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GEOSCIENCE

Dynamics of the Continental Lithosphere

Himalaya, Dynamics of a Giant 3

Current Activity of the Himalayan Range

Coordinated by
Rodolphe Cattin
Jean-Luc Epard

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Himalaya, Dynamics of a Giant 3

In memory of distinguished professors
M. Gaetani, P. Molnar and A. Steck

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Tributes

In the past five years, three of our friends, colleagues and mentors Maurizio Gaetani, Peter Molnar and Albrecht Steck have passed away. Their outstanding contribution to the knowledge of the Himalayan range has influenced many authors of this book. We pay tribute to them in the following paragraphs. We dedicate this book to these three exceptional professors.

The mountains of Asia, and the charm of romantic geology – A tribute to the legacy of Maurizio Gaetani (1940–2017) by Eduardo Garzanti

Student of Ardito Desio, organizer of the 1954 Italian conquest of K2 and younger colleague of Riccardo Assereto, killed by a landslide during the second Friuli earthquake of September 9, 1976, the everlasting love of Maurizio Gaetani for Asian geology began in 1962, with his Thesis fieldwork in the Alborz Mountains of Iran. During summer 1977, as Ladakh opened to foreigners, Maurizio first discovered with Alda Nicora the Cretaceous/Triassic boundary in the Zanskar Range. On August 1, 1981, we took a bus from Delhi to Lahul and crossed with horses and horsemen the Baralacha La and Phirtse La to describe the stratigraphy of the Paleozoic–Eocene succession of the Tethys Himalaya. New expeditions were led by Maurizio to Zanskar in 1984 and 1987 to reconstruct the paleogeographic history of northern India, from the newly identified Early Paleozoic Pan-African orogeny to Upper Paleozoic Neotethyan rifting and the subsequent Mesozoic passive-margin evolution terminated with early Paleogene collision with the Asian arc-trench system.

In the meanwhile, Maurizio's Karakorum adventure had begun with the 1986 expedition to the Hunza Valley. From then on, Maurizio's unique dedication to Karakorum geology is testified by 10 expeditions he led to Chitral, Wakhan, Shimshal and Shaksgam, during which every meter of the stratigraphic section from Ordovician to Cretaceous was measured to reconstruct the opening of Paleotethys and Neotethys and their subsequent closure during early and late Mesozoic orogenies. The amazing amount of work carried out during these surveys is condensed in the magnificent geological map of North Karakorum and summarized in his last paper "Blank on the Geological Map". The legacy of Maurizio Gaetani is to remind us that, no matter how much technology is involved, any scientific adventure is primarily a romantic adventure.

Maurizio Gaetani has contributed to about 50 articles published in peer review journals. Here is a list of his major contributions:

Gaetani, M. (2016). Blank on the geological map. *Rendiconti Lincei*, 27(2), 181–195.

Gaetani, M. and Garzanti, E. (1991). Multicyclic history of the northern India continental margin (northwestern Himalaya). *AAPG Bulletin*, 75(9), 427–1446.

Gaetani, M., Nicora, A., Premoli Silva, I. (1980). Uppermost Cretaceous and Paleocene in the Zanskar range (Ladakh-Himalaya). *Rivista Italiana di Paleontologia e Stratigrafia*, 86(1), 127–166.

Gaetani, M., Garzanti, E., Jadoul, F., Nicora, A., Tintori, A., Pasini, M., Khan, K.S.A. (1990). The north Karakorum side of the Central Asia geopuzzle. *Geological Society of America Bulletin*, 102(1), 54–62.

Zanchi, A. and Gaetani, M. (2011). The geology of the Karakoram range, Pakistan: The new 1: 100,000 geological map of Central-Western Karakoram. *Italian Journal of Geosciences*, 130(2), 161–262.

Always on the cutting edge and looking for new ideas to advance Earth Sciences – Peter Molnar (1943–2022) by Vincent Godard, Rodolphe Cattin and György Hetényi

In the final phase of preparing the three volumes of this book, we sadly learned of the passing of Peter Molnar. Peter was a giant of the Earth Sciences, whose contributions would be too long to list exhaustively in this tribute; he left a remarkably enduring mark on Himalaya–Tibet research.

Peter's scientific career began at a pivotal moment for Earth Sciences. He has significantly contributed to developing and applying the new paradigm of Plate Tectonics. Using innovative approaches based on tectonics, seismology, paleomagnetism and satellite imagery, Peter revolutionized our understanding of continental deformation and lithosphere behavior. Although Peter worked on a wide range of problems and geoscientific contexts, the India–Asia collision and the dynamics of the Himalaya–Tibet system have very often been at the core of his investigations. He has left a lasting imprint on research in this region, particularly by his desire to understand the mechanical processes at work during the deformation of this orogenic system.

Consistent with his comprehensive and integrated approach to geodynamic problems, Peter explored a wide range of ideas and processes related to the Himalaya–Tibet system's global role, and initiated several ideas and research directions that are still active today. One example, among many, is the study of the physical relationships and interaction of mechanisms between the development of Tibet's topography and the Southeast Asian monsoon regime. Among the research fields initiated by Peter, understanding the relationships between erosion, tectonics and climate is undoubtedly one of the most innovative and impactful for our community. Following a series of seminal articles by Peter and his colleagues, the complex interactions between the processes responsible for topographic relief creation and destruction are still actively debated in the Himalaya. Peter's research always focused on a global understanding of these processes, particularly those responsible for the variations in erosion and global sedimentary fluxes related to the evolution of Himalayan orogeny and the late Cenozoic evolution of climate. The fact that so many of these topics are still at the forefront of current research by so many groups worldwide is a major testimony to Peter Molnar's prescience on the dynamics of the Himalaya–Tibet system.

Beyond these outstanding contributions, Peter will be remembered for his great sense of humor and for having always been accessible and available to discuss new ideas with young scientists.

Peter Molnar has contributed to an impressive number of publications, some of which have been milestones in the understanding of the Tibet–Himalaya system:

Bilham, R., Gaur, V.K., Molnar, P. (2001). Himalayan seismic hazard. *Science*, 293(5534), 1442–1444.

Gan, W., Molnar, P., Zhang, P., Xiao, G., Liang, S., Zhang, K., Li, Z., Xu, K., Zhang, L. (2022). Initiation of clockwise rotation and eastward transport of southeastern Tibet inferred from deflected fault traces and GPS observations. *Geological Society of America Bulletin*, 134(5–6), 1129–1142.

Houseman, G.A., McKenzie, D.P., Molnar, P. (1981). Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts. *Journal of Geophysical Research: Solid Earth*, 86(B7), 6115–6132.

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Zhang, P.Z., Shen, Z., Wang, M., Gan, W., Bürgmann, R., Molnar, P., Wang, Q., Niu, Z., Sun, J., Wu, J. et al. (2004). Continuous deformation of the Tibetan Plateau from global positioning system data. *Geology*, 32(9), 809–812.

Geology of the Indian Himalaya – Albrecht Steck (1935–2021) by Jean-Luc Epard and Martin Robyr

Albrecht Steck was the main driving force behind the Himalayan geological research program led at the University of Lausanne over the last 40 years. His work has focused on the Indian Himalaya, particularly on the Mandi to Leh transect. He has directed or supervised eight doctoral theses distributed along this transect. One of the mottos of Albrecht was that any good geological work always starts with a sound geological mapping. Whether in the Alps or in the Himalaya, Albrecht's work excels by the quality of his geological maps. It is becoming a hallmark of Albrecht's work. Indeed, the numerous field missions he led or supervised in Lahul, Zanskar and Ladakh regions allowed the achievement of detailed geological maps covering a remarkable large area of the NW Indian Himalaya.

The research of Albrecht Steck is characterized by the combination of field observations (mapping, stratigraphy, structures and metamorphism) in order to decipher the geometry, kinematics and tectono-metamorphic history associated with orogenic processes. His scientific approach combining a variety of field, structural, petrographic and analytical methods is a hallmark of Albrecht's research. Two publications reflect particularly well the research works led by Albrecht Steck. The first (Steck et al. 1993) concerns a transect from the High Himalayan Crystalline of Lahul to the south to the Indus suture zone to the north; the second (Steck et al. 1998) focused on a complete geological transect through the Tethys Himalaya and the Tso Morari area. The results of these expeditions are also synthesized in a general publication of the Geology of NW Himalaya (Steck 2003). For Albrecht Steck, geology must be made in the field and out of the main touristic roads. His long-term commitment to the detailed study of the NW part of the Himalaya of India significantly contributed to a better understanding of the geology of this region. With Albrecht Steck, the Alpine and Himalayan geological community has lost an eminent researcher and a true Nature lover.

Albrecht Steck has contributed to many geological maps and articles published in peer-reviewed journals. Here are three of his major contributions:

Steck, A. (2003). Geology of the NW Indian Himalaya. *Eclogae Geologicae Helvetiae*, 96, 147–196.

Steck, A., Spring, L., Vannay, J.-C., Masson, H., Stutz, E., Bucher, H., Marchant, R., Tièche, J.-C. (1993). Geological transect across the Northwestern Himalaya in eastern Ladakh and Lahul (A model for the continental collision of India and Asia). *Eclogae Geologicae Helvetiae*, 86(1), 219–263.

Steck, A., Epard, J.-L., Vannay, J.-C., Hunziker, J., Girard, M., Morard, A., Robyr, M. (1998). Geological transect across the Tso Morari and Spiti areas: The nappe structures of the Tethys Himalaya. *Eclogae Geologicae Helvetiae*, 91, 103–121.

Foreword

Rodolphe CATTIN[1] and Jean-Luc EPARD[2]

[1] *University of Montpellier, France*
[2] *University of Lausanne, Switzerland*

The Himalaya is well known as the largest and highest mountain belt on Earth, stretching 2,500 km from the Nanga Parbat syntaxis in the northwest to the Namche Barwa syntaxis in the southeast, with peaks exceeding 8,000 m in altitude. Resulted from the ongoing collision between the India and Asia plates, the Himalaya is frequently used as the type example of a largely cylindrical mountain belt with a remarkable lateral continuity of major faults and tectonic units across strike.

Advances in geoscience over the past few decades have revealed a more complex picture for the dynamic of this giant, with open questions about the initial stages of the Himalayan building, lateral variations in its structures, variations in tectonic forcing, tectonic–climate coupling and assessment of the natural hazards affecting this area.

In this book, we present the current knowledge on the building and present-day behavior of the Himalayan range. The objective is not to be exhaustive, but to give some key elements to better understand the dynamics of this orogenic wedge. The three volumes of this book present (1) the geodynamic framework of the Himalayan range, (2) its main tectonic units and (3) its current activity. The chapters and volumes in this book are self-contained and can be read in any order. However, the three volumes are

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linked and provide together a self-consistent image of the Himalayan dynamic at various temporal and spatial scales.

Volume 3, entitled "*Current Activity of the Himalayan Range*", addresses the couplings and feedbacks between tectonics, erosion and climate. Natural hazards such as earthquakes, floods and landslides are also presented with a focus on recent scientific findings and societal issues. Finally, three studies illustrate the importance of multidisciplinary approaches to understanding the physical and chemical processes involved in Himalayan dynamics.

This volume is coordinated by Rodolphe Cattin (University of Montpellier, France) and Jean-Luc Epard (University of Lausanne, Switzerland) with the help of the editorial team composed of Laurent Bollinger (French Alternative Energies and Atomic Energy Commission, France), György Hetényi (University of Lausanne, Switzerland), Vincent Godard (University of Aix-Marseille, France), Martin Robyr (University of Lausanne, Switzerland) and Julia de Sigoyer (University of Grenoble, France).

All royalties allocated to the authors of this book will be donated to the "Seismology at School" program (see the next pages).

Preface

From Research to Education: The Example of the Seismology at School in Nepal Program

György HETÉNYI[1] and Shiba SUBEDI[1,2]

[1] *Institute of Earth Sciences, University of Lausanne, Switzerland*

[2] *Seismology at School in Nepal, Pokhara, Nepal*

Scientific research aims at observing and understanding processes, and enriching our knowledge. But who is in charge of transferring this knowledge to society, to everyday life? Can we expect any researcher to become a company CEO, an engineer, a policy maker or a teacher? Our answer is no, not necessarily, but efforts can be made in that direction, and there are successful examples.

In the context of Himalayan geoscience research, a tremendous amount of information exists. It cannot be all simplified and all translated to local languages of the Himalaya; nevertheless, we found it essential that such knowledge transfer starts. In the aftermath of the 2015 magnitude 7.8 Gorkha earthquake, through a series of fortunate steps, we found ourselves putting down one of the bricks of knowledge transfer by initiating the Seismology at School in Nepal program. Our primary pathway choice was education: in the short-term, raising earthquake awareness and better preparedness can spread

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through the students to their families, relatives and acquaintanceship; in the longer-term, it is today's school students who will build the next generation of infrastructures.

The program started following a bottom-up approach, with direct cooperation with local schools in Nepal. This ensured motivated participants and direct feedback on the activities and about the needs. The program stands on two main pillars and is described in detail in Subedi et al. (2020a). First, earthquake-related topics have been synthesized and translated to Nepali, together with a series of hands-on experiments, and the local teachers have been trained so that they can teach these in their classes. Second, we have installed relatively cheap seismometers (RaspberryShake 1D) in local schools, which became part of the classroom activities and also recorded waves from earthquakes. This has sparked interest in schools, and the openly and publicly available waveform data is useful for monitoring and research as well. To more closely link these two, we have written a simple earthquake location tutorial that is feasible with typical school computers in Nepal (Subedi et al. 2021).

The program has started in Nepal in 2018; as of 2019, more than 20 schools and seismometers have been involved in the program, and the number is reaching 40 in 2022. There is measurable improvement in students' knowledge (Subedi et al. 2020b), and the feedbacks are very positive. Parallel to classical educational pathways, a series of other activities have been developed in the Seismology at School in Nepal program. Each school has received an Emergency Meeting Point sign in Nepali language. Over 6,000 stickers reminding about earthquakes have been distributed to increase awareness (see Figure 8.10 in Volume 3 – Chapter 8). An Earthquake Awareness Song has been written and composed, and became popular on YouTube (https://www.youtube.com/watch?v=ymE-lrAK0TI). We studied the Hindu religious representation and traditional beliefs about earthquakes (Subedi and Hetényi 2021). Recently, we have developed an educational card game to improve the practical preparation and reaction to earthquakes. Finally, we maintain a website with all information openly available (http://www.seismoschoolnp.org).

The program has so far run on funding that is considered to be small in the research domain, and this has covered the cost of materials and the work in Nepal. More recently, a crowd-funding campaign has been started and evolved successfully – we are very grateful to all funders and donators! In the future, the program aims at growing further, all across Nepal and hopefully all along the Himalaya. This will require more manpower and more funds. The authors of this book have generously given their consent to transfer all royalties to the Seismology at School in Nepal program thank you very much!

There is a strong similarity between this book and the Seismology at School in Nepal program: they both aim at taking research results and carrying them to non-specialists. This book is planned to be published in several languages, and to reach students and interested people around the world. The educational program in Nepal aims at bringing earthquake knowledge to those who really need it as they live in a high hazard area. Both efforts aim at increasing awareness, and, thereby, we hope and wish that their effects reach further across all society.

October 2022

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Subedi, S., Denton, P., Michailos, K., Hetényi, G. (2021). Making seismology accessible to the public in Nepal: An earthquake location tutorial for education purposes. *Bull Nep Geol Soc*, 38, 149–162.

PART 1

Surface Process

1

Orogenesis and Climate

Frédéric FLUTEAU[1], Delphine TARDIF[2,3], Anta-Clarisse SARR[4], Guillaume LE HIR[1] and Yannick DONNADIEU[4]

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[2] *LSCE, Gif-sur-Yvette, France*
[3] *Institut de Recherche pour le Développement, Montpellier, France*
[4] *CEREGE, Aix-en-Provence, France*

1.1. Introduction

Climate is controlled by the incoming solar energy (a quantity that depends on the latitude of the site, the solar constant and the obliquity and climatic precession), the greenhouse effect related to the atmospheric composition and the energy redistribution by atmospheric and oceanic circulation. Climate also depends on the exchanges (energy, matter and momentum) between the components of the climate system: atmosphere, ocean, cryosphere, biosphere, lithospheric surface. A disturbance applied to one or more of these components leads to a destabilization of the system, resulting in climate change. Climate changes have various causes and occur at all timescales. Causes can be internal to the climate system and related to the natural variability of physical processes, such as the ocean–atmosphere coupling or the instability of an ice cap, as well as external to the climate system, such as plate tectonics and one of its features, orogeny.

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coordinated by Rodolphe CATTIN and Jean-Luc EPARD.

In this chapter, we discuss how orogenesis alters the climate system. To do so, we take the example of the uplift of the Himalayan range and Tibetan plateau, as a result of the India–Asia collision (see Volume 1 – Chapter 1). After a short description of the present-day climate in Asia, we describe the climate evolution during the Cenozoic at the global scale and in Asia. We use climate modeling studies to understand the responses of the atmosphere and the ocean to mountain uplift. A climate model is a mathematical representation of the climate system. It simulates the climate at equilibrium with imposed boundary conditions such as paleogeography, atmospheric chemistry, and Earth's orbital parameters. Modifying the boundary conditions thus allows us to quantify the impact of these factors on the climate.

The climatic impact of an orogeny is not limited to the response of the atmospheric and oceanic circulation, but also induces an indirect response of the climate system by affecting the carbon cycle. Indeed, changes in temperature and precipitation that may occur as a result of orogeny will in turn affect the physical erosion of landforms (see Volume 3 – Chapter 2). Additionally, sediments can undergo chemical erosion that will further disrupt the carbon cycle and therefore the climate. Other mechanisms are also likely to act on the carbon cycle, such as the burial of organic matter. This orogeny–carbon cycle–climate relationship has been studied in the case of the Himalayan orogeny.

1.2. Climate in Asia: present and past

1.2.1. *Present-day climate*

Asia has an extremely contrasted climate. A large southern and southeastern area, stretching from Pakistan to eastern China, undergoes the seasonal reversal of monsoon flow (South Asian monsoon from Pakistan to Myanmar and East Asian monsoon from Myanmar to eastern China). A vast region to the west and north of the Tibetan plateau (from Iran to Mongolia) experiences a semi-arid to arid climate, while further north, Siberia is dominated by a continental to polar climate. This dichotomy between the warm and seasonally wet climates of south and eastern Asia and the inland arid belt is due to the presence of high mountain ranges (Himalaya, Karakorum, Pamir, Hindu Kush, Zagros) and the Tibetan plateau, which strongly limits the atmospheric exchanges between the low and mid-latitudes of Eurasia. The Asian monsoon is marked by a strong seasonality of precipitation (with most precipitation occurring during summer), coupled with a reversal of the atmospheric circulation. Halley (1686) described the monsoon as a result of differential heating between the Indian Ocean and the Asian continent. This approach is still widely used (Webster et al. 1998), even though some scientists consider monsoon as the manifestation of the seasonal migration of the intertropical convergence zone.

In winter, in the mid-latitudes of Asia (mostly Siberia), the low insolation and the continentality amplified by the snow albedo-temperature feedback cause extremely low temperatures and generate the Siberian anticyclone, the densest air masses in the Northern Hemisphere, which is maintained by radiative cooling at the surface and large-scale descending motion (Ding and Krishnamurti 1987). A strong temperature gradient between the cold Asian continent and the mild Pacific Ocean results in the advection of cold and dry continental air to the northeastern China. To the south, East Asian winter monsoon generates moderate precipitation over the southeastern China (Figure 1.1) fed by moist air blowing from the nearby Pacific ocean (Figure 1.2).

At the end of the winter season, the increase in insolation over the northern hemisphere favors the rise of surface temperatures, which are also amplified locally by the decrease of albedo due to the melting of snow cover. Over southern Asia, convective systems develop and a low-pressure cell settles over India. At the end of spring, surface heating of a large part of Asia continent leads to the establishment of deep convection. In summer, the peak upper-tropospheric temperatures at 300 hPa (about 9,500 m high) located to the south of the Tibetan plateau are thermodynamically coupled to the precipitating convection (Boos and Kuang 2010). At the surface, a deep low-pressure cell stretches over southern Asia up to the Arabian Peninsula and conveys air masses from the Indian Ocean (Figure 1.2). Despite a moderate mean elevation of about 2,000 m, except in the Ethiopian region, the East African highlands constitute an orographic barrier for the air masses advected by the Indian low pressure. The low-level cross-equatorial flow, referred to as the Somali jet, carries moisture that leads to heavy precipitation over Asia. While reaching India, the humid air mass hits the Great Escarpment of the Deccan Traps, a pile of basaltic lava flows culminating at 1,700 m in the Western Ghats, leading to strong precipitation on the coastal fringe (Figure 1.1), causing recurrent catastrophic floods in the metropolis of Mumbai and its 20 million inhabitants. To the east of the Ghats landform, rainfall is less

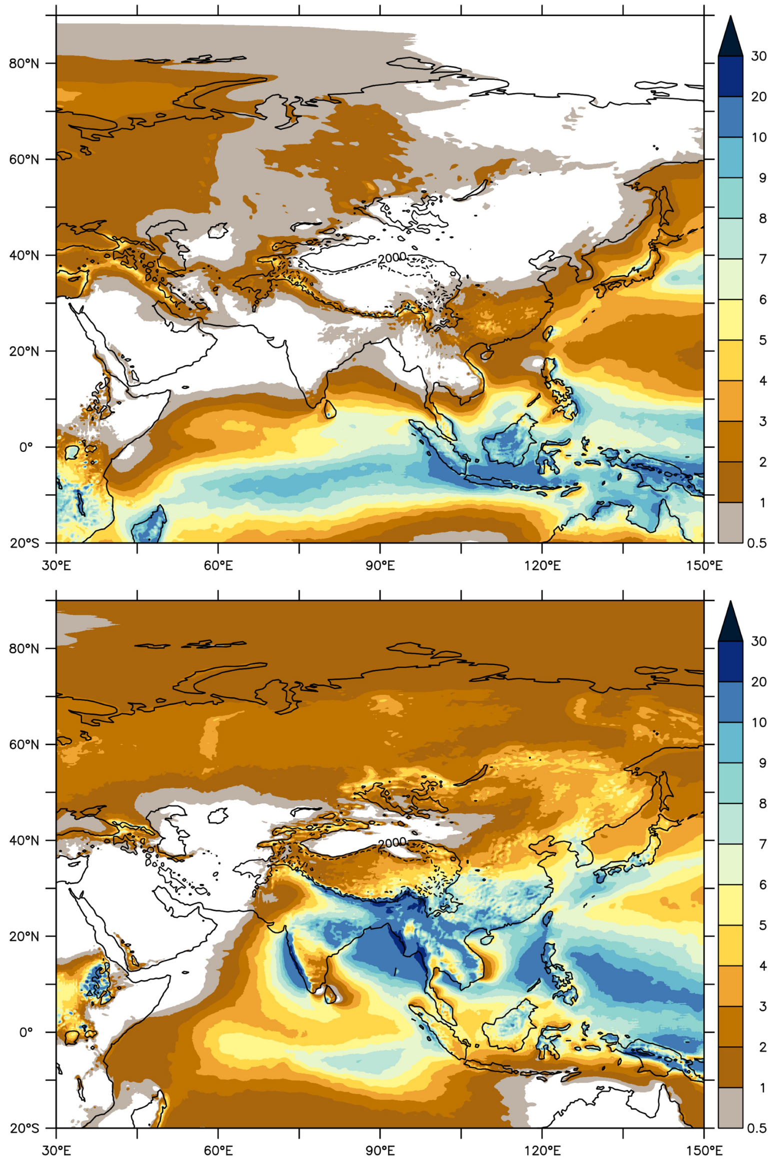

Figure 1.1. *Mean precipitation in winter (top) and summer (bottom) (in mm/day) (data are from ERA5 reanalysis (Hersbach et al. 2019)). Topography contoured at 2,000 m (4,000 m) in a thin solid (dash) line. For a color version of this figure, see www.iste.co.uk/cattin/himalaya3.zip*