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# Fluid-triggered earthquake swarms in the Rwenzori region, East African Rift—Evidence for rift initiation

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ABSTRACT

The Rwenzori Mountains are located within the Albertine Rift Valley in western Uganda. To monitor the microseismic activity in the area we have deployed a seismic network of up to 35 stations for a period of about 20 months. The analysis of the recordings revealed several earthquake clusters within a restricted area NE of the mountain block. The clusters form elongated pipes with 1–2 km diameter and vertical extensions of 3–5 km. Most of them are located in 5–16 km depths; however one cluster reaches down to 22 km. Each cluster is composed of a series of single earthquake swarms with durations between a few days and more than a week, interrupted by intervals of inactivity of up to several months. Some of the swarm events exhibit vertical migration tendencies with estimated velocities between 0.3 and 1 km/day. Local magnitudes range from $M_L = 0.5$ to $M_L = 4.0$ with b-values between 0.96 and 1.2. The source mechanisms of the swarm earthquakes are dominated by normal faulting with tension-axes orientations perpendicular to the rift axis. There are only few strike-slip events and no reverse mechanisms. From petrological considerations we presume that the earthquake swarms are triggered by fluids and gases which originate from a magmatic source below the crust. Melt and/or $CO_2$ are guided along the intersection lines of two steep fault sets that were identified by shear-wave splitting analysis and fault mapping in the Rwenzori area. The existence of a magmatic source within the lithosphere is supported by the detection of a shear-wave velocity reduction in 55–80 km depth from receiver-function analysis and the location of mantle earthquakes at about 60 km. We interpret these observations as indication for an initial rifting process that may eventually lead to the complete detachment of the Rwenzori block from the surrounding rift flanks.



## 1. Introduction

Earthquake swarms are defined as episodic series of seismic events that are clustered in space and time (Mogi, 1963). Unlike a typical mainshock–aftershock sequence, where the aftershocks have significant lower magnitudes than the mainshock, the earthquake swarms are characterized by a gradual increase and decrease of activity with no predominant primary earthquake. They are commonly associated with magmatic intrusions and fluid transport in the crust reducing the resistance of faults, as well as with stress perturbations induced by the release of volatiles like $CO_2$ (e.g. Bräuer et al., 2003; Dahm et al., 2008; Hainzl, 2004; Hainzl and Ogata, 2005). The majority of them are observed in regions of active volcanism (Benoit and McNutt, 1996; Gardine et al., 2011; Karpin and Thurber, 1987). Volcanic earthquake swarms are characterized by large b-values between 1.0 and 2.5 which are commonly attributed to a highly fractured crust and a heterogeneous stress field in these areas (Bridges and Gao, 2006; Mogi, 1963). Numerous earthquake swarms are reported from Iceland. Most of them are discussed in the context of magma movements and dike intrusions accompanying volcanic eruptions (Hensch et al., 2008; Jakobsdóttir et al., 2008; Key et al., 2011; Soosalu et al., 2010; White et al., 2011). In many cases the swarm events exhibit a systematic hypocentre migration reflecting the magma intrusion process. Earthquake swarms were also recorded in several sections of the East African Rift, such as Afar, Ethiopian Rift (e.g. Ebinger et al., 2008; Keir et al., 2011), the southern Kenya rift (Ibs-von Seht et al., 2001; Tongue et al., 1994; Young et al., 1991), and the north Tanzanian divergence (Albaric et al., 2010; Baer et al., 2008). In general, these events are attributed to magmatic dike intrusions. However, although the western branch of the East African Rift reveals significant higher seismic activity than the eastern branch, there have been no observations of earthquake swarms in this part of the EARS so far.

Apart from volcanic areas, earthquake swarms are also observed in intraplate regions such as the Bohemian Massive, the French Massive

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Central, Central Italy, and Long Valley, California. Špičák (2000) gives a compilation of intraplate and artificially induced earthquake swarms. The author finds similar swarm patterns and concludes that the cause is related to intrusion of fluids. The western Bohemia/Vogtland area is one of the most prominent earthquake swarm regions, situated within the Eger rift which is part of the European rift system. Here, earthquake swarms have been reported since the 16th century (Grünthal, 1989). Many investigations manifest that fluids and the transport of mantle volatiles originating from a subcrustal magma body might be the source of the observed swarm activity in this area (Bräuer et al., 2003; Geissler et al., 2005; Špičák and Horálek, 2001; Špičák et al., 1999; Weise et al., 2001).

Ibs-von Seht et al. (2008) analyse earthquake swarms in selected continental rifts. They compare the characteristics of clusters observed in the Rio Grande rift, North America, the Eger rift, Europe, and the Kenya rift, East Africa. They conclude that all investigated swarms occur in rift sections that are influenced by intersecting fracture zones. During the swarm activity the maximum observed magnitudes range from 4.2 to 4.7 and the b-values for all three areas are between 0.8 and 1.0. This corresponds to the magnitude distribution of regular tectonic earthquakes and indicates a difference to earthquake swarms in regions of active volcanism that show b-values significantly higher than 1. There is no clear terminological discrimination between earthquake “swarms” and “clusters”. In general, clusters are a series of earthquakes spatially-concentrated with regular patterns, whereas seismic swarms are concentrated in space and occur within a relatively short period of time. In this paper we use the word “cluster” if we refer only to the spatial distribution of a group of earthquakes. In case we discuss the temporal characteristics we prefer the term “swarm”.

We focus on the observation of earthquake clusters that were detected during a microseismic monitoring campaign in the Rwenzori region of the East African Rift System (EARS) from February 2006 to September 2007. We describe the characteristics, similarities, and differences to earthquake swarms in other regions. Finally we discuss possible mechanisms for the triggering of the swarm events with respect to petrological information from the region.

## 2. Tectonics and seismicity of the Rwenzori region

The ~3000 km long Cainozoic EARS extends from the Afar triple junction in the north to Mozambique in the south. In southern Ethiopia it splits up into two branches surrounding Lake Victoria: The eastern branch passes Kenya and terminates in northern Tanzania, the western branch runs through Lake Albert, Lake Edward, Lake Tanganyika, and Lake Malawi, and ends in southern Mozambique. The 5000 m high Rwenzori Mountains are situated within the Albertine rift, which is part of the western branch of the EARS (Fig. 1). They represent a non-volcanic basement block composed of rocks of Proterozoic and Achaean age (Link et al., 2010) whose origin and relation to the evolution of the EARS are focus of the RiftLink project (www.riftlink.org). The Rwenzoris are bounded by two rift segments: (a) the Albertine rift, extending west of the mountains from Lake Edward in the south to Lake Albert in the north, and (b) the Lake George rift segment running east of the mountains starting at Lake Edward and ending up north of Lake George at about 0.5°N latitude. Previous studies indicate that the Lake Albert rift started in the north and propagated southwards whereas the Lake Edward–George segment started in the Lake Edward region and propagated northwards (Koehn et al., 2008; Morley, 1999). Such propagation may lead to a clockwise rotation of the Rwenzori block (Koehn et al., 2008), which in turn can lead to complex intersecting faults in the NE of the Rwenzori (Koehn et al., 2010), where the Rwenzori may break off the Victoria plate. The area of focus is cluttered with quaternary volcanic craters. Four volcanic fields mark the centres of magmatic activity (Fig. 1); these are the Katwe-Kikorongo and Bunyaruguru fields in the south and south-east, the Ndale field in the east and the Fort Portal field in the north-east of the Rwenzori

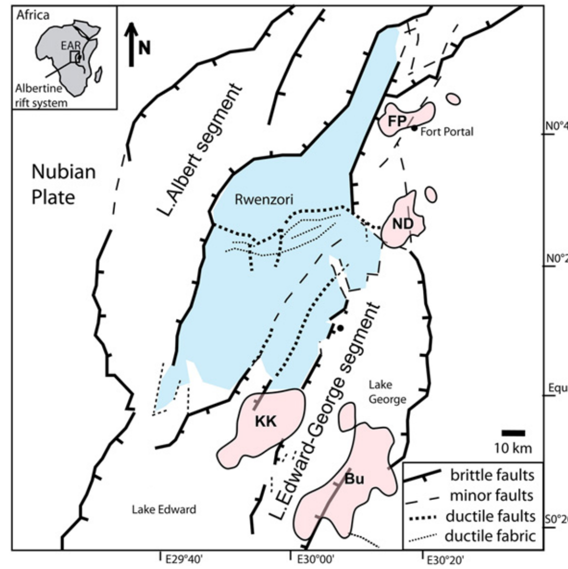


**Fig. 1.** Tectonic map of the Rwenzori area (after Koehn et al., 2008, 2010). The Rwenzori mountains (light blue area) are surrounded by two rift segments, with the exception of a region in the NE, where they are connected to the Victoria plate. Volcanic fields are marked by red areas (FP: Fort Portal, ND: Ndale, KK: Katwe-Kikorongo, Bu: Bunyaruguru).

Mountains. The southern fields are separated and affected by the rift while the northern fields are located on the unrifted Precambrian bridge that connects the Rwenzori Mountain chain with the flanks. The time of volcanic activity ranges from 50 ka in the south (Boven et al., 1998) to Holocene (8–4 ka) in the Katwe-Kikorongo and the northern fields (Barker and Nixon, 1989; Brooks and Smith, 1987).

From global observations it is known that the western branch of the EARS shows significant higher seismic activity than the eastern branch, with the Rwenzori region being the area with highest seismicity of the entire rift system (e.g. Albaric et al., 2009; Fairhead and Girdler, 1971; Foster and Jackson, 1998; Nyblade and Langston, 1995; Twesigomwe, 1997). Previous microearthquake surveys in the Rwenzori region by Maasha (1975), Tugume and Nyblade (2009), and Lindenfeld et al. (2012) confirm the high seismicity rate.

The results of Lindenfeld et al. (2012) are based on a seismometer network covering an area of roughly 80 km×140 km and operating from February 2006 to September 2007 (Fig. 2). The recordings reveal high seismic activity with approximately 800 events per month. The majority of located events lie within faults zones to the east and west of the Rwenzoris with the highest seismic activity observed in the north-eastern area, where the mountains are in contact with the rift shoulders. Local magnitudes range from $M_L = -0.5$ up to $M_L = 5.1$ with a b-value of 1.1. In the northern part of the network with its high station density the earthquake catalogue is complete for magnitudes larger than 0.8.

The hypocentral depth distribution exhibits a pronounced peak of seismic energy release at 15 km. The maximum depth extent varies between 20 km and 32 km and correlates well with Moho depths that were derived from P-wave receiver functions by Wölbern et al. (2010). Vertical profiles indicate that beneath the rift shoulders seismicity extends from the surface down to approximately 30 km depth, whereas beneath the rift valley seismicity is restricted to depths between 10 km and 20 km. However, Lindenfeld and Rümpker (2011) report the detection of a group of mantle earthquakes in this area probably associated with magmatic processes in the lithospheric mantle, (see Fig. S1 in the supplementary information for details).

Fault plane solutions of 304 events were derived from P-wave polarities and S/P amplitude ratios. The majority of the source mechanisms exhibit pure or predominantly normal faulting with highly