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GEOSCIENCE

Dynamics of the Continental Lithosphere

Himalaya, Dynamics of a Giant 1

Geodynamic Setting of the Himalayan Range

Coordinated by
Rodolphe Cattin
Jean-Luc Epard

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

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Contents

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.

Molnar, P. (2012). Isostasy can't be ignored. *Nature Geoscience*, 5(2), 83–83.

Molnar, P. and England, P. (1990). Late Cenozoic uplift of mountain ranges and global climate change: Chicken or egg? *Nature*, 346(6279), 29–34.

Molnar, P. and Tapponnier, P. (1975). Cenozoic Tectonics of Asia: Effects of a continental collision: Features of recent continental tectonics in Asia can be interpreted as results of the India-Eurasia collision. *Science*, 189(4201), 419–426.

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 1, entitled *Geodynamic Setting of the Himalayan Range*, addresses the tectonic framework of the Himalaya and Tibet, the segmented nature of the Himalayan belt and gives two examples of studies focused on near-surface active fault imagery in Bhutan, and hydrothermal system in Nepal.

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

References

Subedi, S. and Hetényi, G. (2021). The representation of earthquakes in Hindu religion: A literature review to improve educational communications in Nepal. *Front Commun*, 6, 668086. doi:10.3389/fcomm.2021.668086.

Subedi, S., Hetényi, G., Denton, P., Sauron, A. (2020a). Seismology at school in Nepal: A program for educational and citizen seismology through a low-cost seismic network. *Front Earth Sci*, 8, 73. doi:10.3389/feart.2020.00073.

Subedi, S., Hetényi, G., Shackleton, R. (2020b). Impact of an educational program on earthquake awareness and preparedness in Nepal. *Geosci Commun*, 3, 279–290. doi:10.5194/gc-3-279-2020.

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

Tectonic Framework of the Himalaya and Tibet

1

Plate Reconstructions and Mantle Dynamics Leading to the India–Asia Collision

Gweltaz MAHÉO[1] **and Guillaume DUPONT–NIVET**[2]

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[2] *Géosciences Rennes, University of Rennes, France*

1.1. Introduction

The origin of the Himalayan range and Tibetan Plateau, the highest morphological feature of the Earth, has always been highly debated. Following the early thermal contraction models of the 19th century, Argand (1924) was the first to suggest that the Himalaya and Tibetan Plateau orogenesis resulted from the convergence of the Indian and Eurasian continents: *le jeu dominant, c'est le rapprochement de deux serres continentales, l'Indo-Afrique et la vieille Eurasie, avec rétrécissement de la Téthys*[1]. In this early view, India (with Africa) and Eurasia continents (named Sial) are moving on a "Sima" basement (previous name of the mantle) and separated on oceanic basin the Tethys (Figure 1.1). This view was applied by Wegener (1929) in his famous

1. The dominant game is the approach of two continents, Indo-Africa and old Eurasia, with a shrinking of the Tethys.

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continental drift model. Wegener also recognized the long journey of India across the Tethys Ocean. Based on evidence of Carboniferous glaciation on the Indian continent, and the lack of such features in Asia, he assumed that India used to be located close to the South Pole while Asia was in the northern hemisphere. Most ensuing models then related the Himalayan building with the shortening of the Tethyan "geosyncline" during the northward migration of the Indian continent across the Tethys Ocean, and recognized the remains of these oceanic domains in the rocks constituting the "Tethyan Himalaya Unit"(Gansser 1964; Holmes 1965, see Volume 2 – Chapter 3)

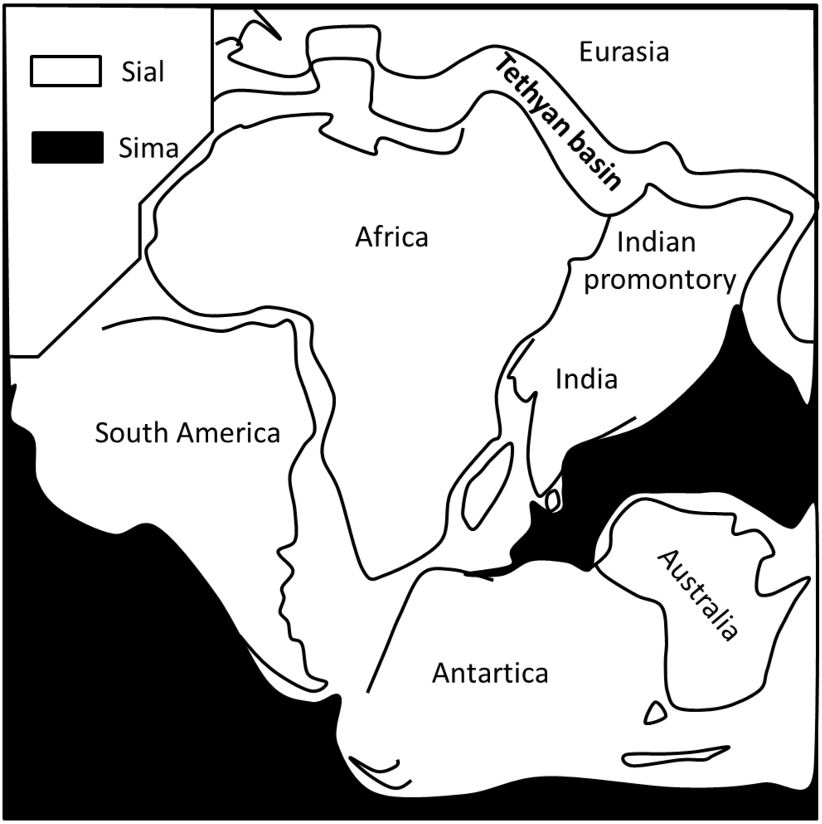

Figure 1.1. *Gondwana configuration before the Atlantic Ocean opening. Redrawn after Argand (1924)*

Then came the plate tectonic model revolution conceptualized by Holmes (1965), initiated by Hess (1962), observations of marine magnetic anomalies and their interpretation to infer tectonic plate motion by Vine and Matthews (1963). Dewey and Bird (1970) proposed that the Tethyan basin was actually made of oceanic crust, recognized oceanic rocks in the Himalaya as remnants of oceanic crust (later called ophiolites) trapped in suture zones between colliding continental plates following closure of the "Neotethys Ocean" (see Volume 2 – Chapter 2).

The first paleogeographic reconstruction of India's northward migration across the Neotethys includes early paleomagnetic results and the development of the global tectonic plate circuits based on marine magnetic anomalies (see section 1.2.1 for methodology; Pozzi et al. 1982; Patriat and Achache 1984; Molnar and Tapponnier 1995). These reconstructions allowed estimating throughout geological history, the rate and direction of the Indian lithosphere displacement with respect to Eurasia (Figure 1.2). A slowdown of India–Asia convergent around 50 Ma was readily interpreted as the timing of continental collision (Figure 1.2; Patriat and Achache 1984).

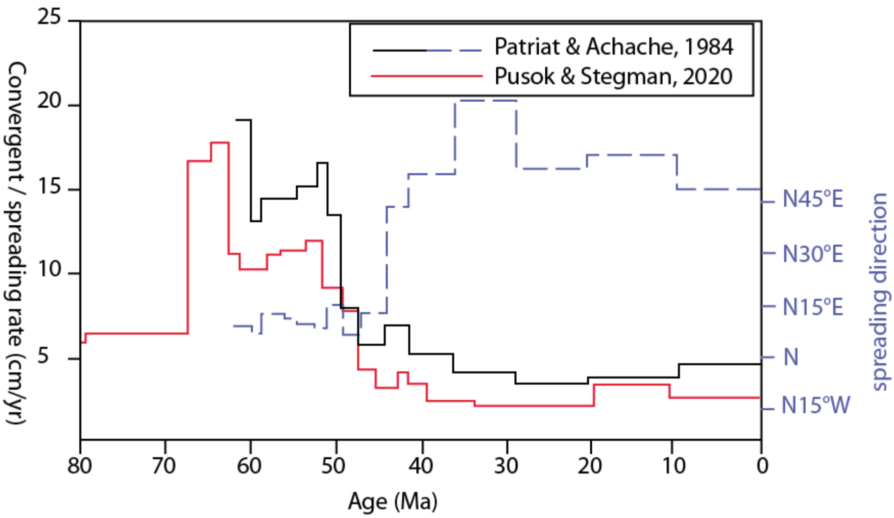

Figure 1.2. *Examples of the spreading rate and direction of the Central Indian Ridge (India–Africa) reconstructions based on marine magnetic anomalies data. For a color version of this figure, see www.iste.co.uk/cattin/himalaya1.zip*

Since this pioneering work, the development of geophysical techniques and the accumulation of geological data has led to refinements in kinematic plate reconstructions and continental deformation allowing for precise models of the paleogeographic evolution and involved geodynamic processes.

In this chapter, we will review current data and models proposed for the India–Asia convergence history, including the age of the continental collision and the geodynamic configuration.

1.2. The India–Asia convergence and the age of the collision

1.2.1. *The India–Asia convergence*

The relative motions of tectonic plates are estimated through time using plate kinematic reconstructions built on the basis of "Euler poles" determined from "marine magnetic anomalies" globally defining a "plate circuit" (Hellinger 1981; Cox and Hart 1986; Torsvik et al. 2012; Müller et al. 2016). Interestingly, in the case of India and Eurasia since 120 Ma, the relative motion cannot be directly measured by marine magnetic anomalies because the oceanic lithosphere of the Neotethys between these plates has been consumed at subduction zones. The convergence is thus estimated indirectly through the plate circuit from India to Africa to South America to North America to Eurasia. Uncertainties thus accumulate and, for example, there are issues in determining the Indian–African kinematics because of the non-rigidity of the eastern African plate separating with the Nubian plate (e.g. Royer et al. 2006). However, uncertainties on the relative positions between India and Eurasia remain relatively low, within a few hundred kilometers depending on how well the corresponding Euler pole is defined and on the age of the geomagnetic reversal defining the marine magnetic anomalies (Capitanio et al. 2010).

The results show that India and Asia have been converging at high rates since 120 Ma with a sharp decrease at approximately 50 Ma that has been originally attributed to the onset of the India–Asia continental collision (Figure 1.2; Patriat and Achache 1984). Note that after 50 Ma, the relative convergence until today amounts to ca. 4,000 km. This implies that, if 50 Ma is indeed the age of the continental collision, this amount of the Indian and Asian continental lithosphere has disappeared in processes such as compressive deformation, continental subduction and lithospheric extrusion