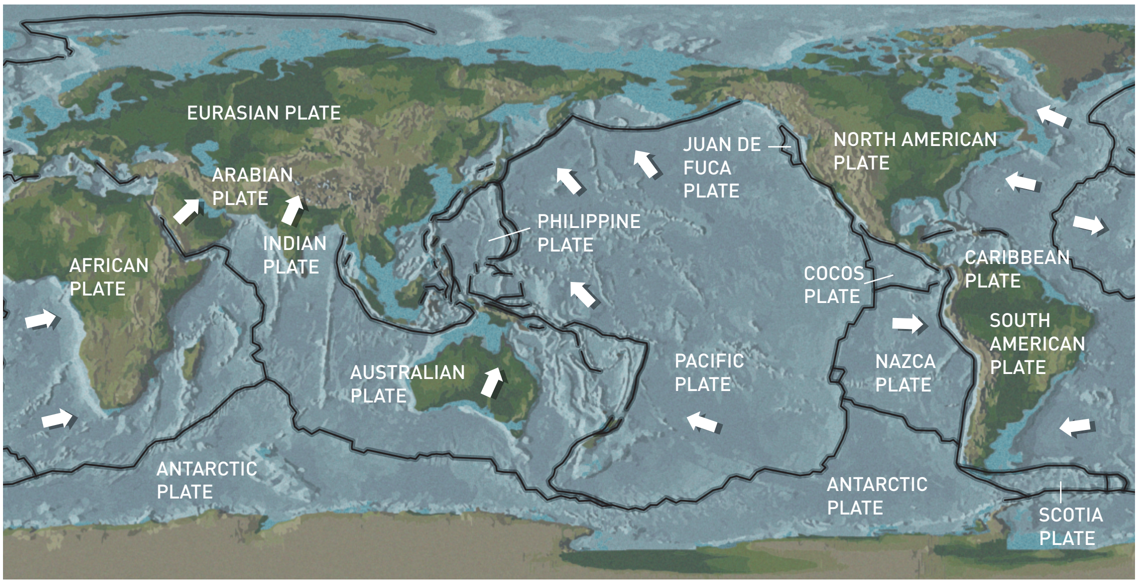
Mysteries of the mountains

*The Crafoord Prize in Geosciences 2014 is awarded to **Peter Molnar** for his contributions to the understanding of continent-continent collision and mountain belt dynamics. With a background in the field of geophysics, he has contributed ground-breaking knowledge about the driving forces of plate motion and the role of continents in the plate tectonic model of Earth's evolution. By means of an innovative combination of geological and geophysical research, integrated with satellite data and modelling, the Laureate has paved the way for a new understanding of mountain-building processes and the dynamics of our globe.*

Geophysicist Peter Molnar set out on his career in the late 1960s, at a time when the theory of plate tectonics was in its infancy. Together with Bryan Isacks (1969), he made a lasting contribution to the collective scientific effort to map not only the interplay of tectonic plate movements, but also the driving forces behind such motion. Their analysis of earthquakes in subduction zones demonstrated that when an oceanic plate sinks into the underlying mantle, sliding beneath another plate, the weight of the down-going plate provides the main driving force for plate motion, this so-called "slab-pull" being inferred to dominate over "push" from the active mid-ocean ridges, where thermal convection in the mantle drives sea-floor spreading.

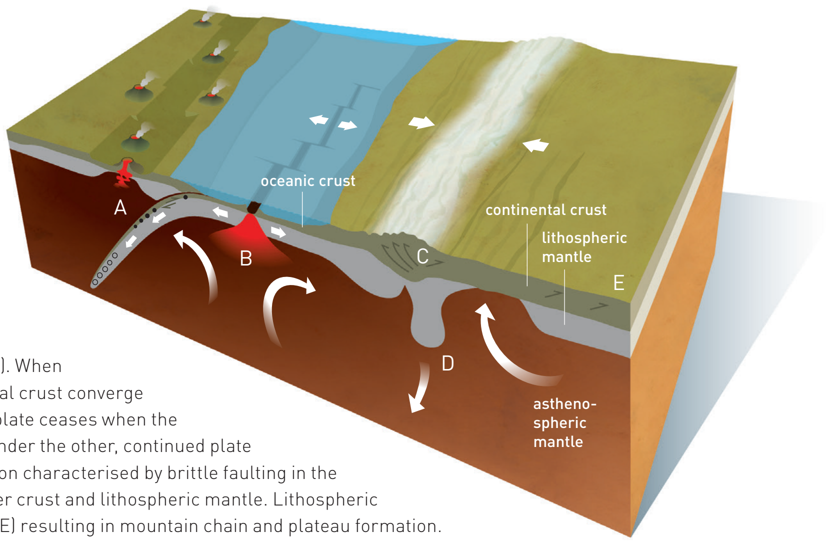
Focus on the continents

Peter Molnar then turned from the analysis of the driving forces behind plate motion to the study of continent-continent collision zones. He realized early on that the explanations of continental tectonics offered by the theory of plate tectonics, which were all based on the concept of rigid bodies moving over a ductile convecting mantle, failed to account adequately for the observed complex deformation patterns in the continental crust. It was quite apparent that many questions remained



The surface of the Earth consists of a number of rigid plates that move relative to each other. New oceanic crust is formed where plates move apart from each other at the mid-ocean ridges. At boundaries where plates move towards each other, the downward motion of old oceanic crust leads to earthquakes and volcanic activity, while the collision of two continents (e.g. at the Eurasian and Indian plate boundary) results in the formation of substantial mountain ranges and high plateaux. Changing plate configurations over geological time will also affect the Earth's climate, with the opening or closing of seaways affecting the flow of water masses between oceans, (e.g. in Southeast Asia and the Caribbean), while high plateaux and mountain ranges affect atmospheric circulation patterns.

to be answered in the study of continents, mountain ranges and high plateaux. How is development of a wide variety of structures over vast areas of the continental crust related to the rather simple explanatory model of plate tectonics? The fact that continental crust, consisting predominantly of silica-rich components, is less dense than the more homogenous oceanic crust, had led to the flawed inference that continental crust could never be drawn down into the mantle. The concept that continental collision, with substantial thickening of the crust, usually involved the underthrusting (depression) of one continent beneath another was well established, but the implications were less well understood. Mountain ranges, resulting from collision of continental plates, attracted the attention of many geoscientists, but an understanding of the dynamics of this long-lasting convergence and uplift remained a mystery. When Molnar and others began to analyse the crust of the Earth, recognizing its rigidity in upper parts and ductility at lower levels, and using a continuum mechanics model, crucial discoveries were made.



Plates and their boundaries. New, hot and buoyant oceanic crust is continuously generated at mid-ocean ridges (B) from upwelling asthenospheric mantle as the oceanic plate moves away from the ridge. When it is old, cold and dense, the oceanic plate sinks into the mantle (left side of diagram). Earthquake mechanisms show that the upper part of the sinking plate (A) is being extended (filled circles), consistent with plate motion being driven by the weight of the slab, which exerts a pull on the plate. At depth, the plate meets resistance from stiffer mantle and the earthquakes record compression (open circles). When plates consisting of both oceanic and continental crust converge (right side of diagram), sinking of the oceamic plate ceases when the continents collide. As one continent is forced under the other, continued plate motion is accommodated by internal deformation characterised by brittle faulting in the upper crust and ductile deformation in the lower crust and lithospheric mantle. Lithospheric thickening occurs over a broad area (from C to E) resulting in mountain chain and plateau formation. Gravitational instability of the thickened lithosphere can cause it to sink into the mantle (D), with upwelling of hot asthenospheric mantle adding to the uplift of the overlying plateau.

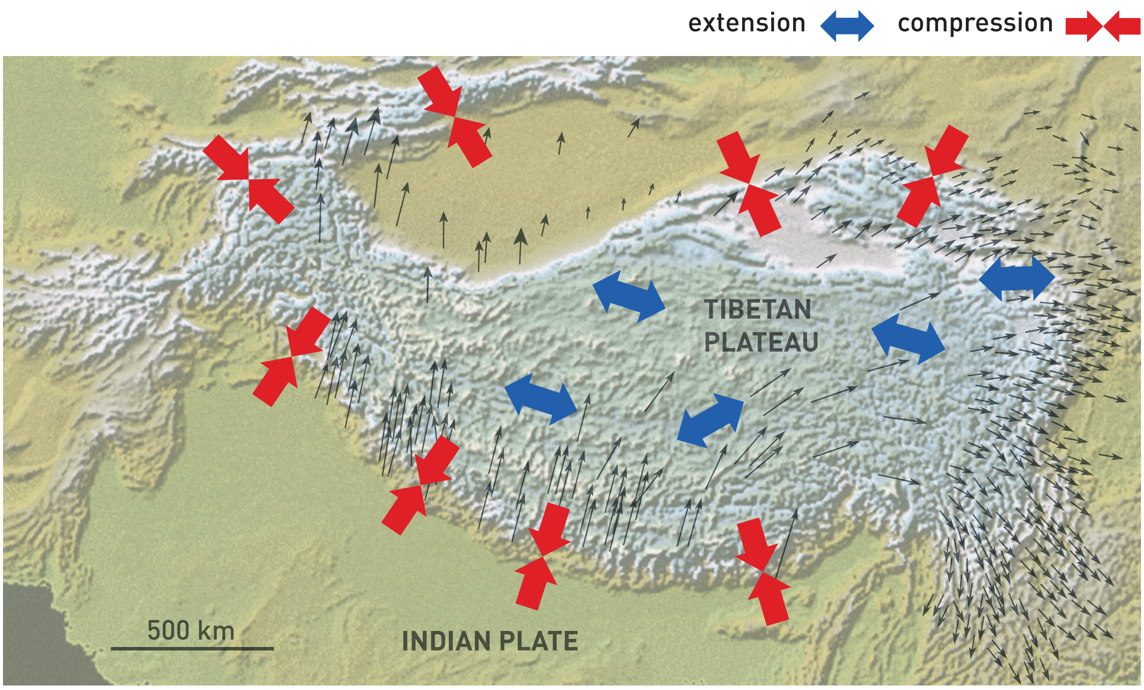
Mountain belt dynamics

Peter Molnar chose to study Asia and the spectacular Himalayan mountain range and Tibetan plateau, where the collision of India and Eurasia that started some fifty million years ago is still an active, ongoing process. Primarily using satellite imagery and analysis of earthquakes, Molnar and Paul Tapponnier (1975) demonstrated that the field of deformation, resulting from this collision, spanned a very large part of southern Asia and involved major mountain-belt parallel fault zones related to lateral escape (extrusion) of the high Tibetan plateau. Molnar and Tapponnier's research highlighted the differences between the deformation in collision zones between two continents, as in the case of Himalaya-Tibet, and that of collisions between oceans and continents, as in the Andes. In the latter case, deformation is concentrated at the plate boundary and above a shallowly dipping subduction zone. However, when continents collide, deformation is spread over a vast area and is promoted by the plasticity of the lower crust. This research on continental dynamics had a major impact among the scientific community; it changed the view of how mountain ranges form and their significance for global plate tectonics.

Further studies of the lithosphere's properties, mostly related to the collision between India and Eurasia, were promoted by seismic profiling and other geophysical investigations; these shed new light on the deeper structure of the mountains and high plateaux. Peter Molnar and his colleagues were able

With a length of c. 2 500 km, breadth of 100–200 km and fourteen peaks over 8 000 m in height, the Himalaya is an impressive mountain chain. Resulting from the collision between the Indian and Eurasian continents, which started c. 50 million years ago, the Himalaya is still an area of active deformation and mountain building and represents a remarkable natural laboratory for the study of continental tectonics. Photo: J-P Dalbéra

to show how cold, dense and therefore gravitationally unstable lithospheric mantle is able to detach and sink, to be replaced by hot, upwelling asthenospheric mantle. This so-called delamination process leads to plateau elevation, volcanism, major faulting in the upper crust and ductile deformation at depth. Studies undertaken in this century, using modern GPS technology, confirm much of what Molnar and his colleagues have inferred about continental dynamics and plate motion since the 1970s.



Kinematics of the Himalaya and Tibetan plateau. Thick arrows show horizontal strain determined from investigations of earthquakes in the region; these are mainly compressional around the edges of the plateau but extensional in the middle due to recent uplift. Thin arrows show actual velocity of crustal movement based on GPS measurements (arrow length is proportional to velocity).

CONTINENTAL DRIFT and PLATE TECTONICS

Ideas about drifting continents go back at least a couple of hundred years, but it was not until about 1910 that a well-defined hypothesis was elaborated. A couple of decades later, a theory was presented claiming that such motion was caused by convection in the underlying mantle.

However, it was not until during and after the Second World War that mapping of the sea-floor and other novel geophysical investigations provided decisive evidence for how and why the continents move. They unveiled a pattern of deep-sea trenches, continuous oceanic ridges and variations in magnetization.

In the 1960s, the ridges were interpreted to result from extensional movements (sea-floor spreading) with generation of new oceanic crust and the trenches inferred to be related to sinking (subduction) of old cold oceanic crust down into the mantle. The sea-floor spreading hypothesis, together with subduction-zone convergence and transcurrent plate motion, elegantly explained many pieces of a global tectonics puzzle that was subsequently corroborated by an extensive ocean drilling program. The outermost part of Earth, the lithosphere, was shown to consist of a number of plates, comprising oceanic and continental crust together with a layer of uppermost mantle, separated from each other by narrow earthquake-prone movement zones and associated volcanic activity.

The plate tectonics paradigm emerged in the late 1960s, primarily from the study of the properties and movements of oceanic plates; their inferred kinematics were subsequently confirmed by GPS measurements. However, plate boundaries involving continent-continent collision were clearly much more complex in their widespread deformation than those involving ocean plates. The study of these continental collision zones is where the research of the Crafoord Laureate 2014 has had its greatest impact.

An incessant and delicate interplay

Peter Molnar has an outstanding ability to achieve fruitful collaboration with prominent scientists in other disciplines. His innovative research has addressed processes in both the asthenosphere and the lithosphere, as well as connections between the lithosphere, the hydrosphere and the atmosphere. He has contributed not only to our knowledge of how mountain ranges are formed and vast plateaux elevated, but also to how the opening and closing of seaways between major land masses can change circulation patterns for both ocean currents and air masses, driving regional and perhaps global climate change.

Sometimes this research has yielded new and unexpected perspectives. For instance, Peter Molnar, Philip England and Joseph Martinod (1993) suggested that sudden elevation, eight million years ago, of the already existing and vast Tibetan plateau to its current altitude of about 5,000 metres above sea-level, resulted in an intensification of the regional monsoon. Thereby, they also initiated a discussion about whether this had created feedback mechanisms such as increased erosion and silicate weathering in the Himalayas, resulting in increased removal of carbon dioxide from the atmosphere, thus affecting the climate on a global scale. The debate about the importance of the Himalayan mountain chain and the Tibetan platea§u for the monsoon has inspired many people and is far from over.

Another example is the discussion of Mark Cane and Peter Molnar (2001) about how the closing of the Indonesian seaway might have affected the global climate three to four million years ago, after which warm water from the Pacific could no longer flow into the Indian Ocean. According to their hypothesis, the African continent's climate became drier, with less rain over East Africa; among other things this might have affected human evolution. The diminished northward transfer of warm air from the tropics might have also caused a colder global climate and ice ages during the Pleistocene Epoch (2.6 million–12,000 years ago).

Statistics and risk assessment for the benefit of society

The Crafoord Laureate's research has also contributed to better knowledge of seismic risks, for instance in the densely populated areas of the southern Himalayas and also in eastern Tibet. Aggregate data and statistics from previous quakes show that these areas are more prone to suffer large-scale earthquakes as a result of the continued underthrusting of India beneath Eurasia and lateral extrusion of the Tibetan plateau. The risk assessments carried out can be used in social planning, for development of better forecasting tools and early warning systems.

LINKS AND FURTHER READING

More information about this year's prize is available on the Royal Swedish Academy of Sciences' website, *www.crafoordprize.se and at http://kva.se/crafoordprize*

Animation

India-Asia Continental Collision. *http://emvc.geol.ucsb.edu/2_infopgs/IP1GTect/dContCollision.html*

Book on plate tectonics

Plate Tectonics. An Insider's History of the Modern Theory of the Earth. Naomi Oreske, 2003: Westview Press Inc. 448 pages. Chapter 17 is written by Peter Molnar: *From Plate Tectonics to Continental Tectonics*.

Selected scientific articles by the Laureate

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THE LAUREATE

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http://cires.colorado.edu/science/groups/molnar/

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