Feature

Extension tectonics in the Afar Triangle

On the Red Sea coast of Africa, the triangular wedge of land named after its Afar people has been created by excess basalt production at a triple junction of divergent plate boundaries. Its harsh desert terrain is a remote wilderness that receives few visitors, yet is a spectacular suite of extension tectonics dominated by sinking grabens, salt basins below sea level, active faults and effusive volcanoes.

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The Afar Triangle is the name given by geologists to a triangle of barren lowland bounded by the Red Sea and the two blocks of Ethiopian Highlands (themselves separated by the Rift Valley). Riven by the desert furnace that is the Danakil Depression, its terrain is a casebook of tectonic geology. Plate divergence is at its most obvious in the Red Sea region, where any map or satellite image reveals the fit of the continental blocks (Fig. 1). The Red Sea itself has opened, and is still opening, where the Arabian plate moves away from the African Plate. This divergent boundary continues east along the floor of the Gulf of Aden, and ultimately extends into the Carlsberg Ridge and the mid-Indian Ocean ridge. The African Plate is breaking apart along the well-known East African Rifts, separating the Somalian Plate from the main continental block (often known as the Nubian Plate in the north).

These three divergent boundaries have a triple junction at the Afar. The Triangle is the one place where the coastlines and plateau margins cannot be fitted neatly back into their pre-divergent entity – because the major constructive process of basalt generation has been a little excessive just here, and has created anew the youthful lowland that is the Afar. There is a valid concept that the East African Rift marks the line of a super-plume rising within the mantle beneath the continental slab, and a hot-spot along this mega-feature has created the enhanced volcanic activity that built the Afar. However, nothing is simple in the field of tectonic movements, and the Afar today reveals a story of volcanic eruptions, fault movements and grand subsidences that are the product of massive rock deformation around a microplate and across a host of even smaller plate fragments.

The Afar terrain

'Hostile environment' is a term tailor-made for the Afar. The land is an awful, hot, barren desert. Just one river enters it, and none leave it. A few salt lakes contain almost the only water not yet lost to solar evaporation. Daily temperatures are 30–40 °C in the cool of winter; summer regularly sees shade temperatures of 50 °C on the floor of the Danakil Depression – and there is no shade. Long-term survival in these conditions is almost inconceivable to a European, but the Afar people live throughout the year in the hottest, driest and most remote areas, including the Danakil floor, far below sea level. They are magnificently adapted to their environment and can walk huge distances across the desert with minimal need for water (Fig. 2). It is not surprising that they are aggressively protective of their water resources; Wilfrid Thesiger described them as the fiercest people he had ever met, and even today visitors are best accompanied by Afar people of the right local tribe to ensure their longevity.

To add to the difficulties, modern politics have divided the Afar

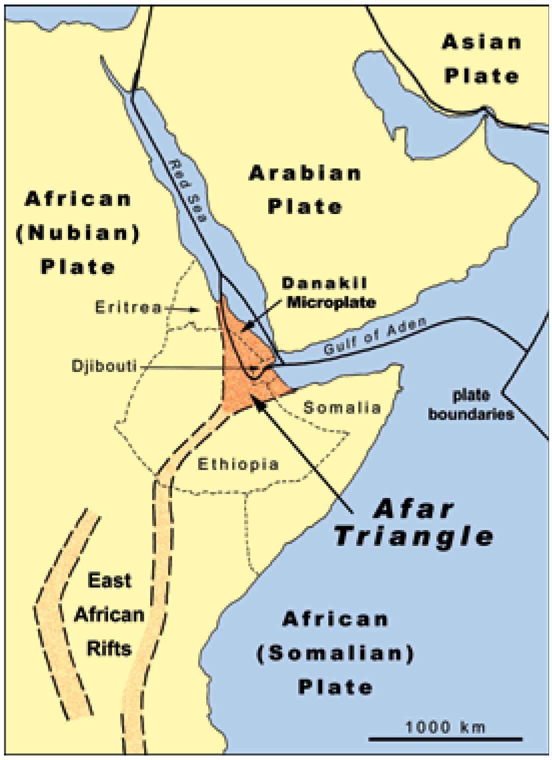
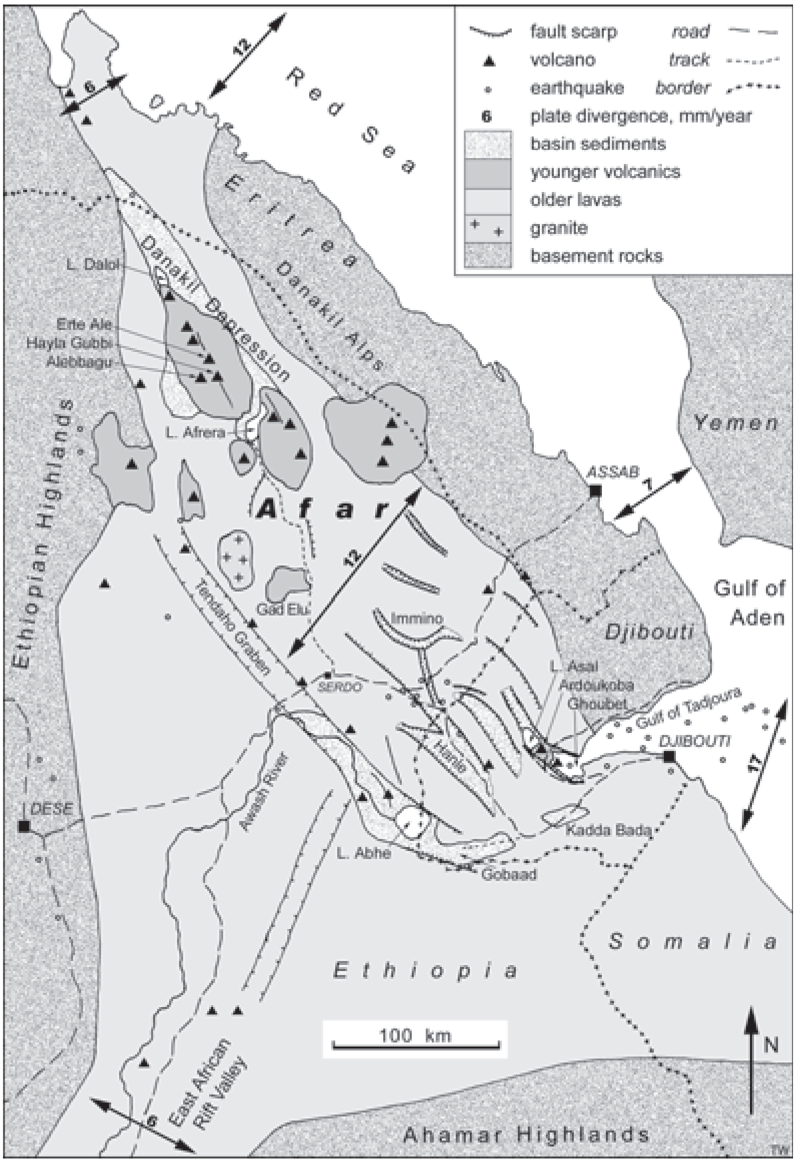


Fig. 1. The plate boundaries that converge on the Afar Triangle.

Fig. 2. Two Afar women drive donkeys along the dust floor of one of Djibouti's rift valleys, with the marginal fault scarp seen behind.

Triangle between four warring nations. Most is in Ethiopia, although a coastal slice became Eritrea after recent wars that are still not totally resolved. Djibouti is a one-time French colony, and its capital with the same name is the only large town in the Afar, though now overrun by refugees from all its neighbours. Somalia laps over into just a corner of the Afar desert. A good road links the Ethiopian Rift Valley to Djibouti (and previously to Assab), but most of the Afar has only rough tracks; access to the Danakil is by pairs of 4WD trucks, or by camel. The Afar's desert environment may be truly hostile, but its minimal weathering and negligible vegetation mean that the geology is beautifully exposed.



The dominant rocks within the Triangle are flood basalts (the older lavas on Fig. 3). Most of these formed within the depression, after the first rift had been lowered between the marginal faults; the oldest of these overlie red beds and date from about 24 Ma, at the start of the Miocene. Locally, these lavas have a total thickness of 4000 m, and their most rapid accumulation was in the period 2.4–0.8 Ma, since the mid-Pliocene. They reach to the present day, as volcanism is still active, and the more recent have formed shield volcanoes in the northern Afar (the younger lavas on Fig. 3). Subsiding rifts have filled with basin sediments that are contemporary with the volcanics; these consist mainly of fine clastic sediments and evaporite sequences interbedded and surrounded by marginal wedges of scree. The Danakil Depression was occupied by an arm of the Red Sea until 65 000 years ago. Outcrops of marine limestones with coral reefs lie around the depression margins and pre-date its isolation from the sea. Younger freshwater limestones also survive in places.

Both west and south of the Afar, the Ethiopian Highlands, with a mean altitude of 3000 m, have cores of Precambrian metamorphics and granites. Much of their area is capped by Mesozoic sandstones and limestones, or by Eocene and Oligocene alkaline basalts. These lavas, commonly hundreds of metres thick, represent outpourings through the continental crust that were a precursor to the rifting of plate divergence. Of similar geology is a much smaller block on the eastern side of the Afar. This is the Danakil Microplate, a fragment of continental crust, isolated within the oceanic rift zone that locally braids to underlie both the Red Sea and the Danakil Depression (Fig. 1). Its basement rocks form the Danakil Alps in Eritrea, and extend into the highlands of eastern Djibouti, whose peaks catch rainfall from the east and therefore support the only forests in the Afar.

The largest single feature of the Afar is the Danakil Depression, which descends to 126 m below sea level over the line of current plate divergence, and would be larger except that half its floor is occupied

Fig. 3. Selected geological features of the Afar Triangle. The continental blocks are identified by the areas of basement rocks, but parts of these are covered by Tertiary lavas; their margins are major fault zones. The area of older lavas has many smaller rift features and younger volcanics that are not marked.

Fig. 4. Marginal fault scarps along the splendid rift valley that is formed on the Dobi graben, seen from the old Serdo-Assab highway.

Fig. 5. Salt flats with crystal growth along polygonal cracks on the floor of the Asal graben, with Ardoukoba volcano in the background.

by shield volcanoes. It is a classic rift valley, but both its margins are formed by wide zones of normal faults eroded into massive mountain slopes lacking in dramatic individual scarps. South of the Depression, the rift breaks into many smaller rifts that indicate the complexity of the plate deformation when viewed in detail.

The grabens of Djibouti

On the ground and on a map, the dominant landforms of inland Djibouti are the three great grabens that parallel the Afar axis (Fig. 3) and are the most dramatic feature of its extension tectonics. Their marginal faults are normal and dipping inwards at 70–80°, creating spectacular scarps that have rapidly degraded to stable profiles while building their ramparts of scree. Their rims are little eroded, but the graben floors are covered by playa silts and salt pans. These are true rift valleys, nearly as deep and as steep as the graben structures that define them. The Hanle graben is 3–10 km wide and over 80 km long, if its narrower Dobi extension northwards into Ethiopia is included, with marginal scarps 500–800 m high (Fig. 4). Its margins are characterized by many smaller scarps along normal faults, some of which appear to be cylindrical as they delimit blocks that have rotated by up to 20°. The adjacent graben (Gaggade) is similar except that it is asymmetrical with a higher western scarp.

Deepest and most active of the three main grabens is that containing Lake Assal and the marine bay of Ghoubbet. This massive, curved rift valley is nearly 70 km long and 15–20 km wide, with cliffs rising 600 m along its southern fault boundary. The sea in Ghoubbet is over 200 m deep, and the surface of Lake Asal fluctuates around 155 m below sea level. Lake Asal lies over sediments up to 200 m deep, has thick beds of late Holocene gypsum exposed around its shores, and is depositing salt on its marginal flats (Fig. 5), as its main recharge is by seawater infiltration through the porous basalts.

The rift valley around and north of Asal would be occupied by the sea, were it not for the Ardoukoba massif that stands inside the rift. Much of this is a series of positive fault blocks that appear as horsts, but in reality are graben blocks that have not subsided as far as their neighbours in both directions along the rift. Typical Afar basalts are exposed, along with a range of coarse lithic and crystal tuffs that survive in rotated fault blocks with gastropod limestones that now lie far above the level of either the sea or the interior lake. Capping these blocks are younger volcanics (including those from the Ardoukoba eruption in 1978) that were extruded not from a single volcanic centre, but from numerous fissures and vents across the entire massif. They include basaltic lavas that formed tube-fed flows and ponds draped over and between the fault scarps, along with a scatter of hornitos. Submarine phreatic eruptions have created splendid cinder cones around the western shore of Ghoubbet, including one rising to 160 m to form the island of Guinni Koma, while a number of spatter rings and spatter cones up to 50 m high are spread over the slopes down to Lake Asal. The youngest feature is the large spatter ring that was created during the brief eruption in 1978, along with short flows that emerged from fissures in the adjacent hillsides (Fig. 6).

The most southerly graben is less well-defined, but its sweeping curve houses Lake Abhe on the Ethiopia-Djibouti border. It is a southerly continuation of the Tendaho graben (which also has little topographic expression) and has been largely filled by sediments carried in by the River Awash (Fig. 3). It also has some small cinder cones along its margins and on its floor. Lake Abhe lies more than 200 m above sea level, but has no outlet, as the entire inflow of the River Awash is matched by evaporation losses and leakage into the porous basalt aquifers. The lake is now only 15 m deep, and its shallow basin allows its area to vary in response to environmental change; its width was just 10 km across in 1997, compared to

Fig. 6. Short flows of pahoehoe basalt that emerged from fissure vents during the 1978 eruption of Ardoukoba; a black hornito stands on a less effusive fissure along the crest of the fault scarp.

28 km in 1938. Shrinkage has been partly due to abstraction of irrigation water from the Awash before it leaves the main Ethiopian rift valley, but climatic variations account for a modest expansion in recent years. An aridity peak on the Ethiopian Highlands left the lake dry from about 17 000 to about 10 000 years ago, but for most of the subsequent 6000 years its level was about 150 m higher than it is now. These past high levels have left sedimentary terraces and wave-cut notches on the adjacent hillsides.

Lake Abhe is perhaps best known for its splendid travertine towers. There are hundreds of these scattered across the flats on the eastern lakeshore (Fig. 7); the stark, barren pinnacles create a dramatic landscape that was chosen as an 'alien-world' background for filming *Planet of the Apes*. Each tower was formed where a carbonate-saturated, geothermal spring emerged in the contemporary lake floor and deposited the calcite due to reaction with the lake water. The towers are spread over an area of about 2000×500 m, but many of them stand roughly in east-west lines that lie over bedrock fissures beneath the graben sediments. Individual towers are up to 60 m tall, the last time lake levels were that high being about 1000 years ago. Hot springs now emerge on the mud flats between the towers, notably around the bases of the larger towers; some are boiling, some produce methane and most smell of hydrogen sulphide (*Abhe* means rotten in the local language).

Fig. 7. The landscape of tufa towers at Lake Abhe, with the current lake shore this side of the farthest towers.

The towers are all made of yellow botryoidal calcite that can be described as either travertine or tufa (though there is no sign of algal control of the deposition) and has the appearance of chemically precipitated 'cave coral' deposits. Most towers are inactive, with fallen blocks around their flanks (Fig. 8), but some have steaming vents emerging high on their sides. New towers may be forming beneath the lake, but are as yet unseen.

Fig. 8. Tufa towers up to 30 m tall on the mud flats of Lake Abhe.

Patterns of plate movement

Djibouti's grabens are just one aspect of the Afar's complex suite of tectonic features that have evolved from ground deformation at a triple junction of divergent plate boundaries complicated by independent movement of the intermediate Danakil Microplate. Though preceded by the Eocene production of flood basalts and the Arabian Plate breaking away from Africa in the Oligocene, plate divergence in the Afar really came of age when magma production evolved into tholeiitic basalts in the Miocene (about 15 Ma). These were true oceanic basalts, and following the earlier alkaline basalts, they indicated that magma was rising cleanly from mantle sources once the continental plates had moved apart. Initial divergence was directly along the line of the Red Sea, but then the Danakil Microplate broke away and palaeomagnetic signatures have shown that it has moved independently of the Nubian Plate since about 11 Ma. The new axis of divergence, down the centre of the Afar, has become increasingly important ever since. These plate boundaries have not yet evolved into true spreading ridges (as found on mid-ocean floors). However they are clearly constructive, as is also indicated by the surfaces of both the Ethiopian Highlands and the Danakil Alps sloping away from upturned crests at the Afar margins.

Current rates of relative movement of the plates have been determined by repeated, high-grade geodetic surveying over periods of up to 25 years.

Spreading rates have recently been confirmed with repeated satellite imagery, and are also matched by geological evidence based on accurate dating over the last few million years. Movement patterns are indicated by measured values on Figure 3. Total divergence of the Arabian Plate from the African plates is 17–19 mm/year, but this is split between the two divergence zones that lie either side of the Danakil Microplate. Movements within and along these two zones vary in response to anti-clockwise rotation of the microplate.

Earthquakes are, naturally, common in a region as tectonically active as the Afar, and their distribution over the last 50 years falls into distinct zones that indicate the currently active areas of faulting (only major epicentres are marked on Fig. 3). The main seismic zone passes westwards along the Gulf of Tadjoura, then curves northward through the Djibouti grabens to merge with a zone on the Nubian marginal faults along the flanks of the Ethiopian Highlands. This latter zone extends southwards along the Nubian plate margin and into the Rift Valley, and northwards to join, then follow, the axis of the Red Sea. In the southern Red Sea, a much less active zone defines the eastern side of the Danakil Microplate. A few recent quakes have approached Magnitude 6. In 1973, one in the Gulf of Tadjoura caused damage to Djibouti's docks. In 1969, 24 people were killed when the village of Serdo was totally destroyed by a quake that was the largest of a swarm of 250 shocks (Magnitude >3) on the nearby graben faults. Another series of earthquakes in 1989 was also centred on the grabens, and destroyed bridges on the road to Assab. The Mekele earthquake of 2002 originated on the marginal faults of the Ethiopian Highlands, west of Erte Ale. Fault movement is also still visible along the eastern margin of the Asal Graben where screes on the graben floor subsided in the 1978 volcanic event to expose a fresh band of the rift wall (Fig. 9).

Rotation of the Danakil Microplate has been largely responsible for the complex horizontal movements in a zone of plate fragments that now lie between the grabens of inland Djibouti. The graben faults delimit the blocks that are displaced by 'bookshelf faulting', where the sub-parallel blocks have each rotated clockwise (and have been pulled apart) as their northern ends have been dragged eastwards. Paleomagnetic orientations of the Pleistocene lavas have shown that adjacent blocks have rotated by different amounts (up to 11° in 1.8 Ma), with the slack taken by differential opening of the intervening grabens. Reorientation of the dozen rotated blocks, and deconstruction of the graben movements, produces an excellent fit that indicates an unbroken tectonic unit at the start of the Pleistocene. Movements have evolved over time, and the most active zone was originally the Lake Abhe graben, but is now the Asal-Ghoubbet graben (which also has the youngest volcano).

Fig. 9. An active fault scarp along the eastern margin of the Asal-Ghoubbet graben, with a fringe of pale rock newly exposed along the crest of the scree slopes that have subsided along with the graben floor on which they stand.

Repeated geodetic surveys across the Ethiopian Rift Valley have shown that about 80 per cent of the extension is accommodated by magmatic emplacement, as basaltic dykes and lavas. The other 20 per cent of extension is expressed in normal displacements on the marginal faults and grabens. It would appear that comparable figures apply to extension in the Afar, except for the zone of greater rifting that is currently active between Abhe and Asal in inland Djibouti. Lavas cover most of the Afar surface, and graben fault exposures show the great thickness of the lava pile, but there are no great dyke swarms yet exposed at the surface. Only isolated dykes are known (Fig. 10), some of which have offsets of the country rocks due to normal fault displacements on their margins. The recent fissure eruptions on Ardoukoba also suggest there is dyke emplacement. The current rotation of the Danakil Microplate appears to influence volcanic activity; at

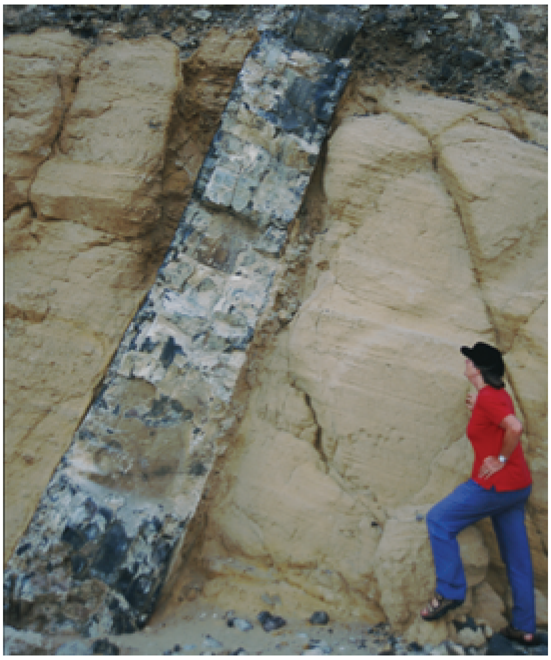


Fig. 10. One of many small basaltic dykes exposed in the marginal slopes of the Asal graben, intruded into dipping basin sediments.

its northern end, minimal divergence from the Nubian Plate precludes modern extrusive activity, while all the active and recent volcanoes are further south where divergence is greater.

The Danakil Depression and Erte Ale

At the northern end of the Afar Triangle, the Danakil Depression is a massive rift valley between the fault scarps of the Ethiopian Highlands and the Danakil Alps. Cut off from the sea since the Pleistocene, it has lost its water to desert evaporation and is dry down to Lake Dalol, 126 m below sea level. Lake Afrera is a second salt lake, with its surface at –118 m. Between the two lakes, the multiple shield volcano of Erte Ale occupies much of the depression floor. At the south end of the Depression, the sloping floor rises to the graben zone beyond Serdo on outcrops of block-faulted Neogene lavas; these are interrupted by the Pleistocene (400 ka) Gad Elu Obsidian, some of it with folded bands of pumice, and by the Affara Granite, unroofed since its Oligocene emplacement.

Away from the lava flows, the Depression is floored by playa flats of silts and evaporites. Littoral and reef marine limestones of mid-Pleistocene age (200–80 ka) survive in places around the Depression margins, as evidence of times when it was an arm or gulf off the Red Sea. Reefs now lie at altitudes of –30 to +90 m, with individual shoreline beds changing levels by tens of metres, indicating the complex and locally variable rates of subsidence within the graben. Evaporites are over 1000 m thick beneath the floor of the Dalol basin, and date from 125–65 ka, before the Danakil Gulf was finally isolated from the Red Sea. The surrounds of Lake Dalol are noted for their hot springs and fumaroles that have created crystal pools, micro-terraces, mini-hornitos and colourful structures in sulphur, halite and other minerals.

Afrera is a less spectacular lake, but is also fed by geothermal springs, and its brines are now exploited by extensive salt pans, where precipitation is very quick in the hot dry desert. Its basin has outcrops of Holocene (10–7 ka) lacustrine limestones and diatomites that are now well above the present lake level, in part due to tectonic uplift.

Afar's only volcano that is currently active is Erte Ale, rising from the floor of the Ethiopian sector of the Danakil Depression. It is a classic shield volcano with gentle slopes of basaltic lavas, and almost no tephra, except that it is markedly elliptical in shape, because both the central vents and the main parasitic vents lie over a major fissure zone along the axis of the Depression. Its position over the divergent plate boundary makes it a fine subaerial example of a mid-ocean ridge volcano. Its perimeter is more than 100 m below sea level within the depression, and its summit rises to 613 m above sea level. As part of the same edifice, Hayla Gubbi is an adjacent and lower shield volcano with a fresh but inactive crater over the same fissure zone (Fig. 3). Alebbagu is an inactive composite cone rising to 1150 m; it is built largely of andesite lavas, with some rhyolite lavas and pyroclastics ranging from basic to acid, and stands over a parallel fissure system. Gade Ale and the smaller smoking cone of Dalla Fila lie at the northern end of the elongate shield, overlooking Dalol.

Erte Ale is a splendid shield volcano, with its slopes of basalt pahoehoe and aa lavas, notable for the numerous breached lava tumuli and broken by a scatter of parasitic fissure vents, many of which are capped by small late-stage hornitos (Fig. 11). It is, however, unique in that it contains a lava lake that has been persistently active for at least 100 years. The crest of the mountain is marked by an elliptical caldera 1700 m long and 600 m wide, inclined to the south and with marginal walls about 20 m high except at its two ends. A large northern crater and a smaller central crater both lie within the caldera. Recent extrusions of basalt have emerged from both craters and from fissures on the caldera margin faults. Consequently, the entire caldera floor is formed of fresh pahoehoe (Fig. 12). Most of this dates from 1974, though there have been minor vent overflows since 1997. The surface is distinguished by thin shells and crusts over miniature tubes, and these readily collapse under the footfall of any of the few visitors to the site. Marginal fissure eruptions have shrouded the northern end of the caldera walls, where hornitos now form Erte Ale's highest point, and most of the lavas have flowed south to where they flowed over the lowest point on the caldera rim.

Fig. 11. A small hornito that was built by ejected blobs of lava spatter, on the flanks of Erte Ale.

Many years ago, the northern crater of Erte Ale was the dominant vent, containing a lava lake that was variably 100–300 m across. At times the lake surface was 150 m below the rim, but at other times it overflowed, until it cooled enough to crust over and become inactive, probably early in 1975. Soon afterwards, it suffered a major drain-back of magma; this left a deep crater that has since been partially refilled with collapsed wall debris and some fresh lava, including a very large central hornito. It is still unstable, with a number of pit craters and highly productive fissure fumaroles around its rim. These fumaroles produce thick clouds of oxygen-deficient, sulphurous fumes that make the caldera floor very inhospitable when the wind is from the north.

Erte Ale's central vent is a spectacular pit crater, developed by collapse when magma pressure declined beneath it. Only 60 m across when first recorded in 1968, it is now 150 m across, and about 80 m deep. A lava lake once covered its entire floor, and has periodically overflowed. In recent years, the lava has drained down, and the lake has only occupied about half its area at a level lower than a terrace of solidified lava. As on any lava lake, the surface is formed of rafts of partially cooled crust, whose continual movements are a small-scale version of plate tectonics, with liquid lava exposed along lines of both divergence and subduction. Measured with an optical pyrometer from the crater rim, the liquid lava has a temperature of about 1200 °C, while the chilled rafts that cover most of the surface are at about 500 °C. Regular infra-red images from a satellite recorded a sudden decrease in overall heat flow in January 2003, and this correlates with a shrinkage of the lava lake to its present size of little over 30 m in diameter. The shrunken lava lake is highly turbulent, with only small rafts on its surface between fissures with upwelling and fountaining lava (Fig. 13). The old lake surface around it is cooled but unstable, and is currently breached by a small active hornito; this adds to its height by spitting out a molten blob of new lava every few minutes.

The continued survival of the lava lake relies on a substantial heat supply that matches its thermal loss into the atmosphere. This heat supply can only be due to rising magma, yet there is a complete lack of lava extrusion (except when the lake has temporarily overflowed in the past). By implication, there must be considerable igneous intrusion of new magma taking place from a pipe that lies beneath the lava lake. It appears that Erte Ale currently has beneath it a zone of active intrusion of dykes and sills; these are filling new fissures and keeping pace with the opening within the zone of plate divergence, and are thereby preventing further subsidence within the graben.

The active volcano is just the most visual aspect of the Afar's complex interplay of tectonic activity, volcanic extrusion and igneous intrusion that are all so beautifully revealed, and together offer a classic example of plate divergence processes.

Suggestions for further reading

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Fig. 12. A tangle of pahoehoe basalt flows just below the central crater inside the Erte Ale caldera, seen from the top a large, old, adjacent hornito.

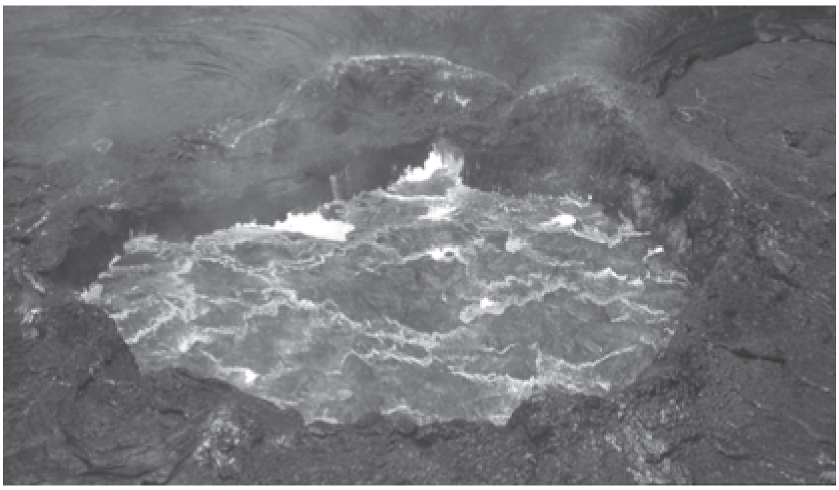

Fig. 13. The small lava lake inside Erte Ale's central pit crater.