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Recent seismicity on the Kerguelen Islands

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Abstract The Kerguelen Archipelago, one of the largest oceanic archipelagos in the world, was built by an active hotspot interacting with a ridge between 110 and 40 million years ago; since then, the ridge has migrated over 1000 km away and the archipelago's volcanic activity has been steadily decreasing. Despite the lack of recent active tectonics and the quiescent volcanism of the Kerguelen Islands, there have been several observations of seismic events of unknown origin in its vicinity. The only seismic instrument within 1000 km of the archipelago was installed on Kerguelen's main island in the 1980s. In this study we apply an AI-assisted P- and S- arrival detection algorithm to the continuous waveforms recorded by this seismometer over the past 20 years. We reveal that the Kerguelen main island hosts abundant seismicity. This seismicity exhibits swarm-like characteristics in several clustered locations while at other places the earthquakes appear more steady over time. We locate most events near the largest ice cap of the main island. We propose that the origin of the earthquakes can be linked to residual volcanic, magmatic, or hydrothermal activity at depth, all of which can be favored by flexural stress caused by the documented fast retreat of the ice cap. This seismicity may also indicate that the Kerguelen hotspot shows signs of unrest.

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Non-technical summary The seismicity around the Kerguelen Islands (Indian Ocean) remains poorly known. This is mainly due to the low density of seismological stations in the area around the island. In this study we analyze the continuous seismological signal, recorded by the only seismological station that is in operation on the island. Using an artificial intelligence algorithm we identify numerous earthquakes that we locate on the main island of Kerguelen or in its immediate vicinity. This abundant seismic activity is present during the whole duration of the study (20 years) and thus suggests a remnant magmatic activity on the island possibly favored by the melting ice cap.

1 Introduction

The Kerguelen Archipelago, located in the oceanic domain of the Antarctic plate (Indian Ocean ; 49°S, 69°E; see Figure 1), represents the northernmost, sub-aerial part of the Kerguelen plateau and is the third largest oceanic archipelago after Iceland and Hawaii (Giret, 1990). It has a unique geological history: first a strong ridge-hotspot interaction built the Kerguelen oceanic plateau (110-90Ma), then a change in spreading rate of the Southeast Indian Ridge caused the Kerguelen and Broken-Ridge Plateaus to rift apart ($\sim$ 45Ma), building the northern plateau (e.g. Coffin et al., 2002). Today, the Kerguelen Islands are located over 1000 km away from the closest tectonic plate boundary, the southeast Indian Ridge (Figure 1). They have experienced slowly decaying volcanic activity from 40 Ma to the present, with the last eruptions occurring a few thousand years ago (Gagnevin et al., 2003).

Despite the distance of the Kerguelen Islands from active tectonic plate boundaries and their quiescent volcanism, there have been several observations of seismic events in their vicinity. The largest recorded earthquake occurred in 1973 (Okal, 1981, 1983; Wiens and Stein, 1984; Adams and Zhang, 1984; Bergman et al., 1984): it had a primarily normal faulting mechanism, was located quite far from the Kerguelen Islands themselves, and was attributed to thermal and bending stresses associated with an asthenospheric channel (Okal, 1983; Bergman et al., 1984). Since the 1980s, there have been no further studies of the seismicity of the Kerguelen region in the international literature. The International Seismological Commission (ISC) catalog shows a handful of earthquakes with locations close to Kerguelen (Table 1), all recorded since the French global seismic network Geoscope (Institut de physique du globe de Paris (IPGP) and École et Observatoire des Sciences de la Terre de Strasbourg (EOST), 1982) installed broad-band seismic stations on Kerguelen (in 1983), Crozet (in 1986), Amsterdam (in 1994), and Petrel Island in east Antarctica (in 1986). Each of these stations, including the one installed at Port aux Français (PAF) on Kerguelen, records local earthquakes of magnitude lower than 4.0 that remain undetected by the others, or by any other station world-wide. The recent seismicity visible on the island includes some episodes of elevated activity in 2014 and 2017. In particular, a M4.7 earthquake on 6 October 2017 produced surface deformation that was captured by InSAR (Raphael Grandin, personal communication).

The origin of the seismicity of the northern Kergue-

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len plateau remains largely unknown. The seismicity of the Antarctic plate is generally low and spots of elevated activity might indicate the presence of a specific underlying tectonic structure (Reading, 2007). For example, in Antarctica, denser station coverage has unveiled intraplate tectonic earthquakes linked to a rift zone (Lough et al., 2018). However, no such tectonic feature is visible on the Kerguelen Islands. Seismicity can also occur in diffuse plate-boundary zones, as seen elsewhere in the Antarctic plate (for example the 1998 M_w8 Balleny islands earthquake Antonioli et al. (2002)). However, there is no evidence that a zone like this exists in the Kerguelen region. Most of the Antarctic intraplate activity is confined to coastal regions of the continent and seems to be caused by crustal uplift due to glacial unloading (Reading, 2006). A similar uplifting mechanism operates in Fennoscandia and has been linked to the occurrence of earthquakes (Steffen and Wu, 2011). However, the Kerguelen Archipelago is distant nearly 2000 km from the Antarctic continent, and the surrounding southern Indian Ocean has a very low seismicity. It is unlikely, therefore, that the Kerguelen seismicity is linked with the glacial unloading of Antarctica (Reading, 2007).

Another hypothesis involves remnant volcanic hotspot activity. Volcanic activity linked to the Kerguelen hotspot took place mainly between 122 Ma and 90 Ma (Jiang et al., 2020). As the Kerguelen Islands drifted southwards and progressively disconnected from the hotspot, the erupted volume decreased (Jiang et al., 2020). Recent volcanic activity has been documented within the Kerguelen Plateau, in particular on Heard and McDonald Islands, about 400 km from the Kerguelen Islands (Stephenson et al., 2005). The last major eruptive event on the Kerguelen Islands occurred 26±3 thousand years ago (Gagnevin et al., 2003), but some volcanic activity still seems to continue. An airborne thermal survey of the eastern part of the main island (Grande Terre) found evidence of fumaroles and hot water springs located near the limits of the island's ice cap, suggesting a deep heat reservoir (Ballestracci and Nougier, 1984). It seems possible, therefore, that some of the recorded earthquakes could be related to a circulation of hydro-thermal fluid or magma at depth.

Before being able to address the question of why earthquakes occur on the Kerguelen Islands, we need a more detailed picture of this seismicity and of its evolution. To obtain this, we analysed all available continuous waveform data recorded by the seismometer installed at Port aux Français (PAF), detected several thousand local and near-regional earthquakes, and located them using single-station methods. We describe our findings in this paper.

2 Data and Methods

Given the remoteness of the Kerguelen main island, most of its local earthquakes are recorded by a single seismic station: PAF (Port aux Français, Geoscope global seismological network), which is equipped with a Streckheisen STS-1 seismometer. The station started operating in 1983 and has produced continuous, 20 sample-per-second data streams since 1999. For this study, we used the three-component waveforms recorded at PAF between 7 January 1999 and 31 December 2021 (over 20 years of continuous data). The station stopped working completely between 2013/03/11 and 2013/09/16, during which time the original STS-1 electronics were upgraded to their Metrozet E300 successors. The East component STS-1 sensor malfunctioned during several months in 2017. Fortunately, a short period Mark-L4C sensor installed a few meters from the STS-1 instruments was operating during the 2017 malfunction, so we substituted waveforms from the L4C instrument in our analysis for that time period.

To identify earthquakes and automatically pick P and S-wave arrival times, we cut the continuous three-component data-streams into 24-hour windows and processed them using the EQTransformer algorithm of Mousavi et al. (2020). This algorithm relies on a deep neural-network architecture both for earthquake identification and phase picking and has been trained on a worldwide database of local to regional waveforms. We kept the detection level threshold probability and the P and S picking probabilities at their default values, i.e. 0.3, 0.1, and 0.1. The EQTransformer algorithm identified 6826 P-wave picks and 6864 S-wave picks in our data-set. As we were only interested in seismicity local to Kerguelen and required both a P and an S pick to locate the earthquakes, we retained only those events whose S pick followed its P-wave pick by less than 20s; this led to the identification of 6591 events.

We estimated the locations of these events from our single-station three-component data by combining epicentral (source-station) distances obtained from S-P travel-time differences with back-azimuths obtained from the direction of horizontal polarization of the P-wave arrival. We estimated the epicentral distances by matching the observed S-P travel-time differences with those computed in a 1D velocity model. Past geophysical campaigns in the region had found that the crust in the central region of the main island is thicker than normal oceanic crust (16-20 km) and that the crust-mantle boundary exhibits a 2-3 km thick transition zone (Recq et al., 1990, 1994; Charvis et al., 1995). This depth of the Moho is compatible with the value of 24 km inferred from receiver function analysis at PAF (Kumar et al., 2007). We adopted the 1D P-wave velocity model of the area proposed by Gregoire et al. (2001) based on a compilation of seismic measurements (Table 2). As we have no information regarding the V_P/V_S ratio below the main island, we decided to use the location of the 2017, M4.7 of October 6th as a reference. We performed various locations changing the V_P/V_S ratio and each time computing the distance between our location of this M4.7 event and the location of its associated surface rupture. The minimum distance of 9.5 km between the two locations is obtained for a V_P/V_S ratio of 1.85 and we retained this value for our analysis.

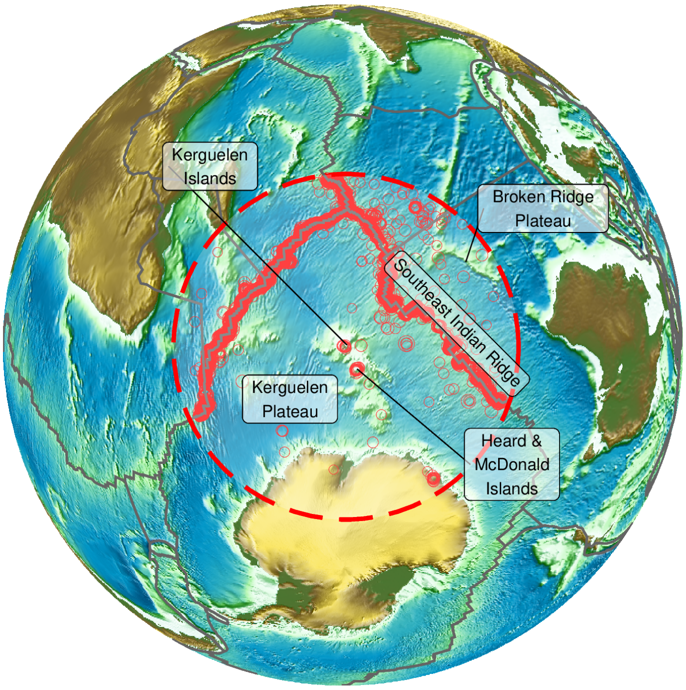

Figure 1 Regional map with the locations of the Kerguelen Islands and relevant bathymetric/topographic features. Tectonic plate boundaries are displayed as thick gray lines DeMets et al. (2010). All earthquakes within the NEIC, USGS catalog within a 30 degrees radius from the main Kerguelen island are shown as red circles.

Date	Time	Latitude (°S)	Longitude (°E)	Depth (km)	Magnitude	Source
1973-03-20	18:13:25	57.82	83.59	33	5.2	ISC
1973-05-03	23:11:06	46.14	73.22	18	5.9 (Mw)	ISC
1974-09-21		46.15	53.63	33	-	ISC
1980-04-24	23:44:41	48.78	69.24	10	4.6	ISC
1980-04-25	01:54:21	48.72	69.17	10	4.7	ISC
1980-04-25	15:50:06	48.56	69.47	10	4.9	ISC
1981-04-06		57.99	82.50	0	4.7	ISC
2007-07-28	15:32:50	49.16	68.92	4	5.3	ISC
2014-03-12	17:54:03	49.30	69.62	19	4.5	NEIC
2014-03-12	18:15:11	49.32	69.55	20	4.9	NEIC
2014-03-15	14:00:13	49.17	69.51	10	4.3	NEIC
2014-03-15	14:20:59	49.35	69.45	10	4.6	NEIC
2014-03-15	14:57:01	49.22	69.57	16	4.7	NEIC
2014-03-15	15:42:47	49.40	69.58	10	4.3	NEIC
2014-03-15	15:48:08	48.97	69.69	10	4.4	NEIC
2014-03-21	04:39:24	49.66	69.73	10	4.7	NEIC
2015-06-10	03:12:29	49.33	69.75	10	4.7	NEIC
2017-10-06	18:43:44	49.22	68.949	14	4.7	NEIC
2017-10-15	22:21:31	49.104	68.991	15	4.6	NEIC

Table 1 Seismicity of the northern Kerguelen plateau available from global catalogs. Earthquakes from 1973 to 1981 were discussed by Adams and Zhang (1984); the two earthquakes in 1973 were also discussed by Okal (1981). Magnitude are mb (body-wave magnitudes) unless otherwise indicated.

Depth (km)	V_P (km/s)
0.0	3.8
1.0	4.8
10.0	7.0
18.0	7.5
20.0	8.0

Table 2 P-wave velocity model used for locating earthquakes, derived from (Gregoire et al., 2001).

We computed S-P travel-time differences as a function of distance for the P-wave velocity model in Table 2 and this V_P/V_S ratio using the code from Heimann et al. (2017). We allowed the earthquake depths to range from 1 to 20 km depth, then averaged the S-P travel-time distances over the entire depth range. We inferred the epicentral distances by matching these average values as a function of distance to the recorded S-P travel-time differences.

We estimated the back-azimuths using the method proposed by Roberts et al. (1989): we applied a high-pass filter above 2 Hz, isolated the P-wave pulses within a 1 s window starting 0.15 s before the P-wave picks, then computed the back-azimuths, ϕ, as

$$\phi = \arctan\left(\frac{-\langle y_e y_z \rangle}{-\langle y_n y_z \rangle}\right), \quad (1)$$

where y_e, y_z, and y_n are respectively the east, vertical and north component of the P-wave pulse. We also computed the uncertainty on the value of ϕ using equation (11) of Roberts et al. (1989). We found a mean azimuthal uncertainty in our locations of about 9°. A further source of location uncertainty, touching both distance and azimuth estimates, can arise from the use of an incorrect or over-simplified seismic velocity model (we used a 1D velocity model but the wave-speed under this volcanic island archipelago is likely to vary in 3D).

We kept only those events for which the joint probability of the P and S phase picks was higher than 0.1 and whose azimuth uncertainty was below 40°. This led to a final selection of 4507 events. For each earthquake, we estimated a local magnitude following the original Richter approach (Richter, 1935). This magnitude estimate, computed at a single site, is subject to large uncertainties, and should be interpreted as a relative magnitude among the recorded events of each cluster rather than an absolute magnitude.

3 Results

We located numerous signals originating very close to the seismic station, in the direction of the permanent scientific base-camp. Due to their location, we supposed them to be anthropogenic, and we discarded all signals located at epicentral distances less than 5 km. This left us with 3158 non-anthropogenic events.

The locations of these earthquakes, shown in Figure 2, indicate that they are not evenly distributed around the main island but form diffuse clumps and streaks at different distances from the Port aux Français station. To investigate the temporal distribution of earthquakes in each seismically active region, we grouped earthquakes into clusters based on their spatial distribution. We grouped events with similar locations first visually, then using a simple clustering algorithm. For the clustering step, we used the density-based spatial clustering DBSCAN (Ester et al., 1996). We used a 2 dimensional metric for clustering events based on the S-P time and azimuth (See Text S1). The algorithm identified 4 clusters comprising at least 90 earthquakes each, shown in colour in Figure 2. The clusters span 4 bands of epicentral distances that thicken as a function of distance from the Port aux Français station. We show in Figure 3 the magnitude of the earthquakes in each cluster as a function of their occurrence times.

The farthest cluster from the station, clusters 1, is located on the west of the island and contain 1404 events. It is the more populous cluster and is located 10 to 20 km north-north-west of the Cook ice cap. The earthquakes in this cluster occurred almost continuously over the past 20 years, with periods of increased activity in 2007 and 2017. Cluster 2 (east of the ice cap) contains 459 earthquakes, most of which occurred during a seismic sequence in March 2014. The two remaining clusters, clusters 3 and 4, are located southwest of Port aux Français, at distances of 20 and 40 km. The timing of earthquakes in these two clusters indicates that cluster 3 (the closer one) first appeared in 2007, and has since been activated in several short bursts. Cluster 4 (the farther one) was active at the end of 2011 and has since become nearly quiescent.

Also shown as purple circles on Figure 2 are 1007 events that do not belong to the 4 main identified clusters and are distributed evenly over the entire region; these may be mislocated because of low signal-to-noise ratio around the P-wave arrival time or may represent true diffuse seismicity.

4 Discussion

We have produced the first catalog of seismicity of the Kerguelen Islands covering a period of over 20 years (1999-2021). We have found clusters of events on either side of the Cook ice cap in the west of the island and others in the south-east of the island. All clusters lie on concentric circles around the seismic station PAF; these circles have narrow widths for the clusters close to the station and larger widths for those farther from the station. Such distributions are expected from the uncertainties inherent in single-station location methods.

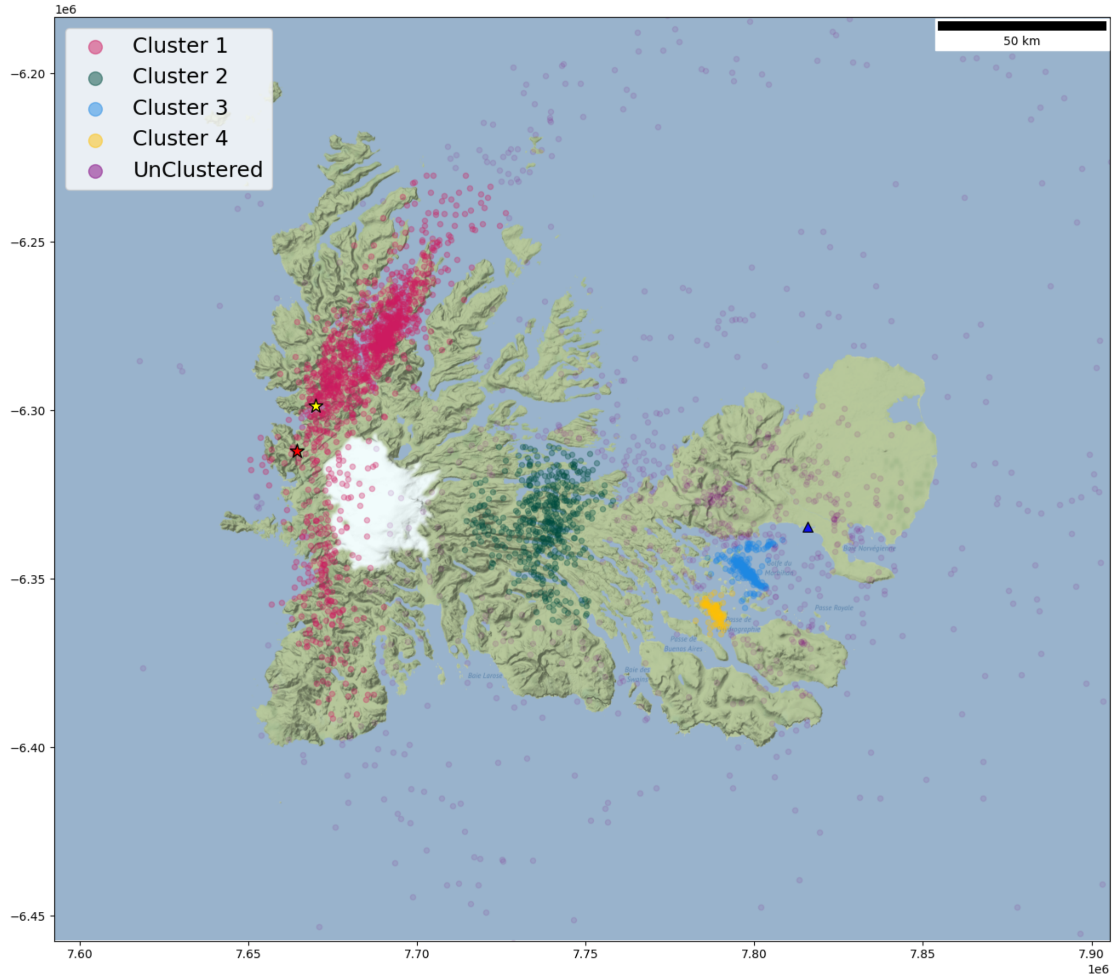

Figure 2 Map of all earthquakes located in this study (circles). Colored circles indicate earthquakes that belong to identified clusters (red: cluster 1, green: cluster 2, blue: cluster 3, yellow: cluster 4); purple circles indicate earthquakes do not belong to a cluster. The yellow star indicates our location of a M4.7 earthquake on October 6th, 2017; the same earthquake produced surface deformation visible from InSar and was located at the position of the red star (Raphael Grandin, personal communication). The blue triangle marks the location of the seismic station used in this study (PAF, Port aux Français). The white area shows the contour of the Cook ice cap.

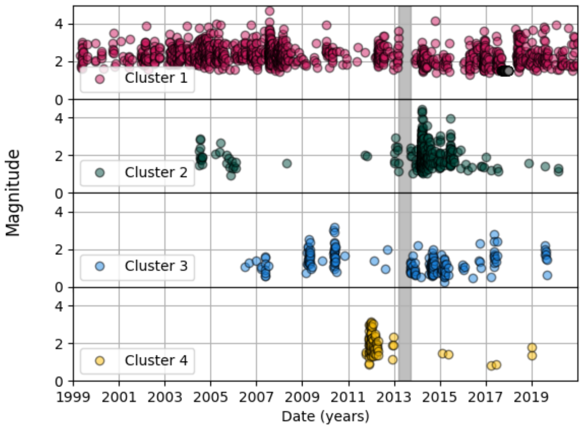

Figure 3 Magnitude of earthquakes as a function of time in each cluster. The color of each circle refers to its cluster. Gray circles indicate events that occurred during the time period in 2017 in which the broadband seismometer at PAF (Port aux Français) stopped functioning (no magnitude are available for these events and all magnitudes were fixed to 1.5). The gray background indicates time period when no instrument was recording.

Inferring the causal mechanism of earthquake clusters is notoriously difficult in regions of little to no tectonic deformation such as the Kerguelen main island. Some clusters are dominated by a single larger event at their onset (e.g. cluster 2) and exhibit a number of smaller events that decay over time in both size and frequency; these behave like mainshock-aftershock sequences whose amplitude and frequency follow Omori's law (Omori, 1895; Utsu et al., 1995), but give no indication of the causal mechanism for the mainshock itself. Other clusters lack a large event and exhibit an increased rate of earthquakes over a short time (e.g. clusters 3 and 4); these behave more like seismic swarms (Zhang and Shearer, 2016). Such swarms may be driven by fluids and are often encountered in volcanic environments or in other regions of the crust where pressurized fluids are present (e.g. De Barros et al., 2019; Duputel et al., 2019), however we lack, at present, geophysical evidence indicating that fluids are present at depth at the locations of these clusters. Another way to investigate if sub-surface mass (fluid) movements caused a particular seismic swarm is to identify signs of migration of the seismicity (Chen et al., 2012), however the uncertainties of our single-station locations are too large for us to perform this investigation. Deployment of a seismic network on the main island will help to constrain the depth and focal mechanisms of these earthquakes and will provide better location accuracy.

Among the possible explanations for the long-lived and nearly continuous seismicity in northwestern Kerguelen (cluster 1), we wish to draw attention to the elastic rebound caused by rapid melting of the Cook ice cap. The glacial wastage that has occurred over the last 60 years on Kerguelen is one of the fastest on Earth (Favier et al., 2016). After a stable period between the 1800s

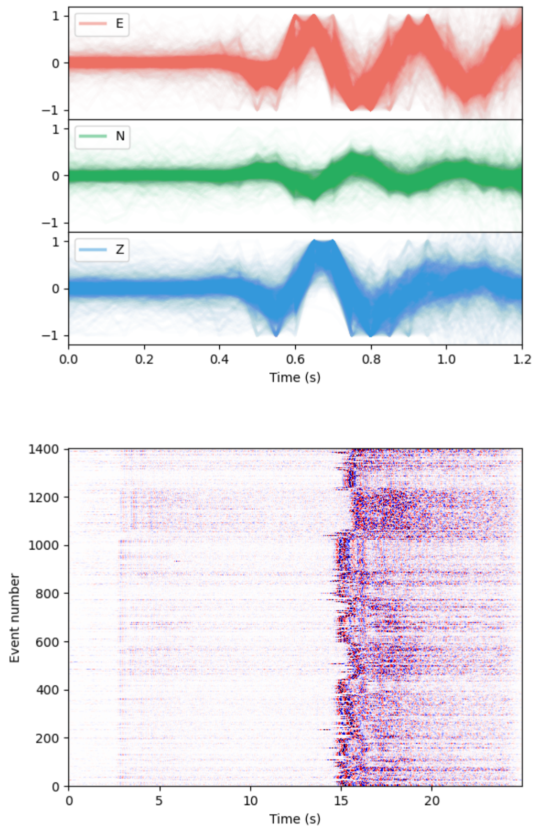

Figure 4 Top: Superposition of seismograms of all events located in cluster 1. The seismograms are windowed around the P-wave arrival on the three components (E: East, N: North and Z: vertical). Bottom: Waveforms recorded on the East component for all seismograms of cluster 1. Events are ordered chronologically and amplitude are normalized for each event. All seismograms have been aligned on the P-wave arrival. We observe that the P-wave pulses are coherent for all events of the cluster and that the S-P time is nearly identical as well.

and the 1960s (Frenot et al., 1993), the Cook ice cap retreated rapidly, losing 20% of its surface area in 40 years (Berthier et al., 2009). During this time, the ice retreat accelerated from 1.9 km^2/year between 1963 and 1991 to 3.6 km^2/year between 1991 and 2003, equivalent to a thinning rate of 1.4-1.7 m/year which is still measured today (Favier et al., 2016). Such rapid ice wastage abruptly reduces the vertical stresses previously imposed by the weight of the ice and causes immediate elastic rebound of the lithosphere, associated with flexural stress, crustal uplift, faulting, and seismicity (e.g. Stein et al., 1989; Stewart et al., 2000). Ice wasting can decrease the pressure on shallow magma reservoirs and increase melting within them, as seems to be occurring in regions of Iceland's rift zone that are subject to glacial unloading (Sigmundsson et al., 2010). Ice retreat also influences stress conditions in shallow magma chambers and hence modifies their failure conditions and promotes dike intrusions (underground mass transfers) that can trigger seismic swarms (Albino et al., 2010).

Although it is unknown if the Kerguelen main island has a shallow magma reservoir that could be influenced in this way by melting of the Cook ice cap, recent observations of crustal deformation indicate ongoing uplift over the western part of the archipelago, possibly linked to elastic rebound (Raphael Grandin, personal communication). We propose that the ice-wasting scenario may explain part if not all of the recent seismicity that surrounds the Cook ice cap, by a combination of flexural stresses, melt generation, and mass transfers at shallow depth.

5 Conclusion

Our analysis of the seismicity of the Kerguelen Islands with a single seismic station, over more than 20 years, revealed that the islands host significant seismic activity. This activity is temporally heterogeneous: in some regions it exhibits swarm-like behavior ; in others, such as the main active zone northwest of the Cook ice cap, it appears continuous over the full time extent of our study. As the Kerguelen Islands are located far from any plate boundary, we tentatively explain their persistent recent seismicity by the combination of flexural stress and the promotion of a magmatic activity, both caused by the unloading resulting from the ice wastage of the Cook ice cap over the recent years. Documenting the depth of these earthquakes, their focal mechanisms and the sign of possible migration would help to refine our understanding of this activity but would require the installation of temporary network close to the active regions.

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Data and code availability

All data from the GEOSCOPE PAF station are available through FDSN webservices on RESIF data center https://seismology.resif.fr/networks/#/G/PAF. All of the data recovery and some processing have been done using the Obspy python package (Krischer et al., 2015). Some figures have been created with the GMT software (Wessel et al., 2013). The catalog of located earthquakes is available on Zenodo (Lengliné et al., 2023).

Competing interests

The authors have no competing interests.

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