PLATE TECTONICS

Piecing together rifts

Earth's crust is formed where tectonic plates rift apart and upwelling magma solidifies. Disparate observations from rifts beneath the oceans and on land provide insights into the dynamics of rifting and opportunities for synthesis.

Douglas R. Toomey

The global system of Earth's spreading centres — where tectonic plates separate and new crust is formed from cooling magma — accounts for approximately 80% of magmatic activity on Earth. Virtually all of these spreading centres are found beneath the ocean. Mid-ocean ridges play an important role in the exchange of mass and energy between the solid Earth and its hydrosphere, but because they are vast and remote, it is challenging to unravel their secrets. Analogous to the parable of the blind men who try to describe an elephant based on feeling only its tail or trunk, individual views of rifts, although perhaps true, are incomplete. To understand the entire system requires a synthesis from different perspectives, including results from rifts found above sea level. Three studies in *Nature Geoscience* suggest that formation of crust at rifts is more complicated than previously thought, and call into question the usefulness of the traditional neat classification of all ridge processes according to spreading rate alone[1–3].

Early models of plate-spreading centres assumed that the delivery of magma to the rift between two plates is symmetric about the axis of rifting[4,5]. Moreover, it was thought that the creation of new crust from cooling magma (magmatic accretion) is limited to a narrow strip within a kilometre or two of the ridge axis (Fig. 1), based on maps of eruptive fissures[6]. Early geophysical studies at fast-spreading mid-ocean ridges further revealed that directly beneath the rift axis lies a narrow, steep-sided magma chamber within the crust[7]. Together, these observations indicated that mantle melt is efficiently focused beneath the rift and the axial magmatic systems are limited to this narrow zone.

Models of plate spreading have also proposed links between the speed at which plates move apart, the depth of the axial magma chamber[8] and the rates of magmatic accretion[9,10]. Where plates spread apart quickly, heat from the mantle is rapidly delivered to the rift axis and a shallow magma chamber forms that is centred on the rift axis. Because a column of crust at the rift axis moves quickly away, magmatic accretion along the margins of the magma chamber is also rapid. In contrast, where plates spread apart more slowly, the heat supply is also slower and the magmatic system is generally deeper. Thus, magmatic accretion at slow-spreading ridges may be slower or more protracted. Such simple concepts have proved lacking in recent years, however. A steady stream of results from fast-spreading ridges shows evidence for off-axis delivery of mantle-derived melt[11], off-axis crustal magmatism[12], anomalously young off-axis lavas[13] and off-axis seafloor hydrothermal activity[14].

Canales *et al.*[1] use data from a novel three-dimensional multichannel seismic reflection experiment to provide strikingly detailed images of magma bodies beneath the flanks of the East Pacific Rise, a fast-spreading mid-ocean ridge in the Pacific Ocean. The images reveal a network of off-axis magma bodies that have intruded into the crust, just two kilometres beneath the sea floor, and that extend laterally for several kilometres. The presence of these off-axis magma bodies can explain the occurrence of anomalously young lavas found on the distal flanks of the East Pacific Rise[13]. Remarkably, the magma bodies have been discovered at

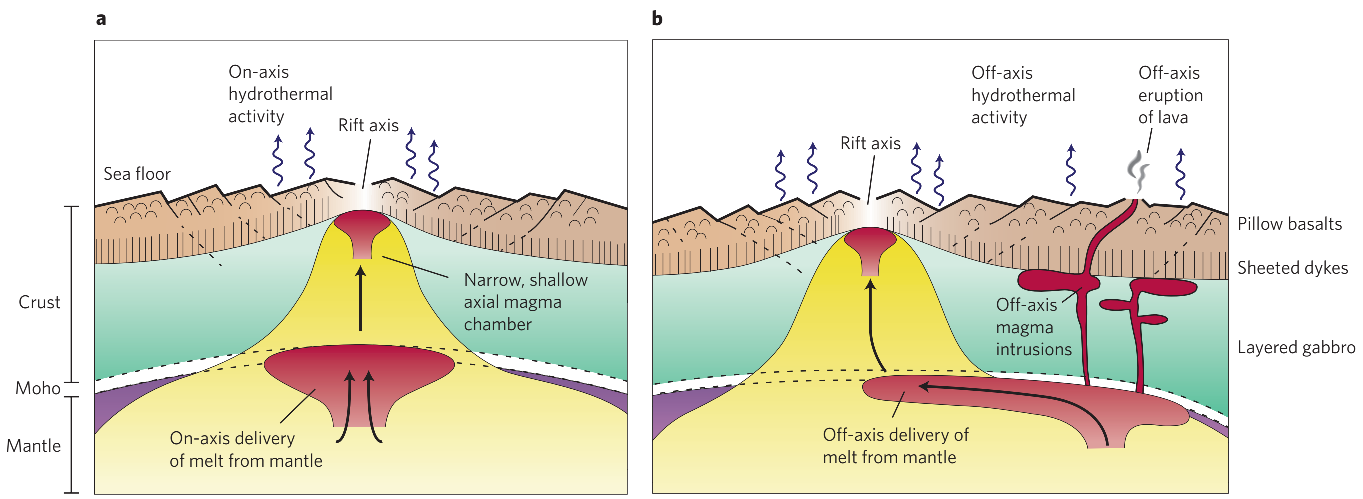

Figure 1 | Schematic models of magmatism at fast-spreading ridges. The formation of new crust at rifts is more complicated than previously thought[1,2]. **a**, Early models of fast-spreading ridges proposed that magmatic accretion was confined to a shallow, narrow magmatic system centred beneath the rift axis, and that crustal accretion was rapid. **b**, New models of crustal accretion at fast-spreading ridges includes an axial magmatic system as well as off-axis magma bodies and crustal accretion, off-axis emplacement of lavas and off-axis hydrothermal activity[1,12–14].

one of the most intensely studied sections of the entire mid-ocean ridge system. This site is characterized by relatively frequent eruptions along the axis of the ridge and volcanically driven hydrothermal activity. That a network of off-axis melt lenses has only recently been discovered in such a well-studied area underscores just how much there is yet to learn about rift magmatism.

Rioux *et al.*[2] also investigate the fast-spreading East Pacific Rise. Specifically, using U-Pb systematics, they date the timing of cooling of zircon crystals in rocks from the lower crust that are exposed at Hess Deep, a cavernous gash on the flanks of the East Pacific Rise. Given that the plates neighbouring the East Pacific Rise spread apart rapidly, Rioux *et al.* expected to find a narrow range of ages, in line with the idea that the margins of a narrow magma chamber move away rapidly to form new crust. Instead, they found that rocks at Hess Deep cooled and crystallized over prolonged timescales that are comparable to those at slow-spreading ridges such as the Mid-Atlantic Ridge[10]. The broad range of cooling ages of the zircon crystals could result from an axial magmatic system that is anomalously wide, leading to drawn-out cooling and formation of the rocks. Alternatively, the broad range of ages could stem from intrusion of young magma bodies at a distance from the rift into the surrounding older crust.

Taken together, the studies by Canales *et al.*[1] and Rioux *et al.*[2] reinforce the emerging view that magmatic accretion of new crust at fast-spreading ridges is much messier than previously thought (Fig. 1). Although the majority of new crust is certainly constructed by the axial magmatic systems, there is evidence from the Oman ophiolite — oceanic crust that is today exposed on land — that as much as 20% of crustal rocks may be intruded at off-axis locations[15,16].

Globally, 98% of Earth's spreading centres are found beneath its ocean. This watery cover is both a boon and a hindrance. Although it facilitates the use of sophisticated marine geophysical imaging experiments[1], it prevents the use of geodetic methods that use radar. Pagli *et al.*[3] demonstrate the power of interferometric synthetic aperture radar methods in their study of the slow-spreading Afar rift in Africa. They identify a body of magma that is 1 km deep and 8 km long, located at very shallow depths in the crust. Remarkably, current models of rifting predict shallow, elongate magma bodies to exist exclusively at fast-spreading ridges[8]. Because it is not covered by an ocean, Afar lacks the cooling effects of sea water and hydrothermal circulation. It is therefore likely that the shallow, elongate magma body is a mark of the high temperature of the rift, otherwise found only at fast-spreading ridges. If so, this study emphasizes that the boundary conditions applied by Earth's ocean play a central and perhaps under-appreciated role in shaping magmatic systems at rifts.

Finally, a synthesis of geodetic and seismic data from historical episodes of subaerial rifting at Afar and Iceland[17] reveals characteristics of rifting events that are unpredicted. For example, at both locations the initial emplacement of the widest and most voluminous intrusions of magma seem to occur farthest from the centre of the rift segment. Smaller intrusion episodes closer to the rift centre then follow. The observed pattern of dyking and intrusions could result from lateral variations in the mechanical strength of the crust[18], which is largely controlled by the thermal structure.

Rifting and magmatic accretion are apparently far from simple. New crust can be formed during intrusive magmatic events that occur over a broad region spanning many kilometres on either side of the rift. The plate-spreading rate may not be the sole controlling factor of the structure and geometry of a magma chamber, or of the rate at which new crust is accreted. Instead, where and how heat is delivered and removed from a rift — in the form of magma transport from the mantle below and hydrothermal interactions with the ocean above — also have important roles.

In the parable of the blind men and the elephant, the emperor remarks that the true description of the beast requires reconciliation between apparently opposing observations. The studies in this issue[1–3,17] show that so it is with rifts, too. ❐

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CLIMATE SCIENCE

Constraints on the high end

The plausibility of the high end of global warming projections in recent assessments is a subject of debate. A study of multi-model climate simulations argues that we need to take the possibility of strong warming seriously.

Isaac Held

Useful guidance on how much warming to expect requires estimates of uncertainties in climate projections. In its 2007 assessment report, the Intergovernmental Panel on Climate Change (IPCC) placed a wide uncertainty range on possible climate trajectories for the coming century. Since then, several studies have implied that the lower half of this range is more plausible than the upper half[1,2], so a re-evaluation of the high end of projected temperature increases is particularly important. Writing in *Nature Geoscience*, Rowlands and colleagues[6] conclude that by 2050, global mean temperatures are likely to be 1.4 to 3 °C warmer than during the period 1960–1990, if greenhouse gas emissions continue along