Waveforms cross-correlation from Natron-Manyara (Oldoinyo Lengai) array to find repeating earthquakes

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Supervisor: Professor Cynthia J. Ebinger

February, 2024

Declaration

I hereby declare that this thesis is the product of my own work and has not been presented for a degree at the University of Rwanda or any other academic institution. All visited/used sources in this research have been cited.

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Date: August 16, 2024

Certification

This is to certify that the master's dissertation entitled "**Waveforms cross-correlation from Natron-Manyara (Oldoinyo Lengai) array to find repeating earthquakes**" was carried out by Jean Paul HAGUMIMANA in partial fulfillment of the requirement for the Award of MS Degree in Geophysics in University of Rwanda, College of Science and Technology.

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ABSTRACT

In the field of seismology, waveform cross correlation has been known to be a powerful method to find repeating earthquakes and to get insights into their source mechanisms based on the waveform similarities. Oldoinyo Lengai, the only known carbonatite volcano in the world is in the East African Rift, which exhibits complex tectonic and magmatic processes within a geologically active setting. We perform waveform cross-correlation analysis to identify repeating earthquakes to distinguish between faulting, magmatic, and hydrothermal systems in this region. Using seismic data from a network of stations, we apply a correlation coefficient of 0.9 to detect high similarities between waveforms. Our results reveal only a few repeating earthquakes, suggesting that extensional strains accommodated by multiple faults with varying orientations rather than being localized to border fault zones. The presence of non-similar waveforms highlights the complexity of seismic processes, including pressurized magma bodies and hydrothermal activity. While continuous monitoring is essential for mitigating seismic hazards, our findings underscore the need for long-term studies to better characterize the processes leading to repeating earthquakes. Although earthquake prediction remains challenging, long-term monitoring can provide valuable insights into the underlying mechanisms and improve our ability to assess and mitigate seismic risks. Contrary to the statement that events located in the same family have same source mechanisms, we observed different source mechanisms within earthquake families, indicating a heterogeneous tectonic environment with irregular strains. Therefore, combining waveform analysis with other techniques such as focal mechanism plotting can help resolve ambiguities in distinguishing source mechanisms. Overall, this research contributes to a better understanding of seismic activity in the East African Rift and its implications for seismic hazard assessment and mitigation strategies.

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1. Introduction

In the field of seismology, the use of earthquake waveform cross-correlation analysis has played an important an important role not only in distinguishing features of seismic signals recorded at different stations. Highly correlated earthquakes can be grouped into families for further analysis (*Zaliapin et al. 2013, Hardebeck et al. 20023*). Cross-correlation techniques also have been used to improve accuracy of P-arrival picks in earthquakes location (*VanDecar and Crosson, 1990; Shearer, 1997*).

Repeating earthquakes are defined to be seismic events that repeatedly occur at the same or nearby locations and exhibit consistent geometric characteristics with nearly or similar magnitudes or hypocenters (*Uchida et al. 2019, Templeton et al. 2008*). They can be identified by accurately determining their hypocenters, through waveform coherence $coh(w)$,

$$coh(w) = , \sqrt{\frac{!"_{!"}(\$)!^{\#}}{"!!(\$)"^{""}(\$)}} \quad (1)$$

Where $S_{\&'}(w)$ is the cross spectrum between earthquakes x and y calculated from the Fourier transforms of the original waveforms (*Uchida et al. 2019, Schimmel M. 1999*). Alternatively, they can be evaluated by analyzing their waveform similarities by performing waveform cross correlation of data from seismic arrays, or on cross-correlation coefficient, $C(\tau)$,

$$C(\tau) = \frac{1}{N}\sum_{t=1}^{N} f_x(t) f_y(t+\tau) \quad (2)$$

Or

$$C(\tau) = \int_{-\infty}^{+\infty} f_x(t) f_y(t+\tau) dt \quad (3)$$

Where $f_{\&}$ and $f_{'}$ are two times series or seismic signals being compared, N, the discrete samples (for equation 2) and τ, the lag time representing the time delay between the two signals (*Uchida et al. 2019, Gouedard et al. 2008, Schaff et al. 2005*).

Repeating earthquakes are caused by stresses that are repeatedly released at the same location, and they are useful to monitor the temporal changes in subsurface structure, investigating variations in stress levels around volcanoes as well as in earthquakes hazards assessments (*Armeanu et al. 2022, Petersen and Pankow 2023, Rodgers et al. 2015*).

The waveform cross correlation arrays' applications are extended to study of earthquake families given a specific correlation coefficient value (*Hardebeck et al. 2002*), and to detecting and characterizing specific types of seismicity, to assess the first motions of seismic waves which in turn provide details about the origin and characteristics of the source that produces them. Therefore, first motions are useful tools in understanding the kinetics of the earth's material relative to the seismometers (*Stein & Wysession, 2009*).

Oldoinyo Lengai volcano, the only carbonatite volcano in the world, has regular eruptions, and damaging earthquakes (*Oliva et al. 2019*). It formed in the East African Rift, which is under crustal extension (*Ebinger et al. 2011, Plasman et al. 2017*). However, this region is not marked on the global observation of repeating earthquakes as by January 2019, yet some studies prove that repeating seismic events are plentiful in certain active volcanoes as well as landslides areas (*Uchida et al. 2019, Oliva et al. 2019,* https://volcano.si.edu/). The aim of this study is to use waveform cross-correlation arrays, to identify repeating earthquakes to distinguish between faults, magmatic and hydrothermal systems within the Oldoinyo Lengai, Naibor Soito and Gelai (OLNS-G) regions of the Eastern Rift System (ERS) and to develop new tool useful to understand the kinetic of earth's material for our lab and others (Figure 1).

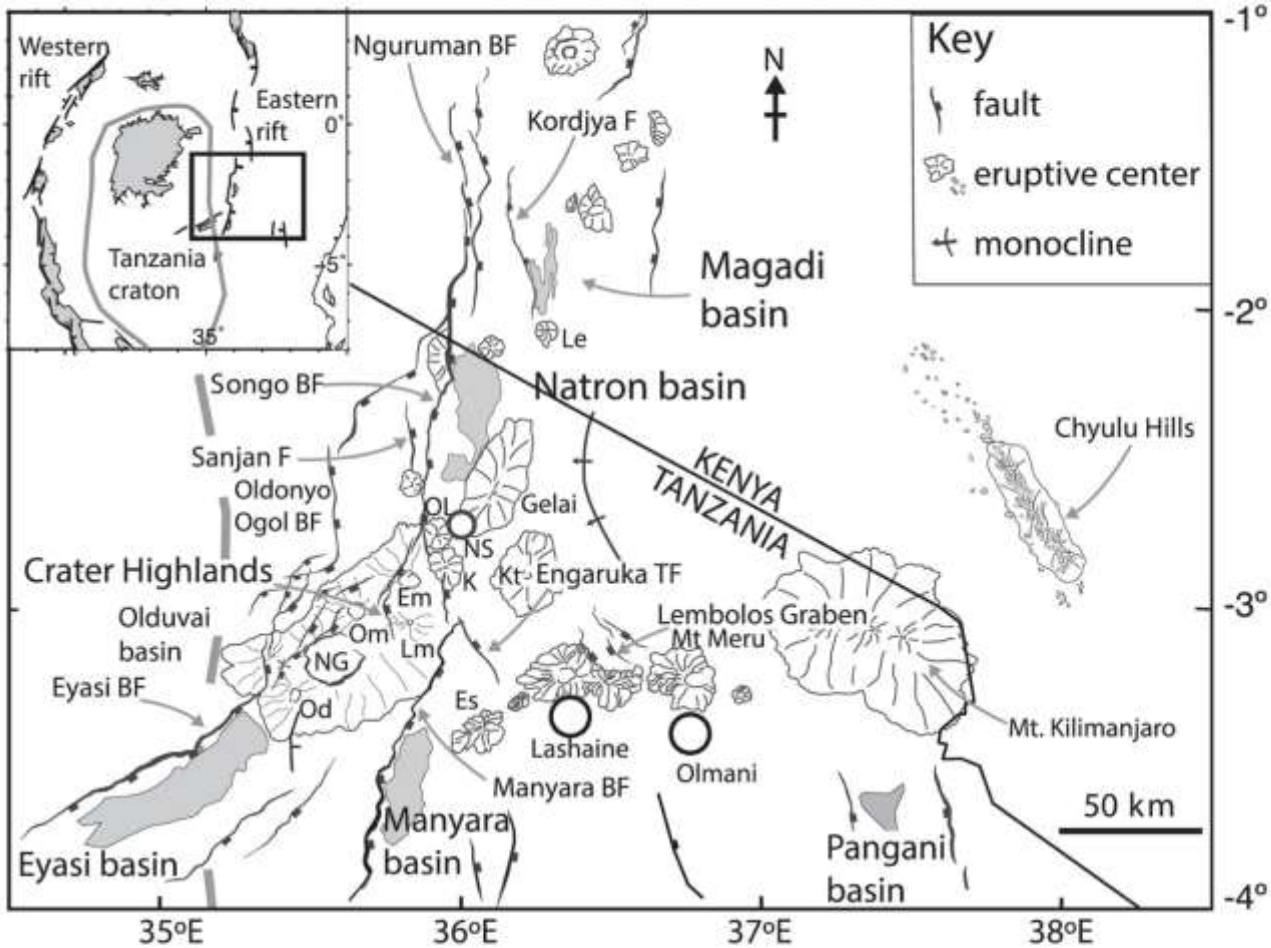

Figure 1. Tectonic setting of Magadi-Natron-Manyara region with OL, the Oldoinyo Lengai and Em, the Embagai volcanoes respectively. NS stands for Naibor Soito (Weintsein et al. 2017).

2. Background

The North Tanzanian Divergence (NTD) in East African Rift, marks the boundary between the Nubian and Somalian plates that are separating at a rate of less than 6mm/year (*Weinstein et al. 2017, Plasman et al. 2017*). This extensional regime is attributed to the presence of a mantle upwelling beneath the EAR, which transfers heat, causing magmatism, and exerts horizontal and vertical forces that drive the lithospheric stretching and thinning (*Ebinger et al. 2012, Weinstein et al. 2017, Rey et al. 2021*). It is a process which *Ebinger et al. 2012* described using a three-stage model. This model, they demonstrated that the continental lithosphere beneath this region initially exhibited heterogeneity, particularly with greater thickness. For the first stage (0-5 My), the stratified lithosphere gradually reduced in thickness due to a combination of brittle and ductile deformation processes. The thinned lithosphere was then replaced by the ascent of the asthenosphere, results in the transfer of heat and induces decompression melting (figure 2A), which in turn lead to brittle crustal deformation through slipping along major boundary border faults with significant offsets. This changes in the thickness of various density layers induces isostatic rebound of the basin and flanks, consequently enhancing asymmetry. In the second stage, lithospheric thinning continued through faulting and ductile deformation, with rising asthenosphere leading to more melting. Strain localization occurred in narrow zones marked by magmatic intrusions into the crust, termed magmatic segments, accommodating strain at lower tectonic stresses than faulting (figure 2B). Finally, the final stage explains that tectonically and magmatically thinned lithosphere will rupture in heavily intruded zones, to form seafloor spreading and creation of new oceanic lithosphere (figure 2C).

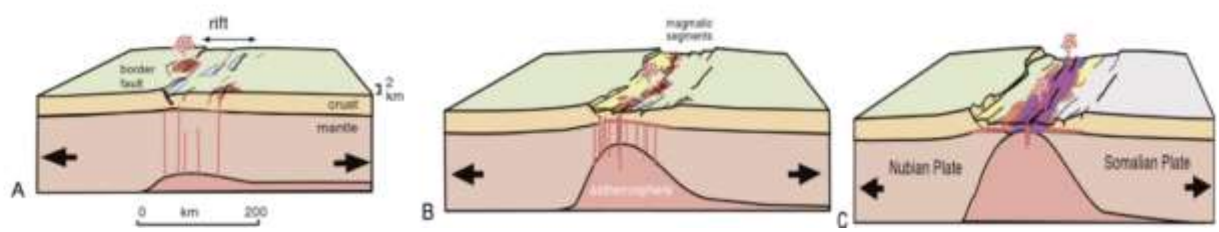

Figure 2. A three-stage model that demonstrated the continental rift process (*Ebinger et al. 2012*).

In relation with the above model, it was found that volcanism in EAR began about < 7Ma in the N-S trending rift zone, formed at the eastern edge of the Archaean craton in the thinner Pan-African lithosphere (*Mana et al. 2023,2014; Foster et al. 1997*), and some recent studies provide information about the crustal and mantle structure beneath Oldoinyo Lengai - Naibor Soito and

Gelai, indicating an asymmetric crustal thinning with depths ranging from 28 to 41 km with a lowvelocity lower crustal layer at depths of 15–18 km (*Plasman et al. 2017, Roecker et al. 2017, Reiss et al. 2022*) and a low-velocity mantle layer at depths of 60–70 km, which suggests potential modifications within the lithosphere possibly due to melt accumulation or deformation processes (*Tiberi et al. 2019*).

This compositional changes within the crust, particularly near volcanic centers, indicates the presence of hot pressurized fluids that migrate from deep magmatic plumbing system (figure 2), leading to higher variations in the Vp/Vs ratio values (1.71 – 1.81) that increase to >1.85 for seismograms closer to volcanic structures (*Plasman et al. 2017, Roecker et al. 2017, Reiss et al. 2022*). Furthermore, the abundance of tectonic earthquakes ($M \leq 4.7$, but commonly small magnitudes intensely located to depths 5-16 km) in the Oldoinyo Lengai-Naibor Soito-Gelai volcanic chain primarily occur along a NE-trending belt between Embagai volcano and Gelai volcano (figure 1), demonstrated active deformation related to extensional tectonic forces, with seismicity occurring on approximately N-S planes and N50–808E planes (*Weinstein et al. 2017*).

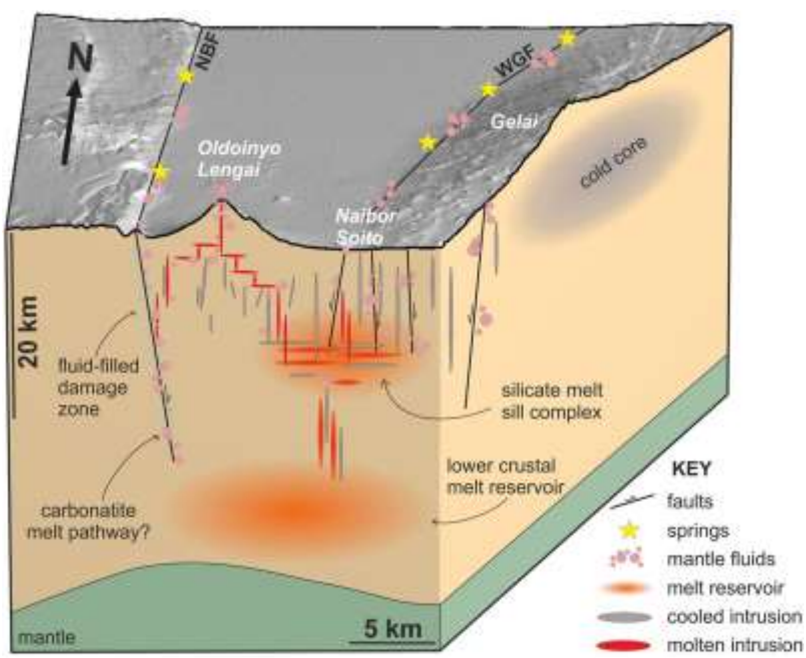

Figure 3. Schematic explanation on how magmatic fluids facilitate not only the development of volcanic centers, including OL and Gelai but also assist seismicity in this region. (*Reiss et al. 2022*).

Additionally, the presence of magmatic intrusions particularly through a pressurized sill complex suggested a significant interplay between tectonic stress, magmatic processes and seismicity highlighting the 2007 dike intrusion beneath the Naibor Soito monogenetic cone complex and the southern flank of Gelai volcano (*Oliva et al. 2019*). While figure 2 schematically explains the continental rift process, Reiss et al. 2022 explained how magmatic fluids ascend within the plate to assist seismic activities in this OL-NS-G region (figure 3).

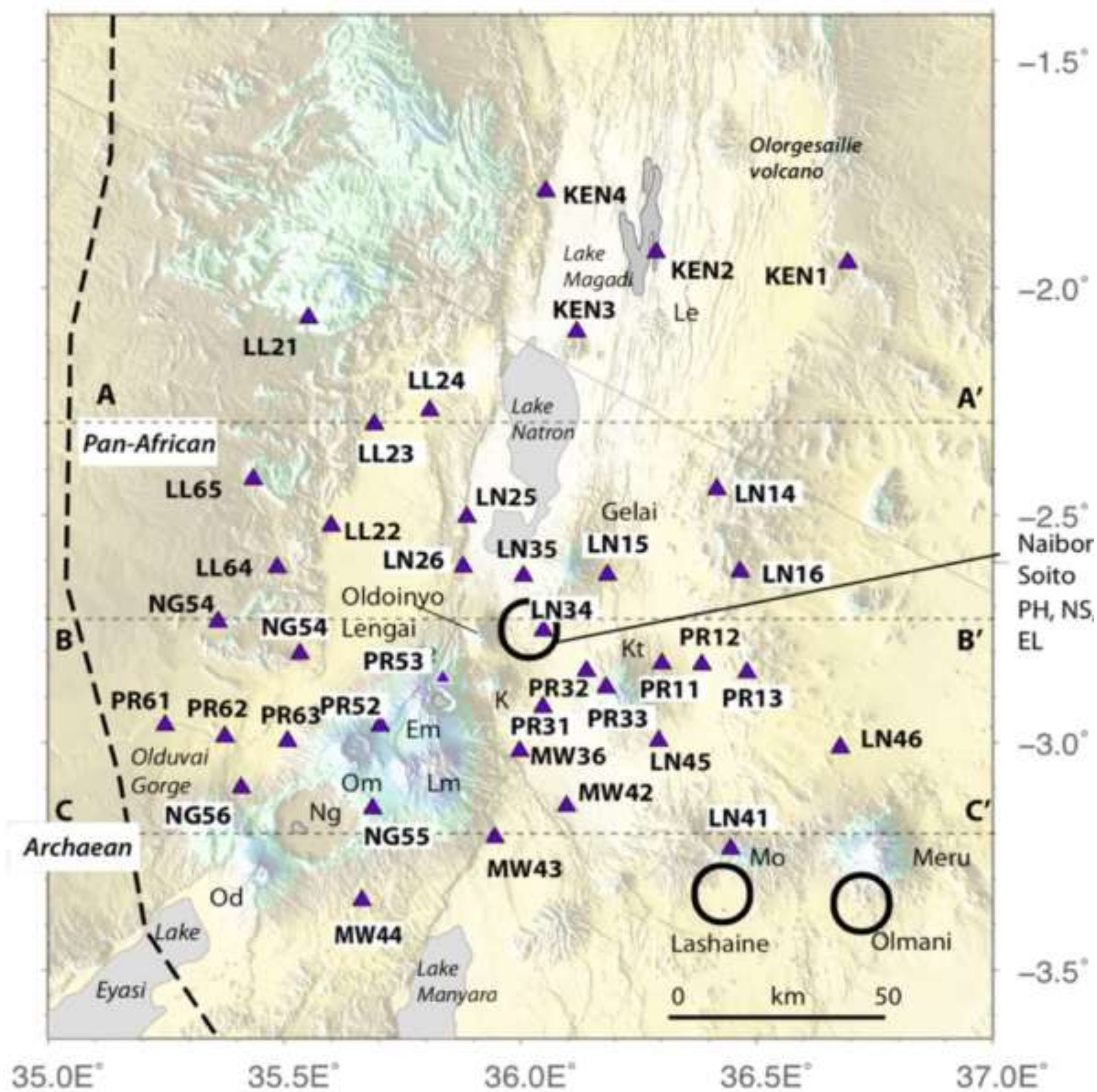

Figure 4. Distribution of CRAFTI-CoLiBrEA seismometers deployed in Magadi-Natron-Manyara region between 13 January 2013 and 8 December 2014. The xenolith localities are shown by black circles *(Weinstein et al. 2017).*

3. Data and methods

In this study, waveforms filtered within frequency range of $1 \quad to \quad 15Hz$ to increase the SNR (Signal to Noise Ratio) of seismic data and improve the detection of the P-waves first arrivals. A time window of $0.3s$ $(-0.15 \quad to \quad 0.15s)$ centered on the P first motions were cross correlated using GISMO, with events pairs exhibiting a correlation coefficient of ≥ 0.9 to find repeating (figure 6) and families (figure 7) of earthquakes respectively. Using GISMO (Generic Information System for Multi-scale Observation) MATLAB toolbox, a tool which was developed mainly by Celso Reyes, and Mike West to be used for processing and analyzing seismic waveform data from arrays (*Thompson et al. 2017, Reyes & West 2011*), we were able to perform waveform cross-correlation, to investigate events that are generated by repetitive sources by identifying seismic waveforms that have higher degree of similarity within an array. Locations from double difference relocations in Weinstein et al. (2017) are used in this report.

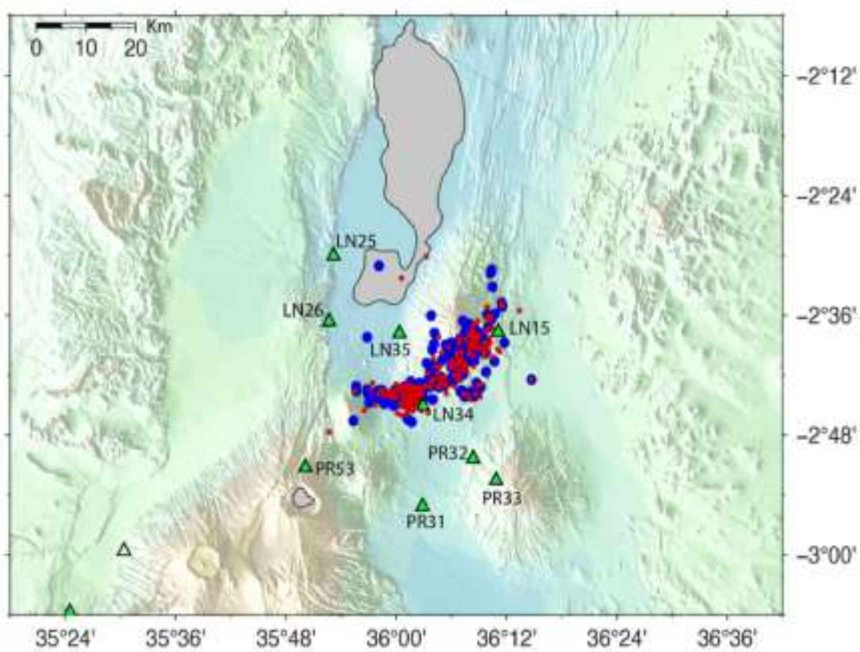

Figure 5. Map showing seismic stations used in the analysis, and locations of all events that are highly correlated with ≥ 90% for two main families (261 events in the first family indicated with a red circle, and 197 events in second one indicated with blue circle). Locations from double difference relocations in Weinstein et al. (2017) are used in this report. Here, we used big blue size

and small red size for spatial clarification of events belonging in each family. Used stations are all named and shown with green triangles in the map.

From the 39 broad-band temporal seismograms which were installed in Magadi-Natron-Manyara region (2013 – 2014) by CRAFTI and CoLiBrEA, enhanced by two permanent stations (KMBO and KIBK) of the GEOFON global seismic network (figure 4, *Plasman et al. 2017*), we selected 9 stations (LN15, LN25, LN26, LN34, LN35, PR53, PR31, PR32 and PR33) encircling the OLNS-Gelai region as for good azimuthal coverage and good proximity to the crustal earthquakes (figure 5), considering only P-phases.

Family 1 Family 2

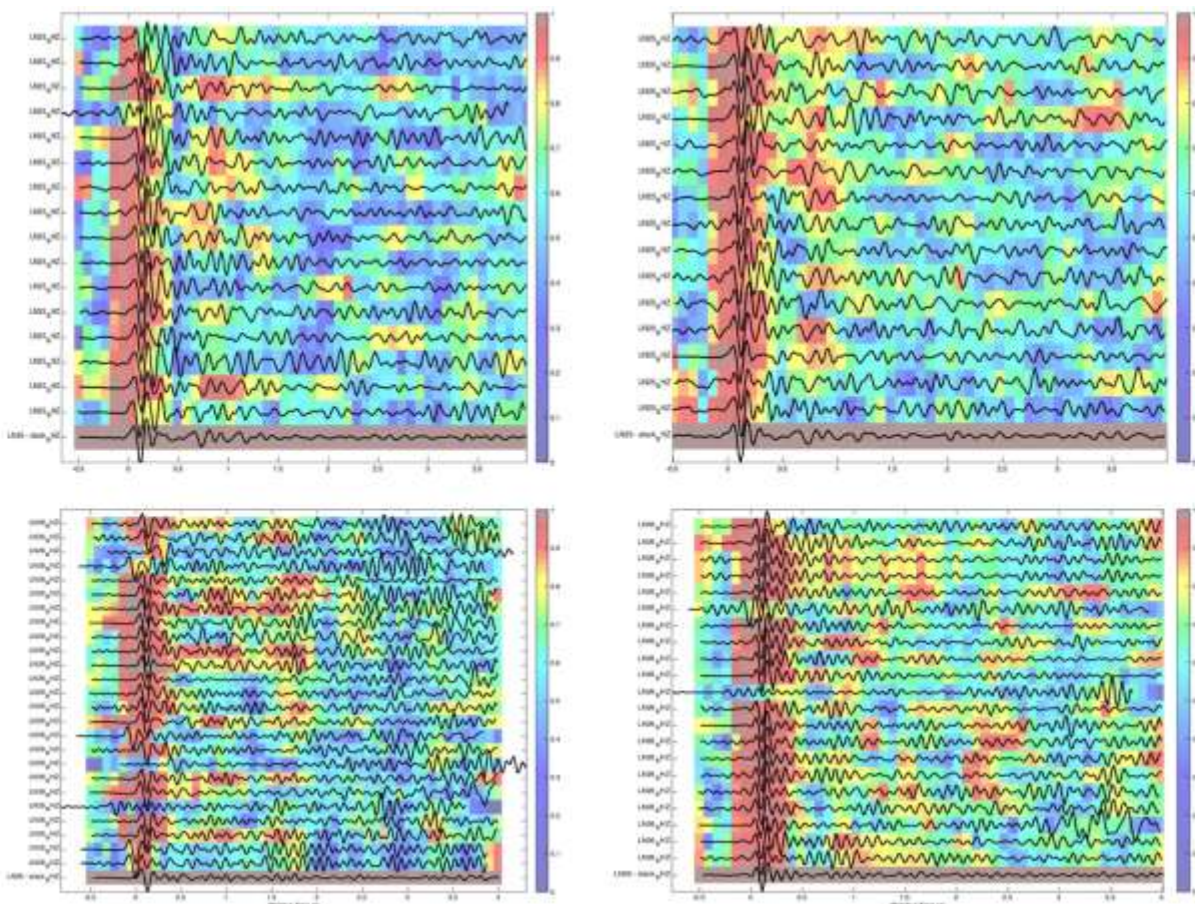

Figure 6. Interferograms for a better visualization of some samples of the few repeating earthquakes obtained from highly cross-correlated P-waveforms of 2 stations LN26 and LN25.

Initially the waveforms obtained from these stations were filtered with a Butterworth bandpass filter ranging from 1 - 15Hz to increase the signal to noise ratio (SNR) of seismic data and improve the detection of P-waves first arrivals (*e.g, Schaff et al. 2005, Bensen et al. 2007*), followed by 4.5 seconds for crop time window which is better to analyze the similarities of waveforms based on both P- and S-waves first arrivals (figure 6) as we check for repeating earthquakes (*Petersen and Pankow. 2023, Armeanu et al. 2022, Hardebeck et al. 2002, Uchida et al. 2019*). To identify and characterize seismic events with high precision and accuracy, we considered only those families with a correlation coefficient (CC) of 0.9 between pairs of waveforms. PR53 had only few earthquakes which were not enough for cross-correlation, therefore, our results and conclusion are built on the other 8 stations' records.

Family 1 Family 2

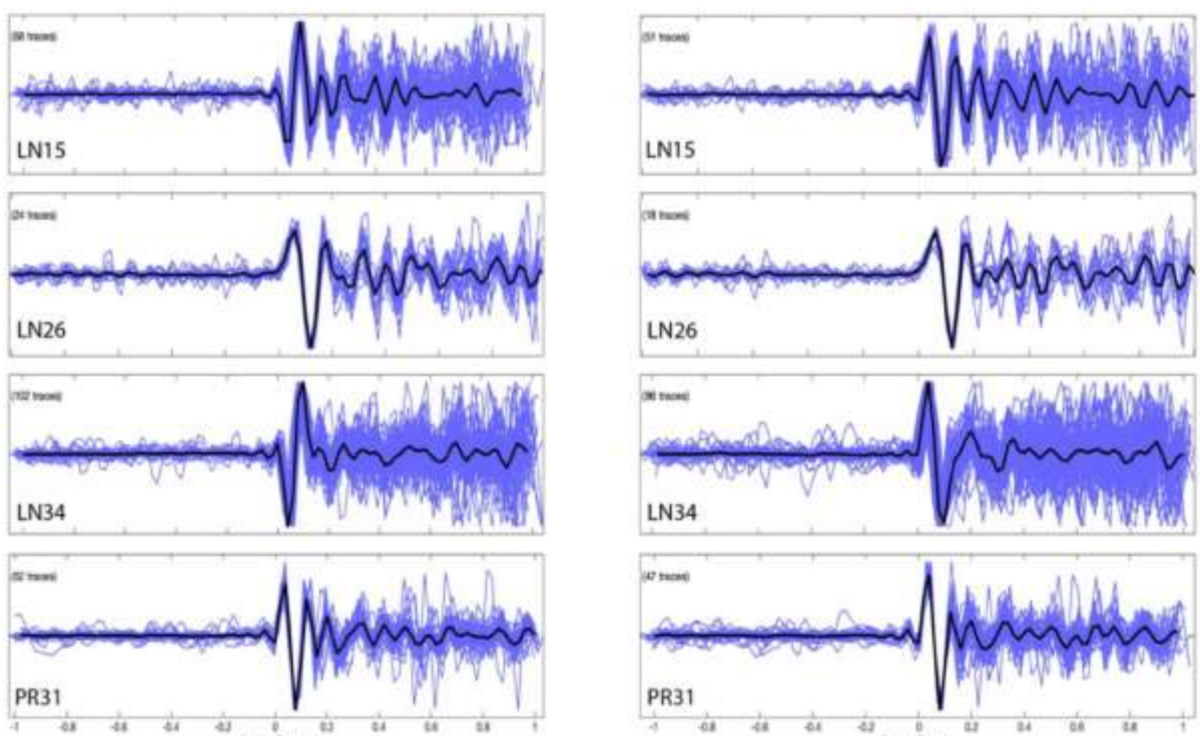

Figure 7. Overlay traces for the two main earthquake families based on arrivals from 4 of the 8 stations used in the analysis. Both LN15 and LN34 recorded a dilation (down) first motions while LN26 and PR31 recorded a compression (up) motion for family 1. All the four stations recorded compression (up) first motions.

An example of some repeating earthquakes is shown on figure 6. For each station, we minimized the overall waveform distortion by aligning waveforms after applying and plotting crosscorrelation matrices and lag times matrices using a time window of [-0.15 – 0.15] sec. With the same filter and correlation coefficient, we applied a time window of 2sec, to have the polarity of the first motions of waveforms, from which we can refer on to know the Earth's directions (the material movement) relative to each station. The sample of waveforms for 2 main families from 4 representative stations is shown in the figure 7.

To further investigate whether all events located in the same family share the same source mechanisms, we used Weinstein et al. (2017) focal mechanism solutions (Tables 1 and 2) determined from the first-motion modeling program FOCMEC (Weinstein et al. 2017). Examination of focal mechanisms solutions corresponding to Family 1 and Family 2 shows that multiple source mechanisms occur within the same families (figures 8).

Table 1. FOCMEC solutions with up to 10 solutions and $2\sigma_{strike}$, $2\sigma_{dip}$, $2\sigma_{rake}$ are all < 10. (Weinstein et al. 2017)

Date			Time					Depth	Focal mechanism				#		#	Ev
yyyy	mm	dd	hh	mm	ss.ss	Lon (º)	Lat (º)	(km)	Strike	Dip	Rake	M^L	Sol	$2\sigma_{strike}$	Picks	#
2014	01	29	02	47	17.43	36.1872	-2.6603	7.3	252.1	35.3	-81.3	1.4	4	6.2	17	19
2014	03	24	07	38	23.51	35.9955	-2.7512	14.0	249.8	44.0	-60.5	2.1	3	1.5	20	31
2014	06	05	17	50	51.48	36.0285	-2.7442	17.5	255.0	50.0	-90.0	0.0	6	10.0	20	26
2014	06	05	17	51	45.46	36.0287	-2.7442	17.3	90.1	52.8	-64.6	2.6	3	6.0	26	25
2014	06	07	19	33	55.90	36.0332	-2.7472	9.7	269.2	50.2	-83.5	2.8	3	5.0	23	27
2014	06	29	01	49	26.22	36.1088	-2.6682	6.0	252.3	65.1	-84.5	2.2	3	9.4	31	16
2014	06	30	06	13	19.34	35.9738	-2.7247	9.2	245.0	20.0	-90.0	2.3	1	0.0	26	21
2014	07	21	19	58	37.69	36.0172	-2.7605	14.7	114.2	60.2	54.8	1.1	1	0.0	18	29
2014	08	05	06	15	04.17	36.0143	-2.7278	15.9	95.7	55.6	-77.8	1.6	3	4.8	13	23
2014	08	21	22	09	14.15	36.0720	-2.6858	9.1	232.9	44.8	-44.8	1.4	2	5.8	19	15
2014	09	08	05	45	50.24	36.0123	-2.7183	9.4	58.0	45.9	-76.0	2.4	1	0.0	21	22
2014	09	11	07	45	56.31	36.0323	-2.7277	10.0	202.0	58.7	-60.4	1.7	5	6.3	19	24
2014	09	22	13	34	54.78	36.0013	-2.5740	14.4	47.3	65.1	-84.5	1.7	1	0.0	16	12
2014	09	23	22	15	36.76	36.0222	-2.7488	9.6	197.4	51.6	-70.7	2.9	1	0.0	24	30
2014	09	29	00	00	22.60	36.1628	-2.6550	6.0	330.0	25.0	-90.0	1.4	1	0.0	14	18
2014	10	27	22	34	06.40	36.1318	-2.6640	8.6	303.6	30.4	-80.1	2.1	1	0.0	27	17

Table 2. FOCMEC solutions with up to 10 solutions and $2\sigma_{strike}$, $2\sigma_{dip}$, $2\sigma_{rake}$ are all < 20. (Weinstein et al. 2017)

Date			Time					Depth	Focal mechanism				#		#	Ev
yyyy	mm	dd	hh	mm	ss.ss	Lon (º)	Lat (º)	(km)	Strike	Dip	Rake	M^L	Sol	$2\sigma_{strike}$	Picks	#
2013	01	27	20	25	22.34	35.9947	-2.7357	10.9	120.2	66.6	-68.1	1.3	7	7.3	19	56
2014	05	10	21	02	22.46	36.1647	-2.5990	8.0	97.0	35.5	30.6	1.4	7	4.8	17	50
2014	06	25	11	11	15.80	36.1102	-2.6720	6.8	250.0	20.0	-90.0	2.2	2	1.5	26	52
2014	08	07	01	11	36.73	35.9627	-2.7492	10.1	71.7	50.7	-77.0	3.4	3	15.4	28	60
2014	09	11	09	20	52.11	36.0313	-2.7295	10.1	74.2	60.5	-78.5	1.7	4	0.5	19	57
2014	09	15	16	15	16.78	36.0363	-2.7290	11.6	265.1	7.1	44.9	1.5	6	12.1	13	54

Each family is made of a combination of individual families from each of the 8 stations. That is events in the i^{th} family (with $1 \leq i \leq n \quad and \quad n = number \quad of \quad families$) from station j ($1 \leq j \leq 8$) gathered to form a local family.

4.Results

Within time window of -0.15 to $+0.15 sec$, a minimum of 84% of highly correlate events to > 90% (CC ≥ 0.9) at each of the 8 stations were obtained. Many of them have consistent P-waves arrivals but more less similar waveforms (figure 6), leading to very few repeating earthquakes (*Schaff et al. 2005*). According to Hardebeck et al. 2002, similar waveforms suggest that the mechanisms underlying the events are also similar. These events should also indicate consistency in the observed polarities of the first motions of P-wave at a specific station, to insight the source mechanism. The high similarities between waveforms in the same family prove that earthquakes in that family share same source mechanisms.

The waveform cross correlation of the P-phases from the chosen stations shows existence of many families, among which we have just presented two as examples with whose waveforms are nearly but not similar (figure 6). The focal mechanisms for both families (earthquakes around Naibor Soito as well as those around Gelai) are all normal faulting earthquakes with different orientations and nearly similar locations, and no difference on how they are spatially distributed in families (figure 7). Considering a negligible strike slip component of nodal planes in the second family, they are all normal faulting earthquakes but with different source mechanisms.

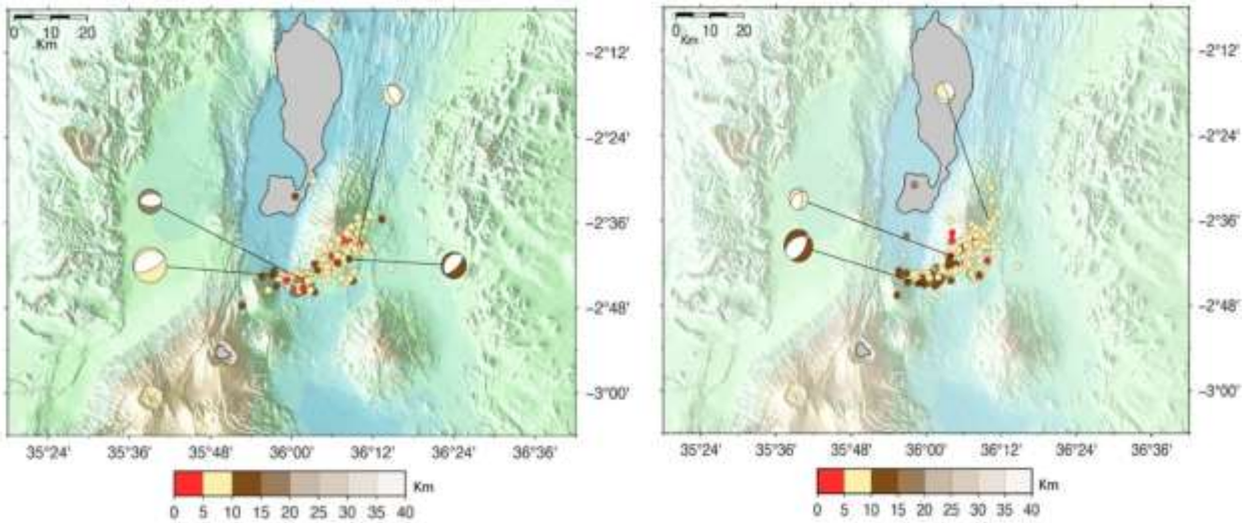

Figure 8. Possible focal mechanisms for both families from all the 8 stations. NSE and NE normal faulting earthquakes for the first family (LHS). NS and NE normal faulting earthquakes (with small strike-slip components) in the second family.

Family 1

Family 2

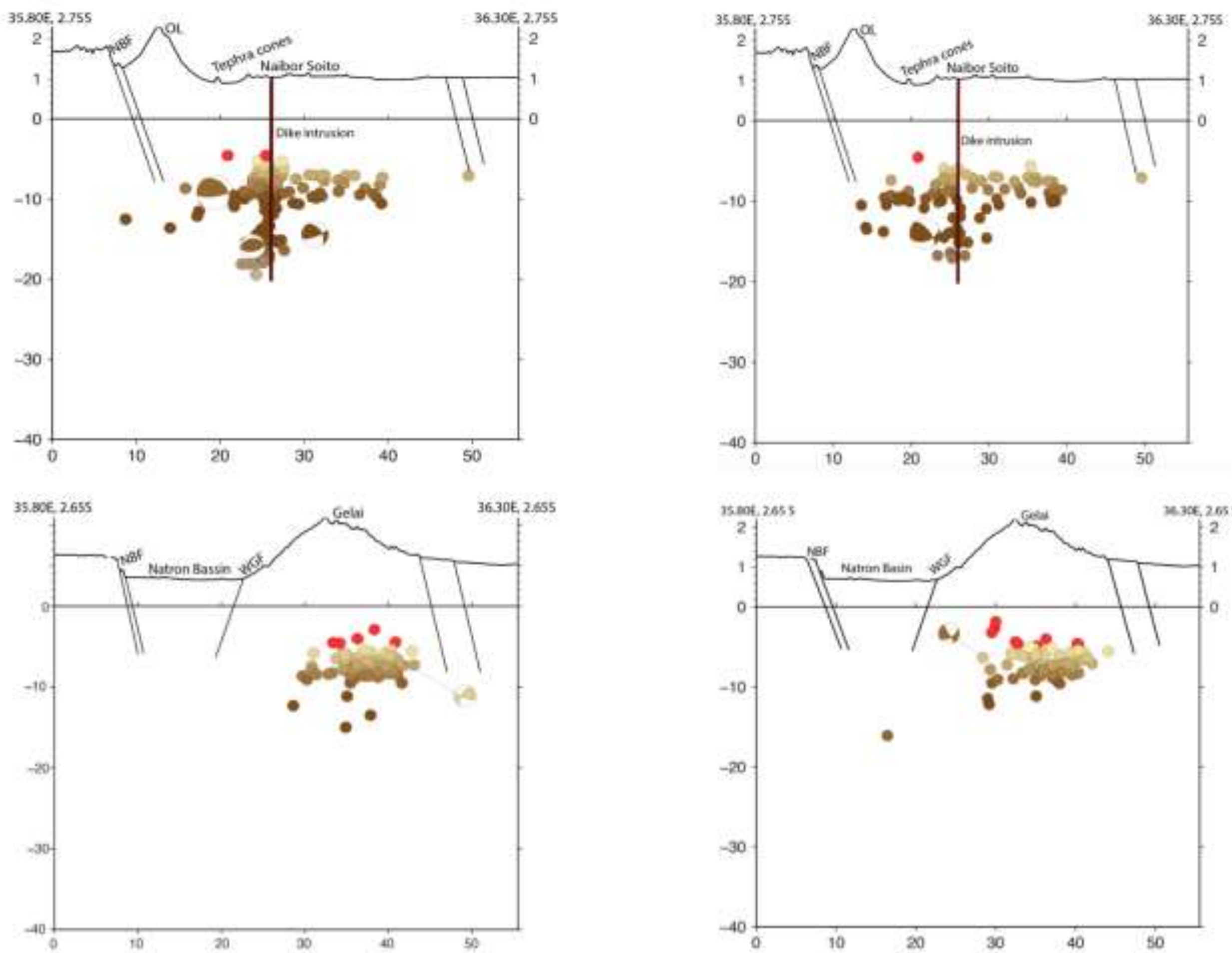

Figure 9. Cross-section profiles for both families showing topography of the region (faults and eruptive centers). The profiles are projected to a maximum of 5km North and South.

5.Interpretation.

Only very few highly correlated waveforms are similar (figure 6), hence very few repeating earthquakes exist in OL-NS-Gelai. This implies that many tectonic faults and tectono-magmatic faults around pressurized magma bodies having different orientations accommodate extensional strains. In this magmatic rift zone, strains are shared along many faults, hence the extensional strain is not localized to the border fault zone (Oliva et al. 2019, Weinstein et al. 2017). Additionally, events located in the same family with non-similar waveforms (figure 6) indicate irregular strains resulted as consequences of non-localized building pressures. So, many source mechanisms and source zones with irregular strains, mark the region to be made of complex tectonic setting and, hence hard to isolate a particular source mechanism (*Green & Neuberg. 2006*). These slightly differences in source mechanism are shown by different focal mechanisms of some detected earthquakes. Some have oblique normal slip motion along NE nodal planes, other with oblique normal faulting along NS striking planes (figure 7). This proves that this region is seismically active due different source mechanisms, like pressurized magma, dike intrusions and possible active faults (*Oliva et al. 2019, Roecker et al. 2017, Reiss et al. 2022*).

Another reason which can be attributed to the existence of few repeating earthquakes can be the irregularity changes in building pressure between rocks' asperities (*Ruina 1983*), the hydrothermal processes and change of buoyant magma leading to non-periodic weakening of crustal rocks leading to the lower dense magma to rise ($\rho_{/} - \rho_0 > 0$) with a non-periodic pulse (*Lister and Kerr 1991*). Most of the seismicity of the two families indicate that strain is distributed across multiple faults with Pleistocene offset around Oldoinyo Lengai and Gelai volcanoes, Pleistocene tephra cones and spatter mounds, and Naibor Soito. These shallow earthquakes are located to a depth between 6 – 20km beneath NS and 6 – 16km beneath Gelai complex volcano (figure 9).

6.Discussion

Waveform cross-correlation analysis serves as a powerful tool in identifying seismic events. By focusing on the mathematical principles underlying cross-correlation, particularly when comparing earthquake waveforms, researchers can find repeating earthquakes to distinguish between magmatic, hydrothermal, and fault system (*Uchida et al. 2019*). Understanding the concept of repeaters contributes to the understanding of different earthquake sources and has also an implication in seismic hazard assessment, as well as in early warning systems which can potentially help in improving hazard assessments and mitigations. We found few repeaters in OLNS-Gelai region. Following the few repeating earthquakes, it is hard to predict where future earthquakes will be in this region. Continuous monitoring would be the solution to mitigate the seismic hazards (*Fischer et al. 2023*). We used seismic data recorded for two years, which is obviously a geological short time to find repeating earthquakes that can be caused by rifting process. However, this cannot be taken as a negligible time, to find repeating earthquakes, which can be attributed magmatic and hydrothermal processes. Therefore, we trust our findings. At least 84% of events from all the 8 stations were highly correlated to $\geq$ 90%. We attribute this highly percentage of correlations to the seismicity resulting from the pressurized pressure and dike intrusions rather than the ongoing rifting processes. Therefore, a long-term monitoring (e.g of 10 years) may be needed to find repeaters which may be driven by rifting processes (*Uchida et al. 2019*).

Events located in the same family have same type of fault (normal, reverse or strike slip faults), but not necessarily same source mechanisms nor same processes, unless they all highly/exactly similar waveforms. Therefore, the ambiguity or challenges that may persist in distinguishing source mechanism can be removed by applying additional techniques, like plotting focal mechanisms for example.

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