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Ambient seismic noise tomography reveals a hidden caldera and its relation to the Tarutung pull-apart basin at the Sumatran Fault Zone, Indonesia

Trond Ryberg [a,*], Umar Muksin [a,b], Klaus Bauer [a]

[a] GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany
[b] Department of Physics, Syiah Kuala University, Banda Aceh, Indonesia

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ABSTRACT

We analyzed the noise recordings of a short-period seismic network to derive a shallow crustal S-wave velocity model at the Sumatra Fault in Northern Sumatra, Indonesia. By correlating the noise of 40 seismic stations' recording for 9 months, we could recover Rayleigh waves from vertical component recordings with sufficient signal-to-noise ratio. Group velocities of the Rayleigh waves could be determined in the period range from 0.71 to 4.4 s. These group velocities were used to invert for 2D group velocity maps at specific periods. Finally, the derived group velocity maps were inverted for a 3D S-wave velocity model. This model shows a region of a strong velocity decrease off the Great Sumatran Fault Zone, at the northeastern margin of the young Tarutung pull-apart basin. This observed low velocity block coincides with a caldera-like morphological feature which is interpreted as the surface expression of a hidden volcanic caldera. Considering the surface manifestations of geothermal activity around this anomaly, we conclude that the caldera is still acting as a heat source. On the other hand, the weak morphological expression at the surface indicates a certain age of the caldera which might be older than the Tarutung pull-apart basin. The findings provide important constraints on general concepts for the formation of pull-apart basins along the Sumatran fault and their relation to volcanism.

1. Introduction

The geological setting in northern central Sumatra is mainly controlled by the tectonic and volcanic processes related with the N-trending convergence and subduction of the Indo-Australian plate under the Eurasian plate (Bellier and Sébrier, 1994; Sieh and Natawidjaja, 2000; McCaffrey, 2009). As the subduction is oblique at the Sumatran trench, strike-slip deformation along the Sumatran Fault Zone (SFZ) accommodates the convergence component parallel to the trench. The 1650 km long SFZ developed along the mechanically weak zone of the magmatic arc and consists of right-lateral strike-slip fault segments. A series of pull-apart grabens were formed from step-over at segment boundaries. Volcanic structures such as veins, quaternary volcanoes and collapse calderas are found more frequently within major step-over fault zones and associated pull-apart grabens and basins (Bellier and Sébrier, 1994). On a regional scale, the location and geometry of the Sumatra fault possibly is controlled by the position of the volcanic arc (Hamilton, 1979; Bellier and Sébrier, 1994). On a local scale, the Sumatran fault system appears to influence the position of volcanic features (Hickman et al., 2004). However, the causality in these processes is not well understood.

Our passive ambient noise seismological study reported here is covering a segment of the SFZ that is characterized by two pull-apart structures: the Tarutung basin in the center of the layout, and the Sarulla graben at the southern edge of the station distribution (Fig. 1). The Tarutung basin was identified as an example of the youngest stage of pull-apart basins, in context with the evolution of the Toba caldera which formed 75 ka (Bellier and Sébrier, 1994). The local geology is dominated by the widespread distribution of the Toba tuff (Fig. 2). Two older volcanic centers are located at both ends of the Tarutung basin as indicated by red triangles in Fig. 2. Of much larger extension is the Hopong caldera (~1.5 Ma) which shows a well-pronounced topographic expression at the northeastern margin of the Sarulla graben (Hickman et al., 2004). Nukman and Moeck (2013) reported a caldera-like feature of similar size as the Hopong caldera at the northeastern end of the Tarutung basin. However, apart from a very weak morphological indication, there was no evidence for such a caldera structure around the Tarutung basin.

Seismic body waves from local earthquakes recorded by the seismological network shown in Fig. 1 were used to locate the seismicity and determine a tomography of Vp and Vp/Vs of the Tarutung basin and surrounding geothermal area (Muksin et al., 2013a,b, 2014). Here we use the identical network recordings but apply methods of seismic ambient noise analysis in order to derive complementary images of the studied region.

* Corresponding author.

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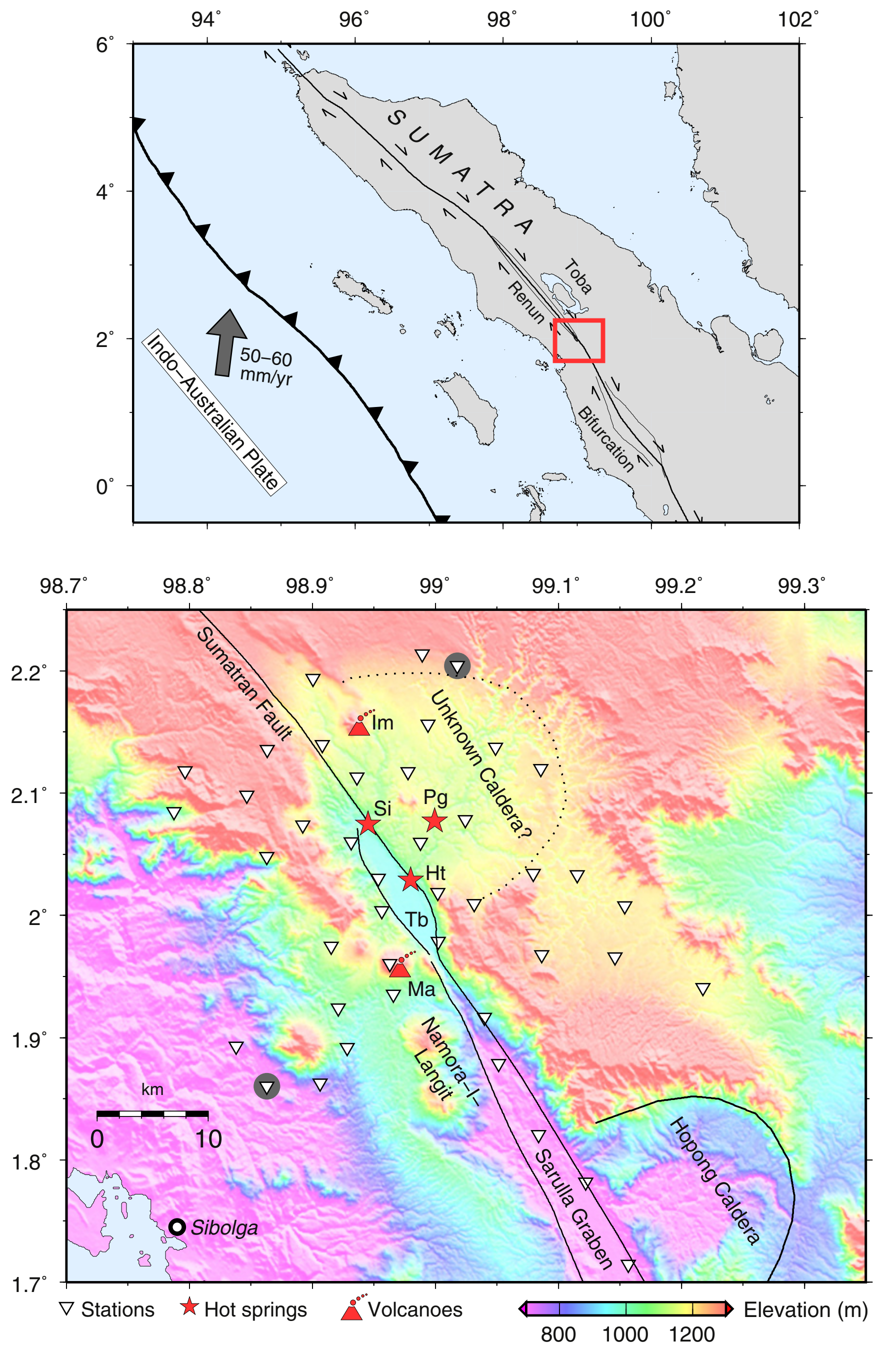

Fig. 1. Map of study region in North Sumatra/Indonesia shows the seismic station distribution (triangles), hot springs (stars) and volcanoes (red icons). The topography is indicated by a color scale which focuses on the visibility of the Hopong Caldera (double ring structure) and a previously unknown, but predicted (Nukman and Moeck, 2013) caldera NE of the Sumatra fault. Simplified structures of the Sumatran fault after Nukman and Moeck (2013). Tb = Tarutung basin, Im = Imun volcano, Ma = Martimbang volcano, Si = Sipoholon hot spring, Pg = Panyabungan hot spring, Ht = Hutabarat hot spring.

2. Ambient seismic noise

Over the last decade, it was shown that Rayleigh waves in Green's functions between station pairs can be successfully extracted from sufficiently long recordings of ambient seismic noise and can further be used for structural analysis with tomographic methods. By cross-correlation the recordings of diffuse wave fields (i.e. noise), the Green's function or seismic impulse response can be retrieved, assuming that the noise sources are randomly distributed in space. Most of the research and application of this technique focuses on the retrieval and further analysis of surface waves (Campillo and Paul, 2003; Shapiro et al., 2005). For an overview of the technique see Waapenaar et al. (2003), Schuster (2009), Shapiro et al. (2005) and Campillo and Roux (2014).

Commonly, surface wave analysis of ambient noise based studies focuses on crustal and upper mantle investigations ranging from global to local scales. Several surveys, targeting at volcano related structures had been reported (Stankiewicz et al., 2010; Jaxybulatov et al., 2014) which could successfully image a magma chamber in the Lake Toba (Sumatra) caldera. It proved to be sufficient to analyze seismic noise recordings of only several month duration to reveal volcanic structures. Other ambient noise studies in volcanic environments (Zulfakriza et al., 2014; Matos et al., 2015; Shomali and Shirzad, 2015; Mordret et al., 2014;