Chapter 19
Afar Triangle: Rift Valleys and Volcanoes over Plate Divergence

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Abstract The barren deserts of the Afar Triangle constitute a basaltic ocean-floor terrain on a divergent plate boundary that is above sea level because it lies over a hot spot. Grabens and rift valleys including the Danakil Depression exhibit active normal faulting. Active dyke emplacement is indicated by heat loss from the Erta Ale lava lake. Both these processes accommodate the crustal extension, and excess magma input creates scattered volcanic eruptions.

Keywords Danakil • dyke • extension • graben • rift • volcano

19.1 Introduction

The Afar Triangle is a 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 geomorphology. Plate divergence is at its most obvious where the Red Sea has opened, and is still opening, between the Arabian and African plates. 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 locally excessive constructive process of basalt generation has created anew the youthful lowland that is the Afar.

19.2 Afar Terrain

'Hostile environment' is a term tailor-made for the awful, hot, barren desert of the Afar (Fig. 19.1). Just one river enters it, and none leaves 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. The permanent inhabitants of the desert are the various Afar tribes, renowned for their fierce and justifiable protection of scant water resources. They range across land that is now divided between Ethiopia, Eritrea and Djibouti, and are joined by migrants and refugees who gather to work in very hard conditions extracting the salt from the Danakil floor. The Afar's desert environment may be truly hostile, but its minimal weathering and negligible vegetation mean that the geology and geomorphology are beautifully clear to see (Waltham 2005).

The dominant rocks within the Triangle are flood basalts. 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 million years ago. Locally, these lavas have a total thickness of 4,000 m. Volcanism is still active, and the more recent lavas form shield volcanoes in the northern Afar. Subsiding rifts have filled with basin sediments that are contemporary with the volcanics; these consist mainly of fine clastic sediments and evaporite sequences inter-bedded and surrounded by marginal wedges of scree. Both west and south of the Afar, the Ethiopian Highlands, with a mean altitude of 3,000 m, have cores of Precambrian metamorphics and granites, much of them capped by sandstones, limestones or alkaline basalts. East of the Afar, the Danakil micro-plate is a

P. Migoń (ed.), *Geomorphological Landscapes of the World*,
DOI 10.1007/978-90-481-3055-9_19,

Fig. 19.1 Bare rock, long fault scarps and sediment basins characterise the Afar desert, with a few acacia trees providing the only signs of life in a harsh environment (Photo T. Waltham)

fragment of continental crust, isolated within the oceanic rift zone that locally braids to underlie both the Red Sea and the Danakil Depression (Fig. 19.2). Its basement rocks form the Danakil Alps, whose peaks catch rainfall from the east to support ragged forests – and shelter the Danakil Desert in a deep rain shadow.

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 by shield volcanoes. It is a classic rift valley, but both its margins are formed by wide zones of normal faults that are eroded into massive mountain slopes and lack 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.

19.3 Rift Valleys of Djibouti

The dominant landforms of the Djibouti sector are four great rift valleys that parallel the Afar axis and are the most dramatic consequence of its extension tectonics (Fig. 19.3). Their marginal faults create spectacular scarps that have degraded to stable profiles while building their ramparts of scree. Subsidiary scarps along some parts show rotational movement of down-faulted wedges over curved fault planes. Their rims are little eroded, but their 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.

Deepest and most active of the rift valleys is that containing Lake Asal and the marine bay of Ghoubet. It is nearly 70 km long and 15–20 km wide, with cliffs rising 600 m along its southern fault boundary. The sea in Ghoubet is over 200 m deep, and the surface of Lake Asal fluctuates at 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 there is salt precipitation on its marginal flats, as its main recharge is by seawater infiltration through the porous basalts. The rift valley around Asal would be occupied by the sea, were it not for Ardoukoba, a zone of young volcanic rocks draped over minor fault blocks that stand inside the rift. These include the basalt lavas extruded in 1978 from numerous fissures and vents (Fig. 19.4), along with scattered hornitos and a large spatter ring that grew in the brief climax of that eruption.

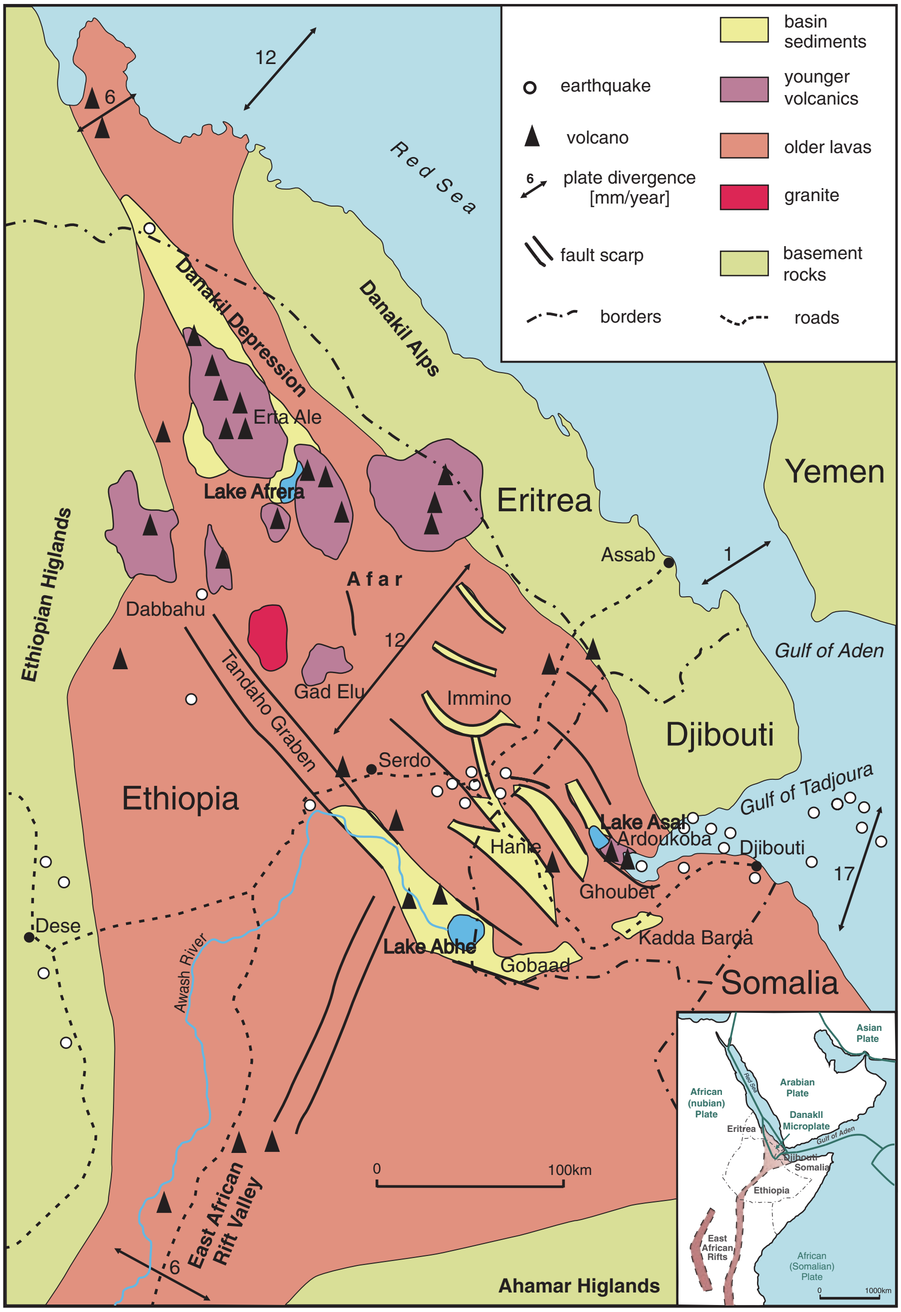

Fig. 19.2 Outline map of the Afar Triangle, with the main features of its geology and geomorphology. The basement massifs consist of older rocks with or without a variable cover of Tertiary basalts

The most southerly rift valley houses Lake Abhe on the Ethiopia–Djibouti border. It has been largely filled by sediments carried in by the River Awash, so that the lake lies more than 200 m above sea level and is now only 15 m deep. The site is best known for its hundreds of splendid travertine towers. Each tower was formed where a carbonate-saturated, geothermal spring emerged in the contemporary lake floor and deposited the calcite due to reaction with lake water. The towers are spread over an area of about 2,000 × 500 m, and individual towers are up to 60 m tall, some with steaming vents high on their sides; lake levels were last at their crests about 1,000 years ago.

Fig. 19.3 The Dobi, a northern branch of the Hanle valley that reaches into Ethiopia, a splendid rift valley with degraded marginal fault scarps on each side of a basin of sediments that sits on the graben floor (Photo T. Waltham)

Fig. 19.4 Basalts that were formed in the Ardoukoba event of 1978, in the Asal-Ghoubet rift valley. A short-lived fissure eruption produced lavas at various points along a fault line opened in tension, and a hornito on the ridge marks the line of a second, parallel fissure (Photo T. Waltham)

The distribution of earthquakes over the last 50 years falls into distinct zones that indicate the currently active areas of faulting within the Afar (only major epicentres are marked on Fig. 19.2). The main seismic zone passes westwards along the Gulf of Tadjoura, then curves northward through the Djibouti grabens to merge with a zone along the western margin of the Danakil Depression which acts as a single large graben.

19.4 Danakil Depression

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. It is also a true rift valley, created by a graben with down-faulted bedrock. 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 Erta Ale occupies much of the depression floor.

Away from the lava flows, the Danakil is floored by playa flats of silts and evaporites. Littoral and reef marine limestones of mid-Pleistocene age (200–80 ka)[1] survive in places around the margins of the Depression, remnants of its occupation by an arm of the Red Sea until 65,000 years ago. 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 1,000 m thick beneath the floor of the Dalol basin, and date from the same period before the Danakil Gulf was finally isolated from the Red Sea.

The surrounds of Lake Dalol are noted for their hot mineral springs and fumaroles that have created crystal pools, micro-terraces, miniature 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 rapid in the hot dry desert.

19.5 Volcanoes of Danakil

Of the 34 volcanoes listed within the Afar Triangle, five have recorded activity within historical time. The largest and most frequently eruptive is Erta Ale, rising from the floor of the Ethiopian sector of the Danakil Depression. It is a classic shield volcano with gentle slopes of basaltic pahoehoe and aa lavas, numerous small hornitos and almost no tephra. 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 Danakil. Its perimeter is more than 100 m below sea level within the depression, and its summit rises to 613 m above sea level (Barberi and Varet 1970; Yirgu et al. 2006).

The crest of Erta Ale is marked by an elliptical caldera 1,700 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. Most of this dates from 1974, though there have been minor vent overflows since 1997.

Many years ago, the northern crater of Erta 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 sulphurous fissure fumaroles around its rim.

Erta Ale is unique in that it has contained lava lakes that, between them, have been persistently active for at least 100 years (Fig. 19.5). The currently active lake lies within the central vent, which 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 normally covers all or part of its floor, and has periodically overflowed. The lava has a temperature of about 1,200°C, while the rafts of chilled crust that cover most of its lake surface are at about 500°C.

Dabbahu is a small stratovolcano closer to the western margin of the Danakil. A Plinian eruption in September 2005 lasted over 3 days, when a fissure vent along its northern flank produced silicic ashfall and a small pumice dome. This localised explosive activity appears to have been a consequence of rising basaltic magma encountering a small silicic reservoir at shallow depth.

19.6 Evolution

Current rates of relative movement of the plates that are diverging beneath the Afar have now been determined by satellite radar interferometry of the ground surface distortion (Fig. 19.2). They match well earlier data from repeated geodetic surveys and also geological

[1]ka stands for 1,000 years

Fig. 19.5 The lava lake in the central crater of Erta Ale, when it was reduced to about 30 m in diameter during a period of low heat flow in the early 2000s (Photo T. Waltham)

evidence based on accurate dating over the last few million years. Total divergence of the Arabian plate from the African plates is 17–19 mm/year, but only about 12–13 mm/year are represented by expansion within the Afar, west of the Danakil micro-plate. The plate divergence is largely accommodated by dyke emplacement and normal faulting, while magmatic inflation, distributed ground extension, fissure opening and earthquake activity add to the extensional processes that are all so well-demonstrated in the Afar (Fig. 19.6).

Normal faulting is the second major component of crustal expansion, and its activity in the Afar is indicated both by seismic events and by the presence of the great rift valleys formed along actively subsiding grabens. There is now a wealth of data on tectonic extension and graben subsidence across the normal faults of the Asal-Ghoubet rift valley (Abdallah et al. 1979; Ruegg et al. 1979; Vigny et al. 2007; Doubre and Peltzer 2007). Graben subsidence has the floor of the rift valley subsiding relative to the adjacent highlands at a rate currently around 7 mm/year. This is distributed across a number of faults within the overall graben structure. At outcrop, each of these faults is steeply inclined, but relationships between the horizontal and vertical components of displacement indicate that the faults curve to dips of 45° or less at depth.

Long-term creep and subsidence of the grabens is interrupted by intervals of more rapid movement. The 1978 event at Asal saw 2 m of ground extension that was accommodated by the brief volcanic eruptions, by dyke emplacement at depth and by around 1 m of graben subsidence. Surface expression of that fault movement is still visible along the eastern margin of the graben where screes resting on the rift valley floor subsided to expose a fresh band of their headwall fault scarp (Fig. 19.7). The 2005 event at Dabbahu was dominated by dyke emplacement, but produced nearly 2 m of subsidence within the narrow central rift across the volcano. Lacking comparable shock movements, the area around Lake Dalol recorded 40 mm/year of subsidence through the mid-1990s (Amelung et al. 2000).

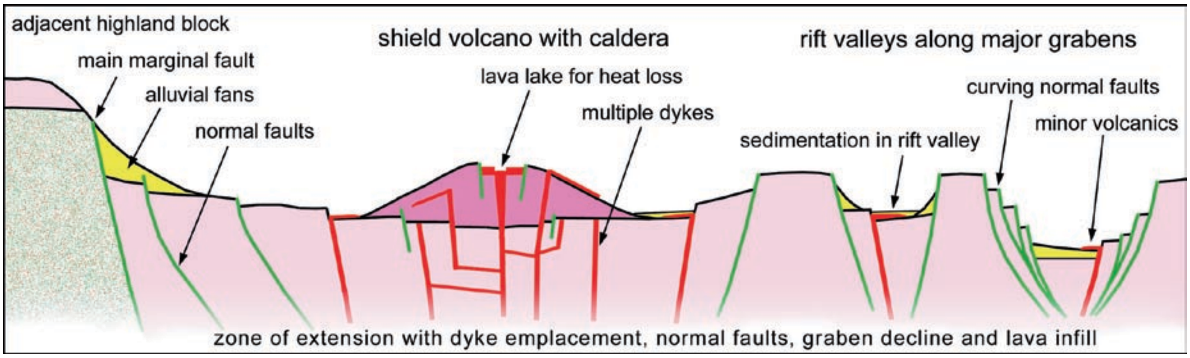

Fig. 19.6 Diagrammatic and greatly simplified profile to show the main features of ground extension in the Afar, incorporating features of both the Erta Ale volcano in the Danakil Depression and the main grabens in the Djibouti sector

Fig. 19.7 A minor fault inside a graben has created a slice of fresh fault scarp along the crest of screes that subsided on the down-faulted block, within the Asal-Ghoubet rift valley (Photo T. Waltham)

All these patterns of graben subsidence due to ground extension are superimposed on a broader profile of uplift due to magmatic inflation. Centred on the Asal rift valley, an elongate dome 40 km wide is currently rising at about 8 mm/year, slightly faster than the graben is subsiding within it. Further north, beneath the Danakil Depression, a higher rate of magma injection diminishes the graben activity and increases the volcanic activity. The continuing survival of Erta Ale's lava lake relies on a substantial heat supply to match its thermal loss into the atmosphere (Oppenheimer and Francis 1998). This heat supply is from rising magma that is feeding a zone of active emplacement of dykes and sills. Within the immediate vicinity of the volcano, these intrusions currently fill new fissures to keep pace with the plate divergence, so that they largely prevent further fault-related subsidence in the Erta Ale sector of the main graben.

A more detailed record of dyke emplacement has been obtained from modelling the 2005 event at the Dabbahu volcano with data gathered from radar interferometry and seismic records (Wright et al. 2006). This suggests that about 2.5 km^3 of basaltic magma was injected into a dyke that developed over a length of 60 km; it had a mean width of 3.5 m to match the crustal opening. While the dyke reached a depth of about 7 km, none of its basaltic magma reached the surface. This contrasts the 1978 Ardoukoba event where lava did emerge from short lengths of open fissure, even though the ground extension and mean dyke width were nearer 2 m. It appears that about one-fifth of the Dabbahu dyke material was derived from magma chambers beneath the Dabbahu and Gabho volcanic edifices, as indicated by broad areas of contemporary ground subsidence; the other 2 km^3 was primary magma that rose from greater depths. This dyke emplacement all occurred within about 1 week.

A longer record of ground movement is provided by the fragmented horsts that now lie between the grabens of inland Djibouti. Rotation of the Danakil microplate has dragged their northern ends eastwards, while their southern ends have been held firm against the Somalian plate, to create a pattern of 'bookshelf faulting', where the sub-parallel blocks have each rotated clockwise (Tapponier et al. 1990). Palaeomagnetic orientations of the Pleistocene lavas have shown that adjacent blocks have rotated by different amounts (up to 11° in 1.8 million years), with the slack taken by differential opening of the intervening grabens (Acton et al. 2000). Deconstruction of the graben movements 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-Ghoubet graben.

19.7 Conclusions

Though the Afar is a segment of crust that has subsided between the diverging plates of Africa and Arabia, it is essentially an ocean-floor environment that is rising due to magmatic inflation over a mantle plume. Continuing extension is accommodated by dyke emplacement and normal faulting. While dyking is dominant at depth, curved fault planes account for most of the movement at and near the ground surface. The landscape is therefore dominated by series of conspicuous and active fault scarps except where greater rates of magma injection create active volcanic edifices. The combination of well-developed rift valleys and fresh volcanic features makes the Afar the world's finest example of a landscape developed over a zone of crustal extension.

The Author

Dr **Tony Waltham** recently retired from many years as a university lecturer in engineering geology in Nottingham, UK. His main research interest was in karst and specifically in engineering problems of construction on cavernous ground. Author of the popular textbook *Foundations of Engineering Geology*, and of many other books, he has travelled widely, mainly to areas with great caves or active volcanoes.

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