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KivuSNet: The First Dense Broadband Seismic Network for the Kivu Rift Region (Western Branch of East African Rift)

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ABSTRACT

The Kivu rift is located in the bordering region of the Democratic Republic of Congo and Rwanda, in the western branch of the East African rift. Here, the active volcanoes Nyamulagira (the most active in Africa) and Nyiragongo (host to the largest persistent lava lake on Earth) threaten the city of Goma and neighboring agglomerations, and destructive earthquakes can also affect the region. Despite this high level of hazard, modern seismic monitoring infrastructure was lacking in the area until very recently, leaving many aspects about the volcanic activity and seismicity up to speculation. In order to remedy this unsatisfactory situation, the first dense real-time telemetered broadband seismic network, KivuSNet, was deployed in the region, with the first two stations in 2012/2013 followed by six additional ones in 2014. Since October 2015, a network of 13 stations is running in the Kivu rift, and with currently seven additional stations in the process of installation, this network is under continuous development.

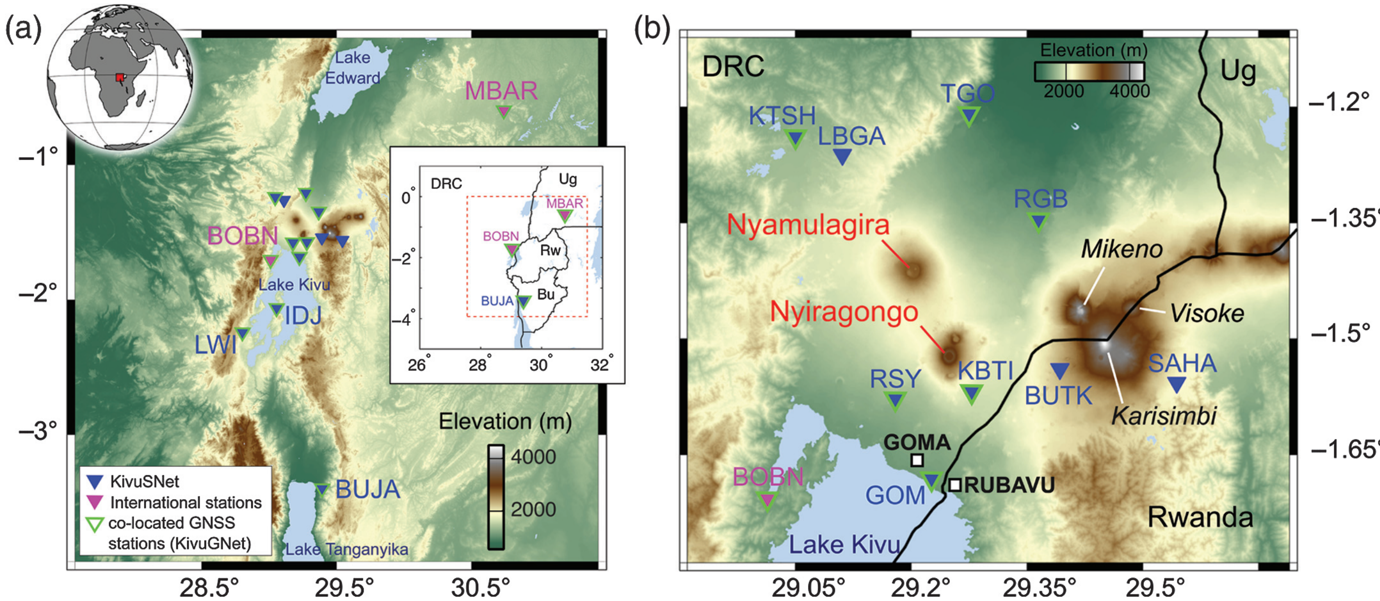
KivuSNet opens a new window for the seismological knowledge in this highly active rifting region. It allows for unprecedented insights into tectonic and volcanic seismicity, tremor patterns, and Earth structure as well as for sustainable real-time monitoring of the volcanoes. Together with the often collocated KivuGNet geodetic stations, KivuSNet closes a dramatic observational gap in this region. This article presents the key features of the network, discusses technical aspects, and provides an overview of first results obtained using the thus far acquired data, showing KivuSNet's wide potential.

Electronic Supplement: Figures of power spectral density.

INTRODUCTION

The Kivu rift (KR) region lies in the bordering region of the Democratic Republic of the Congo (DRC) and Rwanda in central Africa (Fig. 1). It belongs to the western branch of the East African rift system and as such is characterized by extensional tectonics and rifting-related volcanic activity (e.g., Smets *et al.*, 2015; Wood *et al.*, 2015, and references therein), finding its expression in the Virunga volcanic province (VVP) that is home to two of Africa's most active volcanoes. Mount Nyiragongo is a stratovolcano hosting the largest persistent lava lake on Earth. Its neighbor Nyamulagira, in contrast, is a large shield volcano. Although it poses a significantly smaller threat to the local population, it has a notable impact on its environment through its frequent eruptions, and recently, a lava lake reappeared in its pit crater for the first time since 1938 (Smets *et al.*, 2014).

The hazard posed in particular by Nyiragongo is considerable. As a result of political instability and recurring armed conflicts, the KR region and especially the city of Goma located only 15 km south of Nyiragongo has experienced rapid and sustained population growth over the past decades, leading to a dramatic increase of the population exposed to this hazard. Today, more than a million people live in Goma (DRC) and Rubavu (Rwanda). Two catastrophic flank eruptions in 1977 and 2002 demonstrated Nyiragongo's devastating potential (e.g., Hamaguchi *et al.*, 1992; Tedesco *et al.*, 2007), the latter causing a major humanitarian crisis and leaving more than 100,000 people homeless. Nyamulagira poses a smaller immediate threat to the local population but depicts frequent and voluminous eruptions. Besides the volcanic hazard, destructive earthquakes can occur in the KR region, such as the 2002 Kalehe (M_w 6.2, Wauthier *et al.*, 2015) or 2008 Bukavu-Cyangugu (M_w 5.9, d'Oreye *et al.*, 2011) events, or more recently the 2015 M_w 5.7 Katana earthquake (Geirsson *et al.*, unpublished manuscript, 2016, see Data and Resources). Lake Kivu is further known to contain large amounts of dissolved CO_2 and CH_4, with the potential risk of a limnic eruption (Schmid *et al.*, 2005). Despite this scientifically unique setting and high hazard



▲ **Figure 1.** Maps depicting the current layout of the KivuSNet network. (a) Larger scale map of the Kivu rift (KR) region depicting all KivuSNet stations (blue inverted triangles) and two stations installed prior to the KivuSNet development (magenta inverted triangles): MBAR, an international station in Uganda (Ug) that is available via Incorporated Research Institutions for Seismology (IRIS), and Bobandana (BOBN), which was installed in the framework of AfricaArray. A green contour around the symbol indicates that the seismic station is collocated with a Global Positioning System station from KivuGNet. The insets show the location of the region of interest on a world map and the political borders. (b) The enlarged Virunga volcanic province region, with volcanoes Nyamulagira and Nyiragongo. The network provides good azimuthal coverage around the volcanic field except on the western side.

level, little is known on the dynamics of these volcanoes and the seismicity characteristics in the KR region, mostly due to the lack of appropriate monitoring infrastructure and the difficult working environment.

Over the past years, a consortium of Belgian and Luxembourgian scientists, in collaboration with local institutions in DRC, Rwanda, and Burundi, continuously developed the first modern dense broadband seismic network in the KR region, KivuSNet (Oth *et al.*, 2013; complementing the Kivu geodetic Global Navigation Satellite Systems network, KivuGNet, Geirsson *et al.*, 2016, unpublished manuscript, 2016, see Data and Resources), in the framework of several scientific projects, the most recent one being Remote Sensing and *In Situ* Detection and Tracking of Geohazards (RESIST, see Data and Resources). The aim of this network, which reached a total of 13 stations in October 2015, is to (1) help close the gaps in the scientific knowledge on the KR region and its volcanoes, and (2) establish the required infrastructure for improved monitoring, both of the Nyiragongo and Nyamulagira volcanoes and the tectonic seismicity around Lake Kivu.

The goal of this article is to present the wide potential of this new seismic network in a previously nearly unmonitored region with difficult field access and environmental conditions. Initial efforts for instrumenting the region were carried out following the 2002 Nyiragongo eruption (Pagliuca *et al.*, 2009, who installed four short-period and three broadband digital stations). These led to an initial monitoring network, which could not, however, be maintained operational over the long term. We describe the KivuSNet network layout and station installations, present data acquisition and telemetry, and discuss network performance through power spectral density (PSD) analysis. We close the article with unprecedented insights into the seismicity characteristics of the KR, the potential of the network for continuous volcano monitoring, and with an outlook on future work with these unique data.

THE NETWORK

Network Configuration and Site Selection

KivuSNet has been designed with the goal to detect, locate, and characterize volcano-related seismic activity occurring within the VVP as well as tectonic earthquakes occurring south and north of it (Fig. 1), based on the thus far available knowledge on the seismic activity in the area. For this reason, we looked for station sites minimizing the azimuthal gap for events occurring within the volcanic field, and stations Idjwi (IDJ), Lwiro (LWI), and Bujumbura (BUJA, Burundi) were installed around Lake Kivu and down to Lake Tanganyika to get better constraints on tectonic events in these areas. A list of stations with installation dates and instrumentation information are provided in Table 1 (see also the Station Design and Instrumentation sections).

However, although seismic site selection is usually driven by the desire to find a low-noise recording environment (no or very limited anthropogenic noise sources), preferably with the possibility of installing the sensor directly on the bedrock and having ease of logistics (e.g., Petersen *et al.*, 2011), the key aspect driving site selection in the KR region is the rather volatile security situation. Consideration of this aspect involves protecting

Table 1
List of Installed KivuSNet Stations

Code	Station Name	Latitude (°)	Longitude (°)	Altitude (m)	Datalogger	Seismic Sensor	Corner period	Infrasound	Date Installed (yyyy/mm/dd)
BOBN	Bobandana	−1.7063	29.0132	1529	RT130*/Centaur	Trillium	120 s		2012/02/23
BUJA	Bujumbura	−3.3960	29.3960	1107	DM24	ESPC	60 s		2014/09/11
BUTK	Butaka	−1.5389	29.3924	2557	Centaur	Trillium	120 s		2015/09/29
GOM	Goma	−1.6812	29.2267	1524	DM24	ESPC	60 s	✓	2013/04/30
IDJ	Idjwi	−2.0642	29.0606	1566	DM24	ESPC	60 s		2015/09/25
KBTI	Kibati	−1.5690	29.2784	1992	Centaur	EPSC	60 s	✓	2015/09/12
KTSH	Kitchanga	−1.2384	29.0499	1717	DM24	ESPC	60 s		2014/09/12
LBGA	Luboga	−1.2620	29.1109	1809	DM24	ESPC	60 s		2014/08/08
LWI	Lwiro	−2.2392	28.8025	1760	DM24	EPSC	60 s		2014/09/16
RGB	Rumangabo	−1.3452	29.3654	1610	DM24	ESPC	60 s		2014/02/13
RSY	Rusayo	−1.5770	29.1798	1680	Centaur	Trillium	120 s		2015/09/28
SAHA	Sahara	−1.5574	29.5436	2217	Centaur	Trillium	120 s		2015/09/30
TGO	Tongo	−1.2081	29.2733	1415	DM24	ESPC	60 s	✓	2014/09/09

Stations are ordered alphabetically following their station code. The table shows station name, latitude and longitude (in degrees), altitude (in meters), which digitizer/acquisition module and sensor are installed, the corner period of the seismic sensor, the presence of an infrasound array, and the date of first installation. All seismic data are acquired at sample rates of 200 Hz (local storage only) and 50 Hz (local storage and real-time transmission), whereas the infrasound data are acquired at sample rates of 100 Hz (local storage only) and 50 Hz (local storage and real-time transmission).
*The RefTek RT130 datalogger at station BOBN was replaced with a Nanometrics Centaur datalogger on 4 October 2016. Prior to this date, data at BOBN were acquired with a sample rate of 40 Hz.

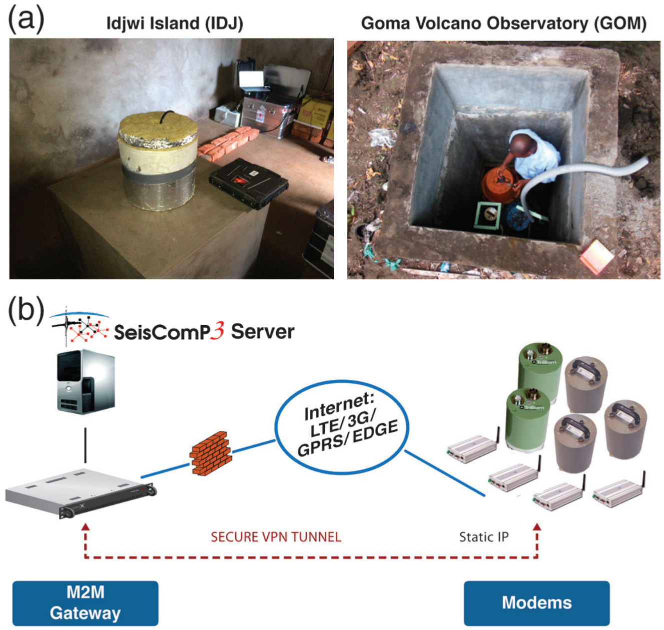
the installations from theft (e.g., solar panels and batteries) and associated vandalism (e.g., short circuiting of digitizers when batteries or solar panels are stolen), and ensuring the possibility for field crews to securely access the chosen sites. These constraints combined with the requirements for a reasonable network geometry severely limit the number of options, and much larger compromises have to be made than for most other local/regional networks worldwide. Several stations are located within MONUSCO (United Nations Organization Stabilization Mission in the DRC) military compounds or other highly secured facilities, such as the Virunga National Park rangers' bases (stations TGO, KTSH, KBTI, and RGB). Some stations were installed in preexisting sites owned by Goma Volcano Observatory (GVO) (stations RSY, LBGA, GOM) and Centre de Recherche en Sciences Naturelles (CRSN) (station LWI). Other sites were renovated (station BUJA in Burundi) or newly built (stations IDJ in DRC and SAHA and BUTK in Rwanda). Most of the stations have a sentinel onsite 24-7 year-round. The area between Nyiragongo and Nyamulagira is unfortunately not accessible for security reasons, making it impossible to sustainably operate stations directly in the heart of the volcanic field.

Despite these limitations, KivuSNet provides a good azimuthal coverage around the volcanic field, with the exception of a larger gap on the western side. GVO was recently granted funding for the acquisition of seven additional broadband stations by the MONUSCO and the DRC government, and at least three of these are planned for deployment within this gap. Stations SAHA and BUTK installed on Rwandan territory allow for improved detection levels of possible seismicity around the supposedly dormant eastern volcanoes. A small eruption in 1957 at Visoke volcano (Tazieff, 1977) or the recently detected swarm seismicity underneath the western flank of Karisimbi from the analysis of a temporary array of eight broadband stations installed in Rwanda (Wood *et al.*, 2015), however, provide hints that these volcanoes might pose an underestimated hazard.

Station Design and Instrumentation

Besides the abovementioned limitations in terms of site selection, station design is also subject to limitations, given the partially difficult access to some sites and the availability of appropriate construction materials. Because of these constraints and budgetary limitations, borehole installations or elaborate vault constructions could not be carried out.

Most sites are equipped with a purpose-build observation hut, and the seismic sensors are installed on a concrete seismic pier with variable surface sizes (ranging from around 0.5×0.5 to 1.5×1.5 m) in the center of the hut. The seismic piers have been anchored as deep as possible, reaching the bedrock in most cases, and have been decoupled from the concrete floor of the observation hut. At stations GOM and BUTK, the sensors are installed in vaults 2–3 m deep (Fig. 2a), whereas at station SAHA the sensor is installed in a small surface vault. At BUTK and SAHA, the nonsensor equipment is installed in a secured area in public buildings. The sensors are thermally insulated with Styrodur boxes filled with Styropor chips or RockWool covers (Fig. 2a) originally designed for pipe insula-



▲ **Figure 2.** (a) Photographs of sensor installations at stations IDJ and GOM. All sensors are either installed on a seismic pier or in a shallow vault directly installed on the bedrock. (b) Network communication setup illustration for real-time data transmission and remote-station configuration access. Each station is equipped with a modem for cellular data communication, and a secure VPN tunnel is established with the datacenter in Luxembourg (see the Data Acquisition and Transmission section).

tion, with chosen diameters fitting as closely as possible the used sensors and insulation thickness, varying from 5 to 10 cm. Continuous power supply is guaranteed using 110–150 W solar panels in combination with appropriately sized batteries.

All sites are equipped with either Güralp CMG-3ESPC (60 s–50/100 Hz) or Nanometrics Trillium Compact (120 s–100 Hz) seismometers (Table 1). Data digitization is carried out with 24 bit digitizers, using Güralp CMG-DM24S3(6)EAM and Nanometrics Centaur dataloggers. Station BOBN, installed in 2012 in the framework of the AfricaArray project (see Data and Resources), was the first permanent high-quality broadband station in the area and was equipped with a RefTek RT130 datalogger until replaced by a Centaur on 4 October 2016. Many of the KivuSNet sites also house a KivuGNet geodetic station (Geirsson *et al.*, unpublished manuscript, 2016, see Data and Resources; Fig. 1). In addition, stations GOM, TGO, and KBTI are each equipped with a three-element, triangular-shaped infrasound array with ∼20 m aperture manufactured by Boise State University (Johnson and Ronan, 2015), and these stations are therefore equipped with six-channel dataloggers.

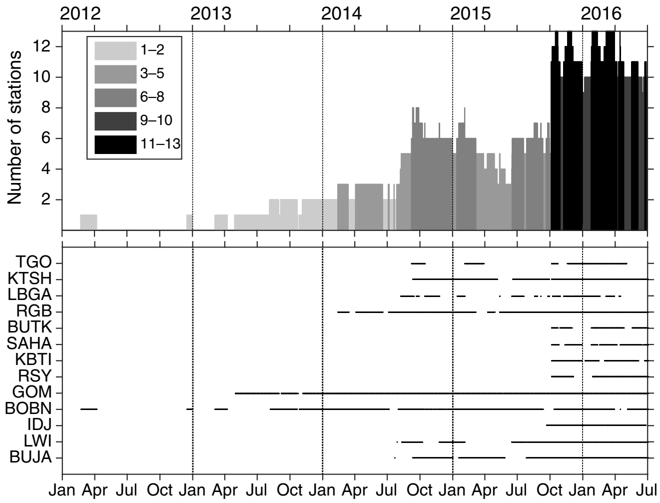
Data Acquisition and Transmission

The digitizers are operated at a sampling frequency of 200 Hz, with secondary channels at 50 Hz transmitted in real time by cellular data network to the data center in Luxembourg. Infrasound data are acquired at a sampling frequency of 100 Hz, with 50-Hz secondary channels transmitted to Luxembourg as well. All data are recorded onsite in miniSEED format on flash storage and regularly collected by the technicians of the responsible institutions. In the first stage of network development (prior to October 2015), this manual download procedure was the only mode of data acquisition. This led to a number of issues, such as long wait times for data in cases where some stations could not be accessed by field crews for extended periods of time and significant data gaps in case of station malfunction that could only be detected upon the next field visit. In particular lightning-related station failure is a common issue in this region, which is located within the main hotspot of lightning activity worldwide (Christian *et al.*, 2003).

In order to remedy this unsatisfactory situation and ensure rapid data availability, each station was equipped in September/October 2015 with a Viola Systems (recently acquired by ABB) modem for wireless communication via cellular data (LTE/3G/GPRS/EDGE) network, in combination with an M2M gateway unit located in the data center in Luxembourg establishing secure VPN connections with all stations (Fig. 2b). AfricaArray station BOBN was also upgraded with such a modem. Station LBGA is thus far only equipped with a one-way communication (push-mode) modem and will be upgraded with a VPN-capable modem later in 2016. All modems and the M2M gateway unit belong to the Arctic product series. Although we are well aware that cellular data networks can be affected by outages during and following major earthquakes or during severe volcanic crises, a solution based on Very Small Aperture Terminal (VSAT) satellite communications is prohibitive both from a budgetary and practical point of view (securing the antenna against theft, drawing too much attention to the installations, and high power consumption). Radio transmission was also tested in the area (Pagliuca *et al.*, 2009; Geirsson *et al.*, unpublished manuscript, 2016, see Data and Resources), but was restricted to short range and line-of-sight configuration. In addition, the radio transmission systems are also more sensitive to lightning damage and not as flexible for remote management of the stations.

The solution based on cellular data allows for overall robust continuous monitoring and the recognition of potentially pre-eruptive seismicity changes, which by itself is a game changing development in the KR region. At all sites, cellular data network coverage from at least one operator is sufficient (in some cases we need to use a high-gain antenna) to reliably transmit continuous three-component 50-Hz seismic data streams as well as mass position information (sampled at 4 Hz, only for Güralp instruments), state-of-health channels and three infrasound channels sampled at 50 Hz from TGO, GOM, and KBTI, as mentioned previously. Each station is given a static IP address reachable within the computing network of the data center in Luxembourg thanks to the VPN tunnel, and the data are transmitted using the SeedLink protocol (Hanka *et al.*, 2000) (Fig. 2b). Although the connection is reasonably often interrupted for short periods of time, the gaps resulting from these dropped connections are as a rule reliably backfilled after connection is reestablished.

Data acquisition and archiving, as well as initial automatic real-time analysis, is carried out using the SeisComP3 software (see Data and Resources), with a main acquisition server



▲ **Figure 3.** Timeline (January 2012 – June 2016) representing the availability of KivuSNet seismic data since the installation of station BOBN in 2012. (a) Number of stations available each day as gray shaded histograms. (b) Timeline of data availability for each station. The two periods of August/September 2014 and September 2015, during which time several stations were installed, mark significant boosts in the number of available stations. Note that real-time data transmission was set up in September 2015, with the exception of station LBGA.

in Luxembourg. From there data are forwarded to a second redistribution/backup SeisComP3 server that is also able to take over acquisition in case of main server failure. Because of the lack of the required computing and network infrastructure (such as broadband internet access and reliable power supply), we could not telemeter the real-time data streams directly to GVO in Goma at the design stage of the transmission infrastructure, which is why this had to be set up with the M2M gateway and the main SeisComP3 acquisition server in Luxembourg. Since early October 2016, direct real-time retransmission of the data streams is carried out to two newly installed SeisComP3 servers at GVO in Goma and the Rwanda Natural Resources Authority in Kigali. Besides the real-time transmission of 50 Hz data streams, this system allows for remote station control and configuration, strongly simplifying their management and allowing for the rapid detection of problems and, quite often, a remote solution, or if required, the quick dispatch of a field crew. Thanks to this remote station access and daily checks and maintenance, the recording reliability has dramatically improved, making this network the densest permanent ever deployed in this region and unrivaled across the largest parts of Africa.

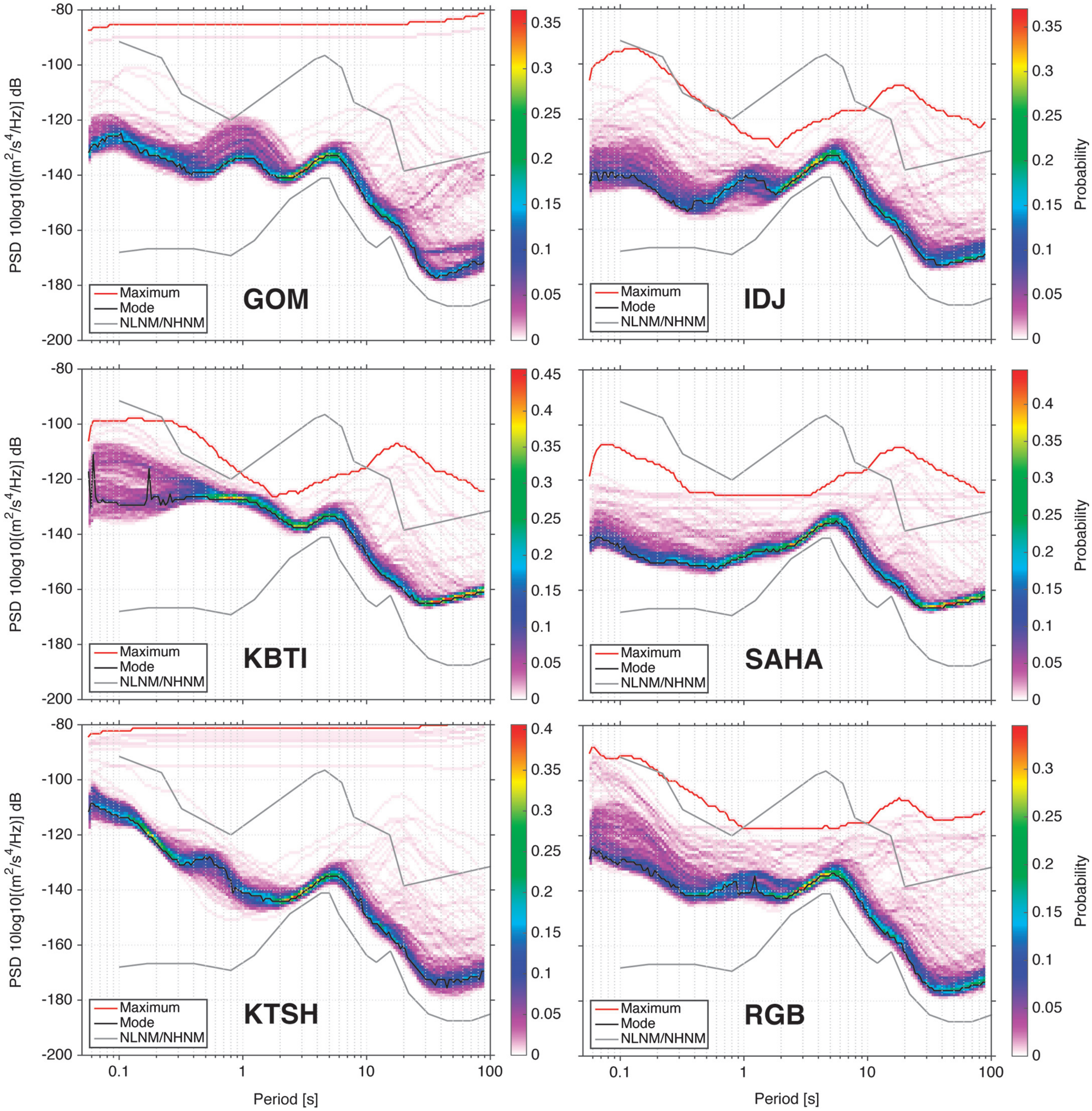
Figure 3 shows a graphical representation of the data availability starting from 2012 (see also Table 1). While BOBN was installed in 2012, the station unfortunately provided little data until mid-2013, due to technical issues and the highly problematic security situation during the M23 rebellion in 2012/2013. This was followed by the installation of GOM station in April 2013 and RGB in February 2014. The remaining stations were installed in August–September 2014 (LBGA, TGO, BUJA, KTSH, and LWI), providing a first functional network setup, and September 2015 (KBTI, RSY, IDJ, BUTK, and SAHA), leading to the current configuration. From August to September 2014, up to 8 stations (6 in the VVP) are available for analysis, and from October 2015, usually 10 to 13 stations were always functional and accessible in real time.

Station Performance in Terms of Power Spectral Density

In order to assess the performance of the stations in terms of noise characteristics, we carried out a PSD analysis for the vertical and horizontal components in the frequency band 100 s to 20 Hz. In order to compare noise levels at the various stations, we calculated PSD probability density functions (PDFs) for a nine month period from October 2015 to June 2016 following the processing described by McNamara and Buland (2004), with 50% overlapping 1-hr time windows subdivided into 13 segments overlapping by 75%. Smoothing was done by calculating full-octave averages in 1/16th octave intervals. We also tested lower levels of smoothing, and the overall conclusions are the same.

Figure 4 shows the calculated PSD PDFs for the vertical component at six stations (the horizontal components are shown in Ⓔ Figs. S1 and S2, available in the electronic supplement to this article), together with the new low-/high-noise model range from Peterson (1993). These examples show the typical effects seen at all sites of the network. Overall, all stations show quite low noise levels in the microseismic band (periods of ∼4–16 s), probably reflecting the fact that the region is located well in Africa's continental interior. Although it can be expected that Lake Kivu contributes to the noise in the microseismic band (daily noise cross-correlation functions calculated for this frequency band tend to indicate a source in the south for all stations in the VVP), the PSD levels remain quite low. It is worth noting that the period band of around 0.5–5 s (0.2–2 Hz) is the band dominating the typical volcanic tremor signals in the VVP (J. Barrière, personal comm., 2016 and manuscript in preparation). This reflects in the relatively narrow high-probability PSD distribution in the ∼2–5 s period range, as well as the often visible PSD peak around a period of 1 s (e.g., GOM, IDJ, RGB). At KBTI and KTSH, this peak is shifted to lower periods (∼0.5–0.8 s), and at KBTI and SAHA, the range 0.5–1 s is characterized by a narrow, high-probability PDF. At lowest periods (below ∼0.2–0.3 s), most stations are comparatively noisy due to anthropogenic sources. GOM is located directly within the city of Goma, whereas KBTI is placed relatively close to a dirt road with common truck traffic. KTSH is installed in a military compound and RGB at the base of the Virunga Volcano National Park rangers. In contrast to these stations, IDJ, SAHA, LBGA, and BUJA (the latter two are not displayed in Fig. 4) are relatively quiet sites at short periods.

At long periods (∼20–100 s), the PSD levels strongly vary from station to station and are probably related to the quality of the seismic pier. This is particularly visible in the horizontal-component PSDs (Ⓔ Figs. S1 and S2). At KTSH for instance, the pier is rather narrow and high, making the horizontal components more prone to tilt, whereas the pier at station IDJ (see also Fig. 2a) is of good quality. Note that at station GOM the



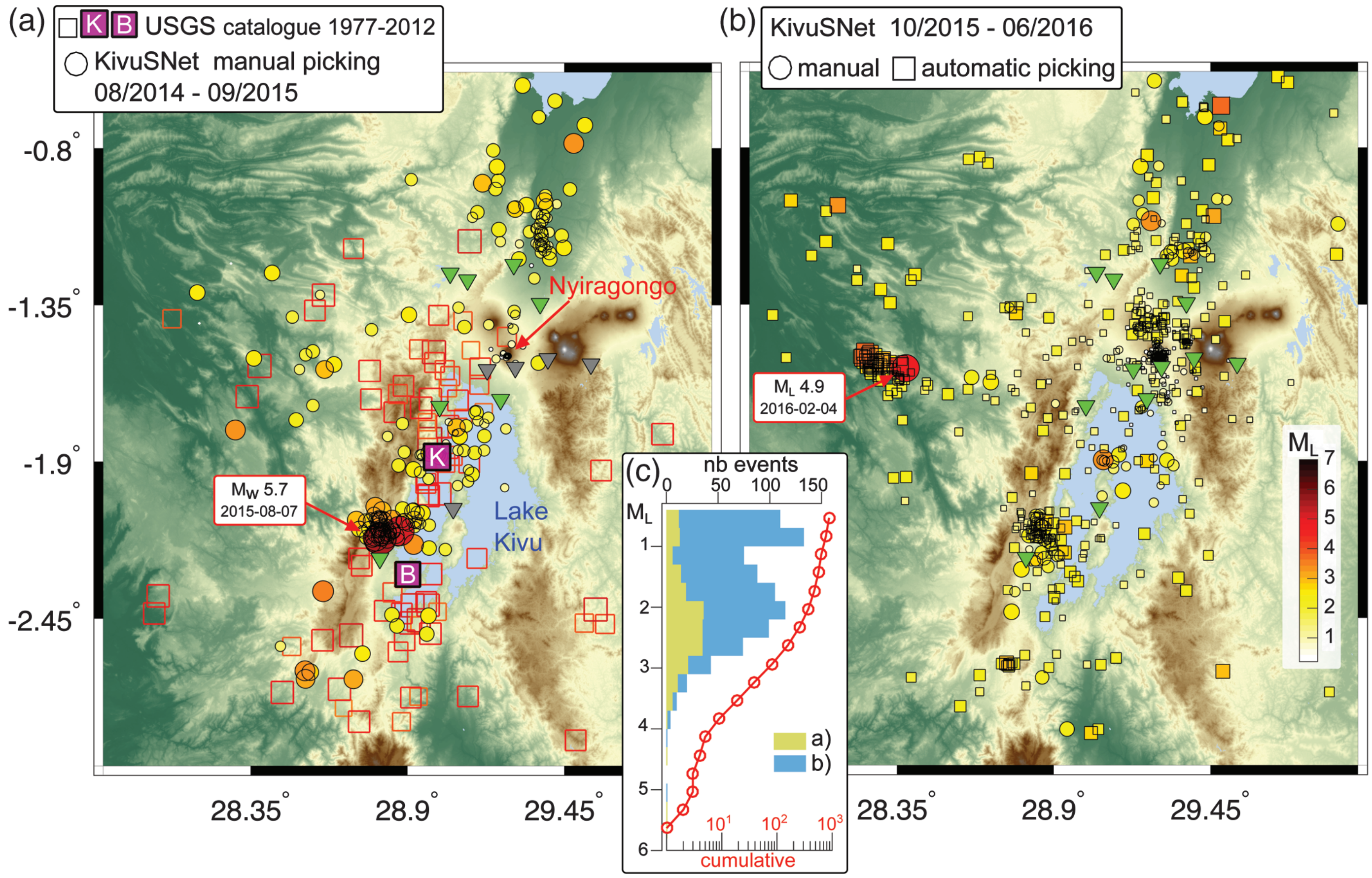
▲ **Figure 4.** Examples for the seismic background noise level using power spectral density (PSD) analysis following McNamara and Buland (2004). The vertical component PSD probability density function estimates for the time period October 2015 – June 2016 are shown. The plots cover the 0.05–100 s period range (respectively 0.01–20 Hz). Note the PSD peak at a period of around 1 s at stations GOM, IDJ, and RGB, as well as the peak at around 0.5–0.8 s at station KTSH. See the Station Performance in Terms of Power Spectral Density section for further details.

horizontal components of the seismic sensor were dysfunctional for a part of the considered time period, which reflects in the narrow high-power band in the PSD PDFs.

Considering the difficulties for station siting and construction outlined above, the stations overall show a good performance level, well suitable for the study of local seismicity and tremor signals.

UNPRECEDENTED INSIGHTS INTO THE KR SEISMICITY PATTERNS

KivuSNet allows for the first time a more detailed look into the seismicity patterns of the KR region. Much of what is known on the KR seismicity stems from instrumental global earth-



▲ **Figure 5.** Seismicity maps for the first two years of KivuSNet operation. (a) U.S. Geological Survey (USGS) catalog events for the 1977–2012 time period and the seismicity detected and located using KivuSNet between August 2014 and September 2015 (212 events have been manually picked and located during this 13-month time period). Active seismic stations during this time period are indicated as green inverted triangles, whereas not-yet-installed stations are shown as gray inverted triangles. The two most significant events prior to KivuSNet deployment are the 2002 M_w 6.2 Kalehe (K) and 2008 M_w 5.9 Bukavu-Cyangugu (B) events. The location of the 2015 M_w 5.7 Katana earthquake and its detected aftershocks is indicated by a red arrow. (b) Seismicity detected and located using KivuSNet from October 2015 to June 2016, which corresponds to the time period since the full development of the current network. 670 events have been automatically detected and located during this 9-month time period, of which 198 were manually repicked and relocated. The location of the 2016 M_L 4.9 Walikale event is indicated by a red arrow. (c) Event count histograms relative to M_L for the two indicated time periods (only KivuSNet results, no USGS catalog data). The red circles and dotted lines represent the cumulative number of events with magnitudes larger or equal to the given M_L value on log scale.

quake catalogs, such as made available by the International Seismological Centre (ISC) or the U.S. Geological Survey (USGS), and the sparse regional recordings and limited historical information available for the area (Delvaux *et al.*, 2016). These catalogs represent by nature a sparse subset of the upper-magnitude seismicity of such an active region. Figure 5a shows 83 events extracted from the USGS catalog (see Data and Resources) from 1977 to 2012, almost all of them with magnitudes well above 4 and dispersed in the region.

During the recent development phase of the KivuSNet network, 882 earthquakes have been reliably detected and located since August 2014 (Fig. 5), part of these manually picked. Automatic detection is carried out using standard short-term average/long-term average analysis in the SEISAN processing system (Havskov and Ottemoller, 1999), and automatic arrival-time picking is accomplished with the routine RTPICK, originally developed for the real-time earthquake detection package RTQUAKE designed for SEISAN (Utheim *et al.*, 2014). RTPICK is based on the algorithm FilterPicker (Lomax *et al.*, 2012), which was used with standard parameters and a minimum number of five stations and phases. Because of the lack of a long-term and dense observation database for the area, only a rough 1D velocity model could be used in this process, stemming from receiver function analysis at two earlier broadband stations that do not exist anymore (Mavonga *et al.*, 2010, see Ⓔ Fig. S3). Using this model, locations have been calculated using the NonLinLoc software (Lomax *et al.*, 2000, see Data and Resources). For the same reason, M_L estimates have been calculated with the default settings of SEISAN, using standard parameters for southern California (Hutton and Boore, 1987).

The presented results should hence be considered as preliminary, and the determination of a more robust local velocity model as well as a region-specific M_L scale calibration are key elements in the coming months of work with the KivuSNet data. All event information including location uncertainties can be found in the QuakeML catalog file available in the Ⓔ electronic supplement to this article.

The USGS catalog data show that larger earthquakes with magnitudes above 5 are reasonably rare in the area, with 24 such events in the USGS catalog since 1977. Most notable were the 2002 Kalehe (M_w 6.2, Wauthier *et al.*, 2015) and the 2008 Bukavu-Cyangugu (M_w 5.9, d'Oreye *et al.*, 2011) events (Fig. 5a), the latter causing 37 fatalities according to the local authorities in DRC and Rwanda. On 7 August 2015, the M_w 5.7 Katana earthquake occurred just a few kilometers northeast of station LWI (Geirsson *et al.*, unpublished manuscript, 2016; see Data and Resources). This was the first major event in the area that was recorded by KivuSNet (Fig. 5a), although unfortunately stations IDJ, BUTK, SAHA, KBTI, and RSY were not yet installed at that time. Three people were reportedly killed and significant damage occurred in the epicentral area, and the event was followed by an intense aftershock sequence. The vertical-component recordings of this event are shown in Figure 6a, in which the record at station LWI is expectedly clipped.

Most of the tectonic seismicity in the region concentrates in the southwestern part of Lake Kivu around the KR large-offset western border fault (Wood *et al.*, 2015), well coinciding with mapped faults in the area (d'Oreye *et al.*, 2011, and references therein). Some tectonic activity is also visible in the northwestern part of Lake Kivu, north of the VVP at the western border of the rift and further west outside the KR in the area of Walikale, where an M_L 4.9 event was recorded on 2 February 2016 followed by several aftershocks (Fig. 5b).

Figure 5b also provides a glimpse of the intense seismic activity around Nyiragongo and Nyamulagira volcanoes automatically located within the first nine months of complete network operation. Although it may seem from Figure 5b that the activity at Nyiragongo would be more intense than at Nyamulagira, this is not generally the case, and the relative intensity of seismic activity between the two volcanoes is highly variable. The seismicity around Nyamulagira is dominated by long-period (LP) events, which are hard to locate with classical phase picking methods due to the emergent nature of their onsets. A typical example for these events is given in Figure 6b, showing the waveforms of a shallow M_L 1.5 LP event located at Nyamulagira. To properly deal with these events, we are currently in the process of implementing a picking-free, cross-correlation-based location approach that enables us to robustly locate most events with emergent onsets and/or low-signal-to-noise ratio. A detailed description of this work is beyond the scope of this article and will be the subject of a dedicated publication.

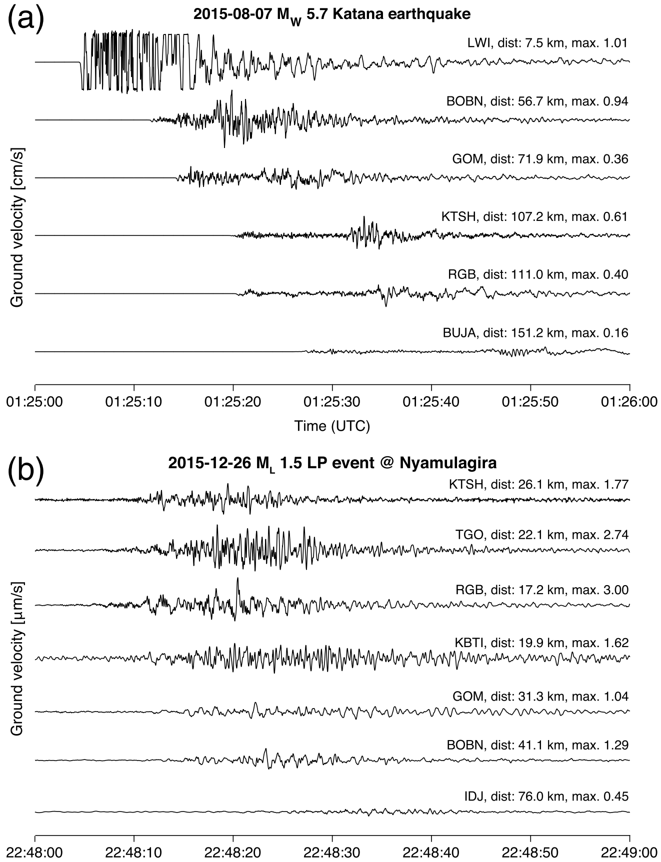
Although it is still too early to go into an in-depth discussion on the details of the event catalog and the magnitude of completeness, events with M_L 1 and partially even lower can be well detected with KivuSNet (Fig. 5c). Even though basic (if not trivial) in many other places worldwide, the seismicity information in Figure 5 is an absolute novelty in this region and proves the potential of KivuSNet both for the scientific study of the KR magmatic system and tectonic activity as well as for an adequate monitoring of the KR volcanoes, which is an issue of prime importance in this densely populated and highly vulnerable region.

POTENTIAL OF KIVUSNET IN THE CONTEXT OF VOLCANO MONITORING

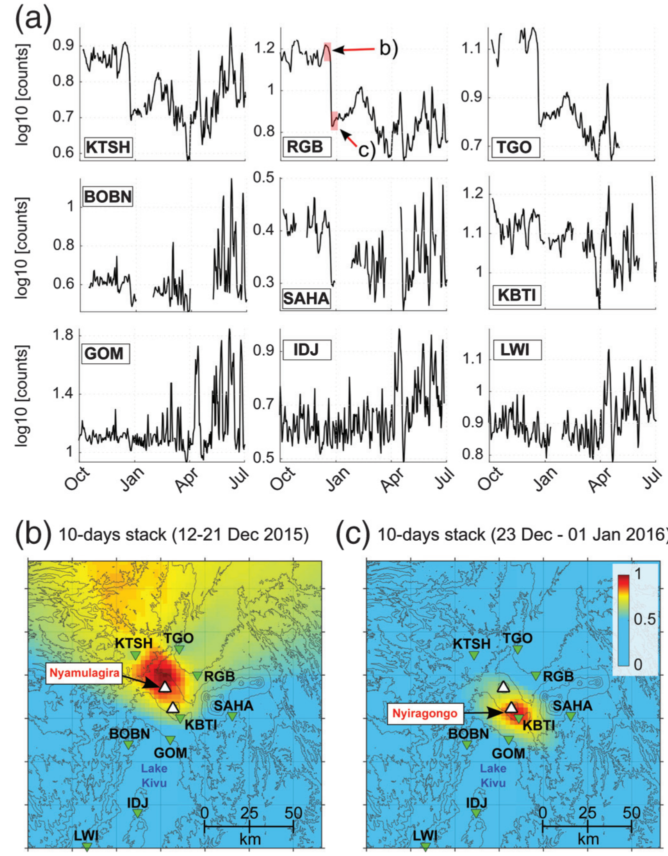
One of the main aspects in the design of KivuSNet is the ability to monitor continuously and in real time the volcano-related seismic activity in the VVP, particularly around Nyamulagira and Nyiragongo. This involves, for instance, the detection and location of long-period (LP), very-long-period (VLP), and volcano-tectonic (VT) events (see for instance Chouet, 2003) as well as the tracking of tremor sources (e.g., Droznin *et al.*, 2015) and analysis of temporal seismic velocity changes (e.g., Brenguier *et al.*, 2008) and their interpretation within the context of the volcanic system. Although ideally one would like to install several stations as close as possible to the edifices and, in particular, between the two volcanoes, this is unfortunately impossible for security reasons as outlined above. Nonetheless, the first results obtained with respect to volcano-related seismicity and tremor monitoring are highly encouraging.

Figure 7a shows the so-called real-time seismic amplitude measurement (RSAM; Endo and Murray, 1991, which is a standard volcano monitoring tool) time series (2-days moving median of 10-min RSAM data), calculated using band-pass filtered data in the 0.5–0.9 Hz frequency band (not raw samples as in the traditional RSAM definition) from October 2015 to June 2016 for 9 stations, 7 of which are distributed around the volcanic field. A sharp drop of the RSAM is immediately visible for stations to the north of the volcanoes (KTSH, TGO, RGB) on 22 December 2015, whereas this drop is much less pronounced (at BOBN, SAHA, KBTI) or not visible at all (at GOM, IDJ, LWI) for stations to the south.

We estimate the daily tremor source location following the approach of Ballmer *et al.* (2013) or equivalently Droznin *et al.* (2015) by calculating daily interstation cross correlations of continuous seismic noise records, so-called noise correlation functions (NCFs), using all available stations of the network (except BUJA, which is too far south; see also Ⓔ Fig. S4). A source scanning algorithm is used to search over a 2D grid of possible source locations, stacking smoothed absolute values of daily NCFs at times corresponding to the expected travel times. Following Droznin *et al.* (2015), the sum of stacked envelope NCFs is called the network response. The most probable source location corresponds to the highest value of the network response, that is, where absolute envelope NCF functions add constructively. Similar to Droznin *et al.* (2015), the best-fitting power-law travel-time–distance model used for these locations ($t = 1.3d^{0.75}$) has been determined using a 2 months stack of NCFs corresponding to a robust continuous tremor source at the Nyiragongo volcano (Ⓔ Fig. S4). Figure 7b shows a 10-day



▲ **Figure 6.** Examples of velocity recordings (vertical component) by KivuSNet. (a) Records of the 2015 M_W 5.7 Katana earthquake at six stations. Note the clipped records at station LWI in the immediate vicinity of the epicenter. Maximum ground velocity amplitudes are indicated in centimeters per second. (b) Same as (a) for a shallow M_L 1.5 long-period volcanic event at Nyamulagira volcano, with maximum amplitudes indicated in micrometers per second.



▲ **Figure 7.** (a) Filtered real-time seismic amplitude measurement (RSAM) timelines from October 2015 to June 2016 for nine stations of KivuSNet (2 days moving median of 10 min RSAM data, frequency band 0.5–0.9 Hz). Note the significant drop on 22 December 2015 most strongly visible at the stations north of the volcanic field (KTSH, TGO, and RGB). (b) Ten day stack of daily tremor location (see text) estimates for 12–21 December 2015 [indicated in panel (a)] and (c) same for 23 December 2015 to 1 January 2016 (indicated in a). Color coding shows normalized network responses (Droznin *et al.*, 2015), with red colors indicating the most probable source region, and the volcanoes Nyamulagira and Nyiragongo are indicated as white triangles. Note the shift in tremor location between (b) and (c).

stack of the outcome of this tremor source location algorithm for the time period 12–21 December 2015, whereas Figure 7c shows the same for 23 December 2015 to 1 January 2016. Comparing these, it becomes evident that during the RSAM drop, the dominant tremor source shifted location from northwest of Nyamulagira to southeast of the Nyiragongo volcano, showing that a significant and rapid change must have occurred within the magmatic system. An in-depth discussion of these observations is however beyond the scope of this article and is the subject of a dedicated study.

CONCLUDING REMARKS AND PERSPECTIVES

This article introduced a new broadband seismic network for the KR region in central Africa, KivuSNet, which is the first dense high-quality broadband seismic network ever operated in this high-risk area. Although network layout and site selection are strongly driven by security considerations and thus require significant compromises with respect to acceptable data quality, the seismic noise analysis and first results are highly encouraging, showing that KivuSNet is a network with great potential, both from a scientific and operational monitoring perspective.

KivuSNet will help to address a long list of scientific needs in the KR region, starting with elementary seismological knowledge as appropriate 1D velocity models and local-magnitude scale calibration, the generation of tectonic and volcano-related seismicity catalogs and event classification required for robust hazard assessment, as well as day-to-day monitoring of volcanic tremor sources and the improvement of the understanding of the internal dynamics of this unique magmatic system. Little is known thus far on the interaction of Nyiragongo and Nyamulagira and their potential for eruption triggering through tectonic earthquakes in the region.

We will continue to gradually improve the KivuSNet network infrastructure together with the local partners and authorities as funding allows, starting with the installation of GVO's recently acquired broadband stations in the second half of 2016, aiming to fill, among others, the large remaining azimuthal gap on the western side. Even though events of magnitude 5 or greater are rare in the KR region, the deadly 2015 M_w 5.7 Katana earthquake shows that complementing some of the KivuSNet stations with accelerometric sensors would be beneficial.

DATA AND RESOURCES

All data used in this article have been collected by KivuSNet (Oth *et al.*, 2013) broadband seismic stations installed in the framework of the several research and infrastructure projects. Station Bobandana (BOBN) has been installed in the framework of AfricaArray (www.africaarray.psu.edu, last accessed November 2016), with instruments funded through AfricaArray and installation support from the Belgian Ministry of Foreign Affairs. A recent datalogger upgrade at BOBN has been carried out with financial support from the Council of Europe Major Hazards Agreement (EUR-OPA) and European Center for Geodynamics and Seismology (ECGS). Station Luboga (LBGA) has been acquired and installed by Goma Volcano Observatory (GVO) with support from the Luxembourgian partners using the Democratic Republic of the Congo government funding. The remaining stations have been acquired and installed with funding from the Direction générale Coopération au développement et Aide humanitaire of Belgium (DGD) (project RGL-GeoRisk); Lotto Belgium; the Belgian Science Policy (Belspo) and the Fonds National de la Recherche (FNR), Luxembourg (project Remote Sensing and *In Situ* Detection and Tracking of Geohazards [RESIST], http://resist.africamuseum.be, last accessed November 2016); and internal funds of the ECGS, Luxembourg, National Museum for Natural History (Mnhn, Luxembourg), and Royal Museum for Central Africa (RMCA, Belgium). As part of AfricaArray, the data from station BOBN are freely available from Incorporated Research Institutions for Seismology (IRIS) with a time delay of three years. All other KivuSNet data are underlying an embargo policy following the conditions of the Memoranda of Understanding between the partner institutions of RESIST. The seismic data acquired during RESIST (2014–2018) will be opened five years following the end of the RESIST project. Data acquired after the end of RESIST will be opened with a time delay of three years. Beyond this embargo policy, data may be shared for collaboration purposes upon request with the approval of all RESIST partners. Data archiving and accessibility will be ensured through the GEOFON program of the GFZ German Research Centre for Geosciences, and KivuSNet is registered within the International Federation of Digital Seismological Networks (FDSN) with network code KV (http://www.fdsn.org/networks/detail/KV/, last accessed November 2016). SeisComP3 software is available at www.seiscomp3.org (last accessed November 2016). U.S. Geological Survey catalog is available at http://earthquake.usgs.gov/earthquakes/ (last accessed November 2016). NonLinLoc software is available at http://alomax.free.fr/nlloc/ (last accessed November 2016). The unpublished manuscript by H. Geirsson, N. d'Oreye, N. Mashagiro, M. Syauswa, G. Celli, B. Kadufu, B. Smets, and F. Kervyn (2016), "Volcano-tectonic deformation in the Kivu Region, Central Africa: Results from six years of continuous GNSS observations of the Kivu Geodetic Network (KivuGNet)," submitted to *Journal of African Earth Sciences, AVCoR Special Issue*.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the funding from the institutions mentioned in the Data and Resources. This article is a contribution in the framework of the projects Remote Sensing and *In Situ* Detection and Tracking of Geohazards (RESIST), funded by the Belgian Science Policy (Belspo), Belgium, and the Fonds National de la Recherche (FNR), Luxembourg, and Geo-risk in Central Africa: integrating multi-hazards and vulnerability to support risk management (GeoRisCA), funded Belspo. Damien Delvaux and Halldor Geirsson provided installation assistance during field work in 2015. We also wish to thank the Congolese Institute for Nature Preservation (ICCN) and the MONUSCO for their continuous support and allowing us to host the stations in their compounds, as well as the entire Goma Volcano Observatory (GVO) teams and the sentinels of the stations, without whom the operation of this network would be impossible. The Centre de Recherche en Sciences Naturelles (CRSN) is gratefully acknowledged for managing the stations LWI and IDJ, the Rwanda Natural Resources Authority (RNRA) for the management of stations BTK and SAR, and the University of Burundi ensures the constant maintenance of station BUJA in Bujumbura.

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Published Online 7 December 2016

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