SINET: *Ethiop. J. Sci.*, 41(1):34-39, 2018 ISSN: 0379–2897 (PRINT)

ISSN: 0379–2897

Short communication

AN ALTERNATIVE STRATEGY FOR FORECASTING VOLCANISM IN ETHIOPIA: LESSONS FROM PRECURSORY PHENOMENA TO 2005 ERUPTIONS IN AFAR

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ABSTRACT: A substantial part of Ethiopia's surface is covered by volcanic rocks ranging in age from 30 Ma to the present day though a significant volume of volcanic rocks as old as 45 Ma are also found in southern part of the country. These volcanic rocks have yielded fertile soils, which are the richest farmlands in Ethiopia. The volcanic terrains provide magnificent landscapes, which are a natural sanctuary of the country. Ethiopia is a country prone to volcanic eruptions. Yet, the actual eruptive processes are catastrophic and can claim life and property. This paper documents the activity that preceded the 2005 eruptions in Afar and discusses them as potential volcanic forecast tools that can serve to raise public awareness of the volcanism.

Keywords/phrases: Ethiopia, Forecast, Precursor, Volcanic eruption

INTRODUCTION

Although the present state of knowledge does not permit the prediction of the exact time and place of eruptions, it is now possible to track the subsurface movements of magma by monitoring the gas emissions (changes in the composition of emissions), ground deformation (inflation or swelling of the summit of a volcano) and earthquakes (long-period earthquakes) that accompany such movements. The continuous monitoring of gas emissions, earthquakes and changes in volcano shape alone is however not sufficient for forecasting eruptions. Understanding of the prehistoric eruptive record and behaviour of a volcano is also critically important to assess the potential for future eruptions and hazards. The past eruptions left their geological records and inform us about the future.

In September 2005, scientists (including the author) at the School of Earth Sciences of Addis Ababa University in Ethiopia predicted an eruption within a few hours from Dabbahu volcano, located 113 km south of Erta'Ale range. Our prediction used events observed in the field prior to eruption such as increasing amount of fumaroles and fracturing of the volcano accompanied by earthquake swarms as an indicator of an imminent eruption. Two hours later, exactly as predicted, the volcano erupted spectacularly.

Ethiopia is generally known to be a volcanic prone country. The volcanic prone region particularly in Afar, is vast and numerous. Nevertheless, Afar is a challenging area to conduct fieldwork. This limits the ability to document comprehensively the prehistoric eruptive records. Furthermore, there is no modern volcano monitoring institution in the country. Geological monitoring of the volcanic prone areas only currently relies on satellite observations, which often misidentify the erupting volcano (e.g., 12 June 2011 Nabro's eruption). It is timely to design a workable volcanism forecast scheme that can outreach for the general public awareness.

The aim of this paper is to document the 2005 precursory volcanic events and to use them as potential volcanic forecast tools. This attempt is not a substitute for modern volcanic observation centre; instead it is an alternative strategy from volcanic forecast perspective. This finding will help scientists to more accurately predict future volcanic eruptions and contribute to efforts to limit the damage they can cause. It is important to underscore that none of the Ethiopian volcanoes is routinely monitored on the ground. At present volcanologists only rely on remote sensing technique to detect magma movement in the subsurface.

VOLCANIC HISTORY OF ETHIOPIA

The Cenozoic magmatism of Ethiopia began in the Eocene and is still active. It occurred in different phases with an apex at about 30 Ma, and generated a wide flood basalt and ignimbrite plateau, several large basaltic shield volcanoes and recent lavas and pyroclastic sequences closely connected to the continental breakup processes (Afar and main Ethiopian rift generation). The plateau sequence, originally extended over an area wider than 600,000 km^2 with a thickness locally exceeding 2,000 m, includes transitional-tholeiitic basalts and in the upper part, mainly silicic ignimbrites (Mohr and Zanettin 1988). The subsequent central volcanism prevailingly generated alkaline and transitional basalts and minor evolved products (Kieffer *et al*., 2004). The youngest volcanism mainly occurred in the Afar and main Ethiopian rift (MER). In the rift it produced a bimodal association of felsic and mafic products.

The more recent volcanism is mainly linked to the Afar and MER opening phases (Fig. 1). Extension began between 18 and 15 Ma in the southern MER (Gidey WoldeGabriel *et al*., 1990; Ebinger and Casey 2001); 5-6 Ma in the central MER (Bonini *et al*., 2005) and at 11 Ma in the northern MER (Wolfenden *et al*., 2004). Extensional strain in the MER it has migrated from Miocene border faults to present day ~ 50 km long, narrow ~ 10 km wide en-echelon 'magmatic segments' (Beutel *et al*., 2010) which are the locus of active faulting, open fissures, aligned cinder cones and associated lava flows, dykes and silicic volcanic edifices. Miocene to Quaternary magmatism is very abundant throughout the down-faulted rift and along its immediate flanks and shoulders. The basaltic cones follow a NNE-SSW alignment which corresponds to the Wonji Fault System. The magmatism is characterised by mildly alkaline basaltic lavas and peralkaline silicic rocks (Peccerillo *et al*., 2003; Dereje Ayalew *et al*., 2016). The intermediate products are scarce along the rift axis, while some trachytic volcanoes are located on the rift shoulders. During the basaltic activity, scoria cones, tuff rings and tuff cones, and small lava flows were generated. Silicic activity occurs in the form of obsidian lava flows as well as explosive eruptions generating widespread pumice and ash deposits (e.g., Fontijn *et al*., 2018). Some authors believe that most of the ignimbrites were erupted from fractures formed during the rift opening, although some were generated by central volcanoes during caldera-forming eruptions (e.g., Fantale, Gedemsa).

VOLCANIC-TECTONIC ACTIVITY IN AFAR

The Afar depression in Ethiopia marks the intersection of two oceanic rifts (Red Sea and Gulf of Aden) and one continental rift (East African rift system). South of around 20° N, the Red Sea system jumps and runs in land through Eritrea and Ethiopia. Along this terrestrial portion of the Red Sea system extension, seismicity and volcanism are localised at discrete magmatic rift segments. Within these segments volcanism tends to be bimodal, with extensive basaltic flow fields and associated scoria cones, and axial silicic volcanic edifices (Lahitte *et al*., 2003). Extension across these segments is thought to occur chiefly by intrusion of dykes into the upper crust (Wright *et al*., 2006; Rowland *et al*., 2007; Ebinger *et al*., 2008; Keir *et al*., 2011). These magmatic rift segments feature either an axial graben (e.g., Dabbahu-Manda Hararo rift zone) or a significant along-axis relief (e.g., Erta'Ale range). Such morphological differences are interpreted to reflect variations in extensional processes and the volcanic output along the rift (Ferguson *et al*., 2010).

OBSERVATIONS OF RECENT VOLCANIC ERUPTIONS IN AFAR

Ongoing rifting episode

Since 2005 the Afar depression experienced unique upheavals and entered into a period of spectacular active rifting event (Gezahegn Yirgu *et al*., 2006; Atalay Ayele *et al*., 2007). The ongoing rifting episode has included the intrusion of 13 volcanic dykes to date. Three of these have resulted in volcanic eruptions. In September 2005, a 60 km long dyke emplaced and a small explosive eruption and rhyolite intrusion (Da'Ure vent eruption) occurred (Fig. 2). This was followed by recurring (and ongoing) dyke intrusions (at least 13 dyke intrusions). In August 2007 and June 2009, basaltic fissure eruptions poured into the cracks developed during the September 2005 event. Table 1 summarises the precursory activity preceding the eruptions.

In addition to the 3 eruptions related to the dyking events, the still ongoing Erta'Ale flank eruption has occurred almost every two years since November 2008. This makes Erta'Ale a unique long-lived basaltic lava flow eruptions. Prior to this, the last eruptive activity in Ethiopia occurred between 1968 and 1973 when the lava lake at Erta 'Ale over spilled. In June 2011, highly explosive volcanic eruption occurred at Nabro volcano, located at the Ethio-Eritrea border. The eruptions produced widespread ash deposits that interrupted air traffic. All of these examples clearly show the region to be volcanically active and that eruptions can happen anytime, sometimes with severe consequences.

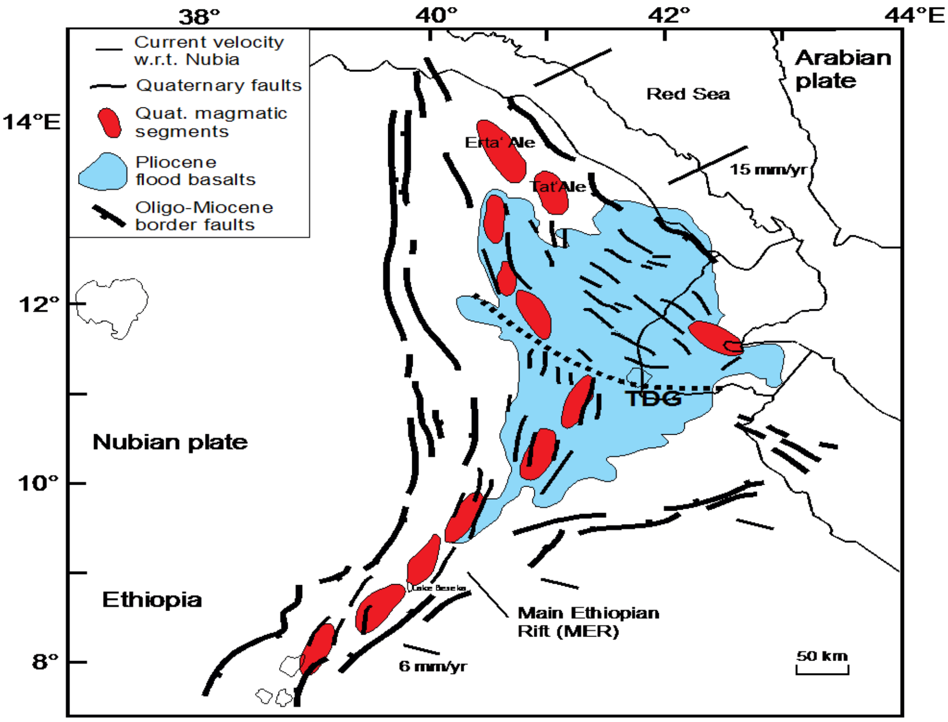

Figure 1. **Location of the active Quaternary magmatic segments - zones of dense faulting and aligned eruptive centres which are the current locus of strain within the Ethiopian rift (southern Red Sea and main Ethiopian rift, after Ebinger *et al.*, 2008). Arrows show plate motions relative to stable Nubia. Danakil Block is a microplate between the Nubian and Arabian plates. TGD is Tendaho-Goba'ad Discontinuity marking the active and ancient boundary between the East African and the Red Sea rifts.**

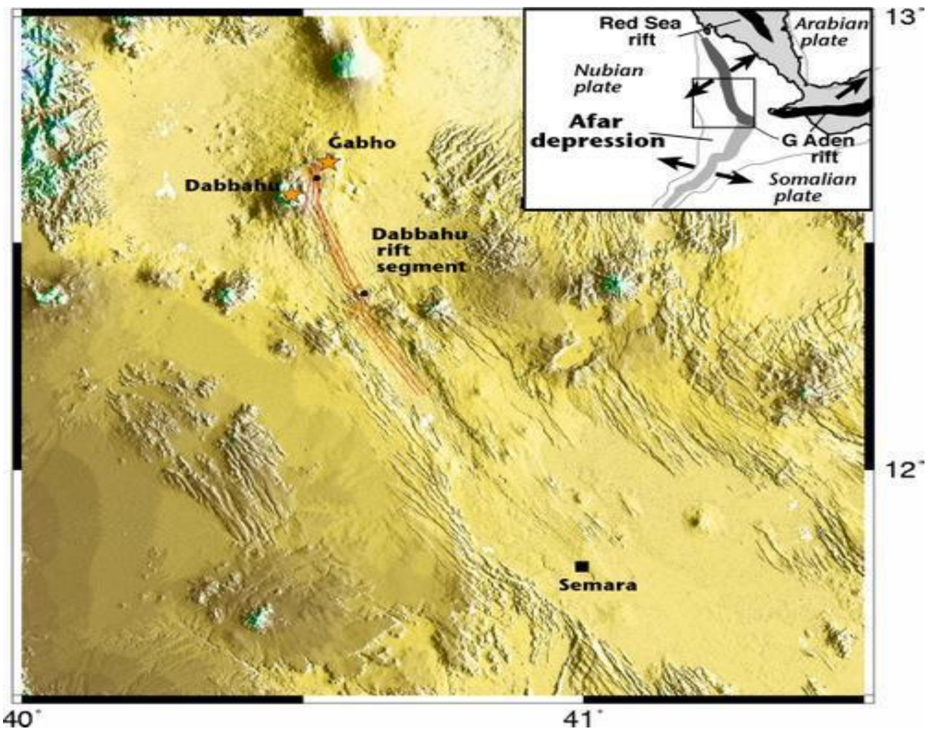

Figure 2. **Topographic relief of the 60 km-long Dabbahu rift segment within the Afar Depression. Inset shows directions of plate divergence between the stable African (Nubian), Arabian, and Somalian plates. (Satellite image courtesy of C. Ebinger).**

Table 1. Precursory activities prior to the onset of recent volcanic eruptions in Afar, Ethiopia.

Eruptions	Signs before the eruption
September 2005 Da'Ure vent eruption and the 60 km long dyke injection	Open fissures and normal faults formed. Pre-existing hot springs have disappeared and replaced by widespread appearance of fumaroles along the newly formed fissures and fault breaks. A boiling noise was heard. Earthquake swarms (with magnitude 4.1-5.2) occurred; the number and magnitude of earthquakes declined sharply after the eruption.
August 2007 basaltic fissure eruption	The eruption was preceded by cracking sounds, fumaroles (SO_2) and a small ground tremor.
June 2009 basaltic fissure eruption	Large fumaroles (SO_2) were detected. A magnitude 4.4 earthquake identified.

Data sources: Gezahegn Yirgu et al. (2006); Atalay Ayele et al. (2007); Additional information gathered during field investigation prior to eruption and from local inhabitants.

Types of precursors to 2005 events

During the 2005 events (Dabbahu or Boina volcano, 12.595°N, 40.48°E; summit elevation 1401 m), the local communities first informed the authorities about the unusual activity. Then the Ethiopian scientists (including the author), assisted by helicopter, visited immediately the area. The team noted changes on the volcano, such as emission of enormous fumaroles and fracturing of the volcano (normal faults, open fissures, cracks, landslides) accompanied by earthquake swarm. We also interviewed the inhabitants about the unusual activity. The local communities emphasized that the types of precursors that were observed include unusually heated ground surface, strange sound/noise, unpleasant odour, displacement of spring locations and ground tremors. They witnessed that these precursors lasted a month and eventually created civil unrest. Based on the precursors gathered both from field survey and local communities, the scientistes predicated an eruption in a few hours. As predicted exactly, the volcano erupted spectacularly.

Observations of the eruptions themselves

The scientists went back to Dabbahu after the eruptions. Eye witness reports indicate the on 26 September at about 13:00 (local time) a very strong earthquake occurred. That was followed by a dark column of "smoke" that rose high into the atmosphere and spread out to form an umbrella- or mushroom-shaped cloud. Emissions darkened the area for 3 days and nights. The eruptions threw out pre-existing near-surface rocks. The team noted that the explosive eruptions generated widespread light-colored ash deposits (up to 15 cm thick) accompanied by a rhyolite intrusion (Fig. 3). The extensive ash fall deposits extended as far as Teru village, 40 km SW of the eruption site. The ash layer contains ejected wall-rocks measured 2-3 m across. The team heard a sound from below within the fractures (an elongated vent), resembling the sound of a helicopter engine or a boiling liquid.

Impacts on local communities

The impacts of the eruptions on local communities were considerably low as a result of the reliable prediction. Inhabitants displaced from their villages following the prediction and resettled in other localities. Only one person injured, and 700 goats, 200 camels and 70 donkeys killed. The extensive ash fallouts covered grazing lands and spring water, causing threats on live stocks. Additionally the volcanic ashes and gases caused respiratory discomfort on the local people.

FUTURE VOLCANIC ERUPTIONS IN AFAR

Structural analysis of existing faults in Afar demonstrated that the brittle surface deformation is to be magmatic (i.e., extension accommodated by large successive dyke intrusions with or without accompanying eruptions) in origin (Rowland *et al*., 2007). Observations from the 1975-1984 Krafla rifting event, Iceland (analogous to Afar setting) indicated that the temporal trend of magma partitioning into intrusive and extrusive changed from an initially chiefly intrusive to a dominantly eruptive activity towards the end of the rifting cycle (Tryggvason 1984). Hamling et al. (2009) indicated that activity in Afar remains similar in pattern to the 1975-1984 Krafla rifting episode, Iceland. If this similarity continues, we anticipate that further eruptions will occur in the coming years, as the tectonic strain is fully released. Ferguson *et al*. (2010) forecasted that a volumetrically significant volcanic phase might occur as the Afar activity progresses.

Figure 3. An aerial view of the fissure vent at Da'Ure (Dabbahu), showing the post-eruptive extensive ash fallouts, pumice dome and fissure vent. (Photograph courtesy of Asfawossen Asrat).

CONCLUSIONS

The Afar region, northern Ethiopia, remains one of the most active geological areas on the planet, and offers an opportunity to understand how the Earth's crust is forming. The Afar region has been unusually active since 2005. An ongoing rifting episode in Afar, which began in 2005, included the intrusion of a 60-km-long magmatic dyke and 12 more dykes were emplaced which are accompanied by three volcanic eruptions. The pre-eruption phenomenon, such as widespread appearance of fumaroles, fracturing (faults, open fissures, cracks and landslides) of the summit of a volcano, unusually heated ground surface, strange sound, displacement of spring locations and the accompanied earthquakes is thought to be precursor of the volcanic eruption, and they can be used for forecasting hazardous volcanic activity.

ACKNOWLEDGEMENTS

I acknowledge Addis Ababa University and Ethiopian Air Force for financial and helicopter support, respectively. This work would not have been possible without the continued support and collaboration from the Afar Regional Government, for which I am very grateful. Constructive comments of the two anonymous journal reviewers strengthed the quality of the manuscript. I thank the Editor-in-chief Gezahegn Yirgu and Associate Editor Ameha Atnafu Muluneh for editorial handling.

REFERENCES

1. Atalay Ayele, Jacques, E., Kassim, M., Tesfaye Kidane, Omar, A., Tait, S., Nercessian, A., de Chabalier, J. B. and King, G. (2007). The volcano-seismic crisis in Afar, Ethiopia, starting September 2005. *Earth and Planetary Science Letters* **48**:70–79.
2. Beutel, E., Wijk, J., Ebinger, C., Keir, D. and Agostini, A. (2010). Formation and stability of magmatic segments in the main Ethiopian and Afar rifts**.** *Earth and Planetary Science Letters* ***298****: 225–235.*
3. Bonini, M., Corti, G., Innocenti, F., Manetti, P., Mazzarini, F., Tsegaye Abebe, and Pecskay, Z. (2005). Evolution of the main Ethiopian rift in the frame of Afar and Kenya rifts propagation. *Tectonics* ***24(1)****: 1–21.*
4. Dereje Ayalew, Jung, S., Romer, R. L., Kersten, F., Pfänder, J. A. and Garbe-Schönberg, D. (2016). Petrogenesis and origin of modern Ethiopian rift basalts: constraints from isotope and trace element geochemistry. *Lithos,* **298-299**: 1–14

5. Ebinger, C. and Casey, M. (2001). Continental break-up in magmatic provinces: an Ethiopian example. *Geology* **29:** 527–530.

6. Ebinger, C. J., Keir, D., Atalay Ayele, Calais, E., Wright, T. J., Manahilo Belachew, Hammond, J. O. S., Campbell, E. and Buck, W. R. (2008). Capturing magma intrusion and faulting processes during continental rupture: seismicity of the Dabbahu (Afar) rift**.** *Geophysical Journal International* **174(3)**: 1138–1152.

7. Ferguson, D. J., Barnie, T. D., Pyle, D. M., Oppenheimer, C., Gezahegn Yirgu, Elias Lewi, Tesfaye Kidane, Carn, S. and Hamling, I. J. (2010). Recent rift-related volcanism in Afar, Ethiopia**.** *Earth and Planetary Science Letters.* **292**: 409–418.

8. Fontijn, K., McNamara, K., Amdemichael Zafu Tadesse, Pyle, D. M., Frewalin Dessalegn, Hutchison, W., Mather, T. A., Gezahegn Yirgu (2018). Contrasting styles of post-caldera volcanism along the Main Ethiopian Rift: Implications for contemporary volcanic hazards. *Journal of Volcanology and Geothermal Research* **356:** 90–113.

9. Gezahegn Yirgu, Atalay Ayele, and Dereje Ayalew (2006). Recent seismo-volcanic crisis in northern Afar, Ethiopia. *Eos, Transactions American Geophysical Union* ***87(33)****: 325–329.*

10. Gidey WoldeGabriel, Aronson, J. L. and Walter, R.C. (1990). Geology, geochronology, and rift basin development in the central sector of the main Ethiopia rift. *Geological Society of America Bulletin* **102(4)**: 439–458.

11. Hamling I, Wright T, Calais E, Bennati L. and Elias Lewi (2010). Stress transfer between thirteen successive dyke intrusions in Ethiopia**.** *Nature Geosciences* **3:** 713–717.

12. Keir, D., Pagli, C., Bastow, I. and Atalay Ayele (2011). The magma-assisted removal of Arabia in Afar: evidence from dike injection in the Ethiopian rift captured using INSAR and seismicity**.** *Tectonics,* ***30:*** *DOI: 10.1029 /2010TC002785.*

13. Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Gezahegn Yirgu, Dereje Ayalew, Weis, D., Jerram, D. A., Keller, F. and Meugniot, C. (2004). Flood and shield basalts from Ethiopia: magmas from the African superswell. *Journal of Petrology* **45(4)**: 793–834.

14. Lahitte, P., Gillot, P. Y. and Courtillot, V. (2003). Silicic central volcanoes as precursors to rift propagation; the Afar case. *Earth and Planetary Science Letters* **207(1-4)**: 103–116.

15. Mohr, P. and Zanettin, B. (1988). The Ethiopian flood basalt province. In: *Continental flood basalts,* pp 63–110, (MacDougall, J.D. ed). Kluwer, Dordrecht

16. Peccerillo, A., Barberio, M. R., Gezahegn Yirgu, Dereje Ayalew, Barbieri, M. and Wu, T. W. (2003). Relationships between mafic and peralkaline silicic magmatism in continental rift settings: a petrological, geochemical and isotopic study of the Gedemsa volcano, central Ethiopian rift. *Journal of Petrology* **44(11):** 2003–2032.

17. Rowland, J. V., Baker, E., Keir, D., Tesfaye Kidane, Biggs, J., Hayward, N., Wright, T. J. and Ebinger, C. (2007). Fault growth at a nascent slow-spreading ridge: 2005 Dabbahu rifting episode, Afar. *Geophysical Journal International* **171:** 1226–1246.

18. Tryggvason, E. (1984). Widening of the Krafla fissure swarm during the 1975–1981 volcano-tectonic episode. *Bulletin of Volcanology* **47**: 47–69.

19. Wolfenden, E., Ebinger, C., Gezahegn Yirgu, Deino, A. and Dereje Ayalew (2004). Evolution of the northern main Ethiopian rift: birth of a triple junction. *Earth and Planetary Science Letters* **224(1–2):** 213–-228.

20. Wright, T. J., Ebinger, C., Biggs, J., Atalay Ayele, Gezahegn Yirgu, Keir, D. and Stork, A. (2006). Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode. *Nature* **442:** 291–294.