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Ian Clark *Editors*

# Water Resources in Arid Areas: The Way Forward

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*To communities in arid regions striving for sustainable and healthy water supply.*

# Preface

The exponentially growing demand for water due to population growth, water-intensive diets, and rising of living standards has considerably stressed water resources worldwide. The challenge is greater in arid areas where evaporation significantly exceeds precipitation, and thus natural water resources are depleting. The water budget deficit in arid areas, the high cost of water supply, and the essential need for food and associated energy value among other challenges all need to be scientifically addressed to propose solutions to world current and future water problems. Multidisciplinary and interdisciplinary fundamental and applied scientific research is essential to contribute to solve water problems. Thus, this book "Water Resources in Arid Areas: The Way Forward" addresses diverse water issues in arid regions through gathering selected outstanding contributions presented at the International Water Conference "Water Resources in Arid Areas (IWC 2016)," which was held in Muscat, Oman, in March 2016. This book presents to the reader different examples of applied and fundamental evolving water science that will hopefully enlighten decision-makers, planners, and communities in making sound judgments for better management of water resources.

The book contains 6 main parts with a total of 28 chapters representing the contributions to different water issues in arid regions. The following themes represent the 6 parts and appear in the book in the following sequential order:

Climate and Water Resources
Groundwater Resources
Water Resources Management
Salinity and Desalination
Wastewater Treatment and Reuse
Agriculture and Irrigation Management

A few decades ago, the arid regions (mostly located in developing areas) were entirely relying on external expertise to assess/understand local and regional water resources challenges and to suggest and implement solutions. The region has now developed fair scientific and technological independence evident from the contributions published in this book. The various applications of isotopes, satellites, exploration techniques, advancements in water treatment and desalination, hydrological modeling among others presented in this book demonstrate this development. The arid regions are playing an important part in the equation of global climatic changes, and the effects are also seen in the region similar to polar areas; therefore, arid regions can be an important player in the international global climatic changes policy and mitigation developments. It is our hope that through presenting these examples and case studies that reader will gain a broader understanding of the current research and developments in water resources of arid areas.

Thanks

Osman Abdalla
Anvar Kacimov
Mingjie Chen
Ali Al-Maktoumi
Talal Al-Hosni
Ian Clark

# Acknowledgements

This book assembles selected papers presented at the conference "Water Resources in Arid Areas: The Way Forward" organized by the Water Research Center (WRC) at the Sultan Qaboos University (SQU), Oman. The highly appreciated generous support provided by SQU for the conference has paved the ground for this book. The review of papers conducted by a pool of experts in various fields of water science (names of reviewers are listed at page XIX) has significantly improved the quality and provided constructive criticism important for quality assurance. We would like to also express our deepest thanks and gratitude to the authors of the selected papers for their valuable contribution. We are also indebted to the office work and support of Ms. Maria Diana Austria, the WRC office coordinator.

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## Part II Groundwater Resources



## Part III Water Resources Management

# About the Editors

**Dr. Osman Abdalla** holds B.Sc. (1988) and M.Sc. (1993) in geology from University of Khartoum and Ph.D. (2000) in hydrogeology from University of Technology, Berlin. He is the director of Water Research Center at Sultan Qaboos University since 2012 and associate professor of hydrogeology at the Department of Earth Sciences, College of Science. His research bridges several areas of physical and chemical hydrogeology in arid areas and intends to develop a solid platform for hydrogeological and environmental research and training of an international standard with emphasis on groundwater recharge and discharge. Dr. Abdalla has established many international and regional collaborations, been awarded over 10 major grants including His Majesty Trust Fund, and published several articles in reputable international journals.

**Dr. Anvar Kacimov** He completed his B.Sc., M.Sc., Ph.D. (fluid mechanics) from Kazan University, USSR, 1982, 1987. He worked at Kazan University, Departments of Seepage and Mathematical Analysis for the period 1982–1998. Since 1998, he worked at SQU, Oman, as assistant–associate full professor, Department of Soils, Water and Agricultural Eng; administratively, HoD (2007–2012); director of Water Research Centre (2011–2012); and dean (2012–2015). His areas of interest include fluid, heat and mass transfer through porous media (soils, aquifers, oil formations) and of applications in hydroecology, soil physics, irrigation and drainage, hydraulic and hydrologic engineering, groundwater hydrology, fluid mechanics, and reservoir engineering. He has published 128 papers in refereed journals (in English) and has co-authored two books (in Russian). He has been awarded Omani Green Research Award with a Special Commendation of Mitsubishi Corporation (2010) and Best Reviewer of Vadose Zone Journal (2005) and J. of Irrigation and Drainage Eng., ASCE (2013).

**Dr. Mingjie Chen** holds a bachelor degree in environmental engineering from Tsinghua University (1997) and a master degree in environmental sciences from Peking University in China (2000). Dr. Chen got his Ph.D. degree in Environmental Sciences/Hydrogeology at the University of California, Santa Barbara in USA in 2005. During his postdoc research from 2005 to 2008 at Los Alamos National Laboratory in USA, Dr. Chen developed an innovative intrusive method to quantify uncertainty of multiphase flow and reactive transport in heterogeneous subsurface area. In late 2008, Dr. Chen accepted a research assistant professor position at Tufts University in USA, leading a numerical modeling team in collaboration with a laboratory experimental team to study bio-enhanced PCE-DNAPL dissolution by anaerobic mixed cultures. At the end of 2010, Dr. Chen joined Lawrence Livermore National Laboratory (LLNL) in USA as an earth scientist. He is a PI or co-investigator of numerous projects funded by Department of Energy (DOE of USA) on underground fossil energy and radioactive waste. Owing to his excellent performance, Dr. Chen was rewarded Directorate Award by Physical and Life Science Directorate of LLNL in 2013. Since 2014, Dr. Chen has been a senior hydrogeologist (associate professor rank) in Water Research Center at Sultan Qaboos University, Oman, while he still remained an associate role of hydrogeology in LLNL of USA. Dr. Chen is mainly responsible for developing research programs in groundwater resources and geothermal energy using high-performance computing. Dr. Chen commits duties of organizing committees of water-related international workshops and conferences, proposal-review panel, and international journal editors.

**Dr. Ali Al-Maktoumi** holds a B.Sc. in soils and water (1998) and an M.Sc. in soils and water Management from Sultan Qaboos University in Oman (2001). He received a scholarship from Oman government in 2003 to continue with his Ph.D. studies in environmental engineering (Water Resources) at the University of Queensland in Australia. After his Ph.D. in 2007, Al-Maktoumi joined the Department of Soils, Water and Agricultural Engineering at Sultan Qaboos University as an assistant professor in the area of hydrology. He contributed to teaching a wide range of courses in the area of arid zone hydrology and water resources management at both B.Sc. and M.Sc. levels. Al-Maktoumi worked as a consultant in a project "Groundwater contamination in a golden mine site in North Queensland, Australia for the period 2007–2008". Through a number of awarded grants, he established scientific collaboration with Utrecht University, Delft University of Technology, UNESCO-IHE, California Institute of Technology, Jet Prolusion Laboratory-NASA, University of Nebraska-Lincoln, University of Putra Malaysia, and University of Jordan. Al-Maktoumi organized a number of training courses in the area of numerical modeling and co-organized a number of international conferences. In research, Al-Maktoumi focuses in feasibility of managed aquifer recharge using treated wastewater in MENA region along with enhancement of recharge dams efficiency. Al-Maktoumi's developed experience in those fields is reflected in his publications.

**Dr. Talal Al-Hosni** holds a B.Sc. in earth sciences (1999) from Sultan Qaboos University (Oman) and an M.Sc. in hydrogeology (2001) from Birmingham University (UK). He received a scholarship from Oman government in 2003 to continue with his Ph.D. study in chemical Hydrogeology at Melbourne University (Australia). After his Ph.D. in 2007, Al-Hosni joined the Department of Earth Sciences at Sultan Qaboos University as an assistant professor in the area of hydrogeology and environmental Geology. He worked as a theme supervisor (Omani Land) in the Omani Encyclopedia for the period 2008–2009. Since 2012, he is a member of the scientific committee for the Oman Mountains Atlas Project. His areas of interest include mainly hot springs, groundwater recharge, intra-aquifers mixing, and usage of bottled water and its impact. Al-Hosni contributed to teaching a number of courses including environmental geology and hydrogeology and developed a number of training courses in the area of EIA of mining and groundwater management.

**Dr. Ian Clark** is a professor in the Department of Earth and Environmental Sciences at the University of Ottawa. Professor Clark completed a bachelor's of science degree in earth sciences and a master's of science degree in hydrogeology at the University of Waterloo, followed by his doctoral degree at the Université de Paris-Sud (Orsay) in isotope hydrogeology and paleoclimatology. Since his earliest work on geothermal systems in western Canada, Ian's research has focused on the integration of geochemistry and isotopes to address the questions on the origin, age, paleoclimatic context, and geochemical history of groundwater and solutes in natural and contaminated settings. He continues to work with his graduate students in diverse hydrogeological environments, ranging from groundwater dynamics in permafrost in the Arctic or beneath the deserts of Oman, to contamination of water resources, dispersion of radionuclides in the environment, and the burial of nuclear waste. Dr. Clark and his colleagues established, just this year, new facilities in the Advanced Research Complex (ARC) at the University of Ottawa for training and analysis in the geosciences. The ARC includes laboratories for geochemistry stable isotopes, tritium, noble gases, and accelerator mass spectrometry (AMS) for radiocarbon and other radioisotopes. Professor Clark teaches geochemistry and environmental isotopes in hydrology and recently published a new undergraduate textbook, Groundwater Geochemistry and Isotopes, which complements his graduate-level textbook (co-authored with Professor Peter Fritz): "Environmental Isotopes in Hydrogeology."

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# Part I
# Climate and Water Resources

# Paleoclimatic Registers from Semi-arid Costal Sediments of Southeastern India: A Multi Proxy Approach

**Anburaj Vidyasakar, Helena Sant'Ovaia, Linto Alappat, P. Morthekai, Seshachalam Srinivasalu, A.K. Singhvi, Ferreira Jorge and Celeste Gomes**

**Abstract** The red sand dunes appear along the south east, -west coast of Tamil Nadu, India between the latitudes and longitudes of 8°07′56″N to 8°22′11″N; 77° 19′84″E to 77°53′40″E. The dune sands from this region were studied through magnetic methods such as magnetic susceptibility measurements and acquisition of isothermal remanent magnetization, geochemistry and X-ray diffraction methods. Optically stimulated luminescence (OSL) dating method was used to constrain the chronology of deposits. Three sections were excavated up to 5–9.5 m with one inland deposit (TPV) and two near coastal sections (THOP and MUT).

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Celeste Gomes—deceased

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The magnetic parameters show both significant contribution of hematite structures and indicate the presence of multi-domain magnetite or mixed mineral contents of magnetite and anti-ferromagnetic minerals in the sample. The occurrence of magnetite in THOP and TPV sections is possibly due to the marine sediments transported by sturdy onshore winds. In XRD data, correlation analysis indicated TPV and MUT sections have a similar type of deposition and THOP did not show any positive correlation with TPV and MUT and even with its own deposition. In comparison with geochemistry data, $\chi$ variation and OSL dates, it was shown that the sample MUT21 (200 cm) with an OSL age of $14 \pm 2$ ka indicated deposition during the humid interval and at $\sim 17 \pm 2$ to $\sim 19 \pm 2$ ka MUT61 (600 cm) depicts the dry period of deposition.

**Keywords** Magnetic parameters · X-ray diffraction · Optically stimulated luminescence · Geochemistry · Teri sands · Hematite · Magnetite

## 1 Introduction

The environmental changes in a region may happen due to climatic variability or as a result of human intervention, which usually lasts for an extended period. Moreover, research on various aspects preceding the climate change suggested that climatic variability has occurred sporadically in the past, notably through a quaternary period in response to different forcing's, e.g., orbital variations and solar activity changes (insolation) (Wolff et al. 2010; Sanchez Goñi and Harrison 2010). It is to be noted that a change in the climate disturbs the coastal areas around the globe causing changes in sea level. Therefore, in the context of Quaternary climate change, it is ideal to study sediment archives along the coast. The study may hold substantial evidence of coastline advance and retreat in adherence to past variations regarding sea level and its landscape response (e.g., Islam and Tooley 1999; Alappat et al. 2015; Brückner (1988, 1989)). Also, reconstruction of the paleo-sea level is a long and intricate process. Hence, it involves reminiscing the fragments of evidence left in nature, recording of those fragments through dating of the event in question and final interpretation of available data (Morner 2010). The red dunes on the southeast coast of India is a potential terrestrial archive of climate change and provide vital information about the landscape response to such variations. Red dunes are referred to as 'teri sands or teris' in the literature and are categorized as inland, coastal and teri (near-coastal) dunes by earlier researchers (Joseph et al. 1997, 1999). According to the standard Tamil dictionary, teri means 'a heap of sand.' Some researchers (Jayangondaperumal et al. 2012) used the term 'wasteland' because the local people deemed it as useless for agriculture.

The foremost intent of the present study is to draw a distinct line between previous dry and wet climatic intervals using various proxies like magnetic studies, Optically Stimulated Luminescence (OSL) dating, X-ray Diffraction (XRD) and geochemical analysis. The soil magnetic parameters are relatively quick and easy to obtain information compared to geochemical, sedimentological and paleontological data. It is helpful in obtaining information about a broad range of climatic and environmental changes (Maher and Thompson 1999). OSL dating has the number of advantages as a chronological tool in coastal environments over other methods, considering its wide dating range, direct dating of events and provides ages in calendar years (Jacobs et al. 2008). It also includes the use of most abundant minerals like quartz and feldspar as dosimeters for age determination, which makes its wide application in the majority of terrestrial sedimentary archives. The qualitative analysis of sediments has been carried out to define major and minor constituent minerals present in the samples collected at different depths in the coastal area by XRD technique. The geochemical analysis of samples can be of greater help in understanding the sediment dynamics underlying behind a particular geological system (Albarède 2003).

## 2 Study Area

The study area is located in the southwest and southeast coast of Tamil Nadu, India between the latitudes and longitudes of 8°07′56″N to 8°22′11″N; 77°19′84″E to 77° 53′40″E. Three representative sections were excavated in the area as indicated in Fig. 1, viz-a-viz; Muttom (MUT; 8°07′56″N, 77°19′84″E), Thopuvilla (THOP; 8° 19′57″N, 77°57′27″E) and Edayanvilai (TPV; 8°22′11″N, 77°53′40″E). The various morphological settings from east and west coast will be further discussed in the following section. At Muttom, Thopuvilla and Edayanvilai, a 9.5, 7.4 and 4 m sections respectively were excavated to reach up to the palaeo-surface.

### *2.1 Regional Climate*

The study area falls under the semi- arid and subtropical climatic conditions. Muttom, Thoppuvillai and Edayanvillai receive most of its rainfall during the summer (during SW monsoon). The climate has been classified according to Koppen and Geiger climate classification as Aw (Peetal et al. 2007). In Muttom, the average annual precipitation is 1093 mm and the variation in precipitation between the wettest and driest month is 178 mm. The average temperature in Muttom is recorded as 29 °C. The lowest average annual temperature in the year occurs in December when it is around 26 °C. In Thopuvillai and Edayanvillai average annual rainfall is 729 mm, and among the wettest and driest months, the change in precipitation is 199 mm. With an average temperature of ~31 °C, May is the hottest month of the year with a mean maximum of 38 °C. The coldest month is the January, with temperatures averaging 26.2 °C (www.climate-data.org).

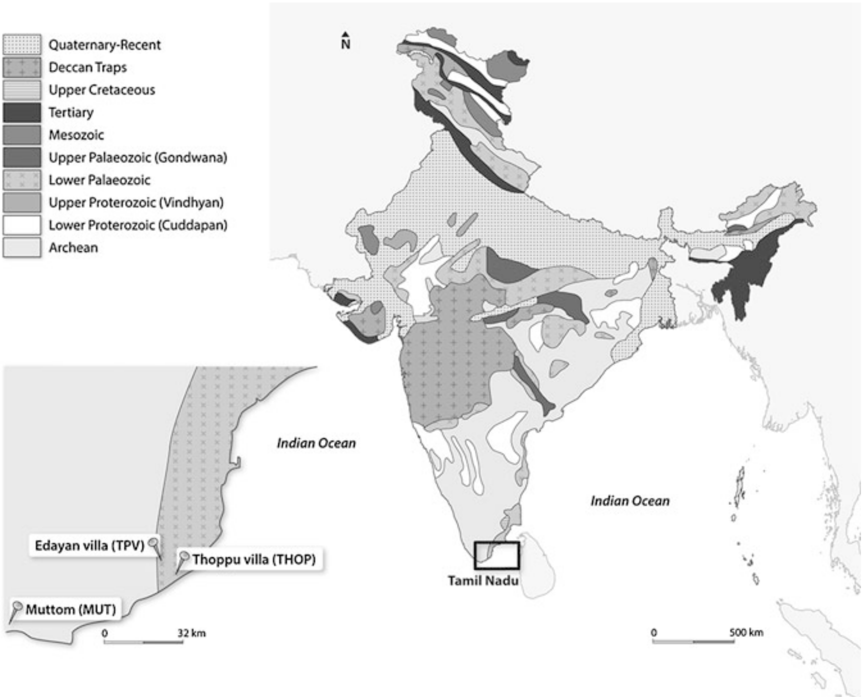


**Fig. 1** Map of the study area with sample location in southeast-southwest coast of India

## 2.2 *Regional Stratigraphy and Geomorphology*

The teri sands in the area cover an area of up to $\sim 500\ km^2$ and thickness at places reach up to $\sim 12$ m (Gardner 1986). The igneous and metamorphic rocks that found below ovari series are from Archean period. The Pleistocene coastal sediments (Ovari Series) sits on Archaean granulitic rocks, most of which are peninsular gneiss, garnet-sillimanite-graphite gneiss and charnockite gneiss (Jayangondaperumal et al. 2012). Idindakarai Series (Fig. 2) overlies the Ovari Series and comprises terrigenous grains of gravel and sand size and shell fragments of shallow marine origin (Jayangondaperumal et al. 2012). The Kanyakumari Series that superimposes on Idindakarai Series consist of fossil coastal dunes concreted with calcium carbonate sediments and also with marine sediments. (Jayangondaperumal et al. 2012). In addition to that, Poochikkadu Series is covered with calcrete and some marine sediments (Jayangondaperumal et al. 2012). The Inland teri sands found in big patches are dark in colour and discontinuous, while coastal teri sands are continuous and light coloured. Marine deposits of Mandapam Series overlie the teri deposits (Jayangondaperumal et al. 2012). Along the shoreward direction, teri sands rest on either of the crystalline basement, the Ovari marine sandstone, aeolianite of

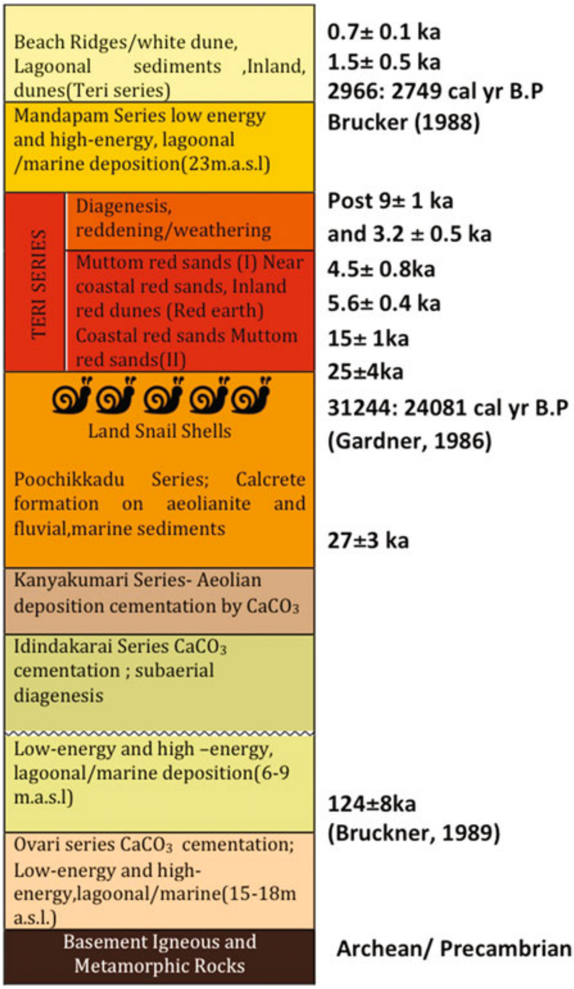


**Fig. 2** Regional stratigraphy from Jayangondaperumal et al. (2012) and some modified ages from Allapat et al. (2013a, b)

Kanyakumari or Poochikkadu Series (Gardner 1986; Joseph et al. 1997). Perceiving sediment texture Joseph et al. (1997), inferred that teri sediments were originated from the wide-open continental shelf during a phase of low relative sea level, and these deposits were transported by high landward winds. According to chandrasekharan and Murugan (2001) sands are rich in heavy minerals like ilmenite, rutile, zircon, garnet, monazite and sillimanite, suggest their source from Precambrian Khondalite, charnockites and granite gneisses rocks.

The geology of the area comprises Archaean granulitic rocks, predominantly peninsular gneiss (garnet-sillimanite-graphite gneiss) and charnockite gneiss (Alappatet al. 2013a, b). The littoral area has Pleistocene and recent fluvial, fluviomarine and marine deposits (Alappat et al. 2013a, b). The rocks of Mio-Pliocene age (early Neogene) namely Cuddalore formation, is exposed towards the northeast at Muttom. Also, at Muttom the red sands occur as a dune against a headland into the Arabian Sea. This landscape is bounded by recent dunes, beach ridges, swales and beaches towards the coast and unveils badland topography with weathering and gully erosion subjecting up to ~10–12 m thick sand unit at its central part. The red sands overlie laterized country rock with a slope towards SE. Moreover, dunes on the east coast are cut by some rivers and streams. River Valliyar joins the Arabian Sea at the northwest side of this cape cutting across the dunes at the coast. Some discontinuous coast, parallel lagoons and swales separate the near coastal dunes. The floodplains of rivers restrict the dune development as discontinuous patches (Alappat et al. 2013a, b).

# 3 Methodology

## 3.1 Field Work and Sample Collection

Three profiles were excavated in the southeast and southwest coast using mechanical excavators and number of trench sections were made at different levels to collect the required samples. In general, the sections were excavated in areas were the thickness of the loose, incoherent sand is less than 1 m thick to reach up to the older sand units by omitting the recent reactivated sand at places. The samples for magnetic susceptibility, textural and geochemical analyses were collected at 10 cm intervals along vertical profiles and were carefully packed in sample bags and labeled for laboratory analyses. Some OSL samples was collected from different units having distinct stratigraphic relations. Samples for OSL dating was collected in 10 × 2 in. aluminum tubes and was sealed light tight immediately after sample collection.

## 3.2 Laboratory Analyses

### 3.2.1 Geochemical Analysis

According to Saravanan (2012, p. 43) the samples were dried in a hot air furnace at 60 °C to eliminate the moisture and 100 g of samples were taken by repeated coning and quartering to obtain a homogeneous representative sample. The following procedures were performed:

(i) *Clay fraction removal*: The samples were soaked in water with 2 g of sodium hexametaphosphate ($(NaPO_3)_6$) overnight and then washed in water (325 sieve mesh) to eliminate the clay portions. The samples were weighed and weight loss was taken as the weight of clay.

(ii) *Organic matter removal*: The samples were treated with hydrogen peroxide ($H_2O_2$) overnight, and rinsed with water (325 sieve mesh) until a clear column of water without any turbidity was achieved. The samples were then dried and weighed, and weight loss was taken as the weight of the organic material.

(iii) *Carbonate removal*: The samples were treated with 10% hydrochloric acid (HCl) to the carbonates in the sediments. After washing and drying, the samples were weighed, and the weight loss was taken as the weight of carbonates.

(iv) *Iron removal*: The samples were treated with 10% nitric acid ($HNO_3$) over night and were then washed (325 sieve mesh) with water until a clear column of water was achieved. The samples were then dried and weighed and the weight loss was taken as the weight of Fe.

(v) *Grain size analyses*: The grain size may have an impact in accordance with heavy mineral composition, usually fine-to-medium grained sand yield the optimum heavy mineral assemblages. Sieving was carried out in ASTM at the 1/2Φ interval. The sieve sets are stacked in descending order with respect to their sizes and were shaken using a mechanical sieve shaker continuously for about 20 min. During sieving, proper care was taken to minimize the sand loss from sieve sets. The samples collected on each sieve were taken separately and weights of individual fractions were tabulated. The sieved sands of 80, 100 and 120 meshes were kept separately for heavy mineral studies. It is a basic premise of sedimentology that every sedimentary unit is formed as a result of its response to a certain set of environmental conditions (Blatt et al. 1980). The geochemical analysis has been obtained from Department of Geology, Anna University, Chennai, Tamil Nadu, India.

### 3.2.2 Magnetic Measurement

To ascertain the strength and type of environmental magnetic carriers in samples, magnetic parameters were measured and scrutinized. Before measuring the low-field magnetic susceptibility, samples were dried at 40 °C and packed in the Department of Geology, Anna University, Chennai, Tamil Nadu, India. Maher (1986) cited the importance of drying samples at low temperature before investigation to evade any possible changes in mineralogy. The specific or mass susceptibility $\chi$ (measured in $m^3/kg$ units) is expressed as the ratio of material magnetization and 'J' per mass unit to the weak external magnetic field, H: $J = \chi H$. Magnetic susceptibility has been measured using KLY-4S Kappabridge equipment in Earth Sciences Institute at the University of Porto, Portugal. In order to know whether the instrument is working correctly, a minimum of three susceptibility measurements of each sample was taken, and the average value was used for the study.

The Remanence assimilated by a sample exposed to a direct magnetic field at ambient temperature is termed as Isothermal Remanent Magnetization (IRM). Moreover, IRM has been measured in a minispin fluxgate magnetometer (Molspin Ltd.) after magnetization in a pulse magnetizer (Molspin Ltd.) in the Department of Earth Sciences, University of Coimbra, Portugal. The IRM acquired in the magnetic field of one tesla (T) was defined as Saturation Isothermal Remanent Magnetization (SIRM). Thus, IRM was imparted at fields of 0/12.5/25/50/75/100/150/200/250/300/500/700/900 mT and up to 1000 mT and backfield was imparted up to 1000 mT. To find the relative influence of antiferromagnetic minerals, Hard IRM using the formula $HIRM = 0.5 \times (SIRM + IRM_{-300\ mT})$ (Alargarsamy 2009), wherein $SIRM = IRM_{1T}$ (Lourenco et al. 2012) was calculated and Hard% (= HIRM/SIRM $\times$ 100) has been determined (Lourenco et al. 2014). The S-ratio parameters were used to determine the relative contribution of hematite versus magnetite by dividing each IRM value with corresponding value from SIRM ($S_{-100} = |IRM_{-100\ mT}/SIRM|$ and $S_{-300} = |IRM_{-300\ mT}/SIRM|$) (Thompson and Oldfield 1986; Maher and Thompson 1999; Evans and Heller 2003). The SIRM/$\chi$ is the ratio between Saturation Isothermal Remanent Magnetization and magnetic susceptibility.

### 3.2.3 X-ray Diffraction Analysis

The mineral composition was determined in non-oriented powder mounts for bulk sample analysis. In addition to that, XRD measurements with Pro Alfa 1 equipment were made at Laboratório Nacional de Energia e Geologia, I.P. The samples used for magnetic measurements were used for the XRD measurements. The selected samples have undergone coning and quartering to ensure they are homogeneous to evade errors during XRD analysis. The estimates of mineral abundances were based on subsequent peak intensities. Hence, for semi-quantification of identified principal clay minerals, peak areas of specific reflections were calculated and weighed (Lapa and Reis 1977). Finally, High Score Plus software was used to correct the intensities and to correlate between each sample in the present study through adopting Pan Analytical X'Pert Pro Alfa1 model, which is 200 times precision-centric and faster than old models. This X-ray Diffraction model requires minimum 4 grams sample with the grain size of 400–450 mesh is kept as the ideal of a sediment sample. Samples are nicely grained and powder mounts are prepared with back loading firm pressure. In this X-ray Diffraction model, Copper tube is used with the wavelength of 1.541874 Å and goniometer radius of 240 mm. The samples analysis time take is 15 s per step.

### 3.2.4 Optically Stimulated Luminescence (OSL)

The OSL dating was used to reveal the characteristics of coastal deposits from various geographical and geological settings and to study the relationship between periods of sediment accretion and environmental change. During the collection of OSL dating samples, the samples were protected from the sunlight exposure using thick black blankets (Fig. 3). OSL dating was carried out at Physical Research Laboratory, Ahmedabad, Gujarat, India. The selected cores were sampled and processed under controlled red light laboratory conditions for luminescence studies. The superficial 1.5 cm were not sampled to prevent possible contamination of bleached and/or disturbed outer parts while retrieving the core. The quartz grain fractions of 100–150 μm or 150–200 μm used from every sample were separated using the standard laboratory preparation procedure and dry sieving (Aitken 1998). Thus, after extracting the grain size of 100–200 μm, samples were treated with 0.1 N hydrochloric acid (HCl) to remove the presence of carbonates, 0.01 N sodium oxalate ($C_2Na_2O_4$) and 30% hydrogen peroxide ($H_2O_2$) were used to remove clay coatings as well as to segregate the grains and to remove the organic matter from samples. The quartz-rich fraction (<2.70–2.62 g $cm^{-3}$) was separated by density separation using an aqueous solution of sodium polytungstate ($3Na_2 WO_4$ $9WO_3$ $H_2O$). Also, the quartz fraction was etched using 40% hydrofluoric acid (HF) for 60 min to remove feldspar contamination. The HF etching also removed the outermost layer of quartz grains to evade the impact of alpha particles in coarse grain sand. The samples were then washed and neutralized with distilled water and sieved again with respective mesh to get rid off grains that had become smaller. The sieved grains were mounted on stainless steel aliquots in a uniform thin layer and fixed with silicon spray shortly before measurement. The methodological details and SAR protocol optimization of red dune sand are detailed in Alappat et al. (2013a, b).

The single aliquot regenerative dose (SAR) protocol for quartz (Murray and Wintle 2000; Wintle and Murray 2006) was used to determine the equivalent dose of the samples. An automated Riso TL/OSL DA-20 reader attached to a 90Sr/90Y beta source was used for the OSL measurements. The quartz grains were stimulated by a blue light emitting diodes (LED) (470 ± 30 nm). A Hoya U-340 (7.5 mm) filter was placed between the photomultiplier and sample to detect luminescence signals from quartz grains. The dose recovery test at different preheat temperature shows that the given dose was recovered effectively at a preheat temperature of 200 °C with a cut heat of 160 °C. The De values were calculated using signals integrated using the first 0.64 s and an early background was subtracted corresponding to 1.12–2.4 s.

The dose rates were calculated from the activity concentrations of decay chains 238U, 232Th and 40K measured using high-resolution gamma spectrometry (High Purity Germanium (HPGe)) at Physical Research Laboratory, Ahmedabad. The dose-rate conversion factors of Guérin et al. (2011) and beta attenuation factors of Mejdahl (1979) were applied for calculation. The cosmic dose rate was calculated based on the method proposed by Prescott and Hutton (1994).