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Temporal Changes in Land-Sea Configuration Inferred from Post-Glacial Sedimentation Pattern in the Western Great Rann of Kachchh, India

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Abstract

The sedimentology and geochemistry, supported by the published AMS radiocarbon and optical chronology of the sediment core raised from the Western Great Rann of Kachchh (WGRK), are used to reconstruct the pattern of post-glacial sedimentation. The study indicates that the hinterland fluvial system (viz. the Indus and the western Himalayan Rivers) was responsible for the sedimentation in the WGRK. The continental sediment fluxes were influenced by the post-glacial gradual strengthening of the Indian Summer Monsoon (ISM). During the latter part of the mid-Holocene, continental sediment flux was reduced due to the expansion of the marine transgression which persisted, albeit with hiatuses, until around 1 ka. The geochemical analysis of major, trace and Rare Earth Elements points to a mixed sediment provenance that varied over time from the post-glacial period to the late Holocene. More specifically, it has been observed that the major contribution, in varied proportions, came from the upper Indus catchment and the Western Himalayan Rivers, with subordinate input of the fluvially reworked aeolian sands. This study thus provides insight into the sedimentological evolution of one of the least studied Quaternary landforms in Western India, which is barely above the mean sea level and currently devoid of any active fluvial system.

Keywords: Western Great Rann, Sedimentology, Geochemistry, Radiocarbon and Optical Chronology, Indian Summer Monsoon

Introduction

Relict tidal flats are prevalent geomorphic features, particularly along coastlines characterized by low-lying alluvial landscapes. They indicate that the terrain was once inundated during tidal ingression, and is currently situated marginally above the ambient tidal amplitude. The sediment associated with the relict tidal flats is not only used to reconstruct temporal changes in the land-sea configuration but also to glean information about climate variability (Kumar *et al.,* 2023; Sharma *et al*., 2020; Allen, 2006; Allen and Haslett, 2002). The Western Great Rann of Kachchh (WGRK) in India is one such geomorphic entity that emerged from the tidal influence in the recent geological past; hence, the upper sediment succession provides information about the temporal changes in late quaternary land-sea configuration (Sharma *et al*., 2020; Tyagi *et al*., 2012). Geomorphologically, it is surrounded by the Indus Delta to the west, the Thar Desert to the north, the Aravalli Hills to the northeast and the Kachchh Mainland in the southwest (Fig.1). It has been suggested that the coupled continental and marine processes influenced the pattern of sedimentation particularly in the WGRK (Tyagi *et al*., 2012; Glennie and Evans, 1976; Srivastava, 1971). In the present day, WGRK remains mostly dry during summers and submerged during monsoons by storm tidal surges. In the geological past, continental sediments were contributed by the ephemeral Nara River, while the marine contribution was routed through the Kori Creek (Sharma *et al*., 2020; Tyagi *et al*., 2012; Glennie and Evans, 1976). There is also a suggestion that the presently extinct Vedic Saraswati River (Ghaggar-Hakra-Nara River system) flowed into the Arabian Sea through the WGRK (Sinha *et al*., 2013; Gupta *et al*., 2011; Ghose *et al*., 1979). Tyagi *et al*. (2012) were the first to provide the chronologically constrained mid-Holocene sedimentation, climate, and tectonics pattern inferred based on shallow sediment sections excavated atmultiple locations in the WGRK. Employing the conventional sedimentology, supported by geochemistry and optical dating, Tyagi *et al*. (2012) and Ngangom *et al*. (2012), suggested that during the mid-Holocene, sedimentation in the WGRK was dominated by a tidal flat environment when the sea was marginally high compared to the present. Whereas the continental contribution (fluvial sedimentation) was limited to the northern fringe, proximal to the present-day parabolic dune field located north of the Nagar Parker Fault (NPF). According to them, the

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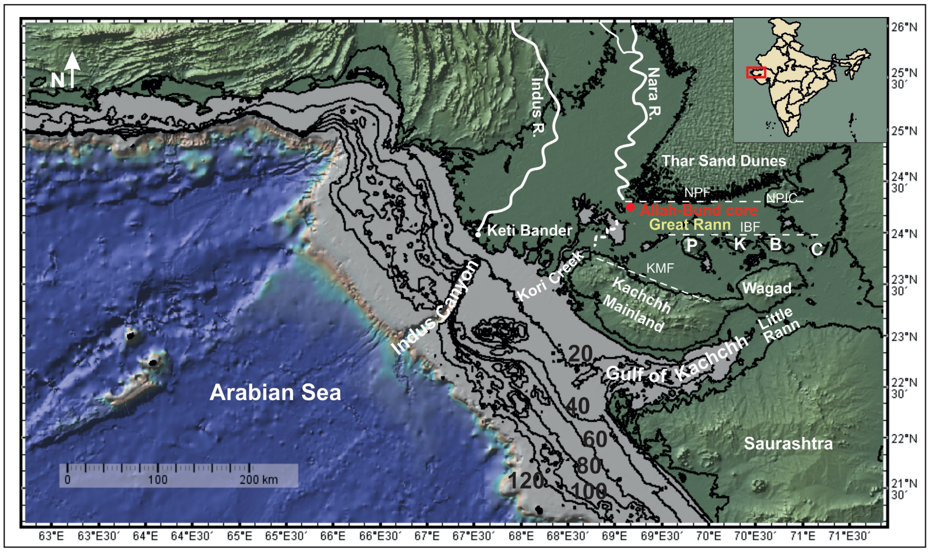

Fig.1. Map showing the location of the study area (Allah-bund core) along with the present bathymetry of Gulf of Kachchh. (NPF-Nagar Parkar Fault; IBF-Island Belt Fault; KMF-Kachchh Mainland Fault; P-Pachham Island; K-Khadir Island; B-Bela Island; C-Chorar Island; NPIC- Nagar Parkar Igneous Complex).

withdrawal of the intertidal environment from the major part of the western Great Rann, at the expanse of continental sedimentation, occurred during the later part of the late Holocene for which a major tectonic upheaval between 2.2-1.4 ka was implicated whereas the present-day geomorphic configuration of the WGRK was attained after the historical Allah-Bund earthquake of 1819 (Tyagi *et al*., 2012).

The monotonous flat terrain of the WGRK lacks deep exposed alluvial succession; consequently, the deep time history on the pattern of sedimentation and climate remained elusive (*e.g.,* Ngangom *et al.*, 2012; Tyagi *et al.*, 2012). The present study, therefore, is based on the sediment core raised proximal to the Nara River (on the Allah Bund scarp). Nara was the major river till the early Holocene responsible for routing the sediments from the western Himalayan Rivers and the upper Indus catchment (Bhatnagar *et al*., 2024). Therefore, the core location becomes important as it would have preserved the sedimentological evidence on the temporal changes in the hinterland versus the near coastal contribution that would allow us to (i) understand the pattern of sedimentation and (ii) ascertain the source of post-glacial sedimentation in the WGRK.

Study Area

The Allah-Bund scarp was created during the 1819 earthquake which brought about significant geomorphic changes in the WGRK. It lies in the hyper-arid climate; hence, the earth's surface processes are subdued, and the sediments are relatively well preserved. The mean annual rainfall ranges from 200 to 380 mm and is contributed by the southwest summer monsoon (Pramanik, 1952). Vegetation is scant, dominated by shrubs, and grows along a few linear tracts containing fine sand below the surface, which likely represent past stream courses.The core is raised from the eastern bank of the Nara River (24°9'44.45" N and 69°9'45.29" E; Fig.1).

Methodology

A 46.5m long sediment core was raised in 63mm-diameter, high-quality PVC pipes of varying lengths. As the core is raised from the Great Rann of Kachchh, the core pipes were taken directly to the radiology (medical) laboratory for the conventional X-ray study and an X-ray photo of each core was acquired to get a preliminary idea of grain size, as broad understanding was needed to target sand layers throughout the core length for OSL purposes. At the core laboratory in the Department of Earth and Environmental Science, KSKV Kachchh University, Bhuj-Gujarat, the core was split open, and physical parameters like color and texture variations were documented. Subsamples were taken at every 5cm for geochemical studies and grain size analysis.

Grain Size Analysis

A total of 427 samples were analyzed for grain size analysis. To achieve a uniform distribution of particle sizes, crumbs and aggregates were broken, ensuring the elimination of any organic matter and trash from the samples. Dry sieve analysis was performed on ~50g of sample that was devoid of carbonate and organic debris. The automated sieving equipment employed both horizontal and vertical vibrations to separate the particles. The sieves were agitated at a 30 Hz frequency for 30 minutes. The B.S.S. aperture size sieves were arranged on phi (φ) intervals, ranging from 30 mesh (0.75 φ) to < 270 mesh (4.25 φ). The separated grain-size fractions were carefully extracted and weighed. The individual weight percentages were obtained by dividing the weight of particles from selected size fractions by the total sample weight.

Major Element Geochemistry

A total of 365 samples were analyzed for major elements. Around 2g of the decarbonated sample was mixed with 0.5g of wax binder to obtain a homogeneous mixture. The mixture was then transferred to 37mm standard aluminum cups and was subjected to pressure of 150kN for 2 mins using hydraulic pressure. The pressed pellets were then run in an XRF machine. The analysis was conducted using the powder-pressed X-ray fluorescence (XRF) spectrometry (Axios, from Panalytical Limited) at the Physical Research Laboratory, Ahmedabad. The analytical precision at 2σ for major oxides is better than 5% (Shukla, 2011).The major oxides thus obtained were systematically mapped onto a triangular diagram, with Al_2O_3, CaO*, and Na_2O forming the apex (Nesbitt and Young, 1982; 1984). It is noteworthy that the weathering process induces a selective depletion of mobile elements (specifically CaO and Na_2O) resulting in a weathering trend that aligns parallel to the Al_2O_3-CaO* + Na_2O axis. This phenomenon can be ascribed to the heightened mobility of Na and Ca during the weathering compared to the comparatively less mobile Al. This analytical approach allows for the examination of elemental variations and the assessment of source rock interactions.

Trace Elements and REE

Approximately 50–60 mg of decarbonated samples and an international standard from USGS, BHVO-2 were dissolved using a mixture of ultrapure hydrofluoric acid (HF) and nitric acid (HNO_3) in 2:1 with a conventional dissolving method (Open digestion). A total of 59 samples were dissolved for Trace elements analysis. Sample dissolution was carefully monitored and a 1000-fold dilution factor was used to prepare the stock solution in 2% HNO_3. To prevent the matrix effect, the analysis was done on substantially diluted samples made from the stock solution. Using blank and various dilutions of the BHVO-2 standard, calibration curves were produced. Our measurements' reproducibility, based on multiple analyses of the same sample, was better than 2% at the 2σ level. Analyses of standard BHVO-2 were performed at regular intervals to ensure accuracy.

Results

Grain Size Analysis

Phase-1 (depth 47–39 m)

Texturally this is the only major phase that contains a significant amount of medium sand, varying from ~7% to ~40%. Fine sand shows a decreasing trend (19–74%), while very fine sand gradually increases towards the top part of this phase (3–53%). Silty-clay shows an increasing trend (0.01–25%) (Fig. 2).

Phase-II (depth 39–24 m)

There is a decrease in medium sand (0.2–27%), with an initial increase in fine sand that decreases towards the top (23–71%). In contrast, very fine sand decreases initially and then increases towards the top of this phase (11–73%), whereas silty-clay varies between 0.1–15% (Fig. 2).

Phase-III (depth 24–15 m)

Grain size shows an overall decrease in medium sand (0.1−0.4%). There is a decrease in fine sand (12–63%) and anincrease in very fine sand (29–76%) with a corresponding increase in silty-clay (1–26%) (Fig. 2).

Phase-IV (depth 15–10 m)

This is marked by a decrease in medium sand (0.2% to 2%). There is a decrease in fine sand (10% to 73%) and an increase in very fine sand (26% to 86%) and silty-clay varies from 0.2–14% (Fig. 2).

Phase-V (depth 10–6 m)

The medium sand shows a consistent decreasing trend (0.1−2%). Fine sand shows an increasing trend from (34–79%) whereas very fine sand shows a decreasing trend (10–49%). There is a corresponding increase in silty clay (0.1–21%) (Fig. 2).

Phase-VI (depth 6–0 m)

This is the terminal phase of sedimentation. Medium sand shows an overall decrease (0.1% to 5%). An initial decrease in fine sand with fluctuations can be observed which varies from (34% to 84%). The initial increase in very fine sand is observed which fluctuates much towards the top (16% to 61%). The silty-clay concentration shows an increasing trend from <1% to 36% (Fig.2).

A−CN−K Diagram

In the A-CN-K diagram, the majority of the samples lie in the zone of incipient to intermediate chemical weathering (Fig.3), indicating that the sediments have undergone moderate weathering largely in the source region. This intermediate weathering state reflects sediment derived from sources that have experienced weathering but not to the extent seen in highly weathered soils or sediments. However, it is necessary to acknowledge the potential for post-depositional weathering in the flood plain. Nevertheless, the weathering trend reflects or mirrors the ambient climatic conditions. This is indicated by the leaching of mobile elements (Ca and Na) while retaining (enriching) relatively immobile elements such as Al.

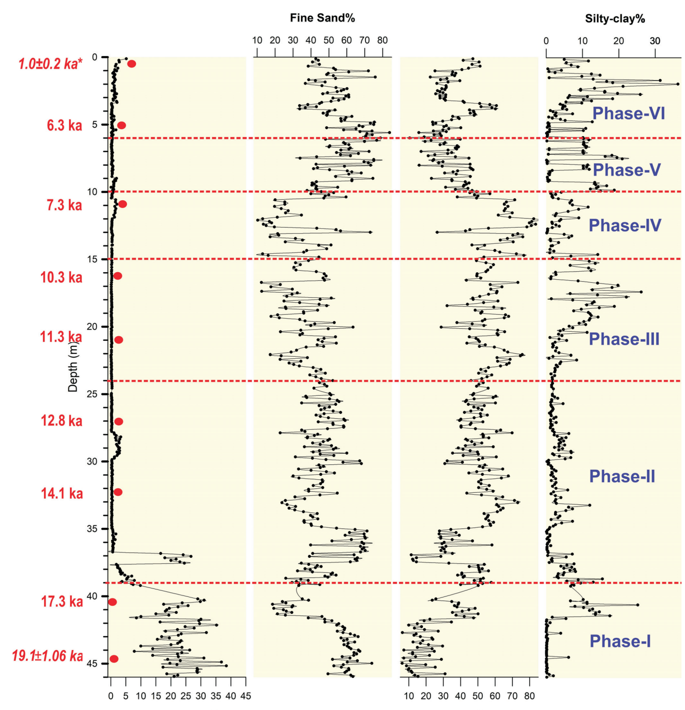

Fig.2. The down core grain size variation in Allah-Bund core along with chronology.Based on the down core variability, six broad phases of varied hydrological conditions were inferred.

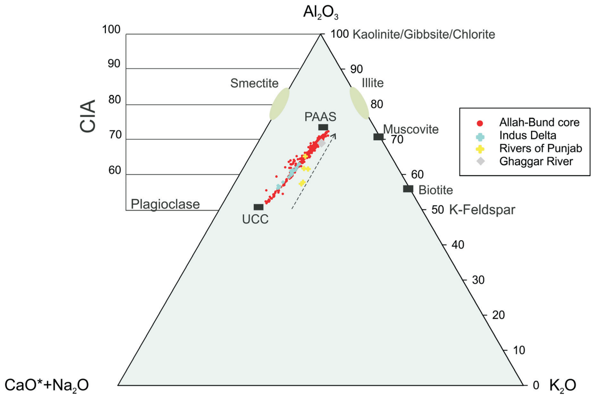

Fig.3. A–CN–K ternary plot (Nesbitt and Young, 1982) showing the composition of Allah-Bund core. Also shown for comparison are Indus Delta sediments (Clift *et al.*, 2010), Rivers of Punjab and Ghaggar River sediments (Alizai *et al.,* 2011) along with Upper continental crust (UCC), and Intermediate weathering products like illite and smectite.

Trace Elements and REE

The study has revealed that the chondrites normalized REE patterns from the Allah-Bund sediment core are characteristic of continental crust material, exhibiting enrichment in light REE (LREE) and a flatter pattern for heavy REE (HREE) (Fig.4a). This LREE enrichment reflects the typical signature of continental-derived sediments. The distinctive negative Eu anomalyis indicative of continental-derived sediments influenced by plagioclase fractionation (as seen in granites), is also evident. (Limmer *et al*., 2012; Rudnick and Fountain, 1995). The depletion in Eu suggests that the source material has undergone significant differentiation, likely through the weathering of felsic rocks, such as granites, where plagioclase is removed preferentially. This negative Eu anomaly strengthens the argument that the sediments were primarily derived from continental sources, supporting our hypothesis of sediment contributions from the Western Himalayas and their surrounding regions. When normalized with upper continental crust (UCC) (Rudnik and Gao 2004), the REE pattern shows flat LREE and depletion in HREE (Fig.4b).

Discussion

To understand the sedimentation pattern within the core sediments of the WGRK, we used the published ages obtained by Bhatnagar *et al*., (2024) on the Allah Bund core. The 46.5 m deep sediment core covers a period of 19.1 ka. The bottom age corresponding to phase-I is dated between 19 ka and 17 ka, implying that the deposition occurred during the terminal part of the Last Glacial Maximum (LGM). This phase indicates a post-glacial enhancement in the fluvial discharge, indicating recession in the hinterland glaciers along with the gradual increase in the ISM.As the sea level was still ~70 m below during this period, (Rao *et al*., 2003), the transportation of medium sand can be attributed to the increase in stream power by the over-steepened stream gradient. The phase-II, dated between 14 ka and 12.8 ka (Fig.2), shows a decrease in medium sand. Overall, this phase indicates a marginal decrease in the fluvial discharge. The post-glacial sea was continuously rising, reaching ~35 m below the present-day sea level around 15 ka (Rao *et al*., 2003). Climatically, the period aligns with the Younger Drays cooling event (YD) (Alley, 2000). The phase-III dated between 11 ka and 10 ka exhibits a decrease in medium sand and an increase in silty-clay (Fig.2). The ages correspond to the early Holocene strengthened ISM (Bhushan *et al*., 2018; Overpack, *et al*., 1996), when the sea level rose more frequently, and deposition continued till the beginning of the mid-Holocene, when the ISM began to show a declining trend (Bhushan *et al*., 2018).

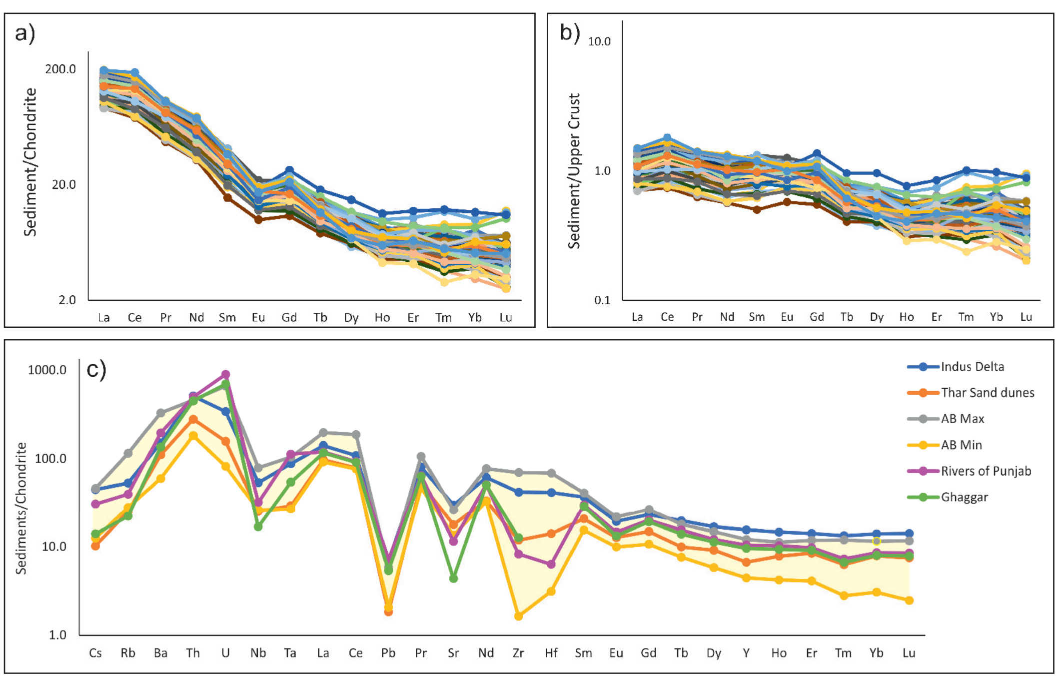

Fig.4. a) Rare earth element geochemistry normalized against chondrite (McDonough and Sun, 1995) for Allah-Bund sediment core b) Normalized values against upper continental crust. Crust values from Rudnick and Gao (2004). c) Chondrites normalized multi-element trace element patterns of sediment samples from the Allah-bund core(yellow field) compared with that of sediments from rivers of Punjab and Ghaggar (Alizai *et al.,* 2011), Indus delta sediments (Clift *et al.,* 2002; Clift *et al.*, 2010), and Thar desert sand (Chatterjee *et al.,* 2017).

This we attribute to an increasing flood plain aggradation. The phase-IV is dated around 7 ka (Fig.2), characterized by an overall decrease in medium sand, and silty-clay suggesting a weakening of fluvial discharge and low flood plain aggradation.Coincidently the period corresponds to the mid-Holocene moderate ISM condition (Dixit *et al*., 2014). During Phase-V, the medium sand shows a consistent decrease while fine sand shows an increasing trend, accompanied by a corresponding increase in silty clay, suggesting restrengthening of the hydrological condition. The Phase-VI is dated between 6 ka and 1 ka, displays an overall decrease in medium sand while fine sand decreases initially and fluctuates more towards the upper part, indicating unstable hydrological conditions. A recent study by Sharma *et al*. (2020) from the northern margin of the Gulf of Kachchh also suggested that during the mid-Holocene, the relative sea level along the Kachchh coast was around 1 m higher, implying significant tidal ingression around the core location. They also observed that the sea level was marginally high around 1ka, extending ~100 km eastward from Kori Creek to the India Bridge.

The A-CN-K plot of the Allah-Bund core sediment data when compared with the Indus Delta (Clift *et al*., 2010) shows a reasonable overlap with some variability (Fig.3). The plot collectively indicates a substantial contribution from the Indus River, with discernible mixed signatures stemming from the Western Himalayan (Punjab) and Ghaggar River systems. Further, supporting our sediment provenance inferences drawn from the major element (A – CN – K plot), we compared the chondrites normalized trace element patterns with those of the Indus Delta sediment (Clift *et al*., 2010), Thar sand dunes (Chatterjee and Ray, 2017), the western Himalayan rivers (Punjab) (Alizai *et al*., 2011) and Ghaggar River (Alizai *et al*., 2011) (Fig.4c). A significant similarity, in the trace and REE pattern with that of the western Himalayan rivers, Ghaggar River and the southern Thar sand dune has been observed in the present study (Fig.4c). This suggests that the WGRK sedimentation besides being dominated by the upper Indus catchment, also received significant contribution from the western Himalayan rivers and reworked Thar sand dune sediments corroborating the observations of previous workers (Alizai *et al*., 2011b, 2016; Giosan *et al*., 2012). Thus, the geochemistry indicated that the post-glacial sedimentation in the WGRK has a mixed provenance where material derived from both fluvial and fluvially reworked aeolian sediments. Currently, efforts are underway to quantify the temporal changes in these varied sources in relation to the post-glacial insolation-driven strengthening of the ISM.

Conclusions

The sedimentology and chronology of the Allah Bund sediment core suggest that continental sedimentation dominated during the terminal part of the Last Glacial Maximum (LGM). The post-glacial strengthening of the ISM is represented by the fluctuating hydrological condition indicated by the presence of medium sand and an increase in silty-clay during low sea stand. A significant decrease in silty-clay around Younger Dryas is attributed to the weakening of the hydrological condition caused due to the weakened ISM. During the early to mid-Holocene, continental flux dominated the WGRK, while the later part of the mid-Holocene shows an enhanced marine contribution that persisted intermittently until around 1 ka. The geochemical study indicates that the post-glacial sedimentation was influenced largely by two major fluvial systems: the upper Indus catchment and western Himalayan Rivers, with seemingly subordinate contributions from fluvially reworked aeolian sand.

Authors' Contributions

AB: Investigation, Formal Analysis, Methodology, Data Curation, Visualization, Software, Writing Original Draft, Reviewing and Editing. **MGT:** Investigation, Conceptualization, Supervision, Visualization, Reviewing and Editing. **MN:** Investigation, Methodology, Supervision, Data Curation, Reviewing and Editing. **ADS:** Methodology, Data Curation, Formal Analysis, Visualization, Supervision, Reviewing and Editing. **GC:** Investigation, Visualization, Reviewing and Editing.

Conflict of Interest

Authors declare that they have no conflict of interests.

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