Young tectonic and magmatic processes in the Himalayan region

When Continents Collide

Dr. Robert Anczkiewicz investigates and dates orogenic processes

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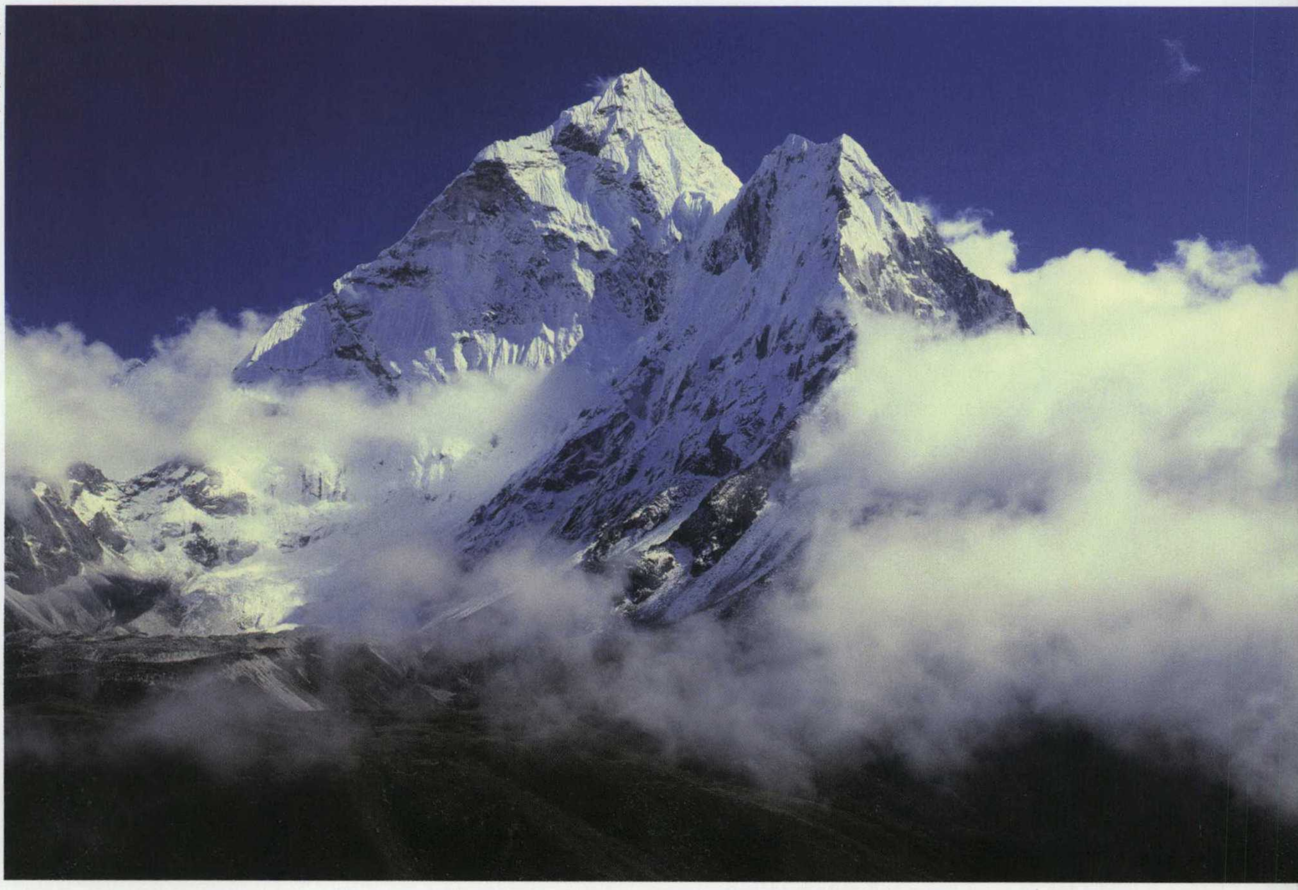
Colliding continents have created the highest mountain ranges on our planet. Mountains like the Himalayas give us a unique opportunity to study the past and present of this ongoing process recorded in once deeply hidden rocks

The theory of continental drift or plate tectonics has come to dominate our way of thinking about the evolution of the Earth. The breakup of larger continents, the merger of smaller ones, and the emergence or disappearance of oceans have all been common occurrences in our planet's history. One of the most spectacular cases of such tectonic movements is the collision of the Deccan plate (now mainly forming India and Pakistan) into the landmass of Asia, which has resulted in the emergence of the world's three highest mountain ranges: the Himalayas, Karakoram, and Pamir. This event had a great impact on the planet's evolution, bringing a reorganization of the movement of tectonic plates plus climate change and the extinction of fauna.

Deccan's migration has been reconstructed on the basis of paleomagnetic study of the Indian Ocean crust. Deccan started heading towards Asia around 100 million years ago in the late Cretaceous, when it was still in the southern hemisphere, having broken



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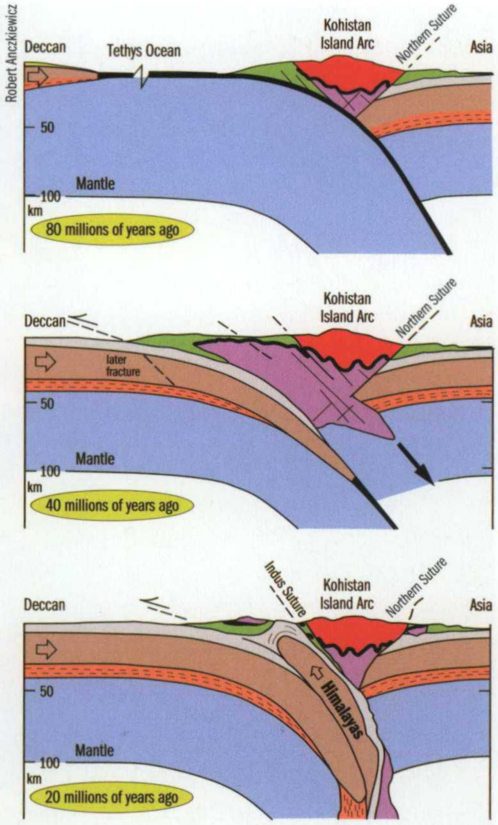
Where today mighty Himalayas rise, millions of years ago there was a now non-existent Tethys Ocean off Africa and Madagascar. The intervening oceanic plate began to slip underneath the southern edge of Asia, forming a subduction zone (such as can now be found on the west coasts of the two Americas). Things were somewhat different in the northwestern region of the collision zone, where the sinking of the oceanic plate and the related magmatic and volcanic activity created what is known as an island arc (a similar island arc nowadays forms the Japanese archipelago). Called Kohistan, the arc has since become a highland area in Pakistan. It was once separated from the oncoming Deccan plate by the vast Tethys Ocean, now non-existent, and from Asia by a shallow sea called a back-arc basin.



The widespread theory of the Himalayas' formation is that they snapped off a plate of crust as it sank into the mantle and resurfaced due to buoyancy

Crushing force

Deccan's approach towards Asia took place at the dizzying speed (geologically speaking) of 15–20 cm per year. As a result of its northward migration, the Tethys Ocean eventually disappeared completely into the subduction zone, slipping beneath Asia. Between 100 and 85 million years ago, the back-arc basin closed up when the islands of Kohistan were pushed into the southern edge of Asia, enlarging its continental surface. Nowadays the area along which these two tectonic units met is called the Northern Suture. Around 55–50 million years ago, northern Deccan suddenly slowed down to less than 10 cm per year. That moment is seen as marking the end of the Tethys Ocean plate's subduction and the start of the direct collision between the two continents: the Deccan and the southern margin of Asia. The border separating the two continents was called the Indus Suture Zone. Deccan's northward movement still continues today, although since around 35 million years ago it has slowed to around 5 cm per year.

The consequences of Deccan's collision with Asia are excellently visible in the northwestern part of the Himalayas in Pakistan. One aspect that makes this location unique is its ease of access. The Karakorum Highway, probably still the world's highest hard-surface road, follows part of the ancient Silk Road once taken by caravans from China and is now widely popular among tourists. Due to the semi-arid climate and the resulting sparse vegetation, most of the route is excellently suited to geological observation. Here, proceeding along a single road, one can trace the structure of the entire Himalayas, especially the Kohistan island arc.

The Himalayas lie to the south of the Indus Suture, and are therefore in the geological sense part of Deccan rather than part of Asia, as is generally thought. As it slammed into the Asian continent Deccan partly slipped underneath it, causing the northern fragments of its crust to fold and stack up. It became much thicker here, reaching a record thickness of 80 km. Simplifying things quite a bit, this model illustrates how mountains form from such collisions.

Under pressure

Another consequence of when one plate slips under another like this is the metamorphosis of rocks. The deeper surface-formed rocks sink below the Earth's surface, the higher the surrounding pressure and temperature become, transforming their mineral components into other minerals that are stable under the new conditions. If rocks so transformed later end up on the surface again as a result of tectonic processes, their mineral composition tells us under what

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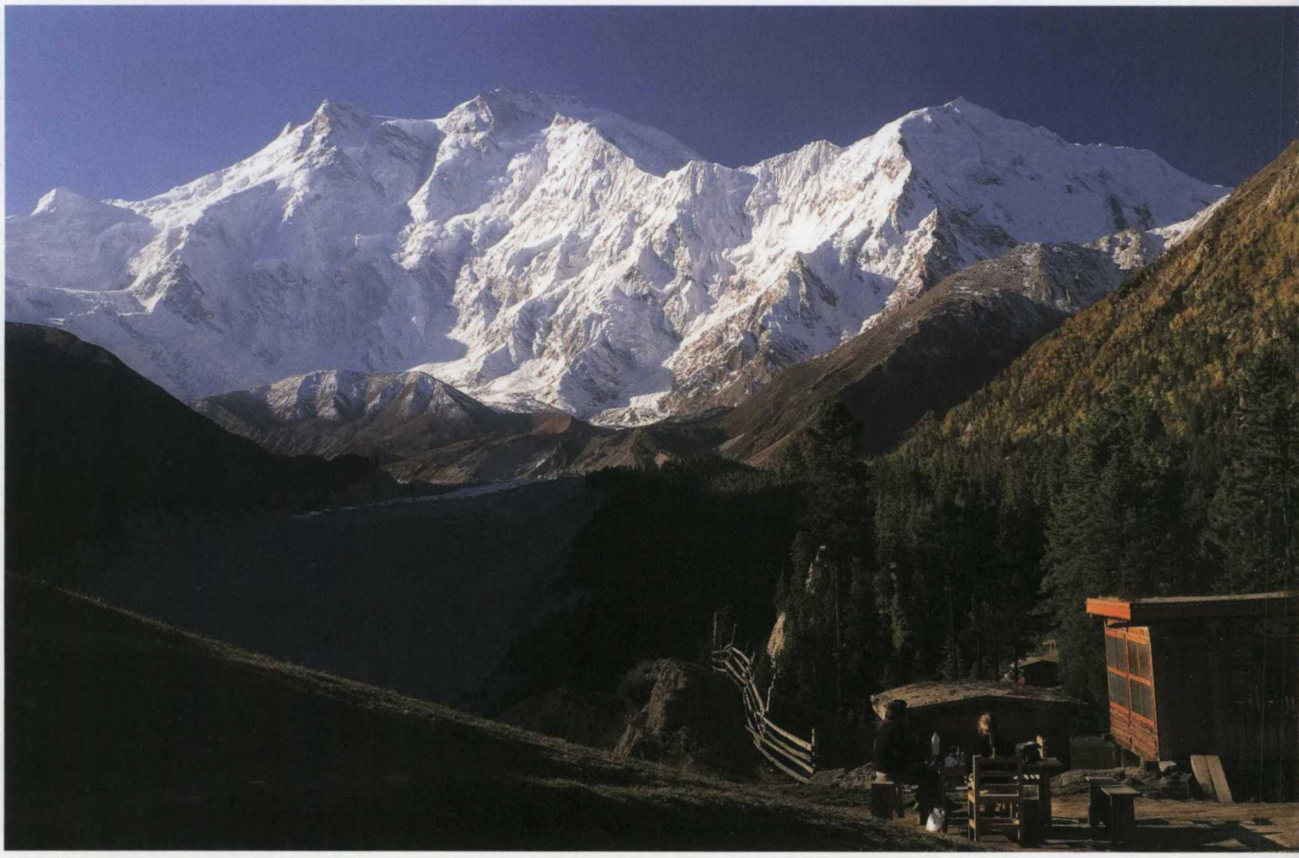

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Nanga Parbat is one of the Earth's most rapidly rising peaks – growing almost 1 cm higher each year

conditions they were formed. Since we are unable to directly observe what happens tens of kilometers beneath the Earth's surface, this is the only way we can study the transformations that occur in rocks that get plunged so far downwards.

One extraordinary and very rare metamorphic rock formed in this way is eclogite, whose composition indicates that it is composed of former surface deposits that were subducted down to immense depths. The first rocks of this type in the Himalayas were found in the Kaghan valley in Pakistan. Research has shown them to contain relicts of coesite – a mineral that forms from ordinary quartz under pressures in excess of 27 kilobars (i.e. 27,000 atmospheres), which corresponds to a depth of around 100 km. That is deeper than the maximal depth of the contemporary Earth's crust. Radiometric data indicates that the Deccan crust was plunged down to such a depth around 47 million years ago, or not quite 10 million years after the beginning of its collision with Asia.

While subduction zones can successfully explain the mechanism by which rocks get pushed down to such great depths, explaining how such rocks later resurface poses a significantly harder challenge for geologists. The current hypothesis for the Himalayas can be likened to a piece of dry wood pushed into water. Once the dragging force ceases to operate, the buoyant wood will resurface. In the case of the Himalayas that wood is the continental crust of Deccan while the role of water is played by the denser rocks of the Earth's mantle. The downward force stops operating when a tectonic fault occurs, snapping off part of the crust as it plunges down into the mantle. This hypothesis has the advantage of allowing for the continuation of the compressive motion bringing Deccan and Asia closer, which is of course still underway.

A rising giant

Isotope methods have shown that the main stage in the upsurge of the most deeply subducted Himalayan rocks ended around 20 million years ago, but rapid upward movements can still be observed today. One such place is the Nanga Parbat massif, the westernmost of the "eight-thousander" peaks and geologically one of the most interesting regions in the Himalayas. The summit rises 8125 meters above sea level, although it gives the impression of being even higher. The Indus valley runs along the foot of the massif at around 1500 meters above sea level, so Nanga Parbat's relative height is nearly 7 kilometers, which is exceptional even in the Himalayas.

Nanga Parbat also delimits the end of the range of the monsoons, a fact that makes the mountain's microclimate very distinct and capricious, earning it the nickname "Killer Mountain." In the 1930s, for instance, 17 climbers from a German expedition died on it. The rate at which Nanga Parbat is rising is also extraordinary. It is estimated that it has been growing by more or less 6 millimeters per year for the past several million years, and periodically, even by 1 centimeter per year (to compare, Poland's Tatra Mountains are rising at less than 1 millimeter per year). This is accompanied by magmatic activity and intensive tectonic movements. Igneous rocks have been found in the region that are only approx. 1 million years old. Young fault lines have also been discovered, along which rocks that were 20 km deep only a few million years ago are now on the surface. Contemporary Indus River deposits are being folded before researchers' very eyes. There are few places in the world where one can observe such a live show of mountain formation.

Bottoms up

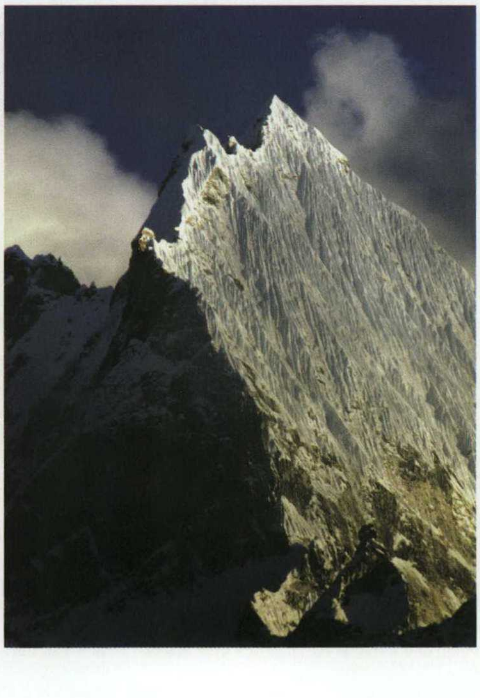
The structure of the Indus Suture changes as one proceeds along the Himalayas. Sometimes a few steps suffice to move from one paleocontinent to another. The suture zone mainly contains the remains of the Tethys Ocean, which separated Deccan from Asia before their collision. Hence the presence of ophiolites relics of former oceanic crust together with the deposits covering them. Also encountered there are blueschists - rocks formed at an early stage of oceanic subduction, containing a distinct blue mineral glaucophane. To the north of the Indus Suture there is a sequence of rocks around 40 km thick representing a complete geological cross-section of the Kohistan island arc. At the very bottom of this sequence is the Moho zone - the boundary separating the Earth's crust from its mantle. Kohistan thus offers a unique opportunity on the worldwide scale to observe this boundary on the surface of the Earth.

Prior to the collision, there was a shallow sea behind the Kohistan island arc. Its remnants can be found in the Himalayas - behind the Northern Suture, separating the Kohistan sequence from the Karakorum plate. Evidence for the existence of a sea basin here, which should persuade even the greatest doubters, can be found in the form of magnificently preserved pillow lavas. They demonstrate that in this mountainous place, around 1000 km from the nearest sea, there was once an ocean under which lava flowed out and immediately hardened. Further northward are the Karakorum mountains, a mark left behind by a smaller collision of plates.

Exploration of the Himalayas is still in its initial phase but the world's highest mountains undoubtedly conceal many more intriguing riddles and equally intriguing answers. ■

Further reading:

Anczkiewicz R., Oberli F., Burg J.P., Villa I.M., Günther D., Meier M. (2001). Timing of normal faulting along the Indus Suture in Pakistan Himalaya and a case of major $^{231}Pa/^{235}U$ initial disequilibrium in zircon. *Earth and Planetary Science Letters, 191*, 101-114.



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Sharp boundaries and flat rock faces seemingly cut by a knife are evidence of the tectonic faults along which the Himalayas rose out from under the surface