary Sciences
Mail Code 100-23
Pasadena CA 91125, USA

T +1 626 395 4239
E avouac@gps.caltech.edu

JEAN-PHILIPPE AVOUAC is the Earle C Anthony Professor of Geology at the California Institute of Technology, Division of Geological and Planetary Sciences, and Director of the Caltech Tectonics Observatory. His research aims at a better understanding of earthquake physics, the mechanisms governing crustal deformation and the evolution of the topography. He has authored more than 110 publications in peer-reviewed journals and two patents. In 2010, he was the recipient of the Von Humboldt Award to a Senior Scientist and presented the Birch Lecture at the American Geophysical Union Fall Meeting 2007.

© JOHN GALTEZKA

large earthquakes are releasing cumulative elastic strain that builds up over centuries. Estimating the strain available to drive an earthquake today thus requires taking data that has been collected only over the past few decades at most, and extrapolating it back over centuries.

MODELLING OF DATA

Modelling of the GPS data provides information about where the MHT is locked, and thus accumulating a deficit of slip to be released in future earthquakes, and where it is creeping. This kind of modelling is purely kinematic but provides very useful information about where the fault is being loaded in preparation for future earthquakes.

> These studies provide information to help assess seismic hazard along the Himalayan front, which is a major societal concern

The ultimate goal is to develop a fully dynamic model in which fault slip is driven by the remote forces induced by plate tectonics at the large scale. Such a model should allow prediction of the full range of possible earthquake scenarios, which is difficult to assess from the historical records given that large earthquakes are few and often poorly documented due to their long return periods (centuries or even thousands of years). Such a model requires some knowledge of the friction law describing how fault slip relates to stress, as this law determines whether a fault patch can lock and accumulate stress to be released by earthquakes, as well as how seismic ruptures nucleate and grow. The law might be derived from observing and modelling how seismicity rate depends on strain rate. Particular attention is therefore focused on detecting variations of strain and seismicity.

SEASONAL VARIATIONS

Avouac's team discovered strong seasonal variations of geodetic strain and seismicity. They found, from comparing with satellite gravimetric measurements of variations in mass at the Earth surface, that these variations are due to surface hydrology. Their analysis shows that groundwater storage variations are indeed particularly strong in the Ganges plain area due to the monsoon regime. The surface-load rise during the summer monsoon induces extension across the Himalaya, while compression follows in the winter when the surface load decreases. The group has also demonstrated that the observed geodetic variations agree qualitatively and quantitatively with this model.

Secular interseismic strain buildup, driven by steady slip on the creeping, deep portion of the MHT, is therefore modulated by surface load variations due to the hydrological cycle. These strain rate variations seem in turn to induce a seasonal modulation of seismicity. Avouac explains why these results are particularly significant: "This finding demonstrates that very small stress changes – induced by a change in the water level at the Earth's surface of a few tens of centimetres – can produce a measurable strain and seismicity signal. Because this signal can be identified and quantified, it can help us understand how earthquakes are born". Ultimately, it constrains the fault friction laws, which can then be used in dynamic modelling of the seismic cycle.

FAULT FRICTION LAWS

Detailed analysis of the correlation between stress and seismicity should help with understanding the earthquake nucleation process and fault friction laws. It is anticipated that the project's findings will advance understanding of the physical parameters that determine whether a fault creeps steadily, or has a stick-slip motion producing repeating seismic slip events. Ultimately, it is hoped that the research will help to determine the spatial and temporal pattern of stress buildup that could lead to future earthquakes in the Nepal Himalaya. This information can then help to develop dynamic models of the earthquake cycle which can be used for seismic hazard assessment, and perhaps one day for earthquake prediction.