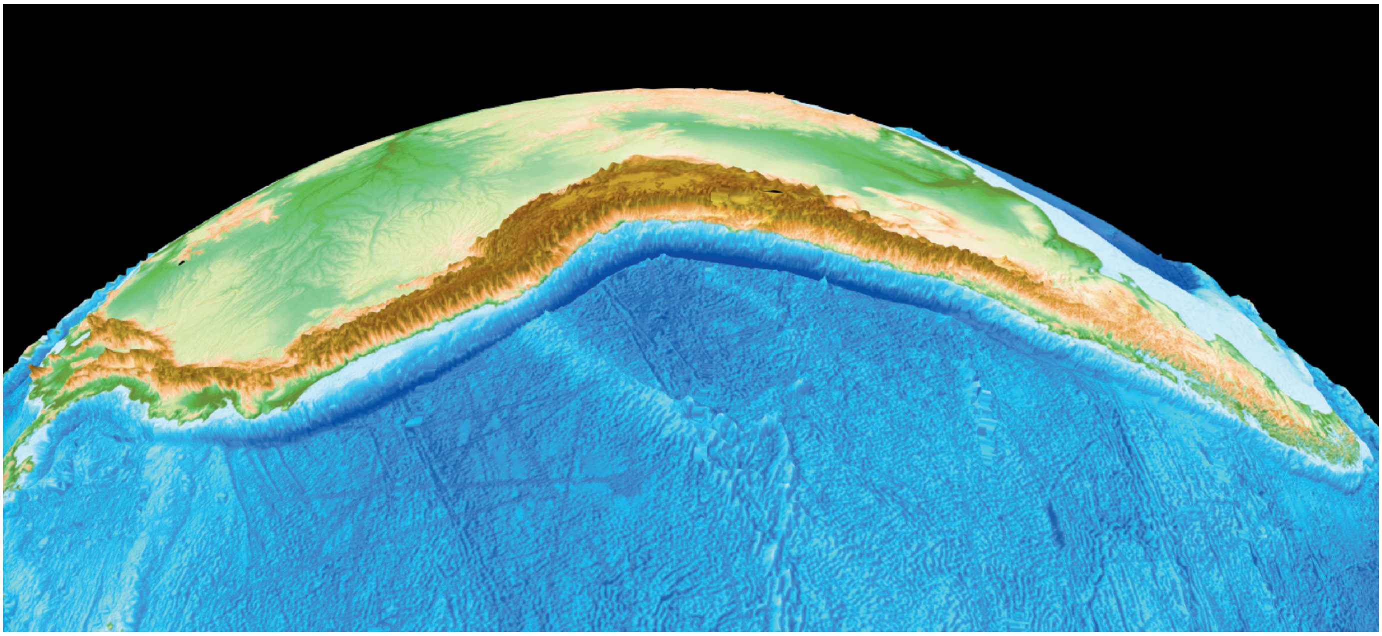
DIETMAR MÜLLER

Figure 1 | Subduction along the western coast of South America. The Andes formed as a result of the Farallon and Nazca tectonic plates under the Pacific Ocean being driven against and beneath South America, a process called subduction. This map shows the topography of the sea floor and of the adjacent Andes. The subduction zone is clearly visible as the deep blue cleft running along the coast. Chen *et al.*[2] have reconstructed how slabs of the plates that are now deeply submerged in Earth's mantle were transported there through subduction. Topographic heights and depths are shown at 20 times their actual values, for clarity.

EARTH SCIENCE

The art of unsubduction

Tectonic plates lost to the deep mantle carry a record of ancient surface tectonic processes. A method for retrieving such records has been developed that could clarify the links between tectonics and mountain building. **SEE ARTICLE P.441**

DIETMAR MÜLLER

The Andes are the longest continental mountain chain on Earth and the highest outside Asia. They formed when an oceanic tectonic plate — the Nazca plate beneath the eastern Pacific Ocean — was driven against and under the South American continent (Fig. 1), a process called subduction. The resulting steady squeeze gradually compressed and thickened the continental crust, causing the Andes to rise. Andean uplift has driven climate change, landscape evolution and biodiversity[1], yet our understanding of what triggered its rise is still incomplete. On page 441, Chen *et al.*[2] propose a new answer to this question.

What exactly is the connection between Andean mountain building and subduction? The established view[3] is that subduction to the west of South America has been continuous since sometime in the Jurassic period (which lasted from about 201 million to 145 million years ago), but that the onset of Andean uplift occurred much more recently, with estimates ranging from the Early Cretaceous period[4] (about 130 million years ago) to the Early Cenozoic era[5] (about 50 million years ago). Despite the differences in these estimates, geodynamicists agree that the interaction of subducted slabs of tectonic plates beneath the ocean with the deep, lower part of Earth's mantle is responsible for the uplift of the Andes[4,5], and modulates the balance of tectonic forces at the planet's surface.

Chen *et al.* fundamentally challenge the view that Andean uplift occurred in the context of a subduction system that had been active for a long time. They suggest that there was a period without subduction along the west coast of South America, before the Andes existed, and that subduction initiation is the key to understanding the birth of this mountain range. They come to this conclusion by using a new way of connecting reconstructions of plate tectonics from images (obtained from studies of seismic waves) of tectonic plates submerged in the deep mantle.

The researchers noticed that the Nazca slab beneath South America reaches depths of only about 1,100–1,300 kilometres, and that beneath these depths there is a slab gap[6] — a region of mantle that separates the Nazca slab from a deeper section of subducted slab. They also noticed that a model[7] of global plate tectonics published by my group (which includes a reconstruction showing that now-subducted crust once formed part of the ocean floor) implies that subduction along western South America was discontinuous and included episodes between 80 million and 55 million years ago when the subducting oceanic plate diverged from the South American continent. I was aware of this feature in our model, but had been cautious in interpreting it, given that reconstructions of the history of subduction along western South America involve factors that are difficult to quantify.

A key uncertainty concerns the effect of the relative motion of East and West Antarctica along the West Antarctic Rift System — the region in which the tectonic blocks beneath East and West Antarctica were pulled apart in the past. Much of this system is hidden under a thick layer of inland ice, which means that there is limited direct evidence for the relative motion of these two tectonic blocks (with the exception of movement that occurred after 43 million years ago[8]). Reconstructions of Antarctic plate tectonics before 43 million years ago therefore rely on circumstantial geological evidence[9]. This matters in attempts to reconstruct the tectonic history of the Andes: to model the past relative motion between South America and plates in the Pacific Ocean Basin, we need to understand the relative movements of the nearby South America, Africa, East Antarctica, West Antarctica and Farallon–Nazca plates, whose collective behaviour affects Andean tectonics (the Farallon plate is subducting under the Americas, and has fragmented into several smaller plates, including the Nazca plate).

Chen *et al*. now ingeniously show that the proposed periods[7] of divergence between South America and the subducting Farallon–Nazca plate are consistent with the extent of subducted slabs in the lower mantle under South America, as measured using seismic imaging, and with the geological history of the Andes. To prove their point, they used a computational method to simulate how subducted ocean floor can be pulled back out of the mantle. This ‘unsubduction’ method reverses the path taken by the deeply buried material and ultimately restores the slabs to the surface.

The results reveal that subduction was initiated around 80 million years ago, and slowly propagated from north to south. Subduction along the entire length of western South America, as observed today, did not occur until 55 million years ago. The subducting slabs first interacted with the lower mantle 10 million to 30 million years after subduction initiation. This new model is consistent with the idea that the Andes started to form during the Cenozoic, and might explain the presence of the slab gap — the authors propose that the gap arose as a result of reorganization of the subduction sometime before 80 million years ago. Chen and colleagues’ reconstruction also suggests that subduction initiation along central and southern South America explains the lull and the subsequent increase in Andean magmatism that occurred around 80 million years ago.

An open question concerns the history of Andean subduction before 90 million years ago; this will be crucial for understanding what caused the slab gap. Information about the subducted plates buried deep in the mantle (far below 1,500 km) in this region might help to improve the constraints on local and global tectonic and geodynamic models. It might also shed light on the origin of the enigmatic reorganization of tectonic plates that occurred around 100 million to 105 million years ago, which led to the termination of subduction along the eastern margins of Australia and Antarctica[7].

Chen and co-authors’ method could potentially be applied to many subduction systems, particularly given that seismic images of the mantle are becoming sharper, and are increasingly being used to unravel the evolution of regions of complex tectonic activity[10,11]. Recent advances[12] in seismic methods and Earth-model development will aid the imaging of the deep mantle, especially in regions where seismic imaging doesn’t work well and where surface instruments for recording seismic images are sparse. These advances, combined with improvements in geodynamic models that assimilate seismic images of the mantle[13,14], will transform our understanding of the evolution of the solid Earth. ■

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DEVELOPMENTAL BIOLOGY

Plant-thickening mechanisms revealed

In roots, stem cells in the cambium region form vascular tissues needed for the long-distance transport of water and nutrients. How these stem cells are specified and regulated has now been illuminated. See Letters p.485 & p.490

SEBASTIAN WOLF & JAN U. LOHMANN

When plants evolved a vascular system containing cells that facilitate the transport of water and nutrients, this not only allowed them to conquer land, but also provided the structural stability that enabled them to increase dramatically in stature, bulk and complexity[1]. The cells that give rise to vascular tissue are specified in the embryo, but in many flowering plants they undergo substantial rounds of proliferation only during post-embryonic development, in a process that drives radial growth and expands the circumference of roots and shoots. This radial growth depends on the division of stem cells located in an inner cylindrical layer of cells called the cambium, which gives rise to wood and the woody fibre used for textiles, called bast.

It has been estimated that woody plant material (arising from cambial cells) accounts for more than half of Earth’s biomass[2]. Yet despite the importance of the cambium, our level of understanding about cambial stem cells and their regulation lags behind our knowledge of stem cells in the plant root or shoot tips, probably because the cambium is more difficult to access, given its location in the interior of fully differentiated organs. Miyashima *et al.*[3] (page 490) and Smetana *et al.*[4] (page 485) now offer insights into cambium development on the basis of studies of roots of the model plant *Arabidopsis thaliana*.

Plant vascular tissue is comprised of water-transporting xylem cells and nutrient-transporting phloem cells, both of which are typically located in a central region of the mature root and stem. These specialized cell types can be separated by the cambium, which is home to dividing cells that drive the expansion of the xylem (which forms wood) and the phloem (which forms bast)[5]. Through an analysis of plants containing mutations in certain genes, and the use of imaging techniques to track fluorescently tagged proteins, Miyashima and colleagues reveal the mechanisms whereby the cell types generated by root-tip stem cells make up the cell layers from which the cambium will form. They show that cambial precursor cells, also known as procambium cells, are specified by a complex molecular network of plant hormones, transcription-factor proteins and microRNAs.

Miyashima *et al.* report that, during an initial growth phase that precedes radial expansion, certain phloem cells at the periphery of the vascular tissue act as ‘organizers’ — cells that promote the division of nearby cells; in this case, the procambial cells. Miyashima