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Luminescence Dating of Holocene Siliciclastic Sediments in Eastern Dahomey Basin, Southwestern Nigeria

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Abstract

Several attempts at reconstructing geological settings and palaeoclimatic changes of the siliciclastic deposits of the Dahomey Basin, SW Nigeria, using relative age dating and correlation methods, have resulted in serious discrepancies on the ages. Therefore, a chronology framework established by an absolute age dating method is requisite to constrain the geological interpretation. This research focuses on quartz optically stimulated luminescence (OSL) dating of the upper siliciclastic sediments to help bridge the lacuna that arose from previous relative geologic dating. Ten sub-surface sediment samples were collected from the eastern part of the basin, and quartz OSL dating using single-aliquot regenerative-dose protocol was conducted for all the samples. The OSL signals appear well bleached prior to deposition and the OSL ages are reliable and robust. Through the application of OSL, the age framework of the uppermost part of sediments in the study area was established. The OSL dating results revealed that these depositional periods fall within the Holocene and are concentrated during two groups: 3.52 ka–1.55 ka, and 0.64 ka–0.05 ka. The samples with ages of 3.52 ka–1.55 ka distribute in the belt-like inland zone approximately parallel to the coastline. This deposition episode appears to be caused by the decrease in relative sea level during late Holocene. Thus, this study sheds light on the understanding past coast dynamics in the region.

Keywords: Luminescence dating; Quaternary; Holocene; Dahomey Basin; Nigeria

1. Introduction

Various research work has been conducted within the Dahomey Basin due to their geologic peculiarity and economic importance (Adegoke, 1980). Exploration of bitumen, limestone, glass sands and phosphates (Nton et al., 2006) has been undertaken with discovery of crude oil in 1908 (Billman, 1982). This has sprung up great geological interest for further research in the basin for hydrocarbon potential (Elueze and Nton, 2004). The knowledge of age of the deposits will provide crucial information for future exploration of these natural resources and understanding the evolution of coastal environment in the Dahomey Basin.

Previous researches had postulated ages for the sediments in the Dahomey Basin through the application of series of relative age dating approaches, including age correlation of the basin (Jones and Hockey, 1964; Reyment, 1965), dating of available pollen (Agagu, 1985) and paleontological approach (Adegoke, 1969; Olabode and Mohammed, 2016). This has resulted in serious age discrepancies ranging from Maastrichtian to Quaternary ages (Olabode et al., 2016). Hence, there is an urgent need to adopt absolute age dating method to resolve and bridge the lacuna arising from the various age differences of the siliciclastic deposits.

Optically simulated luminescence (OSL) is one of the most intensively and veritably used numerical dating techniques to determine the age of Late Quaternary sub-surface sediments (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006; Chen et al., 2015; Zhang et al., 2018). OSL dating techniques (Duller, 2004; Olley et al., 1998, 1999) work well not only on sediments where grains have adequate exposure to sunlight at the time of deposition (Rhodes, 2007), but also on samples which were poorly bleached prior to sedimentation (Zhao et al., 2015, 2017). It is applied by estimating the impact of radiation on the crystalline structure of quartz mineral mostly presented in all sedimentary environments isolated from light (Wintle, 1997, 2008; Murray and Wintle, 2000, 2003). The OSL signal observed from quartz revealed several exponentials relative to different levels of traps (Bailey et al., 1997) and successful OSL dating is dependent on a fast signal component (Murray and Wintle 2000). This research aims to determine the age of the uppermost alluvial deposits in the eastern Dahomey Basin to help bridge the long touted age disparities of the formation in previous research (Jones and Hockey, 1964; Agagu, 1985; Omatsola and Adegoke, 1981).

2. Geologic and tectonic settings of the Dahomey Basin

The Dahomey Basin, also called Benin Embayment, is located on the shore of West Africa (Whiteman, 1982), with coordinate of latitude 6°10'N to 6°25' N and longitude 4°30' E to 4°50' E respectively (Fig. 1). It is a rift or marginal pull-apart basin (Whiteman, 1982) or marginal sag basin (Kingston et al., 1983), part of the West African pre-cratonic basins (Mpanda, 1997) which was initiated during the early Cretaceous separation of the South American and African plates, and opening of the South Atlantic Ocean (Adegoke, 1980; Omatsola and Adegoke, 1981). The Dahomey Basin is a combination of inland, coastal, offshore settings that stretches from southeastern Ghana through Togo and the Republic of Benin to southwestern trending along the east-west direction in Nigeria, with Cretaceous strata along the shore estimated to be about 200 m thick (Okosun, 1990; Olabode and Mohammed, 2016). The geologic, stratigraphic, sedimentological and organic geochemical studies of different parts of the alluvial deposits in the Dahomey Basin have been reported (e.g., Idowu et al, 1993; Adekeye, 2004; Adekeye et al., 2006; Nton et al., 2006; Ikhane et al., 2014).

The study area is located in eastern part of the Dahomey Basin, in the area or vicinity of Ilaje community in coastal environment of Ondo state (Fig. 1). The coastal vegetation along the beach is dominate mangrove (Awosika and Folorunsho, 2010) with some coconut trees, palms, sedges and climbers. The study area is a barrier lagoon coastal complex (Woodroffe and Horton, 2005; Awosika and Folorunsho, 2010), stretching from around Agerige community where the coastline starts a southward variation. It consists of beach ridges adjoined with a foreshore of more than 50 m above the sea level similar to that of modern coast. The beach crest elevation generally ranges from 3 to 4 m above mean water level. Relief ranges from sea level along the coast backed by a wide expanse of tidal flat with the coastal plain relief rising gently from 2 m to about 50 m above mean sea level. This barrier lagoon bar experiences tides, current waves and predominantly of long shore currents generated by south-westerly breaking waves at various degrees. Though the tidal range is relatively small, the effects of tides on the general morphology of the coastline are very significant.

The alluvial sediments here were previously inferred a Pleistocene or Holocene age by relative dating (Omatsola and Adegoke,1981; Agagu,1985). The alluvial plain is lithologically indistinguishable from typical coastal plain sands strata. The high-level terraces are rarely exposed, although few sections were seen around Ofada and Moloki on the Ogun River bank. The sediments are made up of medium to slightly fine grained, well sorted to moderately well sorted sands. Quaternary sediments mainly consist of recent alluvium (Agagu, 1985), underlain by siltstone/ mudstone described by Omatsola and Adegoke (1981).

3. Materials and methods

3.1 Materials

In this study, 10 representative samples were collected from the study area in the eastern Dahomey Basin (Fig. 1). The samples are from sub-surface and unconsolidated in nature. Texturally, the samples are fine to coarse grained sand with an average 85.0% of the samples being medium grained sand. The colour ranges from white to light greyish and brownish red, an indication of high impurities. During sampling, surface sediments were removed, then the stainless-steel tube with 30 cm long and 5 cm diameter was hammered to allow the sample fill the tube. The tube was sealed at both ends using aluminum foil and wrapped with the black nylon to prevent it from sunlight reflection. Then each of the samples was properly preserved in a sealed opaque container and clearly labelled for laboratory analysis.

3.2 OSL dating method

The single-aliquot regenerative dose (SAR) protocol was widely adopted to determine the equivalent dose (D_e) of quartz samples (Murray and Wintle, 2000; Roberts and Duller, 2004; Lai and Wintle, 2006; Rodnight, et al., 2006; Wang et al., 2006; Roberts, 2007; Lai, 2010; Chen et al., 2012). This can then be calculated from the ratio of the natural and regenerated luminescence signals (Murray and Wintle, 2003; Yang et al., 2014). Both natural and regenerative signals (Buylaert et al., 2008; Kang et al., 2013) are normalized with a successive test dose which are used to monitor and correct for a potential sensitivity change. This radiation (α, β and γ) from the radionuclides in the mineral and its natural environment determined by either gamma spectrometry, neutron activation analysis, or alpha counting (Aitken, 1985; Guérin et al., 2012) can be converted into alpha, beta and gamma dose rate using conversion factors (Stokes et al., 2001; Chen et al., 2012).

3.2.1 Sample pretreatment

Preparation of the samples and OSL experiments were conducted under a subdued red light in the luminescence dating laboratory, Key Laboratory of Tourism and Resources Environment in Universities of Shandong, Taishan University, Taian City, China. The two outer ends of each sample in the steel tube were removed for water content and dose rate analysis, while the remaining sediment was pretreated for luminescence measurement.

The remaining samples in the middle part of the tube were pretreated following the routine procedures, including treatment with 10% HCl and 10% H_2O_2 to remove carbonate and organic matter, respectively. After wet sieving, grains in the range of 150–250 μm were extracted. The coarse fraction was then cleaned with 10% HF for 20 minutes to remove coatings and the outer alpha irradiated layer, and rinsed in 10% HCl to remove any precipitated fluorides. Subsequently, the remaining grains were separated by heavy liquid to extract quartz grains ($2.62 < \rho < 2.75$ g/cm^{-3}). The purity of quartz was checked by IR depletion ratio method (Duller, 2003) and 110 °C TL peak (Jain et al., 2004). The quartz grains of each sample were mounted as small (2mm diameter) aliquots on a stainless-steel discs, and twelve discs were measured for each sample.

3.2.2 Dose rate determination

Determination of the sediment dose rate involves assessment of concentrations of U, Th and K in the sample, water content and cosmic ray dose contribution. The environmental dose rate was determined by the U, Th and K concentrations, measured by neutron activation analysis (NAA) method in the Chinese Atomic Energy Institute. The U, Th and K concentrations were converted to dose rates (Aitken, 1998). The total environmental dose rate, including the contribution from cosmic radiation, was calculated according to Adamiec and Aitken (1998). The cosmic ray dose contribution was estimated as a function of longitude, latitude, altitude and depth (Prescott and Hutton, 1994). The in situ water content was measured by weighing the sample before and after drying (mass of moisture/dry mass), and was assigned an absolute uncertainty of ±5%.

3.2.3 Equivalent doses determination

D_e were estimated using the improved SAR protocol (Murray and Wintle, 2000, 2003; Wintle and Murray, 2006; Rittenour 2008). Its determination includes irradiation, preheating and stimulating procedures. The procedures were conducted using an automated Risø TL/OSL DA-20 reader equipped with blue LEDs (470 nm, ~80 mW cm^{-2}) and infrared LEDs (875 nm,

~135 mW cm^{-2}) (Bøtter-Jensen et al., 1994; Stokes, 1999). The irradiation procedure adopted a $^{90}Sr/^{90}Y$ beta source which was fitted on the reader with a dose rate of ~0.10 Gy/s to quartz grains in stainless steel discs. The preheating was set at 160 °C for 20 s, based on the preheat plateau and thermal transfer tests. The optical stimulation was conducted using blue light-emitting diodes (LEDs) for 40 s at 125 °C. This was detected using a 9235QA photomultiplier tube through a 7.5 mm thick U-340 filter. The OSL signals for the D_e determination were derived from the first 0.64 s stimulation minus a background of the following 0.64 s of stimulation.

Preheat plateau test was carried out on samples MHN R2 and ARR R4 to show the variation in dose with different preheats. The aliquots were bleached under blue light for 100 s at room temperature, with an intervening gap of 1000 s, a set of four aliquots were later measured at preheat temperatures from 160 to 260 °C, with a step of 20 °C. The results of the preheat plateau tests (Fig. 2c) showed that the D_es obtained by the SAR protocol are insensitive to preheat temperature in range between 160 °C and 260 °C. For both samples (MHN R2 and ARR R4), all the recycling ratios are close to 1, while the recuperation values are less than 3%, especially at 160 °C.

Young quartz samples may be affected by thermal transfer (Wintle and Murray, 2006). The thermal transfer test as a function of preheat temperature was conducted for sample ARR R4 (Fig. 2d). The unheated aliquots were bleached twice under the blue light for 100 s at room temperature with an intervening pause of 10 ks to allow charge optically transferred into the 110 °C TL peak to decay. For sample ARR R4, four aliquots were determined at each preheat temperature between 160 °C and 260 °C (in increments of 20 °C). As shown in Fig. 2d, there was no significant thermal transfer from 160 °C to 200 °C. Based on the preheat plateau and thermal transfer tests, a preheat temperature of 160 °C was selected for the quartz D_e measurements.

The suitability of the procedure for D_e determination with the selected settings was checked with a dose recovery test (Murray and Wintle, 2003). Nine natural aliquots of the sample ARR R4 were stimulated twice by blue-light stimulation at 125 °C for 40 s. A laboratory dose 1.12 Gy was then administered, close to their expected natural D_es. The average dose recovery ratio is 1.01 ± 0.01, which shows the selected SAR protocol is suitable for D_e determination.

4. Results

4.1 Quartz luminescence characteristics

The dose response curve and natural OSL decay curve (insert) of the representative samples are shown in Fig. 2a and 2b. The decay curve of the samples resembles that of the calibration quartz sample. The blue-light stimulated OSL signals decreased very quickly, which indicates the OSL signals were fast-component dominated and that the sample was appropriate for OSL dating (Jain et al., 2003). The regeneration dose of 0 Gy was used to measure recuperation, which was calculated by comparing the sensitivity corrected OSL signal of the zero dose to the sensitivity-corrected natural signal. Recuperation was in all cases <3% for all samples. The recycling ratio, the consistency between the first regenerative dose and the repeated dose, suggested that the sensitivity changes during analysis were adequately corrected. The recuperation and recycling ratio show the reliability of the SAR protocol.

The preheat plateau tests indicated that the D_es obtained by the SAR protocol are independent of preheat temperature (Fig. 2c). The thermal transfer test shows the variations in D_e were negligible from 160 °C to 200 °C, suggesting suitable preheating temperature range (Fig. 2d).

The D_e values are relatively low, and the majority of the D_e values fall in narrow range between 0.04 and 1.40 Gy. The Abanico plot of D_e distributions (Dietze and Kreutzer, 2019) of two representative samples (MHN R2 and ODE R10) diplay normal and narrow distributions (Fig. 2e and 2f), indicating that the quartz particles were well bleached prior to burial and the optical bleaching of the siliciclastic sediment in this study area was effective. The study sediments may have experienced transportation mechanisms possibly from the tidal current in the adjacent Atlantic Ocean, coupled with flood and erosion from the adjoined basement complexes. Therefore, all the D_e for OSL ages calculation were acquired using the average of twelve discs of each sample. The OSL dating results are summarized in Table 1.

4.2 OSL age of the sediments

The results of OSL age dating, including the dose rates, equivalent doses and ages are listed in Table 1. The OSL ages are also displayed in the map (Fig. 3). The concentration of the radioactive elements in the siliciclastic sediments are 0.36–10.1 ug/g (Th), 0.17–1.98 ug/g (U) and 0.011–0.469% (K) with mean values of 2.275 ppm for Th, 0.49 ppm for U and 0.135 % for K, respectively. The water content ranged from 1 to 20 %. The time-averaged water content available in the sediment throughout its burial is an important, but a difficult parameter to assess (Cordier, 2010). Estimated value of the moisture content in these study sediments may not be well indicative of the entire period of burial, but may reflect the relative contribution to the effective dose rate. The dose rates range from 1.54±0.066 Gy ka^{-1} to 0.22±0.041 Gy ka^{-1}, which are typical for coastal sediments (Kunz et al., 2010), and the D_e values, from 1.4±0.03 to 0.04±0.01 Gy. These yield OSL ages of the siliciclastic sediments ranging from 3.52±0.34 ka to 0.05±0.01 ka. The two oldest samples OKG R3 and MHN R2 have OSL ages of 3.52±0.34 ka and 3.01±0.39 ka, respectively.

The OSL ages show that the deposits are of late Holocene. It was observed that the deposits are thicker in northern part of the study area. The extent of sampling depth was constraint with shallow groundwater table and showed no spatial trend (Fig. 3). However, the spatial changes in age of the samples appear two belt-like distributions, with the exception of young age (1.55±0.15 ka and 0.33±0.08, respectively) at the ORR and ZER barriers in the northeast part of the study area. The inland belt has ages ranging from 3.01±0.39 ka to 1.55±0.15 ka, while the coast belt has ages ranging from 0.64±0.06 ka to 0.05±0.01 ka. These two belts approximately parallel to the coastline (Fig. 3). The ages of samples in this area yield a rate of coastal progradation approximately 20 km in 3.5 ka, i.e. 5.7 km/ka.

5. Discussion

Ages of the study samples range from 3.52 ka to 0.05 ka. The result of OSL dating are reliable as evidenced by the good dose recovery and a signal dominated by a fast component. The very young age for the sediments is in contrast with some previous researches (Omatsola and Adegoke, 1980; Billman, 1982), in which they used relative age dating techniques to adopt a Tertiary age for the sediments. The Tertiary sediment could have experienced reworked processes, transportation and re-deposited in the late Holocene. The variations in ages of these samples might be an indication of various depositional episodes during the Holocene epoch.

The thickness of the investigated siliciclastic sediments varies from 0.4 m to about 0.8 meters, while the deeper sediments could not be sampled in this study due to shallow groundwater table in the region. The spatial changes in age of the samples appear two belt-like distributions, with the exception of young age of the two samples in the hinterland (Fig. 3). Geomorphologically, the belts parallel to the barrier bars along coastlines. It is highly possible that the sediments with age of 0.64 ka–0.05 ka in the belt close to the coastline have disturbed by modern tide activities. Therefore, we mainly focus on the belt with age range of 3.52 ka–1.55 ka.

The deposition episode of 3.52 ka–1.55 ka could have resulted from one or combination of two factors which include: 1) decrease in relative sea level; and 2) increase in flood activity. Decrease in relative sea level is at least partly responsible for this deposition episode. Decrease in relative sea level could be caused by basin uplift and/or decrease in sea level. The knowledge of the tectonic movements in the region during the Holocene has been lacked. Olabode (2015) analyzed tectonic evolution in the Dahomey Basin since Cretaceous, based on data of one dimensional backstripping analysis on three offshore wells, and concluded that the basin has been experienced accelerated tectonic subsidence during Quaternary period. This may provide information of tectonic background for understanding the Holocene sedimentation, but is contrary to the deposition episode in the interval 3.52 ka–1.55 ka that suggests basin uplift.

Decrease in sea level may also contribute to the formation of sediment in this older hinterland belt. However, it is generally accepted that global sea level has been increasing in the Holocene, and there is a progressive decrease in rise rate from 6.7 ka to recent time, within which main rise occurred in the interval 6.7–4.2 ka (Lambeck et al., 2014). Many physical processes, such as crustal rebound, continental levering, ocean syphoning, etc., produce distinctive spatial and temporal patterns in relative sea level during late Holocene (Barnett et al., 2019). It is still an open question what specific mechanism that drive relative sea level in the study region.

Increase in flood activity that brings materials for the sediment may be another factor, although the supply of reworked Tertiary sediments can not be precluded. The rivers (Ofara, Oluwa, Talita and Alape Rivers) drains across the study area. Salzmann and Hoelzmann, based on pollen and geochemical analysis, showed in southern Benin of Gulf of Guinea, an episode of wetting climatic conditions occurred between 3.3 ka and 1.1 ka. This is timely consistent with age of sediments in the range of 3.52 ka–1.55 ka. It is possible that increased river flooding during the wet period had brought more sediments deposited in the hinterland of the study area, in addition to the reworked older sedimentary rocks.

Presently, it is difficult to determine which factors are responsible for the deposition episode during the period of 3.52 ka–1.55 ka. Understanding of previous coastal fluctuations is crucial to envisage the present dynamics of the coasts within the framework of long-term fluctuations (Masselink and Gehrels, 2014). Depositional changes in the coasts occur relative to many factors which includes: sea level fluctuation, basin uplift, flood and sediment supply, climate and human activity. Past changes associated with variations in these factors may inform our understanding of future changes in the coast area. Further investigations with large spatiotemporal coverage in the region are needed in future to better understand the past dynamics of the coasts in the region.

6. Conclusion

This study presents the first OSL dating of the coastal sediments, with large spatial coverage in the eastern Dahomey Basin. The OSL results revealed that the ages of the surficial sediments in the eastern basin range from 3.5 ka to 0.05 ka, indicating that the deposits are very young Quaternary deposits, specifically of Holocene Epoch. The young ages contradict the assertion of some previous researcher (Billman, 1982) who adopt a Tertiary age for the sediments using relative age dating techniques. The age of the sediments varies spatially from the northeast to southwest of the study area, indicating the sediments are result of the regressive depositional episodes that occurred in the study area. The decrease in relative sea level and/or in river flooding during the wet climatic conditions may be responsible for the elder deposition episode of 3.5-1.5 ka in the region. Therefore, this study provides first chronological constraints on evolution of the coast area and the linkage with relative sea level changes (linked with both the sea level and tectonics) during the late Holocene.

Author contributions

Richard O. Fakolade: Investigation, Writing - Original Draft, Visualization. Philip R. Ikhane: Conceptualization, Writing - Review & Editing, Supervision. Qiuyue Zhao: Conceptualization, Methodology, Writing - Review & Editing, Supervision. Qingzhen Hao: Conceptualization, Validation, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. Helena Alexanderson: Methodology, Editing. Zhengtang Guo: Conceptualization, Validation, Resources, Writing – Review & Editing, Funding acquisition.

Data availability

All data included in this study are available upon request by contact with the corresponding author.

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Figure Captions

Figure 1. Maps of the study area (Modified after NGSA, 1969).with locations of the OSL samples.

Figure 2. Quartz luminescence characteristics of the representative samples. (a) and (b) Dose response curves of the typical samples OKG R3 and AGG R8, respectively. Inset shows the natural decay curves. (c) D_e values versus preheat plateau tests for two typical samples of MHA R2 and ARR R4. (d) Thermal transfer test of the typical sample ARR R4. (e) and (f) The Abanico plot of D_e distributions of two typical samples MHN R2 and ODE R10, respectively.

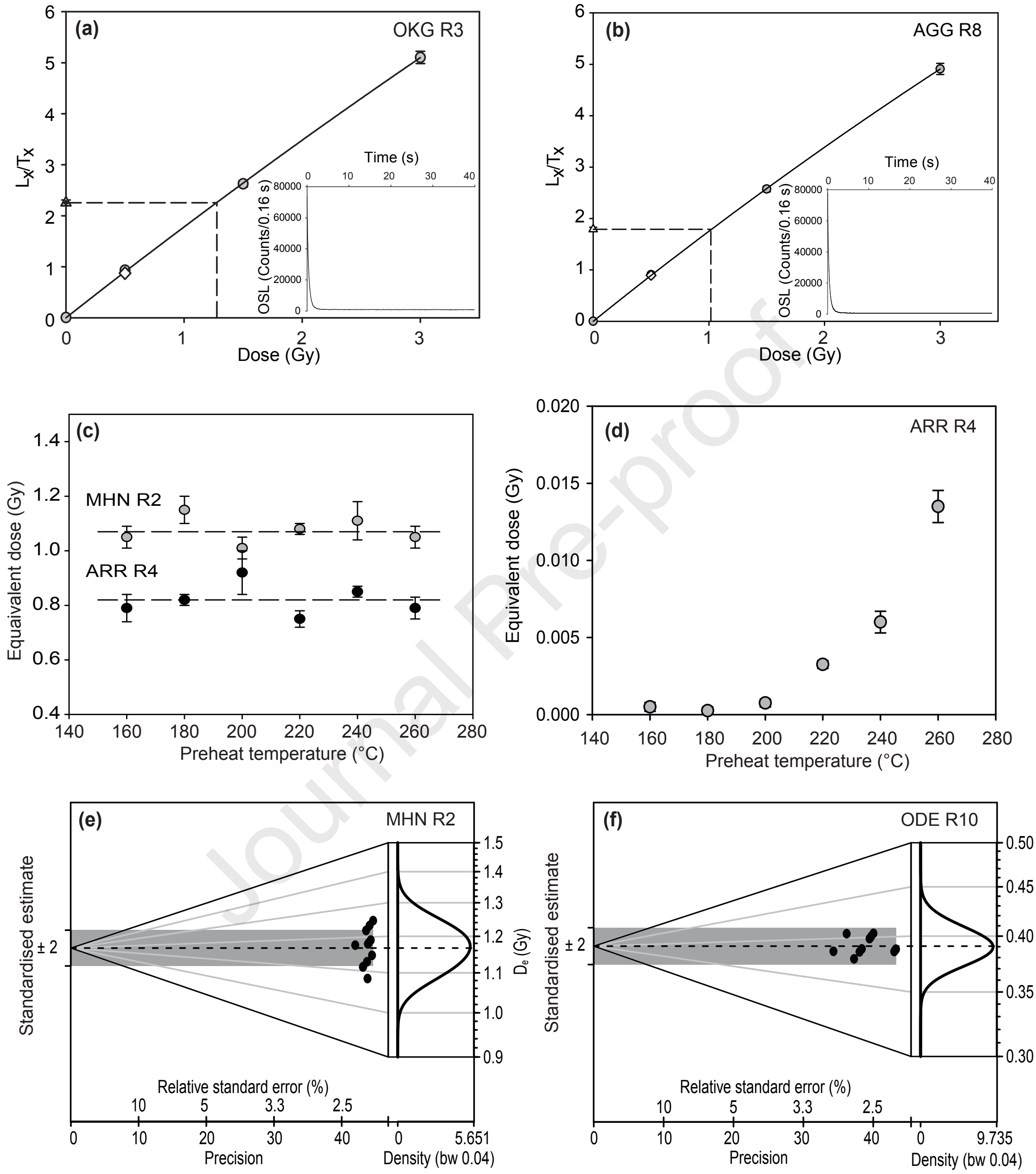
Figure 3. Map of study area showing the OSL ages. The zone outlined by yellow line indicate the first episode of sedimentation in mostly of barrier bar, and the zone outlined by blue line indicate littoral zone.

List of Table

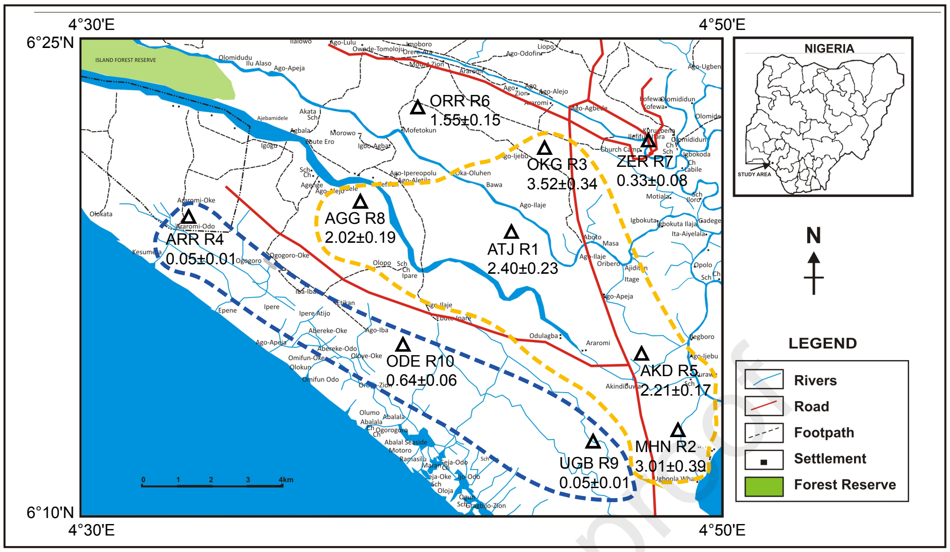
Table 1. Summary of sample location, the burial depth, radionuclide concentrations, calculated dose rate, quartz D_e values and luminescence ages.

Sample code	Latitude (°N)	Longitude (°E)	Altitude (m)	Depth (m)	Grain size (μm)	Water content (%)	U (μg/g)	Th (μg/g)	K (%)	D_e (Gy)	Dose rate (Gy/ka)	Age (ka)
ATJ R1	6.31	4.75	6.00	0.80	150–200	4.0	0.32	1.61	0.054	0.93±0.03	0.39±0.035	2.40±0.23
MHN R2	6.20	4.78	3.20	0.50	150–200	3.0	0.17	1.25	0.011	1.17±0.02	0.39±0.049	3.01±0.39
OKG R3	6.38	4.76	7.60	0.60	200–250	14.0	0.35	1.55	0.011	1.40±0.03	0.40±0.037	3.52±0.34
ARR R4	6.34	4.49	1.46	0.45	200–250	6.0	1.98	10.70	0.216	0.08±0.01	1.54±0.066	0.05±0.01
AKD R5	6.26	4.77	1.97	0.60	150–200	14.0	0.58	1.19	0.090	1.08±0.02	0.49±0.036	2.21±0.17
ORR R6	6.38	4.74	8.50	0.60	150–200	1.0	0.29	2.01	0.024	0.76±0.03	0.49±0.043	1.55±0.15
ZER R7	6.38	4.78	9.40	0.80	150–200	18.0	0.21	0.49	0.011	0.07±0.01	0.22±0.041	0.33±0.08
AGG R8	6.31	4.63	10.40	0.40	150–200	8.0	0.34	0.36	0.175	1.00±0.03	0.50±0.044	2.02±0.19
UGB R9	6.15	4.79	27.20	0.45	200–250	12.0	0.24	1.91	0.469	0.04±0.01	0.79±0.039	0.05±0.01
ODE R10	6.29	4.62	8.50	0.50	150–200	20.0	0.42	1.50	0.299	0.39±0.03	0.61±0.034	0.64±0.06


Atijera
ORR R6
ZER R7
Igbokoda
Shabomi
OKG R3
ARR R4
AGG R8
ATJ R1
ODE R10
AKD R5
Legend
Site for OSL
Town
Aiyetoro
UGB R9
MHN R2
Mahin
Google Earth
10 km
N



(a)
OKG R3
L_x/T_x
Dose (Gy)
Time (s)
OSL (Counts/0.16 s)
(b)
AGG R8
(c)
MHN R2
ARR R4
Equaivalent dose (Gy)
Preheat temperature (°C)
(d)
ARR R4
Equivalent dose (Gy)
(e)
MHN R2
Standardised estimate
± 2
D_e (Gy)
Relative standard error (%)
Precision
Density (bw 0.04)
(f)
ODE R10


4°30'E
4°50'E
6°25'N
6°10'N
NIGERIA
STUDY AREA
N
LEGEND
Rivers
Road
Footpath
Settlement
Forest Reserve
ISLAND FOREST RESERVE
ORR R6
1.55±0.15
OKG R3
3.52±0.34
ZER R7
0.33±0.08
AGG R8
2.02±0.19
ATJ R1
2.40±0.23
ARR R4
0.05±0.01
ODE R10
0.64±0.06
AKD R5
2.21±0.17
UGB R9
0.05±0.01
MHN R2
3.01±0.39
0 1 2 3 4km

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Qingzhen Hao