GEOPHYSICS

How mountains get made

Observations of crustal deformation constrain models of mountain formation

By **Maureen D. Long**

The formation of mountain belts (orogens) in subduction-collision settings, where an oceanic plate subducts beneath continental material, is a fundamental process in plate tectonics. However, the mechanisms by which the continental crust deforms to produce shortening and uplift, and thus high topography, has been a matter of debate. This uncertainty is largely due to the difficulty of making direct observations of deformation in the deep crust to test the predictions made by conceptual models. On page 720 of this issue, Huang *et al.* (*1*) use observations of seismic anisotropy to constrain the geometry of deformation in the continental crust beneath the Taiwan orogen, and thus shed light on how the crust deforms as mountains are formed.

Two general concepts of crustal deformation in collisional orogens have been proposed, known as the thin-skinned and thick-skinned models (*2–4*). In the thin-skinned model, deformation is accommodated mainly in the upper crust, with a mechanically weak detachment surface (a décollement) separating the deforming upper layers from the deeper crustal rocks. In this scenario, the horizontal shortening and uplift required to form the mountains are confined to the upper crust. In contrast, the thick-skinned model invokes the deformation of the deeper crust as well as its shallow portions; here, the basement crustal rocks (as well as, perhaps, the

mantle lithosphere beneath) undergo appreciable deformation. Taiwan represents an excellent locality to test these conceptual models (*5*); it is a young, actively deforming collisional orogen that accommodates the ongoing convergence between the Eurasian and Philippine Sea plates (see the figure).

A key challenge in discriminating among the different models of crustal deformation is the difficulty of constraining deformation in the deep crust. One type of observation that can shed light on deformation in the deep Earth is the characterization of seismic anisotropy, or the directional dependence

of seismic wave speeds (*6*). In many regions of the Earth, including much of the crust, there is a relationship between strain and the resulting anisotropy: As a rock deforms, individual mineral crystals tend to rotate and form a statistical preferred alignment, giving rise to seismic anisotropy. Therefore, observations of anisotropy in the crust can constrain the depth distribution of collision-related deformation in orogens. Detailed observations of crustal anisotropy (and its variation in three dimensions) can be difficult, but recent innovations in observational seismology have advanced its study. These include the increasing availability of dense networks of seismometers, such as the Taiwan Integrated Geodynamics Research (TAIGER) deployment in Taiwan (*7*), and the use of the ambient seismic noise field to extract information about crustal structure, including its anisotropy (*8*).

Huang *et al.* develop a tomographic model of shear wave velocity and anisotropy in the crust beneath Taiwan using measurements of surface waves derived from ambient noise. They find evidence for a sharp change in the geometry of seismic anisotropy at a depth of around 10 to 15 km in the crust. Above this transition region, the fast directions of anisotropy are roughly parallel to the strike of the Taiwan orogen, and correlate closely with surface geologic trends. The authors propose that anisotropy in this upper layer is induced by compressional deformation and shortening. Beneath the transition, the fast directions of anisotropy are roughly parallel to the direction of convergence between the Eurasian and Philippine Sea plates. Here, the authors hypothesize that the deeper layer of anisotropy is caused by shear deformation of anisotropic minerals in the deep crust, induced by the motion of the downgoing plate.

As to what the results tell us about crustal deformation in the Taiwan orogen, and which of the thin-skinned or thick-skinned concepts apply, Huang *et al.* propose a hybrid model that has aspects of both
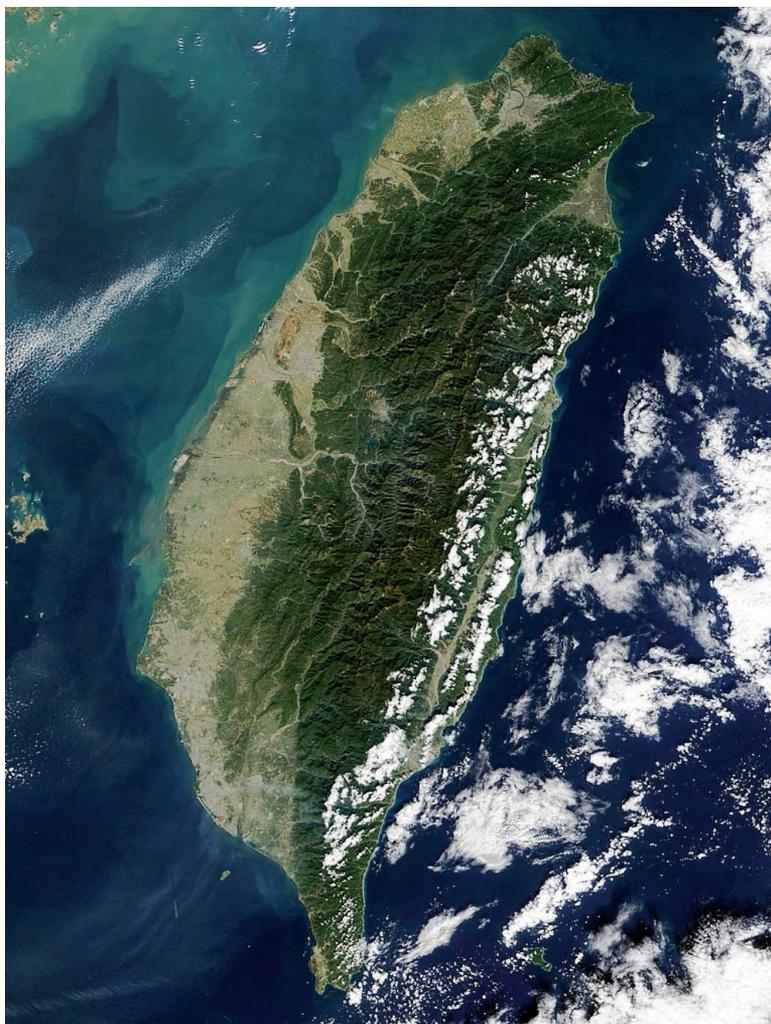
Mountain-forming islands. The island of Taiwan, shown here in a radar image, sits off of the coast of southern China at the convergent boundary between the Philippine Sea plate and Eurasion plate. Huang *et al.* argue that Taiwan's mountainous terrain results from a mix of crustal deformation styles.

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concepts. The presence of strong anisotropy in the lower crust induced by convergence-parallel shearing implies that there is deformation throughout the crust, as suggested by the thick-skinned model. On the other hand, the evidence for a sharp change in deformation geometry at a depth of ~10 to 15 km shares some aspects of the thin-skinned concept. The authors propose that this transition is not a décollement in the traditional sense, as there is mechanical coupling between the upper and lower crustal layers; however, their model does imply that compressional tectonics is active only in the upper layer.

These results reported by Huang et al. have important implications for our understanding of how the crust deforms in collisional orogens, and may prompt a re-examination of other mountain belts. A key question is whether there is widespread lower crustal anisotropy in other orogens, and whether a transition in deformation style in the mid-crust is a universal feature. The implications of such a sharp transition for our understanding of crustal rheology need to be explored. Another important question is to what extent the mantle lithosphere, in addition to the lower crust, participates in deformation. More generally, the observation and interpretation of crustal anisotropy, both in mountain belts and in other tectonic settings, represents an exciting frontier area, enabled by the increasing availability of data from dense seismic networks and the maturation of observational techniques that rely on the ambient noise field (1, 8) or on the analysis of converted waves (9). Furthermore, new constraints on the relationships between strain and anisotropy in crustal rocks (10, 11) are enhancing our ability to relate seismic observations to deformation geometry, opening the door to the detailed and quantitative testing of hypotheses related to the deformation of Earth's crust. ∎

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DEVELOPMENT

Marmoset kids actually listen

Humans and other vertebrates may share a developmental program for vocal learning

By **Daniel Margoliash**[1*] and **Ofer Tchernichovski**[2]

Undergraduate linguistics courses typically present language as unique to humans. Chomsky and others have postulated a language organ that evolved in hominids. This idea found modest support in the lack of evidence for vocal production learning (imitating sounds) in nonhuman primates. But did language suddenly emerge in the *Homo* lineage as a "hopeful monster" (1) who could learn new sounds and meanings? Evidence for vocal learning in nonhuman primates is now emerging (2, 3), and in hindsight, looking at vocal production learning as the sole evolutionary precursor of language might have been shortsighted. Similar developmental processes can lead to different end points, and minor modifications of a primitive developmental program can create very different creatures. On page 734 of this issue, Takahashi et al. (4) provide evidence for a developmental process, rather than its endpoint, which reveals a shared developmental program for animal communication and human language. This indicates an ancestral developmental program that is shared not only between humans and other primates but also across mammals and birds.

Vocal imitation was long thought to be common in birds but rare in mammals. In the past few decades, scientists have reported evidence for vocal production learning in marine mammals, bats, elephants, and primates (2). It is difficult to work with large mammals that breed slowly and require social interactions for normal development, which precludes their being reared in isolation. These difficulties are particularly acute for primate research. Nevertheless, recent results from field studies and in captivity demonstrate shared, learned group signatures in communication calls produced by monkeys and apes. For example, when two troops of adult chimpanzees were integrated in a zoo—an event that is improbable in nature—the referential food grunts of introduced members apparently

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changed to match those of the home territory group (3).

Given that there may be no evolutionary canyon separating human vocal learning from that of other primates, one can attempt to compare vocal development across species that vary strongly in their end points. Takahashi et al. did just that. They thoroughly investigated vocal development in common marmosets (*Callithrix jacchus*), tiny social primates that produce a limited number of call types. In captivity, their calls are dominated by whistlelike calls (phees). The authors report rapid changes in vocal devel-

> *"... Takahashi et al.'s findings point to an ancient substrate for vocal learning that an evolving large hominid brain could take advantage of ..."*

opment driven by social (parent-infant) interactions. These vocal changes are similar to those previously described in human infants (5) and songbirds (6).

Takahashi et al. studied marmoset infants for 2 months from birth. By the end of this period, the juveniles were producing adult-like calls. Using a design that allowed dense sampling of thousands of vocalizations, the authors analyzed developmental changes in acoustic features previously shown to be useful for characterizing birdsong development. They observed significant vocal changes during development (see the figure). Early on, vocalizations were highly variable. Later, acoustic features of calls became clustered, indicating the emergence of ethologically meaningful call types. The numbers of clusters then declined, resulting in part from the transformation of immature call types into mature versions of phees.

To model the marmoset vocalizations, the authors used a nonlinear dynamical systems model of the vocal tract based on shared physical properties of vocal production in birds and mammals (7). Different calls occupied different regions of model parameters, which suggested that the changes are not ac-