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# Seismic characteristics of variable convection at Erta 'Ale lava lake, Ethiopia

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**Abstract**

The active summit lava lake of Erta 'Ale volcano, Ethiopia, offers a unique opportunity to study magma convection. In February 2002, we collected a multiparametric set of seismic, thermal and video data. These data indicate that the lake cycled between periods characterized by low (0.01–0.08 m $s^{-1}$) and high (0.1–0.4 m $s^{-1}$) convection rates, typically lasting tens to hundreds of minutes. Three seismometers placed around the active crater recorded continuous tremor with a dominant frequency of 2 Hz, and energy at frequencies from 0.8 to 12 Hz. Here, we characterize the seismic signature of each regime by its spectral content, wavefield polarization, and tremor source location. For both regimes, the wavefield is mostly rectilinear. Azimuths and incidence angles are consistent with P waves originating in one of two locations: the north edge of the active lava lake, or a region 100–150 m ENE of the lava lake. Because both regimes are dominated by a low frequency, rectilinearly polarized wavefield, we investigate the source location using a method that solves for location and isotropic source power by a weighted least-squares amplitude-based inversion of seismic data. We find that tremor source regions are unique to each convective regime, although some location overlap exists when tremor is located in short time windows. Wavefield composition suggests that the convective phases may share a common source process, but their differing locations indicate that either the source region is non-stationary, or a second source skews the location during the high convective phase. Tremor polarization and location suggests that the low-frequency tremor is caused by bubble coalescence and bursting in a conduit whose surface is the lava lake. The higher frequency signal associated with the high convective regime is associated with a scattered, more complex wavefield superimposed on the low-frequency background tremor, caused by bubble bursting and cracking of cooled crust at the lava lake surface.


*Keywords:* lava lakes; Erta Ale; convection; seismic; thermal; volcanic tremor; polarization analysis; seismic source location

## 1. Introduction

Erta 'Ale volcano (13.60°N, 40.67°E, Fig. 1) is a basaltic shield volcano in the Danakil depression of northeast Ethiopia, with a summit 613 m asl (Barberi and Varet, 1970). Its 1600 × 700 $m^2$ summit caldera features two pit craters. Since the early 1970s, when access was restricted due to political conditions, the southern crater has hosted an active lava lake (Oppenheimer and Francis, 1998). However, active lava lakes have been continuously present at Erta 'Ale since at least 1967, and possibly since 1906 (Dainelli and Marinelli, 1907; Martini, 1969).

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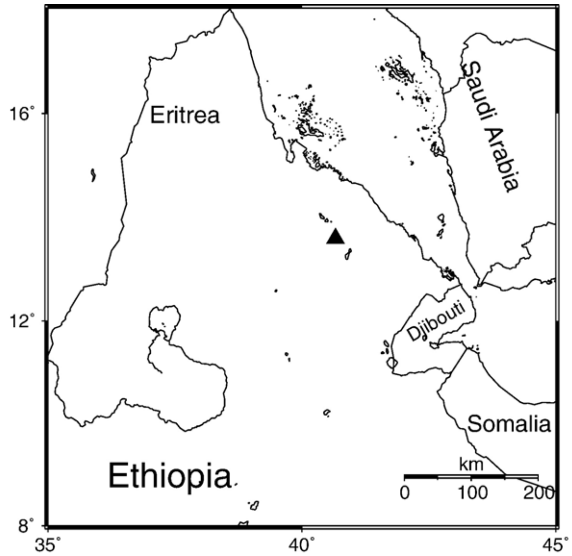


Fig. 1. Map showing the location of Erta ʻAle, Ethiopia. Black triangle indicates location of the Erta ʻAle summit caldera.

Active lava lakes can be considered the exposed upper surface of a convecting magma column, and often indicate a relatively simple conduit (Swanson et al., 1979; Harris et al., 1999). In addition, surface convective features at active lava lakes resemble global plate tectonics (Duffield, 1972) and may be used as a proxy for shallow convective motions (Harris et al., 2005). Long-lived lava lakes require well-developed magma circulation between the reservoir, conduit, and lava lake itself (Francis et al., 1993; Tazieff, 1994; Oppenheimer and Francis, 1998). Magma circulation is necessary to insure summit lava lake longevity, and can persist for tens to hundreds of years (Harris et al., 1999). Thus, active summit lava lakes can provide quasi-direct, long-term, continuous observations of magma system circulation and associated physical parameters, such as volcanic tremor, deformation, heat flux, and gas release (e.g. Le Guern, 1987; Hamaguchi et al., 1992; Kaminuma, 1994; Kyle et al., 1994; Oppenheimer and Francis, 1997; Amelung et al., 2000).

Persistent, active summit lava lakes are relatively uncommon, and have been documented only at a handful of volcanoes around the world. Examples include Ambrym, Vanuatu, since 1996, barring a brief period when a large regional earthquake triggered rock falls, covering the lava lake (Carniel et al., 2003); Nyamuragira, D.R. Congo, from 1921 to 1938 (Hantke, 1939); Nyiragongo, D.R. Congo, for at least 50 yrs, through 1977 (Tazieff, 1977); Kilauea, Hawaiʻi, United States, periodically through 1924 (Macdonald et al., 1970), and periodically during recent eruptive activity (e.g. Duffield, 1972; Tilling, 1987); Masaya, Nicaragua, periodically in the 1980s and 1990s (Rymer et al., 1998); Villarrica, Chile (Witter, 2003); Erebus, Antarctica (Kyle, 1994; Aster et al., 2004); and Erta ʻAle, Ethiopia, since at least 1967, and possibly since 1906 (Dainelli and Marinelli, 1907; Martini, 1969). Finally, a lava lake has recently been discovered on Saunders Island, S. Sandwich Islands (Lachlan-Cope et al., 2001), at which activity persists through 2004 (Patrick et al., 2005).

Here we take advantage of the persistent activity at the Erta ʻAle lava lake to complete a multiparametric study, involving simultaneous collection of seismic, thermal and video data, to better understand the dynamic of the shallow system that feeds this lake. The concept of multiparametric studies (e.g. McNutt et al., 2000) has developed considerably over the last few years, and was greatly expanded upon by the MULTIMO project: multiparametric data sets are now incorporated into modeling work (Neuberg et al., 2006-this issue), used in risk evaluation for occurrence of given eruptive scenarios (Aspinall et al., 2003, 2006-this issue), and are increasingly available via efficient data delivery systems (e.g. Carniel et al., 2006-this issue).

For lava lake systems, considerable advances in our understanding of lava lake processes and conduit dynamics have been possible from such multiparametric approaches. Tilling (1987), for example, used tilt and lava lake level data during the 1972–1974 Mauna Ulu eruption, Kilauea, to show a clear linkage between the summit reservoir and a lava lake system on the volcano flank. Barker et al. (2003) used deformation, lake level and seismic data for lava lakes in Pu ʻu ʻO ʻo to reveal and understand pond filling and drainage due to gas pistoning. Erebus is another particularly well-monitored system (e.g. Kyle, 1994), where, for example, gas flux and seismic data revealed a marked change in activity during 1984 (Kaminuma, 1994; Kyle et al., 1994).

Thus, motivated by the persistence of the Erta ʻAle lava lake, and the success of multiparametric campaigns at other volcanoes, a brief survey at Erta ʻAle volcano, Afar, Ethiopia, incorporated simultaneous seismic, thermal, and video data acquisition (Alean et al., 2005; Harris et al., 2005) to understand the effects of convection on activity within the lake. In this study, we use a combined thermal and seismic data set, constrained by video observations. In Harris et al. (2005) we concentrated on an interpretation of the thermal signal, supported by the seismic data, to track convection processes in the lake. Here, we focus on the seismic signal to search for signals that may be directly associated with variable rates of lava lake convection indicated by the thermal data.