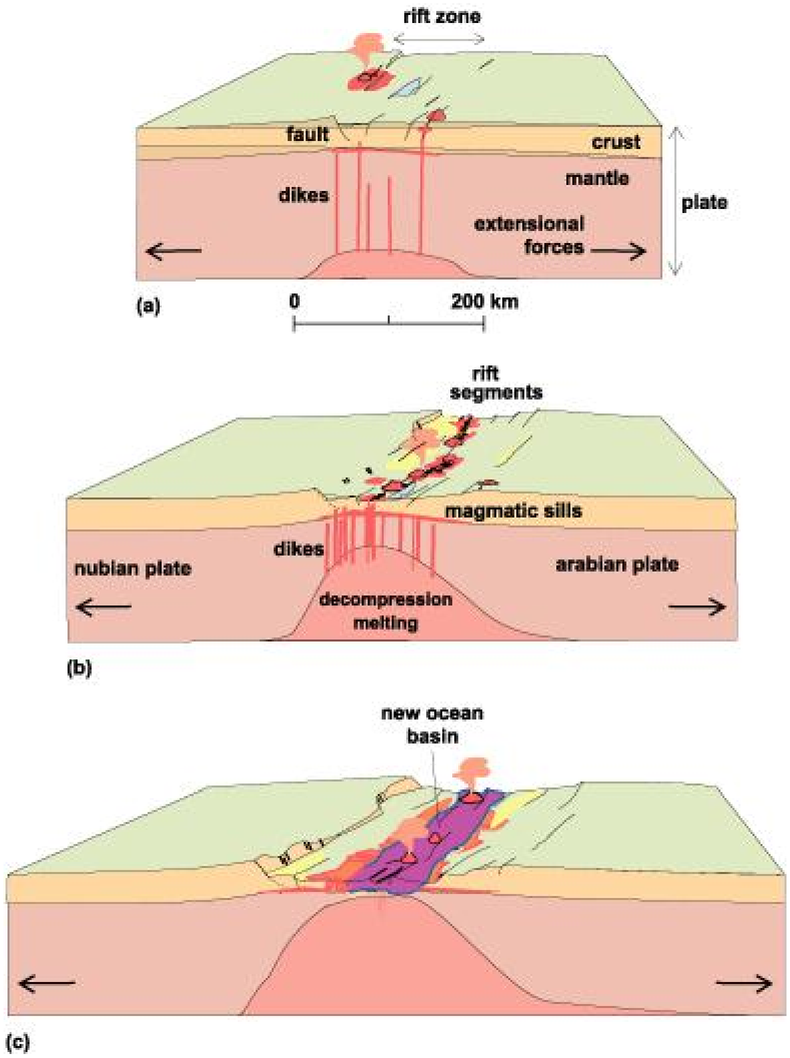
Ocean birth through rifting and rupture

The formation of a new ocean basin begins with the rupture of a more than 100-km-thick (60-mi) continental plate, but only after millions of years of heating and stretching. The deep, fault-bounded valleys above the zones of stretching and heating are called continental rift zones. Fortunately for Earth's inhabitants, the rate of geological processes is extremely slow, and the rupture occurs in episodes separated by hundreds of years. Volcanic and earthquake activity in these episodes affects only a sector of the long narrow rift zones, producing a regular along-axis rift segmentation that is maintained in subsequent episodes. In SeptemberOctober 2005, a 60-km-long (40-mi) segment of the East African rift system in Ethiopia experienced an intense period of localized deformation. Over 162 moderate [body wave magnitude (mb) $\geq$ 4.5 to 3.9] earthquakes and an explosive volcanic eruption occurred over a 3-week period. Subsequent field, remote sensing, and modeling studies showed that molten rock (magma) was intruded into the plate beneath this 60-km-long rift segment, with cracks and faults forming in the brittle rocks above the narrow zones of magma injection. Thus, we directly observed a rare event—the injection of an approximately 8-m-wide (26-ft) column of magma that will quickly freeze to form a new strip of ocean floor. Continued monitoring of the activity will provide vital information for seismic and volcanic hazard mitigation in East Africa.

Rifting and rupture processes

Continents are regions with an approximately 40-km-thick (25-mi), buoyant, quartz-rich crust that is weaker than the 8-km-thick (5-mi) basalt-rich crust of oceanic plates. Both oceanic and continental crust are underlain by an approximately 100-km-thick (60-mi) layer of olivine-rich mantle. Tectonic plates comprise both of these layers (Fig. 1). The plates move at velocities of a few centimeters per year (the rate of fingernail growth) relative to one another in response to forces exerted by the convecting mantle beneath them, interactions between them, and lateral density contrasts within their interiors.

Fig. 1 Three-stage model for the rupture of continental plates. The approximately 150-km-thick (90-mi) continental plates comprise two layers: a weak quartz-rich crust and a stronger olivine-rich mantle. If the forces within, beneath, or at the edges of the plates are large and extensional, the layers will begin to stretch and thin. (*a*) The layered plate begins to thin through brittle and ductile deformation. The mantle rocks beneath the plate rise to replace the thinning lithosphere, and some decompression melting of the mantle may occur. A small volume may reach shallow crustal levels (volcanoes), and some may be accreted at the compositional boundary between the crust and mantle lithosphere. Deformation in the brittle crust occurs by slip along dipping surface, called normal faults. (*b*) With increasing time and strain, the lithosphere will continue to thin by faulting and ductile deformation. Molten rock rises through the heated and weakened plate through vertical cracks to the surface. Most melt does not reach the surface, but freezes in vertical cracks (dikes) that are perpendicular to the extension direction, or in thin sheets (sills) between layers. (*c*) Sea-floor spreading. The thinned and heated lithosphere is now too weak to support the plate-pulling stresses, and melt rises to the surface, producing columns of new oceanic crust. The stretched crust loses heat and subsides; it is now a passive continental margin.



When an extensional (pulling) force is applied to a continental plate, long narrow basins flanked by mountains more than 1000 m (3300 ft) in height form as the plate stretches and thins. These seismically and sometimes volcanically active zones are called continental rift basins (Fig. 1*a*). Mantle rocks rise up under the thinning plate, melting as they decompress. The molten rock, or magma, is less dense than the surrounding rock, and this buoyancy force assists the plate stretching. With few exceptions, the buoyant melt rises up through the plate, transferring heat and weakening the plate. Some of this magma reaches the surface via fissures or volcanoes, and some solidifies in narrow vertical sheets (dikes) or subhorizontal sheets (sills) within the crust. This basaltic magma intrusion process increases the density of the thinning crust, and the basins subside. Tensional forces on the plates sometimes cause brittle faulting of the crust, a process usually marked by earthquakes. Plate stretching is achieved through the combined processes of movement on dipping faults and dike intrusion.

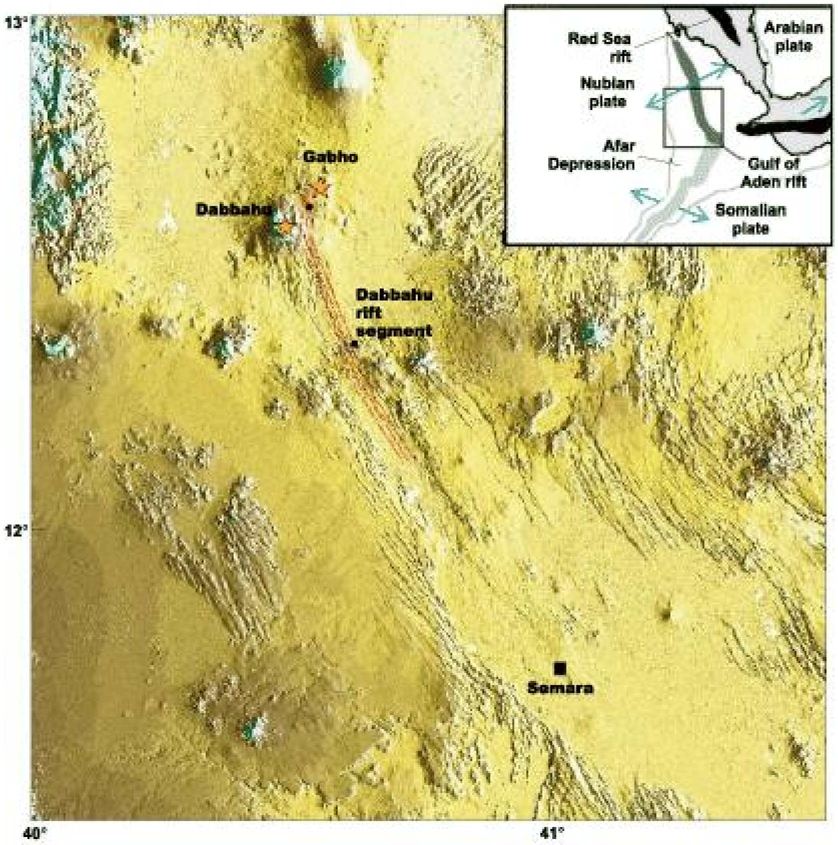
If the forces are maintained for several millions of years, the plate can thin to a fraction of its original thickness. Few continental rift zones actually progress to rupture and createl new oceanic lithosphere. The forces required for rupture are more than 100 megapascals, the equivalent of 500 jumbo-jet engines pulling on a square meter of the plate, and must be maintained for millions of years. With progressive episodes of rifting, the distribution of faulting and magmatism localizes to a narrow zone within the ever-expanding rift basin. The mantle beneath the thinning plate rises to shallower levels, decompresses, and melts. The creation of a new column of basaltic crust sandwiched between the stretched continental crust signals the onset of sea-floor spreading, which may occur above sea level during the first few million years. The denser oceanic crust eventually will subside below sea level as it cools and thickens at a rate proportional to the square root of the time since formation.

The geological record of the rifting and rupture process is preserved along the edges of many ocean basins, such as the eastern and western coasts of the Atlantic Ocean. The ancient sites of plate rupture along these passive continental margins are masked by more than 10 km (6 mi) of sedimentary rocks, and Earth scientists have only recently recognized that most margins experienced voluminous volcanic eruptions prior to plate rupture. An alternative approach to the study of continental breakup and the birth of an ocean basin is to study continental rift zones that are in the process of rupture.

Afar Depression

The East African rift system in the Afar Depression is one of few places worldwide where the process of continental rupture is occurring on land, affording an opportunity to directly observe and quantify the plate separation process. Large tracts of the depression lie at or below sea level, attesting to a long history of stretching and magma intrusion. Another unique feature of this rift system is its position above or near a large deep-seated zone of anomalously hot mantle rocks that both heat the overlying plates and provide a long-lived supply of melt. Within the Afar Depression, three rift systems intersect. The Red Sea rift separates stable Africa (Nubian plate) from the Arabian plate. The Gulf of Aden rift separates eastern Africa (Somalian plate) from the Arabian plate. And the Ethiopian rift system separates the Nubian and Somalian plates (Fig. 2, inset). Rupture has already occurred in the Asal rift, the westernmost arm of the Gulf of Aden rift, which experienced a volcanic eruption and several earthquakes in 1978.

Fig. 2 Topographic relief of the 60-km-long (40-mi) Dabbahu rift segment within the Afar Depression. Inset shows directions of plate divergence between the stable African (Nubian), Arabian, and Somalian plates. (*After T. Wright et al., 2006*)



Little was known about the rates and timing of events elsewhere in the Afar Depression, partly because of the harsh desert environment and limited access to it. Globally we have a short time sequence of observations, with written records of earthquakes and volcanic eruptions spanning just a few centuries in much of Africa, and instrumental recordings spanning about the past 100 years. Thus, with rifting cycles of centuries, some aspects of the rifting process remain undocumented.

2005 Dabbahu rift episode

The September-October volcano-tectonic crisis in the Afar Depression is the largest rifting sequence to have occurred on land, since the 10-year-long Krafla, Iceland, rifting episode, which occurred in a well-developed mid-ocean ridge. The spatial extent and amount of opening are comparable to the Krafla event (Fig. 3). Earthquakes centered on a discrete rift segment, the Dabbahu (Boina) segment, began on September 14, 2005, with a cluster of 98 damaging earthquakes occurring on September 24 and 25 (Fig. 2). On September 26, a volcanic vent opened between two strato-volcanoes near the northern end of the Dabbahu rift segment (Fig. 4). Local pastoralists watched as some scarps (cliffs) moved up to a meter; field teams documented 5 m (16 ft) of offset on faults near the center of the Dabbahu segment (Fig. 5). By comparing satellite radar images acquired before and after the earthquake swarms, we have detected deformation along and across a 60-km-long (40-mi) segment of the rift. Although only a small volume of magma was erupted at the surface, the satellite and surface data showing up to 1-m-wide (3-ft) open fissures and faults cannot be explained by the energy released in the earthquakes alone. Buoyant magma injected into the plate provides rift opening with few earthquakes; dike injection can account for the energy deficit. The rifting episode was probably triggered by the injection of a 60-km-long and approximately 8-m-wide (20-ft) sheet of basaltic magma (dike), with faults slipping above the dikes. The basalts did not reach the surface in this episode.

Fig. 3 View south-southeast along one of many open fissures near the central part of the Dabbahu segment. Some cracks are open fissures, and some are faults with vertical displacements of up to 6 m (20 ft). These formed during the September-October 2005 rifting episode. (*Photo by C. Ebinger*)

Fig. 4 View north toward the Gabho volcano showing the ~600-m-long (2000-ft) volcanic vent that opened in blasts beginning September 26, 2005. On the right (eastern) side of the image, open fissures and normal faults cut the ashes erupted from the vent. The more than 2-km-long (1.2-mi) fault at the right corner slipped over 0.5 m (1.6 ft) on September 26. (*Photo by E. Baker, Royal Holloway University of London*)

Fig. 5 View north-northwest from the central part of the eastern flank of the Dabbahu rift segment. The Dabbahu volcano is about 30 km (18 mi) from this site. The steep scarps were formed by many episodes of slip along dipping fault planes; some faults show more than 3 m (10 ft) of movement in the September-October episode. The faults displaced basaltic lavas (dark rocks) and small pockets of windblown ash and dust (white rocks). (*Photo by C. Ebinger*)

Outlook

Has the Dabbahu rift segment episode stopped? Preliminary results from Global Positioning System (GPS) measurements show continuing deformation in the Dabbahu segment. We draw insights from the 10-year Krafla, Iceland, sequence. A smaller dike intrusion in 1975 marked the beginning of the Krafla rifting episode; as in Ethiopia, the magma did not reach the surface. It was followed by 20 more dike events, many of which produced curtains of fire as they erupted. By analogy to Krafla, there may be more to come over the next few years. Ethiopian geoscientists and international colleagues are monitoring earthquake activity, ground deformation, vent emissions, and satellite images to understand the longer-term response of the plates to this intense applied stress, as well as to detect any resurgence in potentially explosive volcanic activity.

See also: Africa; Earth crust; Earth interior; Earthquake; Fault and fault structures; Magma; Plate tectonics; Remote sensing; Volcano

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For Further Study

Topic Page: Earth Science: Geology and geodesy
Topic Page: Earth Science: Geophysics

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Additional Readings

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