Chapter

Effusive Badi Silicic Volcano (Central Afar, Ethiopian Rift); Sparse Evidence for Pyroclastic Rocks

Dereje Ayalew, David Pyle and David Ferguson

Abstract

We report field observation, textural description (thin section and scanning electron microscope (SEM)) and mineral chemistry (backscattered electron imaging and dispersive X-ray analysis) for rhyolitic obsidian lavas from previously under described effusive Badi volcano, central Afar within the Ethiopian rift. These rhyolitic obsidian lavas are compositionally homogeneous and contain well developed flow bands. Textural analysis is undertaken to understand the formation of flow band, and to draw inferences on the mechanism of emplacement of this silicic volcano. Flow band arises from variable vesicularity (i.e., alternating domains of vesicular, light glass and non-vesicular, brown glass). Such textural heterogeneities have been developed during distinct cooling and degassing of the melt in the conduit.

Keywords: Afar, Badi, flow band, lava, pyroclastic

1. Introduction

Many rhyolite lavas are usually associated with pyroclastic deposits [1–3]. In fact each lava eruption is almost invariably associated with preceding phases of explosive pyroclastic activity [4–6]. This suggests that lavas could be a terminal event of many explosive eruptions during which most of the volatiles of the magma have been removed. Even while the rhyolite lavas being growing explosive activity may continue, as evidenced by the presence of unusually large amounts of obsidian ejecta among the pyroclastic deposits [4].

The principal requirement for the effusive (not explosive) eruption of magma as coherent lava is that the exsolved volatile content of the magma immediately before eruption should be sufficiently low to prevent the build-up of a gas pressure which could cause explosive fragmentation of magma and country rock [7]. Nevertheless, sufficient water is initially available in the magma source regions [3]. Therefore, for coherent magmas to be erupted from magma sources with high volatile contents the magma has to degas [7].

Volcanologic and petrologic studies on the silicic centres which lie within the Afar axial range or off the axis are very scarce. This is partly because of the remoteness and inaccessibility of the area that practically inhibits field investigation. The very few previous studies mainly focused on the extensive basaltic flow fields

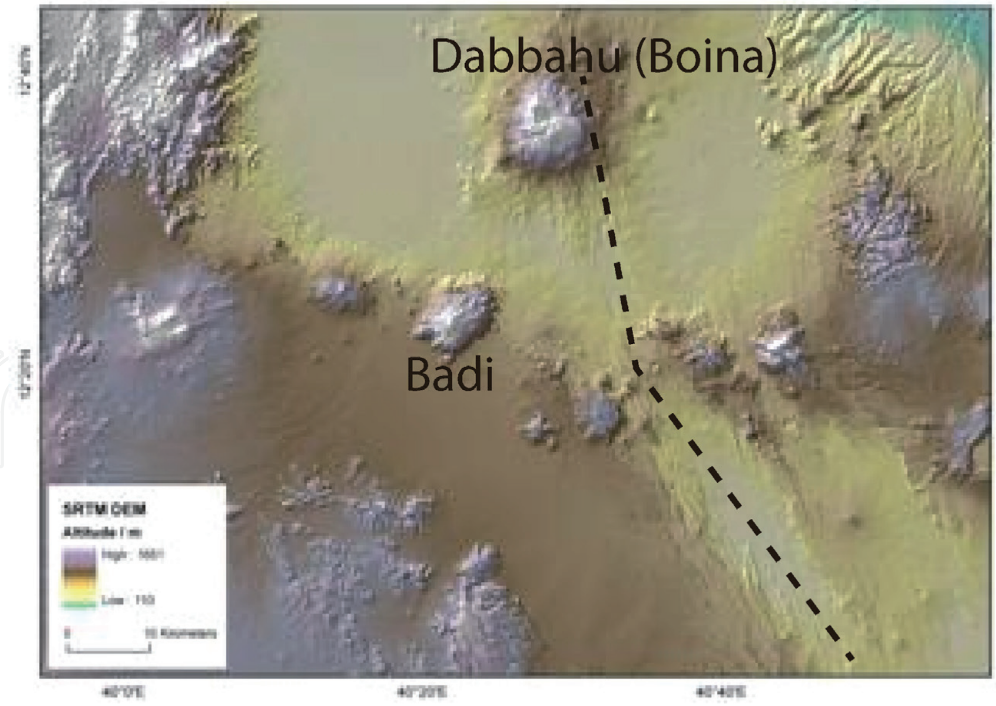

Figure 1.
Topographic relief map of central Afar, showing the location of the off-rift axis Badi volcano. Dashed line represents the 2005 dyke injection (after [21]).

[8–13], which have been interpreted as incipient oceanic ridges. However, there are also comparable volumes of silicic magmas to that of the basaltic counterparts in the region [14–16]. Very little is known about these silicic centers which form a conspicuous central edifice in the axial range of the Afar magmatic segments [15, 17–20].

This study presents field observation; textural description (thin section and scanning electron microscope); and mineral chemistry (backscattered electron imaging and dispersive X-ray analysis) for previously undescribed Badi volcanic edifice from central Afar, Ethiopia (**Figure 1**). Contrary to many localities, whereby rhyolitic lava domes and flows are usually associated with pyroclastic deposits, the Badi volcanic edifice contains several clusters of coalescing silicic domes and lava flows, and sparse evidence for pyroclastic rocks. Thus, this volcano offers a relatively rare opportunity to study effusive silicic volcanic phenomena. The motivation of this work is to understand the mechanism of emplacement of Badi silicic domes and flows with hope to draw inferences on the formation of the flow bands. In order to address these questions we employ textural analysis of the lavas using petrographic microscope and scanning electron microscope (SEM), accompanied by mineral chemistry. To the knowledge of the authors, there are no earlier studies of this kind documented in the literature from the region so far. Petrologic and geochemical studies of some silicic volcanic rocks from Afar including those from Badi have been considered elsewhere [17–20, 22] and are omitted from the forthcoming discussion.

2. Geologic background

Afar depression (the Afar triple junction), roughly 300 km wide, marks the intersection of three rifts: the Red Sea, Gulf of Aden and east African rifts. This extensional province formed within a Palaeogene Ethiopian flood basalt province associated with the Afar mantle plume [23, 24]. Rifting within the Red Sea and Gulf of Aden arms of the triple junction has progressed to oceanic spreading [25], whereas the less-evolved Ethiopian rift is transitional from continental rifting to oceanic seafloor spreading [26]. The crust of the Afar depression is highly extended and intruded with mafic dykes [27]. Crustal thickness ranges from 16 km in the north beneath Erta'Ale range to 24 km in the south [28].

Within the southern Red Sea rift and Afar, the initial development of border faults was roughly coincident with the 31–29 Ma flood basalt sequences in the same area [29]. Strain migrated riftward from 19 to 12 Ma [29], and by ~5 Ma, an oceanic spreading ridge had developed within the south central Red Sea rift [30]. Southward propagation (south of 16°N) of the ridge runs inland through Ethiopia, whereby extension (faulting and dyking), seismicity and volcanism are localized in discrete narrow (<10 km wide) ~60 km long rows/zones within the Afar depression [31]. These rows are referred to as magmatic segments and are characterized by aligned chains of basaltic cones with associated flow fields, shield volcanoes, shallow seismicity and positive gravity anomalies [26]. The available K-Ar data for basaltic and silicic rocks along the terrestrial portion of the Red Sea rift system indicate an age range of 1.46–0.52 Ma [32]. Within these magmatic segments, volcanism tends to be bimodal, with extensive basaltic flow fields and axial silicic centers [15, 18–20, 22]. Profuse fissure basalt volcanism, referred to as "Stratoid Series" [33] covering most of the central and southern part of the Afar depression, occurred about 5 Ma ago where it was most active between 4.5 and 1.5 Ma [34].

3. Methods

Fresh, unaltered obsidians (twelve samples) were collected from Badi volcano, and were examined under petrographic microscope and scanning electron microscope (SEM) at Department of Earth Sciences, University of Oxford, UK. SEM images and chemical analysis (backscattered electron imaging and dispersive X-ray analysis) of samples were acquired.

4. Result

4.1 Field relation

Badi volcano (located at 12.387°N and 40.366°E) lies off the axis of the main rift and is associated with a deviation in the strike of the faults (**Figure 1**). It is a well-defined rounded volcanic center with diameter of emerging from fissural basaltic lava fields. The summit of the center is about 1280 m high above mean sea level (msl) and the base is around 640 m high above msl. The total volume of the volcano is estimated to be about 31.5 km^3. The silicic lava consists of a cluster of several rhyolite domes and flows. There is no central vent; rather each dome/flow has its own vent. The only age constraint available for the silicic part of the Badi edifice is a K-Ar age of 290 Ka for one of the basal silicic domes [32].

The sub-aerial Badi volcanic edifice has essentially two parts (**Figure 2**): the base of silicic domes and flows and then, the upper basaltic flows which have been erupted on to the silicic material. There are no exposed explosive products associated with the effusive activity in Badi volcano, unlike many rhyolitic obsidian flows and domes in the Ethiopian rift valley which are commonly associated with pyroclastic deposits [4, 6, 35–37]. It has been noted that in most volcanic centers of Afar, pryroclastic products are scanty [15]. However, there are large silicic caldera complexes in Afar away from the rift axis [16]. The absence of fragmental magmatic materials at Badi volcano clearly reflects that the effusion of lava domes and flows resulted from the different rheology of the magma.

Figure 2.
Outcrop photos illustrating the eruptive sequence of Badi volcano; Basal silicic domes and flows, and upper basaltic flow.

During our preliminary field investigation, we found evidence for a single, coarse-grained pumice cone deposit, on the side of the volcano. The pumice fall deposits are quite high up elevation wise and lay directly on top of some basaltic scoria cones (**Figure 2**), so they post-date at least some of the later basaltic volcanism and have been erupted after almost all of the silicic domes/flows that make up the main body of the Badi Mountain. Accordingly, the volcanic stratigraphy of Badi volcano from old to young is silicic dome, then basaltic scoria and finally pumice fall deposit. There are certainly no silicic flows interbedded with the pyroclastic material (**Figure 2**). The very large pumices (0.5 m in size or more) suggest reasonably close to the vent. All of the dates for the late stage basaltic activity are around 50 Ka and younger (Ar-Ar and cosmogenic ^{3}He datings, [13]). This indicates that the pyroclastic deposits are much younger than 50 Ka. An interpretation might be that the pumice deposit is the product of a small explosive eruption, sourced from a body of silicic melt that was rejuvenated by the later injection of basaltic magma.

4.2 Texture of flow bands

Field inspection reveals that the rhyolite lavas show a vertical zonation of lava textures related to the mechanism of emplacement (**Figure 3a**). The upper surface of obsidian usually fractures into blocks, probably related to the movement and cooling of the interior of the flow. Beneath these layers is the core (interior) of the dome which is unlaminated and shows columnar joints. The upper outer surface of the dome is made up of obsidian layer which displays a very pronounced layers, or flow bands (**Figure 3b**) defined by a color variation (i.e., alternating domains of light and brown glasses). The flow bands are frequently folded (**Figure 3c**) and exhibit intricate fluidal textures as indicated by highly contorted and intensively crenulated layers (**Figure 3d**). Folds arise as flow layering deforms during flow advance [38].

Petrographic observation of the flow bands (**Figure 4**) shows that the boundaries between the light and brown glass bands are abrupt, reflecting laminar flow state. The brown lamella is relatively thickener than the light one. The flow banding is locally deflected around phenocrysts (**Figure 4**), suggesting that crystallization took place before the cessation of flowage of the lava.

As seen both in the hand specimen and thin section, SEM observation (**Figure 5**) illustrates that the Badi lavas have flow banding/layering defined by alternating lamellae of light and black glasses. Black bands are represented by non-vesicular obsidian, while light layers are vesicular glass. The obsidian domain shows abundant, very small microlites of mainly alkali feldspar, quartz

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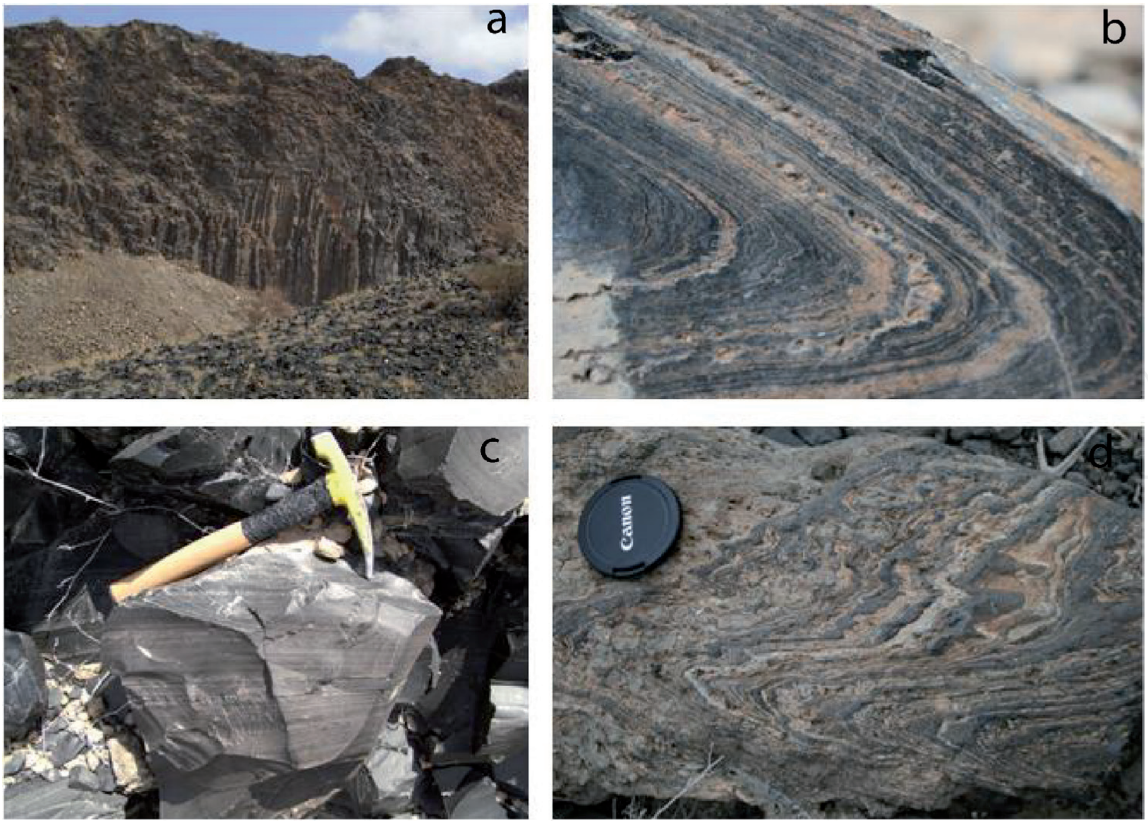

Figure 3.
Outcrop photos illustrating the lithological variability (a) Textutal differences through a rhyolite lava, with a chilled glassy carapace top and a columnar jointed bottom. (b) Black, vitreous obsidian occurring as interbanded layers. (c) Flow-folded obsidian. (d) Fluidal characteristic as evidenced by contorted and crenulated layers.

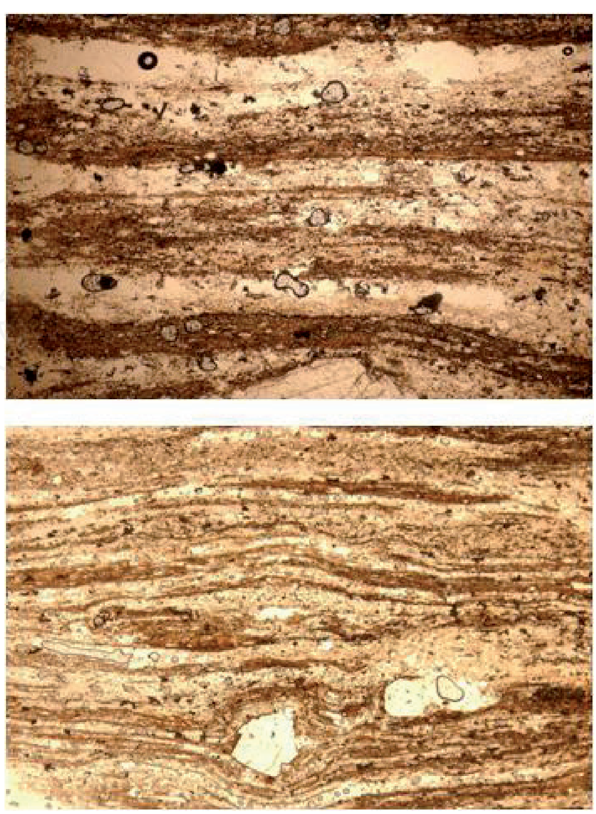

Figure 4.
Photomicrographs illustrating flow banding defined by alternating domains of brown and light glasses (×30, ordinary light). Note flow bands deflected around phenocrysts.

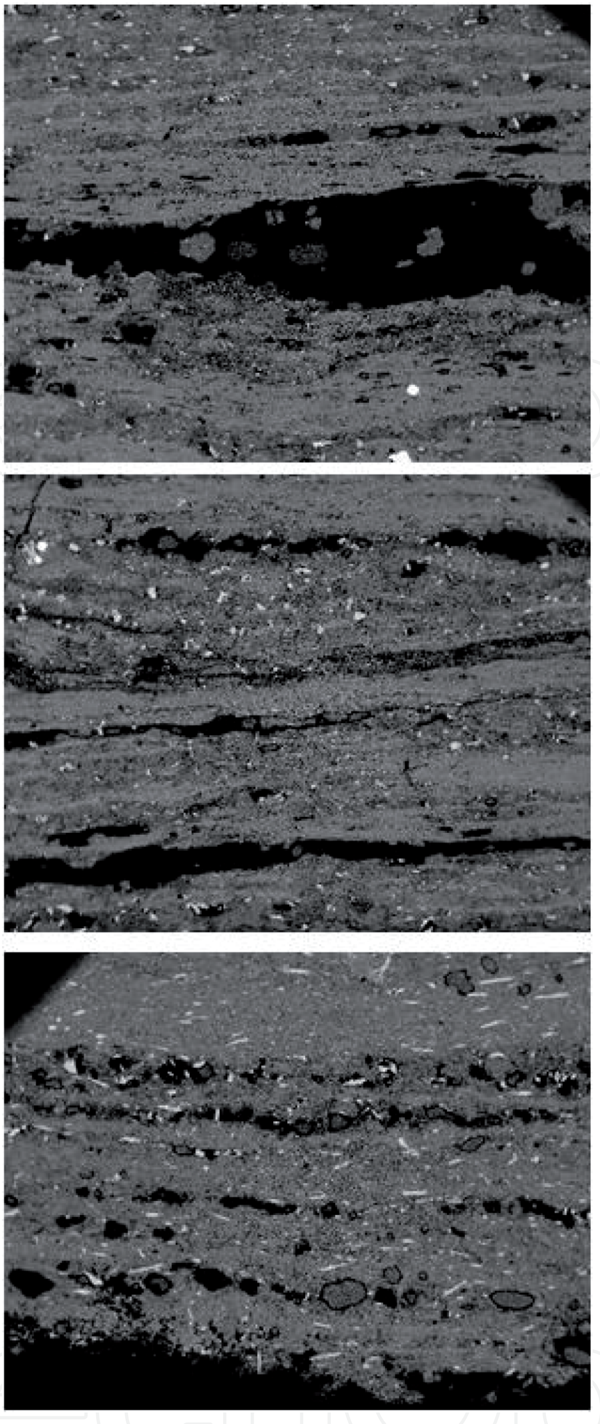

Figure 5.
SEM image illustrating the differences in abundance of vesicles between the flow bands. Note microlites are randomly oriented. Field of view is 9 µm.

and pyroxene set in a glassy matrix. Microlites are generally randomly oriented. It is important to note that there is no notable difference in the abundance of microlites between the two glass domains. Furthermore, the Badi lavas contain neither xenocrystic nor xenolithic materials.

4.3 Petrography

The rhyolite lavas, which form the main part of the Badi edifice, display a wide variety of textures ranging from sparsely porphyritic through aphyric to almost completely glassy obsidians (**Figure 6**). The phenocrysts are unbroken which provides textural evidence that distinguish the flows and domes as lava rather than rheomorphic ignimbrite. They appear to have been in equilibrium without

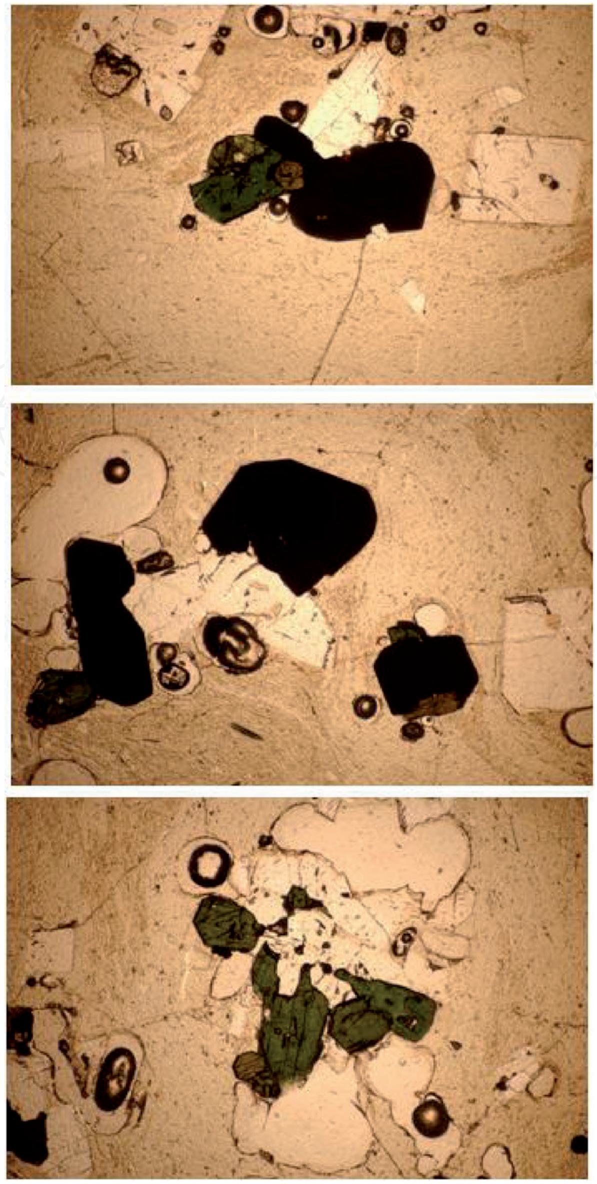

Figure 6.
Photomicrographs illustrating the petrographic characteristics of pertalkaline rhyolites from Badi volcano with phenocrysts of alkali feldspar (euhedral), quartz (rounded), aegirine (green) aenigmatite (dark brown) set in a microcrystalline or glassy matrix (×30, ordinary light).

embayment or resorption. The porphyritic lavas (e.g., samples 01–04, 02–06, 25–02) contain very few phenocrysts or microphenocrysts (< 5 vol.%) of alkali feldspar, quartz, green clinopyroxene and aenigmatite enclosed in a microcrystalline or glassy groundmass which is mainly alkali feldspar, quartz and pyroxene. The aphyric lavas (e.g., samples 01–07, 02–04, 29–03) exhibit very scarce microphenocrysts of alkali feldspar, quartz and green pyroxene embedded in a microcrystalline groundmass which mainly contains alkali feldspar and quartz. They are slightly altered as indicated by a dirty appearance of feldspar. The rhyolitic obsidians (e.g., samples 01–09, 02–04, 03–01, 30–04(1), 30–12, 31–01) contain microlites of alkali feldspar, quartz and pyroxene set in a glassy matrix. The groundmass/matrix is relatively fresh and unaltered devoid of post eruption divetrification and hydration products such as spherulites.

The mineral assemblage in Badi lavas, in order of decreasing abundance, includes alkali feldspar, quartz, green clinopyroxene and aenigmatite, although not all phases are found in every sample. **Table 1** reports the main petrographic characteristics of phenocrysts and matrix of the Badi rhyolite lavas. Accessory Fe-Ti oxides and apatite are present in trace amount and occur as inclusions. Fe-sulfide, possibly

Phase	Mode (vol.%)	Petrographic description
Phenocrysts	(1–5%)	
Alkali feldspar	up to 3%	Typically tabular and prismatic euhedral phenocrysts (1–4 mm in length); unbroken showing simple twinning; rarely cloudy appearance. Equant microphenocrysts (< 1 mm in size).
Quartz	<2%	Subhedral to rounded crystals.
Alkali pyroxene	<2%	Aegirine forms elongated (skeletal) and prismatic crystals (up to 3 mm in length); showing green to brownish-yellow color and pleochroism, and only one perfect cleavage. Aegirine-augite occurs as small euhedral; Equant microphenocrysts (0.6 mm in size); shows both cleavages.
Aenigmatite	<1%	Euhedral crystal with typical dark brown color.
Groundmass/matrix		Generally fresh and unaltered; ranges from entirely glassy to microcrystalline groundmass; alkali feldspar, quartz and pyroxene are the principal microlite minerals; display flow banding defined by variation of vesicle abundances.

Table 1.
Main petrographic characteristics of phenocrysts and matrix of the Badi rhyolites.

pyrrhotite occurs as tiny bleb inclusions within oxides. Alkali feldspar, quartz, green clinopyroxene, and aenigmatite are ubiquitous in the phenocrysts and microphenocrysts. Alkali feldspar is volumetrically the most abundant crystal in the Badi lavas. Phenocryst and matrix compositions of the Badi rhyolite lavas are presented in **Table 2**. Composition of alkali feldspar is anorthoclase or sanidine. Alkali-pyroxene is the most abundant mafic mineral and is mostly aegirine and subordinate aegirine-augite. Aenigmatite is commonly the second most abundant mafic mineral.

The modal presence of alkali pyroxene and aenigmatite, which are considered to be index minerals in the peralkaline salic rocks [39], in Badi rhyolites surely confers a peralkaline affinity. Nicholls and Carmichael [40] indicated that aegirine is the dominant phase in strongly peralkaline composition (pantellerite), whereas hedenbergite seems to be dominating in less peralkaline composition (comendite).

	Anorthoclase	Sanidine	Aegirine	Aenigmatite	Glass
Sample	**01–/04**	**25–/02**	**01/–04**	**01/–04**	
SiO_2	66.52	66.55	53.84	40.15	67.60
TiO_2			1.22	9.39	
Al_2O_3	17.19	18.22	0.72	0.66	12.87
FeO	1.41	0.78	29.67	41.66	5.49
MnO	0.10	0.07	0.34	1.40	
MgO	0.23		0.21	0.05	0.27
CaO	0.04	0.16	1.22	0.38	0.05
Na_2O	7.12	6.77	12.00	6.41	5.82
K_2O	6.68	7.49	0.09		6.93
Total	99.29	100.04	99.32	100.11	99.03

Table 2.
Representative energy dispersive (EDS-SEM) x-ray analyses of minerals and glass of rhyolites from Badi volcano.

The presence of modal aegirine in Badi lavas implies a pantelleritic composition. This affinity is also supported by chemical composition (Hutchinson et al., 2018) in which the silicic lavas from Badi volcano are predominantly pantellerite with minor comendite. The absence of Fe-Ti oxides in the mineral assemblage suggests that the magma was crystallized at low oxygen fugacity which lies at or below the FMQ buffer curve in the T-f_{O2} space [41]. Recent works (e.g., [42]) have shown that the nature of co-existing phases, especially pyroxene, in peralakline rhyolites is controlled by the redox conditions; aegirine crystallizes in more reduced conditions (i.e., in no-oxide field). The co-existence of aenigmatite and aegirine in Badi rhyolites strongly suggests that the original silicic magma was generated, evolved and crystallized in a more reduced condition; at low oxygen fugacity which lies at or below the FMQ buffer in no-oxide field.

It becomes increasingly apparent that some workers (e.g., [37]) have shown the presence of fayalite, hedenbergite and plagioclase in the mineral assemblage of peralkaline rhyolites from Ethiopian rift valley. These minerals are not found in Badi rhyolites. We only observed plagioclase and hedenbergite as xenocrysts in xenolithic material in a single specimen (30-01(4)). These less-evolved inclusions show angular contacts, suggesting that they were solid while the host rhyoltic lava was liquid. We emphasize the importance of indentifying the mineral assemblage found in rhyolites as phenocrysts and xenocrysts.

5. Discussion

5.1 Origin of flow banding

Thin flow banding, defined by discrete lamellae/layers with contrasting color, is a common feature of many effusive volcanic rocks. It is a ubiquitous texture in very viscous, highly siliceous lavas, such as rhyolites (e.g., [3, 43, 44]). Flow band in rhyolite lavas has been described from varying crystallinity and vesicularity [45]. Differences in abundance of microlites and/or vesicles appear to develop either during flow of the melt in the conduit or during late stage cooling and degassing during flow emplacement [45, 46]. Flow banding is thought to be a reflection of laminar flow.

Flow banding in rhyolite lavas may have a variety of origins, including mixing of compositionally distinct magmas [47, 48], or incorporation of xenolithic material in a shear flow [49], or fracture-healing processes of texturally distinct magma [46, 50]. Another type of flow banding origin seems to arise from deformation of domains in the melt that had contrasting water concentration in the melt prior to flow [43]. There is yet little consensus on any of these alternatives.

One of the most important questions to answer is whether or not the banding displayed by the Badi rhyolite lavas is due to textural (i.e., differences in abundance of vesicles) or compositional (i.e., differences in abundance or preferred orientation of microlites) heterogeneities. Flow banding in Badi lavas is defined by alternating domains/layers of contrasting glass colors (light and brown glasses). Brown bands are represented by non-vesicular obsidian, while light layers are vesicular glass (**Figure 5**). Our data set shows that there are no extreme differences in mineral composition or proportion between the light and brown glasses. This appears to indicate that the banding observed in the studied lavas is not due to compositional heterogeneities at least on the basis of mineralogical grounds. Instead it is due to textural differences, caused by variations in vesicle concentration of the glass bands (**Figure 5**).

Such textural heterogeneities due to differences in the abundance of vesicles of the glass may develop either during magma flow in the conduit [46], or during flow emplacement [49]. All of the samples from Badi volcano surveyed both in thin section and SEM do not contain xenocystic and/or xenolithic material. This further provides evidence against incorporation of xenolithic material during the course of the flow of Badi lavas at the Earth's surface. Hence, this textural (vesicularity) heterogeneity could not have developed during late stage cooling and degassing during flow emplacement. Rather such textural variations (heterogeneities) imply distinct cooling and/or degassing histories, and must have formed during flow in the conduit prior to magma extrusion.

5.2 Emplacement of rhyolite domes and flows

Many rhyolitic obsidian flows and domes are commonly preceded or accompanied by explosive episodes [2, 3, 36, 37]. Two contrasting models have been proposed to explain the common sequence of initial, explosive plinian eruptions followed by quite effusions of lava: (1) the volatile stratification model; and (2) permeable foam model. In the former case, a stratification of volatiles in the source magma body is invoked to explain the initially explosive phase [1]. In the later case, one envisions a fairly uniform batch of magma that can release gas as it ascends through the fracture and porous conduit rock [7].

The Badi volcanic edifice is entirely constituted by several clusters of coalescing silicic domes and lava flows; there are no any explosive products associated with the effusive activity. This is in contrary to many rhyolitic obsidian flows and domes (e.g., Fentale and Gedemsa, Ethiopia; Inyo Dome, USA; Pantelleria, Italy) which are commonly associated with pyroclastic deposits [1–3]. These features are also common in most silicic volcanic centers of Afar in which pyroclastic rocks are usually scarce [15].

The fundamental question is whether extrusive rhyolite lavas of Badi volcano represent quenched dry rhyolite magma or have somehow degassed during ascent and eruption to prevent build-up of a magmatic gas pressure. The lack of hydrothermal manifestation, represented by direct escape of exsolving volatiles through the vent immediately before eruption, strongly suggests that the coherent lavas from Badi did not erupt from degassed magma source. Furthermore, amphibole phases are not observed in Badi rhyolites. The absence of amphibole phase in Badi rhyolites demonstrates that the water content of the pre-eruption magma was not enough to stabilize amphibole which requires about 3 wt.% H_2O in a silicic magma to crystallize [3]. The absence of amphibole phase suggests that the Badi rhyolite domes and flows resulted from initially volatile-poor silicic magmas. Hence, the lack of progression from tephra ejection to lava extrusion, contrary to many rhyolite eruptive sequences, at Badi volcano reflects the lava must be nearly as dry as obsidian to escape fragmentation up on extrusion.

Effusions of silicic lavas often pile up over the vent area rather than traveling long distances (e.g., [1–3]), due to their high viscosity that prevents them from flowing far from the vent from which they extrude. It seems that the Badi rhyolites advanced outward. This might be related to their composition (**Table 1** and **Figure 6**) in that the Badi rhyolites are predominantly pantellerite with relatively high Na^+ and K^+ ion concentrations which act as network modifier (i.e., lowering the degree of melt polymerization) thereby relatively lowering the viscosity of the silicic magma [51]. Once extruded, the Badi lava flows outward (the average Badi flow is about 1.5 km) due to their relatively low viscosity.

In addition, the Badi rhyolite lavas are aphyric (with total phenocryst contents of <5%, **Table 1**), suggesting an extremely high magma temperature at the time of eruption. The high emplacement temperature implies that the rhyolite lavas reached the surface through a circular conduit, which presents a much smaller cooling surface to the country rocks [52]. The aphyric condition of rhyolite lavas has been ascribed to unusually low viscosity [53]. The Badi lavas have flowed outward up to 1.5 km. Hence, these lavas may have had reduced viscosity due to their high magma temperature and peralkaline affinity, as the cause of the increased fluidity.

6. Conclusions

The rhyolite lavas from effusive Badi volcano, central Afar, show peralkaline affinity (predominantly pantellerite), as evidenced by the presence of modal aegerine and aenigmatite in the mineral assemblage. These lavas display flow banding defined by alternating lamellae of brown, non-vesicular (obsidian) and light, vesicular glasses. Flow banding is thought to arise from differences in vesicle abundances between the brown and light glasses. Such textural heterogeneity might have developed during magma flow in the conduit prior to magma extrusion. The scarcity of explosive products is explained by the fact that the Badi rhyolite domes and flows resulted from initially volatile-poor silicic magma that prevents build-up of a magmatic gas pressure which could cause explosive fragmentation. The Badi lavas flowed outward due to their high magma temperature and peralkaline affinity as the cause of the increased fluidity.

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Author details

Dereje Ayalew[1*], David Pyle[2] and David Ferguson[3]

1 School of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

2 Department of Earth Sciences, University of Oxford, Oxford, UK

3 School of Earth and Environment, University of Leeds, Leeds, UK

*Address all correspondence to: dereayal@yahoo.com

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