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Geologos 28, 3 (2022): 203–215
https://doi.org/10.14746/logos.2022.28.3.0003

GEOLOGOS

Radiometric dating of the Ootun palaeosol and its implication for the age of the Shifting Sand in Ngorongoro Lengai Geopark (Arusha, Tanzania)

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Abstract

The Shifting Sand is a barchan dune in Ngorongoro Lengai Geopark in Arusha, Tanzania. The geopark, a UNESCO World Heritage Site, is protected by the Ngorongoro Conservation Area Authority. The dune ranks amongst the main geosites that have been attracting numerous tourists; it formed as a result of volcanic ash eruptions that led to tephra deposition on a palaeosol (palaeosurface) in the Ootun area. The easterly winds modified the ash into dunes and headed to the Olduvai Gorge area. The age of the Shifting Sand dune is not known in detail. In the present study, we employ the radiocarbon (^{14}C) dating method to date a subsurface palaeosol bed in the Ootun area where the tephra (i.e., original Shifting Sand materials) was originally deposited. An Accelerator Mass Spectrometer was used to determine the carbon-14 date of the palaeosol so as to estimate the age of the Shifting Sand dune, and an Energy Dispersive X-ray Fluorescent Spectrometer to determine the chemical composition of the Shifting Sand material and the tephra bed for correlative purposes. A radiocarbon (^{14}C) date of 2510 ± 30 years BP for the Ootun palaeosol was obtained to estimate the minimum age of the Ootun subsurface tephra deposited in the area; since then, this started to move westwards towards the Olduvai Gorge area, where it is today defined as the Shifting Sand. The current findings add educational value to the Shifting Sand in Ngorongoro Lengai Geopark and improve our understanding of the eruption history of the Gregory Rift volcanoes.

Keywords: Oldoinyo Lengai volcano, ash/tephra dunes, carbon-14 (^{14}C) dating, UNESCO Global Geopark

1. Introduction

A geopark is a place where geological heritage is conserved and used sustainably to improve economic realities of residents (Mc Keever & Zouros, 2005). It is made up of several appealing and rare geological and palaeontological heritage sites that are particularly significant scientifically. Furthermore, geoparks may have ecological, archaeological, cultural and/or historical value (Eder & Patzak, 2004). Ngorongoro Lengai is the only area in Tanzania with UNESCO geopark status, from April 2018)

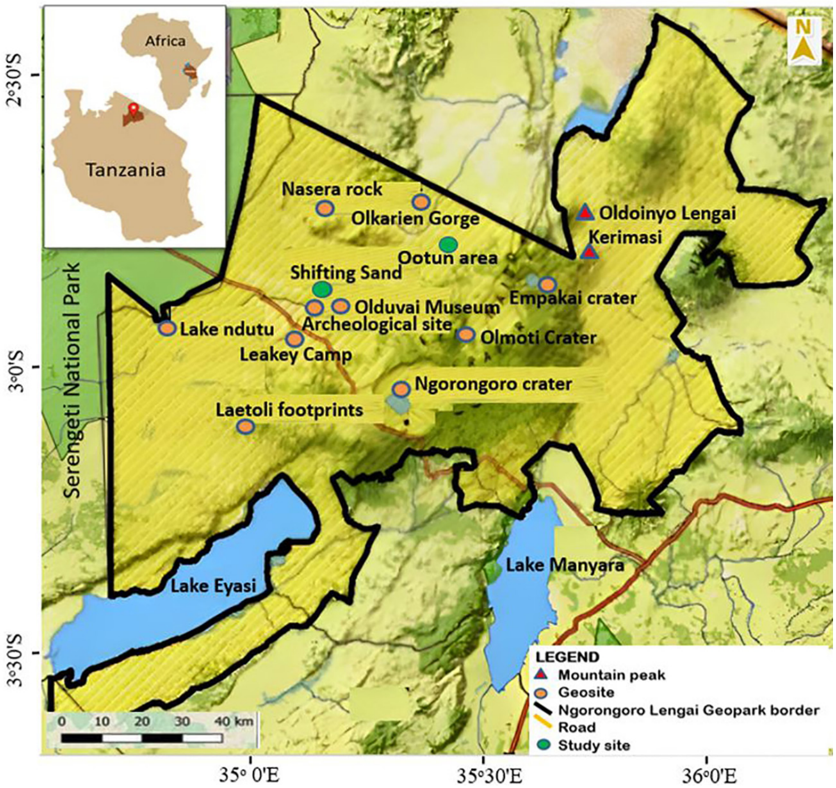

Fig. 1. Location map of the Ngorongoro Lengai Geopark with position of the Shifting Sand and other geosites. The geopark was established in April 2018 and is managed by the Ngorongoro Conservation Area Authority (NCAA).

(https://en.unesco.org/global-geoparks/ngorongoro-lengai and https://www.ncaa.go.tz/pages/geopark). This geopark is protected by the Ngorongoro Conservation Area Authority (NCAA). One of the remarkable features of Ngorongoro Lengai Geopark, among others (e.g., Ngorongoro Crater, Olduvai Gorge archaeological site, Natural springs, Oldoinyo Lengai, illustration of hominid footprints, Nasera rock shelter, Olmoti Crater, Leakey Camp, Olkarien Gorge, Empakai Crater and Eyasi Basin), is the Shifting Sand (Fig. 1).

The Shifting Sand is a dune-shaped mass of sands near the Olduvai Museum (Fig. 1). The name "Shifting Sand" was coined prior to the independence of Tanganyika, the former name of Tanzania, in 1961 (Pickering, 1958). The Shifting Sand dune has been migrating westwards from the Ootun area for thousands of years. As evidence of this movement, in 1958 the Shifting Sand was located at 2°56'48"S and 35°19'24"E, that is, about 1.2 km from its position in 2020 (2°56'41"S and 35°18'48"E). This shows that, as the sand dunes move westwards, their volumes decrease; every researcher has reported different positions, dimensions and volumes at any one particular time (Fig. 2; Hay, 1976; Belsky & Amundson, 1986; Freymann & Krell, 2011; Kafumu, 2020). Since 1969, the NCAA has been monitoring the speed of the dunes (16–20 m/year) by placing beacons at defined distances travelled by the Shifting Sand (Fig. 3).

The ash exposed at the surface can be classified either as primary, being the result of the initial or first deposition of ash falls from a volcanic plume or secondary, which reflects ash accumulation by reworking of primary deposits (Gudmundsdottir et al., 2011). In the present case, the Shifting Sand originated from reworking of primary ash from the Oldoinyo Lengai eruption on the volcano's westerly side in the Ootun area (Belsky & Amundson, 1986; Freymann & Krell, 2011; Sherrod et al., 2013; Kafumu, 2020). The ash falls were scattered 30–40 km west of the peak and laid down as tephra and subsequently redeposited through aeolian processes into barchan dunes by easterly winds and gradually migrated (by rolling) towards the Olduvai Gorge area (Hay, 1976; Belsky & Amundson, 1986; Kafumu, 2020).

By means of eruptive processes such as surge, pyroclastic fall and flow, volcanic materials can be carried hundreds to thousands of kilometres from the volcanoes (Cas & Wright, 1987; Németh et al., 2009). Smaller ash particles (i.e., less than 70 μm) have significant cohesive forces, making it difficult for wind (as a reworking argent) to lift them by direct aerodynamic action. After an eruption, ash particles suspended in the atmosphere for an extended period can travel thousands of kilometres. Particles larger than 500 μm generally cannot be transported normally in saltation and therefore they usually move by creeping and/or rolling (Dominguez et al., 2020).

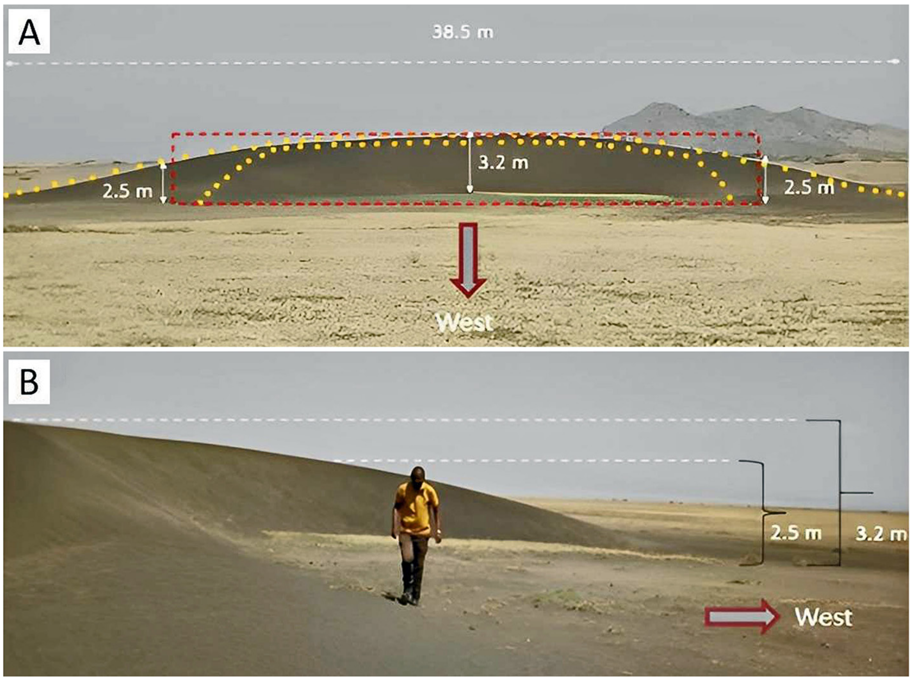

Fig. 2. Current position of the Shifting Sand (2°56'41"S, 35°18'48"E) and its associated dimensions. **A** – Front view; **B** – Side view (field survey in 2020).

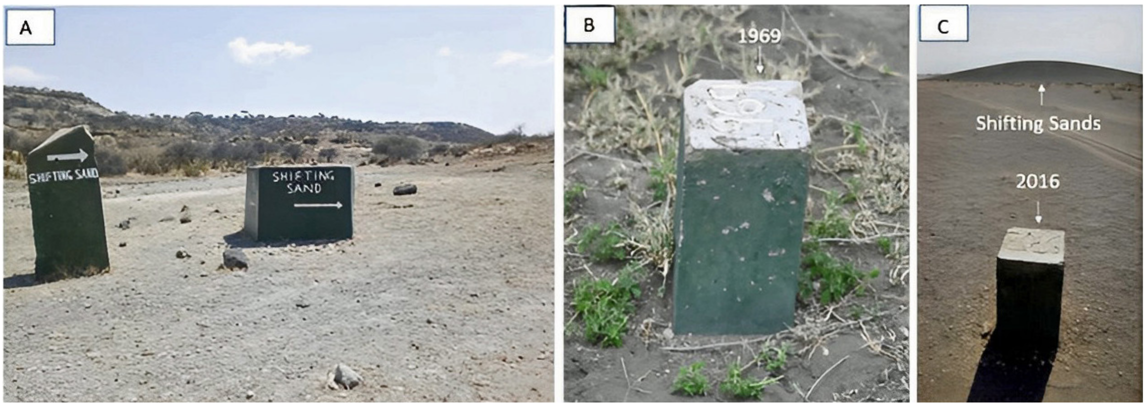

Fig. 3. Beacon marks showing location and movement of the Shifting Sand in the Olduvai Gorge area. **A** – Directions towards the Shifting Sand Geo-tourism site; **B** – The Shifting Sand position in 1969; **C** – The distance travelled by the Shifting Sand between 2016 and 2020 (field survey in 2020).

Tephra deposits made of fine-grained particles are useful for correlative purposes over distances of up to thousands of kilometres. Thus, the study of dating and correlating tephra (tephrochronology and tephrostratigraphy) serves as a valuable addition to archaeological and palaeoenvironmental reconstructions. They may offer distinctive, isochronous indicators that are easily distinguished (Alloway et al., 2007; Lowe, 2011).

Belsky & Amundson (1986), quoting Hay (1976), estimated that the Shifting Sand had been migrating for about 1,300 years from the Gregory Rift Volcanoes (GRV) in Ngorongoro before arriving near the Olduvai Gorge area. However, relative dating by Kafumu (2020) documents that almost 3,000 years elapsed to arrive at the current position. The two age estimates of the Shifting Sand differ significantly. In the present study, we discuss more reliable absolute carbon-14 radiometric dating of the palaeosol in which the "source tephra" was deposited in the Ootun area in order to estimate the age of the Shifting Sand. The palaeosol underneath the tephra bed provides information on the minimum age of tephra deposition (Okuno et al., 1997; Mitsuru & Toshio, 2003). The Shifting Sand is currently migrating westwards and is situated about 45 km west of the Ootun area. Its chronology requires geochemical correlation, which should be estimated from the subsurface tephra of the Ootun. Therefore, the two sites (the Shifting Sand and the tephra bed at the Ootun) have been correlated to confirm the volcanic nature of the materials examined.

2. History of the Shifting Sand; genesis and propagation

It was not until 1958, when the Geological Survey Department, operating under colonial authority, published the Quarter Degree Sheet (QDS) 12 S.W. map (currently QDS 38, Oldoinyo Ogol) containing the Shifting Sand, that it was officially recognised (Pickering, 1958). The name certainly came from the local Maasai community, who believed it originated from "OlDoinyo Lengai" (Oldoinyo Lengai), a mountain located east of the Olduvai Gorge. The sacred Oldoinyo Lengai, also known as the "Mountain of God", is believed by the local Maasai community to be the source of the Shifting Sand (UNESCO, 2022). Academic works, primarily by Hay (1976), Belsky & Amundson (1986), Freymann & Krell (2011) and Kafumu (2020), partially document various aspects of the Shifting Sand, including its origin (and age), behaviour of biota such as insects (e.g., beetles) and chemical composition, respectively. Despite the great technological advancement in instrumentation during the last five decades, many questions, such as the age of the Shifting Sand, remain unanswered.

Barchan dunes are the result of the blowing of the airflow of the atmospheric boundary to the ash deposition surface to attain structural modifications. This is due to the fact that wind shear velocity affects surface shear stress. As a result, on each hillock patch, there is an increase in shear stress in the windward slope in the direction of the crest and a decrease on the leeward side (Raupach & Finnigan, 1997). Barchan dunes have a negative feedback effect which, within every bedform change, is associated with a self-regulatory mechanism due to wind speed and direction. This equilibrium condition is known as a steady-state (Tsoar, 2001). In this way, the barchan dunes in the Ootun area developed and propagated in a windward direction to the Olduvai Gorge area (Figs 4, 5; Hay, 1976; Belsky & Amundson, 1986; Freymann & Krell, 2011). Many of them were dispersed away as their migration normally went hand in hand with a loss in volume of the barchan dunes (Kafumu, 2020).

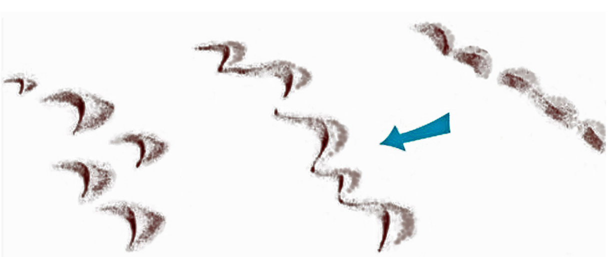

Fig. 4. The transformation of ash surface to barchan dunes as a result of unidirectional wind. The blue arrow indicates the prevailing wind direction (source: McKee, 1979).

3. Material and methods

3.1. Study area

The study area (Ootun area and the Shifting Sand) is situated to the west-southwest of the Oldoinyo Lengai (see Fig.1). The Ootun area is located at 2°46'44"S and 35°36'16"E, while the Shifting Sand is at 2°56'32"S and 35°18'42"E. The Ootun area is about 35 km west of the Oldoinyo Lengai and is characterised by stabilised dunes made of tephra from the Oldoinyo Lengai (Fig. 5). The area provides a favourable platform for receiving and preserving fallouts driven by the wind from the westerly side. Geochronology of the volcanic eruptions and an estimation of the onset of the migrating ash dunes can be established by stratigraphical data. The Shifting Sand is about 80 km from Oldoinyo Lengai and about 2 km north of the Olduvai Gorge (see Fig. 1).

3.2. Sample collection

The Ootun area has a flat (plain) topography (Fig. 6), which is deprived of conventional material for radiocarbon (^{14}C) analysis (e.g., charcoal fragments, wood and plant remains). The present study uses less-conventional palaeosol samples for ^{14}C dating to determine the subsurface tephra age indirectly (Fig. 6; Okuno et al., 1997; Mitsuru & Toshio, 2003; Guilbaud et al., 2022). Four subsurface palaeosol samples, e.g., OBA series – organic buried, and eight tephra samples (two from each pit), namely BASH series – buried ash (Fig. 8), were collected (Table 1; Figs 6–8). In addition, eight samples (two from each point), namely the SS series, were taken from the Shifting Sand. In this case, the sampling points were 8 m apart (compare Figs 2 and 6).

The samples were collected from four pits, 1.3 to 1.5 m deep, in a north-southerly direction and thoroughly mixed up using a plastic bag and hand

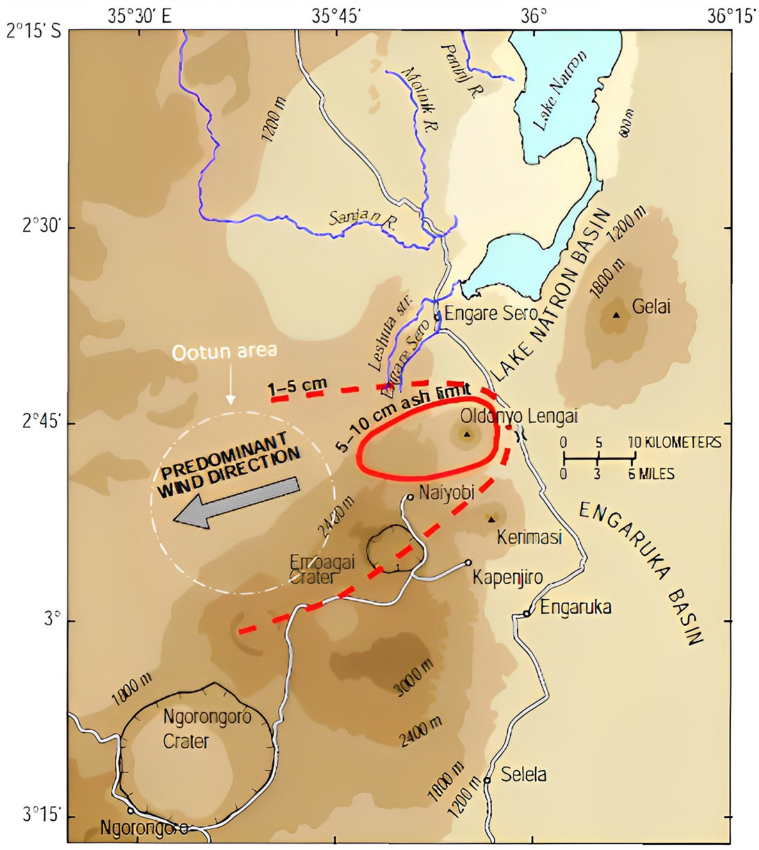

Fig. 5. A map showing wind direction (i.e., barchan dune driving force) and extent of ash fallout from Oldoinyo Lengai of the September 2007/8 eruption. The red dotted line denotes areas with a 1–5 cm thick ash layer, while a solid red line shows the area where the volcanic ash is 5–20 cm thick (source: Sherrod et al., 2013).

Fig. 6. Views of the Ootun area (2°46'44"S, 35°36'16"E) depicting a flat plain topography containing the tephra piles modified into stabilised dunes. Several dunes currently seen in the Ootun area were formed by mixtures of several ash fallouts released at different times from the Oldoinyo Lengai, a distance of about 35 km to the east of the Ootun area – see Figure 7 (field survey in 2020).

Table 1. Sampling budget. For other explanations see text.

Serial number	Sample type	Sample name	Location	Sample number	Mass (g)
1	subsurface palaeosol	OBA series	Ootun area	4	1000
2	subsurface tephra	BASH series	Ootun area	8	1000
3	ash (Shifting Sand)	SS series	Shifting Sand	8	1000

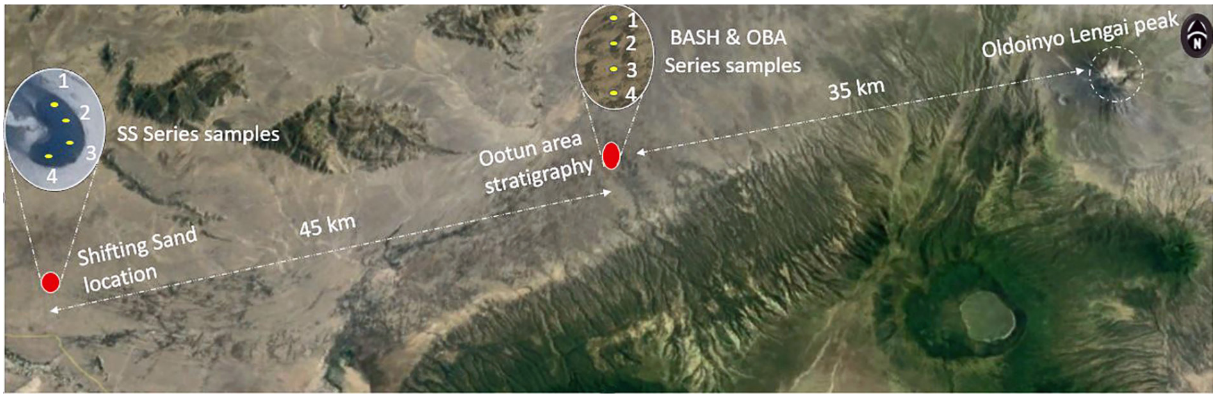

Fig. 7. A map showing the sampling location (Shifting Sand and Ootun area) in relation to the Oldoinyo Lengai volcano. Note the distances between the volcanic ash source area (Oldoinyo Lengai) and the deposition area (Shifting Sand and Ootun area).

gloves (to prevent contamination) for about twenty minutes to one representative sample (Fig. 8; Zehetner et al., 2020). This was done using 5-cm-diameter pipes with a 30-cm-length (compare Figs 6 and 8). In view of the fact that the subsurface tephra bed covers a large area, the total sampling distance of 150 m (50 m x 3) ensures that the stratigraphical depths of four pits and the numbers of layers were uniform across all four pits and matched each other. The composite sample was then sealed in a plastic bag and delivered to Beta Analytics (Miami, Florida, USA) for analysis (Table 1).

3.3. Sample analysis

3.3.1. Radiocarbon (^{14}C) dating of palaeosol

The palaeosol samples were visually inspected for debris, grain size, clasts, inclusions, organic constituents, homogeneity and potential contaminants. The samples were dispersed in de-ionized water, stirred, sonicated and sieved through a sieve with a mesh diameter of 180 µm. The material passing through the sieve was used for the analysis. The removal of carbonates was completed by bathing in 1.25 N HCl at 90°C for a minimum of 1.5 hours, followed by serial distilled water rinses at 70°C until neutrality was reached. Rootlets or organic debris found were discarded during these rinses. HCl was added after drying the samples at 70°C for about 16 to 24 hours under the microscope to ensure all carbonates had been removed. Further microscopic examination was performed to assess its characteristics and determine the appropriate subsample for Accelerator Mass Spectrometry (AMS) dating. The analysis was done using NEC 250 keV Single Stage AMS on a humic acid fraction of the samples. Calibration of radiocarbon ages to calendar years (Ramsey, 2009) was done by applying the SHCAL13 database (Hogg et al., 2013). Conversion of ^{14}C ages and sigma were rounded to ten years as per the 1977 International Radiocarbon Conference and consistent with past laboratory analytic radiocarbon dates. The analysis was performed at the Beta Analytic Testing Laboratory at Miami (Florida, USA). All work on these samples was performed at that laboratory under a strict chain of custody and quality control under ISO/IEC 17025:2017 Testing Accreditation PJLA #59423 accreditation protocols.

3.3.2. Chemical composition of ash and tephra

All subsurface tephra and the Shifting Sand samples from the Ootun area and Shifting Sand were cleaned of debris prior to homogenising and dried at 105°C for two hours. The representative samples weighing approximately 200 g were ground to a particle size of 75 µm, and the chemical composition was done by XRF machine (Lowe, 2011); a Niton XRF machine Model XL3t was employed. A high-performance semiconductor detector and silver and gold anodes were included in the device. All samples were scanned at a maximum of 50 kV and 40 µA. The external helium system was connected to the machine to increase light element sensitivity. After analysing four samples, the certified reference standard DC73026 from the China National Analysis Centre for Iron and Steel (Beijing) was determined. The testing was carried out in a benchtop laboratory setting at the Geological Survey of Tanzania.

4. Results and discussion

4.1. Stratigraphy of the Ootun area

The simplified stratigraphy of the Ootun area shows three distinct beds (Fig. 8). The basal layer is

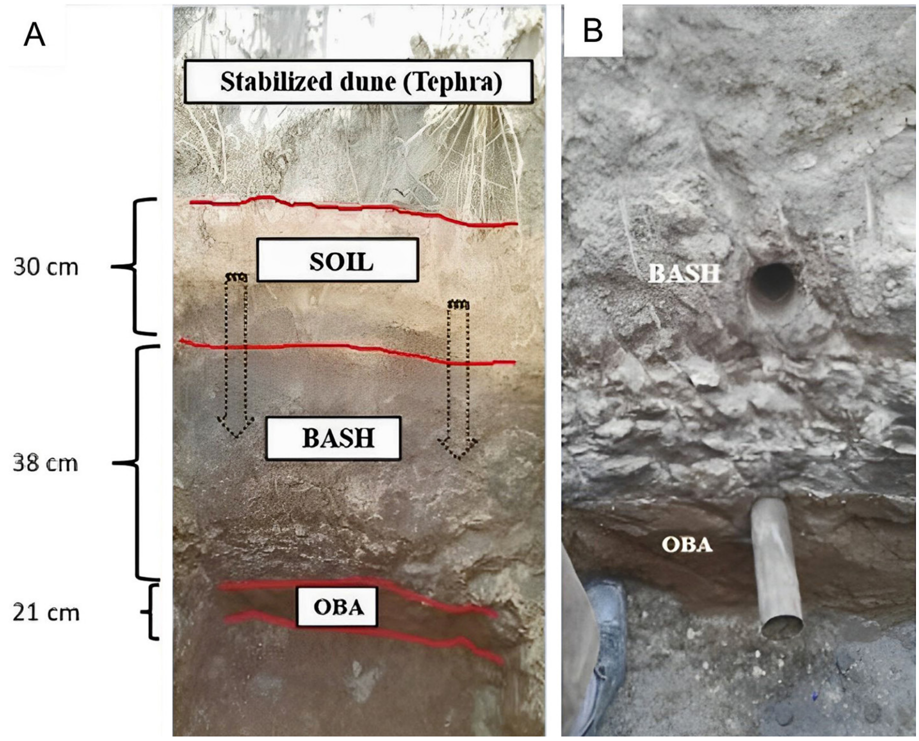

Fig. 8. Sampling of subsurface palaeosols and tephra in the Ootun area (2°46'44"S, 35°36'16"E). **A** – General view of the section sampled; dotted black arrows indicate the direction of water infiltration making zonation unclear between the SOIL and tephra bed BASH (buried ash); **B** – Close-up view of the tool used for sampling.

the black palaeosol (OBA, 21 cm thick), which is the topsoil in the past geological time before the subsurface tephra bed (BASH) was deposited. The middle bed reflects the grey-black subsurface tephra deposition (BASH, 38 cm thick), followed by the current brownish topsoil bed (SOIL, 30 cm thick). The profile is covered by stabilised dunes, which are ash or tephra fallouts from the Oldoinyo Lengai volcano (Figs 7, 8).

The historical massive ash fallout is represented in the 30-cm-thick subsurface tephra deposition (BASH), spread across more than 1,500 m. This event was caused by Oldoinyo Lengai, a polygenic volcanic stratocone located 35 kilometres east of the Ootun area (compare Figs 5, 7 and 8). Oldoinyo Lengai is a well-known active natrocarbonatite volcano (Keller & Krafft, 1990). Ash material from Oldoinyo Lengai periodic eruptions has always been scattered throughout the western part, including the Ootun region. After its most recent eruption in 2007, ash scattered around the Ootun area. The Kerimasi volcano, situated 12 km southeast of the Oldoinyo Lengai (see Fig. 5), ceased its volcanic activities at about 400 ka (Zaitsev, 2010; Żaba & Gaidzik, 2011). The profile also shows the topsoil of 30 cm thick. A considerable geological time (up to a thousand years) would take for such thickness to develop and accumulate in a plain with no history of flooding. While the Shifting Sand dunes migrated across the plain, the 30-cm-thick topsoil layer (SOIL) at the Ootun area was gradually formed (Fig. 8).

4.2. Radiocarbon (^{14}C) dating

The radiocarbon (^{14}C) dating results for the palaeosol samples collectively named OBA, (i.e., OBA-570767, OBA-570767a, OBA-570767b and OBA-570767c) that were collected from the same site was 2510 ± 30 BP (Fig. 9). Therefore, the overlying tephra bed (BASH) must be younger (Fig. 8). The subsurface tephra material analysed most likely came from the Oldoinyo Lengai eruption described by Keller et al. (2006) and estimated to be 3000–2500 BP in age.

According to Okuno and Nakamura (2003), the ^{14}C dating results of the palaeosol are precise and fairly accurate. A recent study by Guilbaud et al. (2022) compares charcoal fragments (conventional ^{14}C method), among others, with palaeosol (less conventional ^{14}C method) and determines the palaeosol ages of nine samples around the shield ranging from 13.2 to 20.2 cal kyrs BP(2σ). The site was previously dated at ~12 calibrated (cal) kyrs BP, using radiocarbon (^{14}C) of the charcoal fragments. Guilbaud et al. (2022, abstract page) reported that

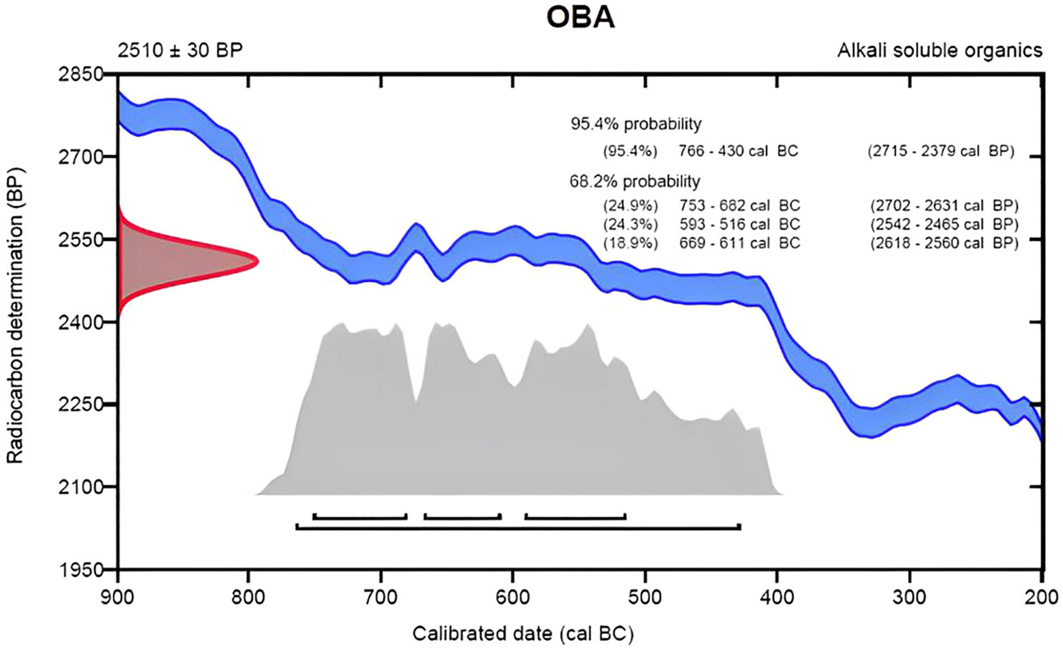

Fig. 9. OxCal software showing a radiocarbon calibration curve for the OBA palaeosol sample. The radiocarbon ages are displayed on the y-axis as years before present (BP), while the corresponding calendar years are displayed on the x-axis. The calibrated line on the blue graph is based on known values for ^{14}C ages, including tree rings. For each standard deviation, there are two lines on the graph. The sample's ^{14}C concentrations are represented by the distribution curve on the y-axis, while the associated sample age probabilities are shown by the grey curve on the x-axis.

the reason for the wide range in palaeosol dating is "erosive conditions related to the sloping topography of the sampling sites and the cool and relatively dry climate of the Younger Dryas."

In an opposing study, the Ootun area is semi-arid with strong winds up to 52.8 km/h (Freymann & Krell, 2011) and a flat plain topography that discourages humic acid and other material migration from the subsurface palaeosol. The radiocarbon (^{14}C) chronology of volcanic eruptions using palaeosol samples has also been carried out elsewhere by other researchers (Okuno & Nakamura, 2003).

4.3. Chemical composition

Chemical analyses of the subsurface tephra of the Ootun area (BASH) and the Shifting Sand (SS) near the Olduvai Gorge have found to have concentrations of SiO_2 ranging from 41.59 to 45.76 wt% (Fig. 10; Table 2). Other oxides are present in the following amounts: Al_2O_3 from 5.97 to 7.76 wt%, FeO(t) (i.e., Fe^{2+}plus Fe^{3+}) from 7.88 to 13.12 wt%, and CaO ranging from 12.51 to 16.39 wt%. The oxides of sodium (Na_2O), potassium (K_2O) and titanium (TiO) are on average in the range of 2–7 wt%. MgO has a relatively higher content (5.41–9.45 wt%), while SO_3 and P_2O_5 are present in amounts much below 1 wt% (Fig. 10; Table 2).

All of the oxides from the two sampled locations (Shifting Sand and subsurface tephra) are substantially comparable. Both results were correlated using various ternary systems and the Total-Alkali Silica (TAS) geochemical tools (Figs 11, 12 and 13). For the correlation of volcanic rocks, the data from Table 2 were plotted in the TAS diagram (Le Bas et al., 1986). All ternary systems and the TAS diagram show a positive correlation with each other. The chemical analysis results of the subsurface tephra samples (BASH) from the Ootun stratigraphy

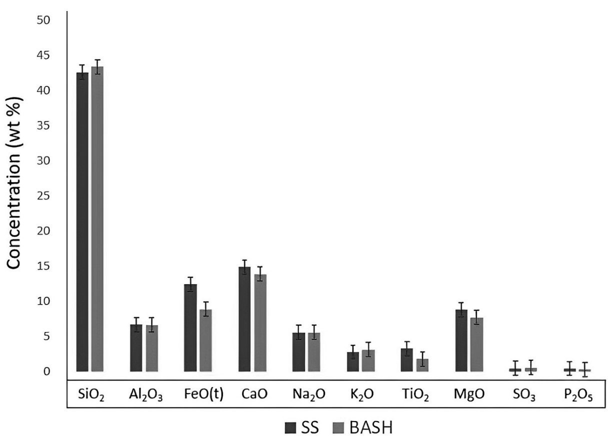

Fig. 10. A graph of the average concentration of major oxides for the Shifting Sand (SS) and subsurface tephra (BASH) samples.

strongly correlated with the Shifting Sand samples (SS) of the Olduvai Gorge area (compare Table 2, Figs 11 and 12).

Through correlation studies, the subsurface tephra of the Ootun area constitutes material that is similar to that of the Shifting Sand. That means that the Shifting Sand was made up of this part of the subsurface tephra of the Ootun area before it migrated to the Olduvai Gorge area by easterly winds. According to the chronological results obtained in

Table 2. Major oxide components (in wt%) for SS and BASH samples; for other explanations, see text.

Sample	SiO_2	Al_2O_3	FeO(t)	CaO	Na_2O	K_2O	TiO_2	MgO	SO_3	P_2O_5
SS 01	42.12	5.97	12.12	16.39	6.22	0.67	3.17	9.45	0.34	0.38
SS 02	43.43	6.57	12.57	15.71	5.24	1.01	2.97	8.78	0.39	0.30
SS 03	41.59	6.48	11.77	15.17	5.68	0.45	2.97	10.10	0.41	0.41
SS 04	43.44	7.76	11.61	16.16	6.22	0.78	3.14	8.14	0.31	0.32
SS 05	44.27	6.16	12.01	16.13	4.89	0.97	3.33	8.21	0.33	0.31
SS 06	42.04	6.49	13.01	15.81	4.98	0.65	3.26	9.17	0.48	0.40
SS 07	42.41	7.11	13.12	15.33	5.73	0.61	3.17	8.16	0.49	0.42
SS 08	41.76	6.37	12.73	16.03	5.24	0.62	3.64	8.14	0.37	0.41
BASH 1	45.76	6.32	7.88	14.98	6.22	2.91	1.45	5.41	0.34	0.16
BASH 2	43.31	6.45	9.56	12.51	6.42	3.12	1.55	6.02	0.35	0.22
BASH 3	42.42	6.33	8.47	15.48	4.77	3.48	1.99	7.61	0.39	0.32
BASH 4	43.12	7.16	9.03	13.12	5.86	3.65	1.14	8.24	0.54	0.23
BASH 5	43.17	7.16	9.11	14.13	4.11	2.45	1.35	8.11	0.75	0.24
BASH 6	43.04	6.34	8.12	12.81	5.92	2.89	2.01	8.64	0.56	0.30
BASH 7	43.14	6.14	10.03	13.34	5.13	3.11	2.22	8.58	0.65	0.25
BASH 8	43.16	6.75	8.38	14.42	5.89	3.02	1.99	8.54	0.45	0.25

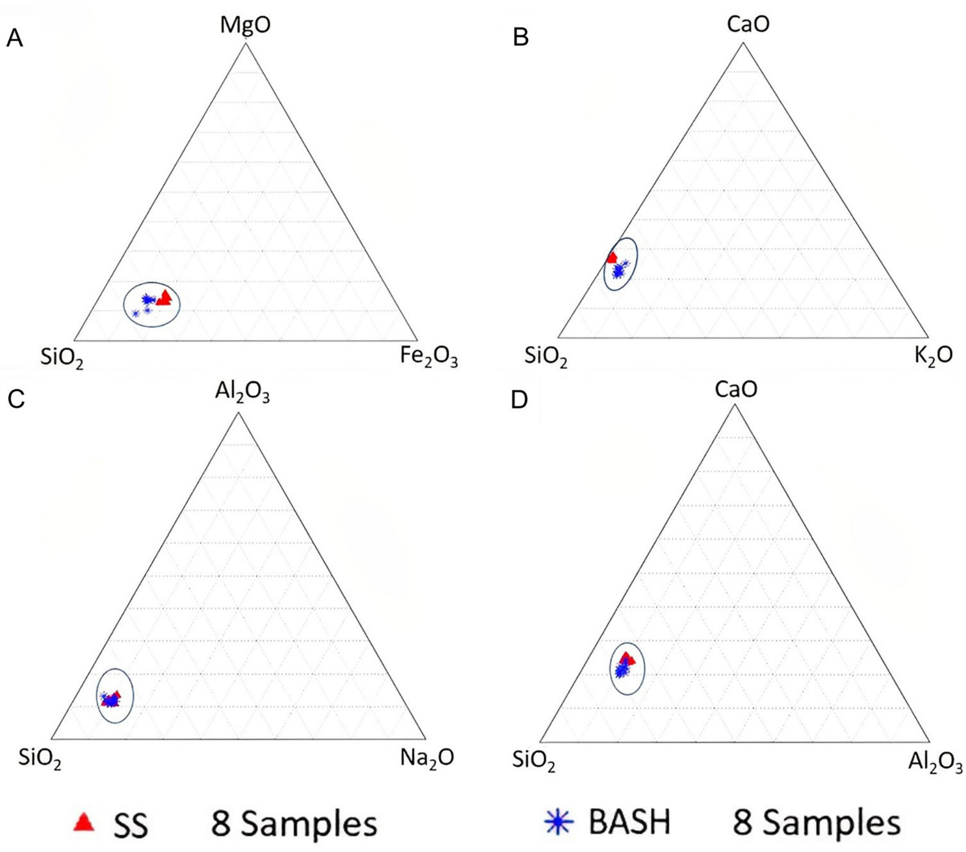

Fig. 11. Ternary systems showing a positive correlation between eight SS and eight BASH samples. For data see Figure 10 and Table 2.

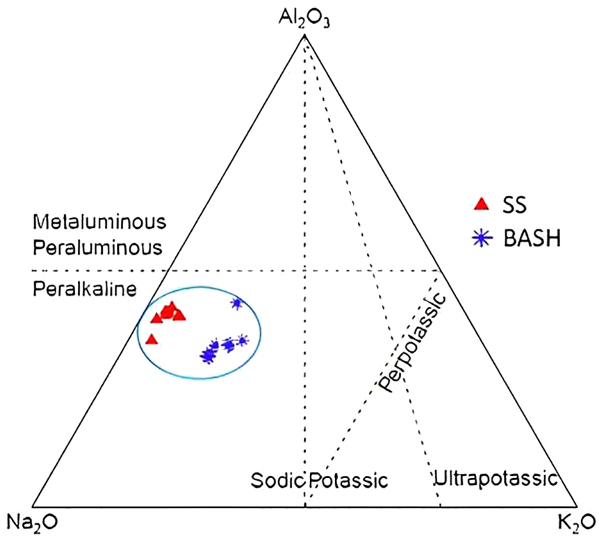

Fig. 12. The Molar Na_2O–Al_2O_3–K_2O plot prepared for the same samples as in Figure 11. For data see Figure 10 and Table 2.

the present study, the subsurface palaeosol age is 2,510 ± 30 years; hence the tephra bed is younger. Thus, the given ^{14}C age (about 2.5 ka) provides the maximum age of tephra deposition (see Fig. 9; Okuno et al., 1997; Mitsuru & Toshio, 2003).

The Oldoinyo Lengai volcano has been producing ejecta on the western side of the mountain for thousands of years, leading to a system of ash dune fields over a distance of more than 45 km, that is, between the Ootun area and the Shifting Sand to the west of the mountain (see Fig. 7). Ash remobilisation is exposed mostly in arid and high-altitude volcanic systems around the Earth. Apart from the Ngorongoro in Tanzania (Fig. 14), there are numerous ash dune fields, for example, in Libya, Hawaii, Saudi Arabia, the Canaries, New Zealand and Yasur on Tanna Island in Vanuatu (Cowie, 1964; McPhie et al., 1990; Németh et al., 2009; Shalabi et al., 2021).

The migration of the Shifting Sand from the Oldoinyo Lengai tephra depositions in the Ootun area, according to Hay (1976) and Belsky & Amundson (1986), started 1,300 years ago. In contrast, Kafumu (2020) suggested that the migration took place over a period of about 3,000 years. Both of these dates were based on conjecture and lack scientific evidence. The present study redefines the age of the Shifting Sand using radiometric (^{14}C) dating to be younger than 2,510 ± 30 years. The average Shifting Sand speed is about 18 m/year, as reported by Belsky & Amundson (1986), Freymann & Krell (2011) and Kafumu (2020). Thus, the distance between the Shifting Sand at the Olduvai Gorge and the Ootun area (45 km) divided by the average speed of the Shifting Sand dune (18 m/year) yields about 2,500 years (see Fig. 9). This is roughly in line with the results obtained in the present study, determining the number of years in which the examined dunes migrated from the Ootun territory to the Shifting Sand area.

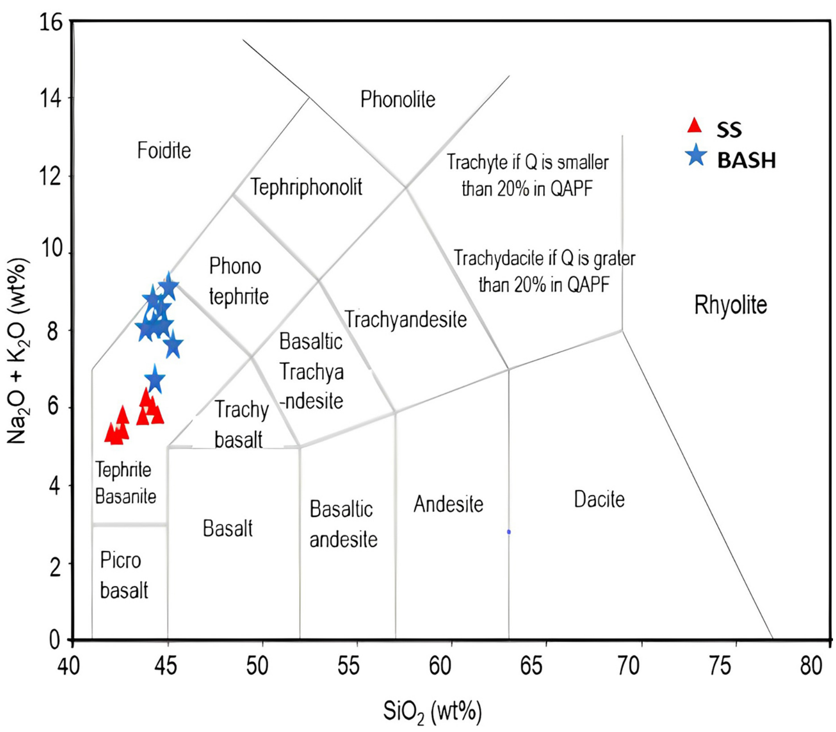

Fig. 13. The TAS diagram plots for the same samples as in Figures 11 and 12 samples to classify volcanic rocks. All samples are placed in the tephrite basanite group. Note that the tephra layer (BASH) is buried and attains little or no alterations at all, while slight chemical and mineralogical alterations due to environmental changes and contamination that have occurred over thousands of years of migration take place in the case of the Shifting Sand dunes (SS); the minor differences in their chemical composition are clearly seen (compare Figs 12 and 13; Table 2).

Based on the geographical features and the prevailing winds, we have created a simplified theoretical model showing the trajectory from the source tephra/ash in the Ootun area to the Olduvai Gorge area (with the Shifting Sand) migrated for about 2.5 kyrs (Fig. 15). The position of the Shifting Sand has changed over time. According to this trajectory, the region has experienced a change in wind direction from west-southwest to west. Most likely, this was caused by the topography of the area, that is, sur-

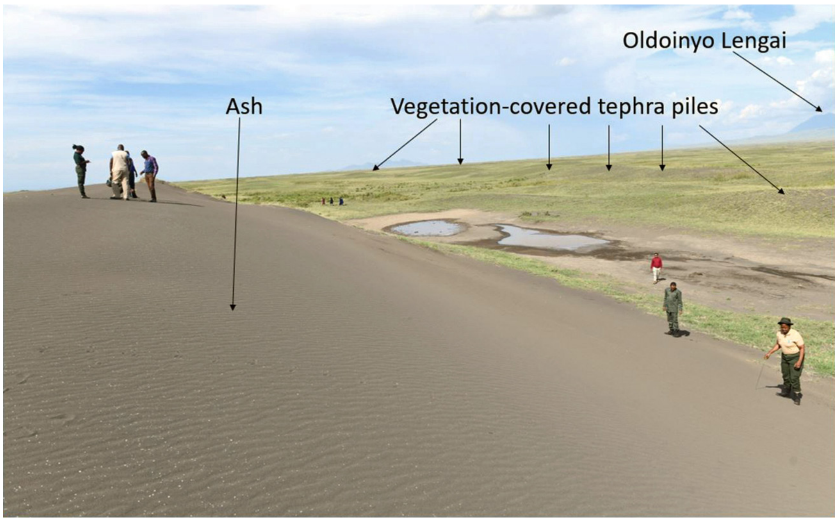

Fig. 14. View of the Ootun area during the rainy season. Note the flat landscape featuring several ash/tephra piles fallouts from the Oldoinyo Lengai volcano.

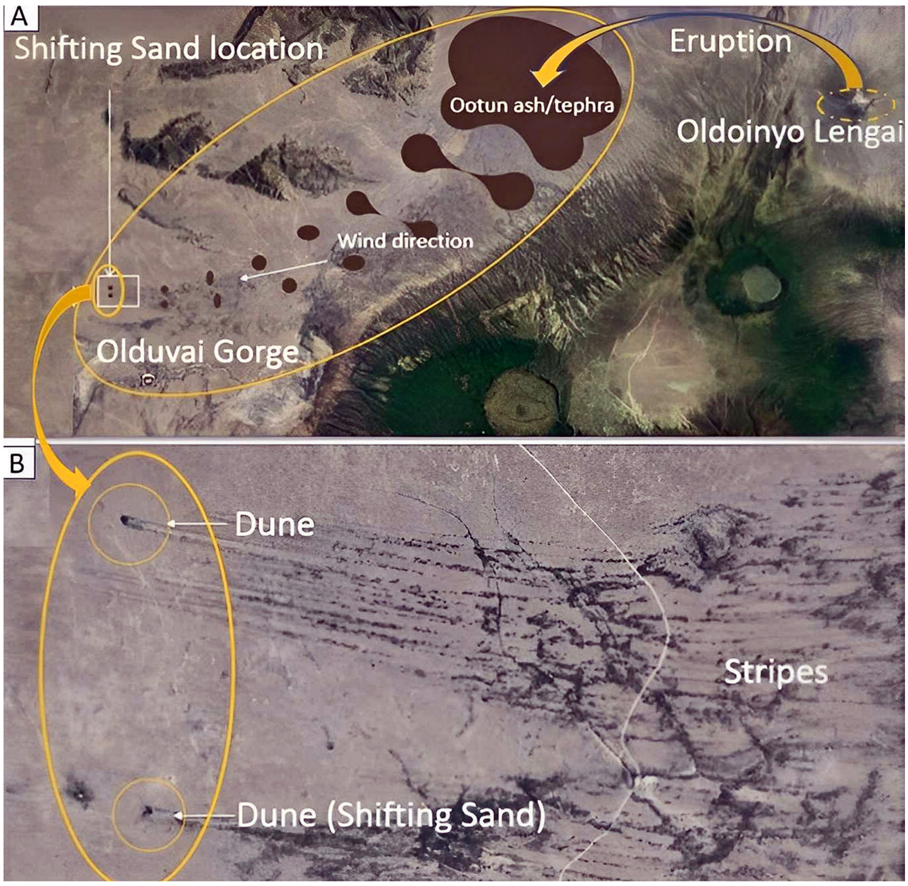

Fig. 15. Simplified theoretical model showing the source (tephra/ash) Oldoinyo Lengai volcano, formation and propagation of the ash dunes from the Ootun area to the Olduvai Gorge area. **A** – General view of study area topography; **B** – Close-up view of the Olduvai Gorge area with exact position of the Shifting Sand dune at 2°56'41"S and 35°18'48"E (source: Google Earth).

rounded by hills (with the extent of NE–SW) in the vicinity of the Ootun area and relatively flat towards the Olduvai Gorge (compare Figs 1, 5, 7 and 15).

Knowledge of the Shifting Sand dune, which includes the source tephra/ash, dune geomorphology and dune propagation, is essential and beneficial to visitors for understanding its history. Such information can be preserved at the Olduvai Museum located in the Olduvai Gorge area (see Fig. 1). All historical data and archaeological evidence in the area regarding the Ngorongoro Lengai Geopark are housed at this museum.

5. Conclusions

The present paper reports radiocarbon (^{14}C) dating results in order to estimate the age of the Shifting Sand dune. The study area is about 45 km from the source subsurface tephra in the Ootun area, at the Ngorongoro Lengai Geopark in northern Tanzania. Accelerator Mass Spectrometry (AMS) was used to measure carbon-14 of the subsurface palaeosol as an indirect method of estimating the age of the source tephra, which was implied to be the relative age of the Shifting Sand dune correlated with the Ootun tephra.

Radiocarbon (^{14}C) dating results of 2,510 ± 30 years have been supplied in this research to define the age of the Ootun subsurface tephra. Consequently, the relative age of the Shifting Sand was determined to be less than 2.5 kyr. Furthermore, the present study adds educational value to the Shifting Sand in the Ngorongoro Lengai Geopark. In brief, it improves our understanding of the history of eruptions of the Gregory Rift Volcanoes (GRV).

Acknowledgements

The authors are grateful for valuable contributions by the management and staff of the Ngorongoro Conservation Area Authority (NCAA) in Tanzania during fieldwork in the study area. Acknowledged also are the laboratory staff of the Geological Survey of Tanzania and the Beta Analytic Testing Laboratory (Miami, Florida, USA) for chemical and radiocarbon dating analyses. Last, but not least, the authors are very grateful to the two anonymous reviewers for critical remarks that have improved an earlier typescript.

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Manuscript submitted: 31 August 2022
Revision accepted: 23 October 2022