

Interpretation of Dune Genesis from Sedimentological Data and Ground Penetrating Radar (GPR) Signatures: A Case Study from Ashirmata Dune Field, Mandvi Beach, Gujarat, India

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ABSTRACT

The coastal dunes located near the Ashirmata region, south of Mandvi beach lies near the straight coast have been studied by making use of sedimentological information and Ground Penetrating Radar (GPR) data. Sedimentological analysis reveals the NNW-SSE trending longitudinal dunes consists of well sorted fine sands with unimodal distribution possibly formed by constant wind gust and also the point out to the origin of sediments from single source; mostly the sediments derived from Indus delta transported to beach by long shore drift and tidal waves, carried inland by local onshore winds. The radargram confirms, the homogenous sand layers with paleosols at shallow depth slip faces are probably formed due to extreme storm activity of Recent.

Keywords: Coastal Dune; Ashirmata Region; Sedimentological Analysis; Ground Penetrating Radar; Paleosol

1. Introduction

Coastal dunes are mostly aeolian landforms develop in ocean-land interface has been active with adequate supply of loose sand-sized sediments transported to inlands by prevailing onshore wind or sea breeze. Coastal dunes are primarily the gradual product of wind rather than waves, which subtly changes the beach morphology with each passage; however major storms erode both [1,2]. The shape and orientation of the dune helps to determine the airflow and it further influences the transport of sands and the formation, and evolution of coastal dunes decide the airflow over it. The prime requirements for the formation of dunes are the supply of adequate sand and sufficient wind that can transport the sand particles and these sand particles should not be cohesive and cemented [3]. The dune type depends on sand availability and directional inconsistency of the prevailing wind pattern e.g., [4] longitudinal dunes are aligned parallel to each other and wind blowing parallel to the dune orientation with high sand availability. The size of the dune depends largely on the supply of sand sized sediments [5]. The prime factors depends on the dune stability are attack by

wave and storms also continuous attack of the waves on dune base causes easy removal of sand by both offshore and along shore [5]. The rates of migration of dunes vary considerably over the year [6,7].

Many studies have done by researchers regarding the grain distribution studies along coastal dune sands [8-11]. Nordstrom [12] suggest that sediment sorting may be more significant than grain size in aeolian transport. Coastal dunes sediments are derived from aeolian activity are typically well sorted with mean grain size of 2 to 3ϕ [11]. The textural analyses and grain size distribution parameters were estimated for the study area by collecting representative samples from top and bottom layers of the dunes by disputing coastal dunes from the windblown sediments.

During the last few decades, Ground Penetrating Radar (GPR) has been used with great success on dunes investigation [13-19] and the GPR signatures revealed the internal stratigraphy and sedimentary structure of dunes by subsurface imaging and found to quite useful. GPR method is predominantly well suited to use in dry, sandy, or cobble-poor sediments [e.g., 13-19]. The depth

of penetration of the radar signals decreases with the use of high frequency antenna as the produced signal undergoes less attenuation and high-quality signals as compared to low frequency antenna [13]. GPR allows rapid imaging of dune stratigraphy and provides information about lateral accretion surfaces, paleosol horizons, and thickness of units and relative chronology of dunes deposition, migration and deflation. Paleosols showing high amplitude response in GPR data is the result of their thickness and lithological contrast with surrounding aeolian sands [20,21]. These horizons indicate a period of soil development during a hiatus in dune activity, often in Eolianite (fossil dune limestone) [22]. But in the study area paleosols represent an erosional surface; occurs at shallow depth and the dune slip faces may be related to

extreme storm activity, which are frequent in Gujarat coast. The most recent aeolian activity started the period in between ~0.6 ka to ~0.2 ka experienced decreased rainfall [23].

Our study is aimed to interpret basic geological driving force for the dune formation from sedimentology and also from GPR data by constructing the internal stratigraphy of the dunes.

2. Study Area and Geological Settings

The study area, Ashirmata dune fields ($22^{\circ}50.230'N$, $69^{\circ}13.057'E$ and $22^{\circ}50.246'N$, $69^{\circ}13.062'E$) lies north of Mandvi beach in Kutch coast, northern flank of the Gulf of Kutch (**Figure 1**).

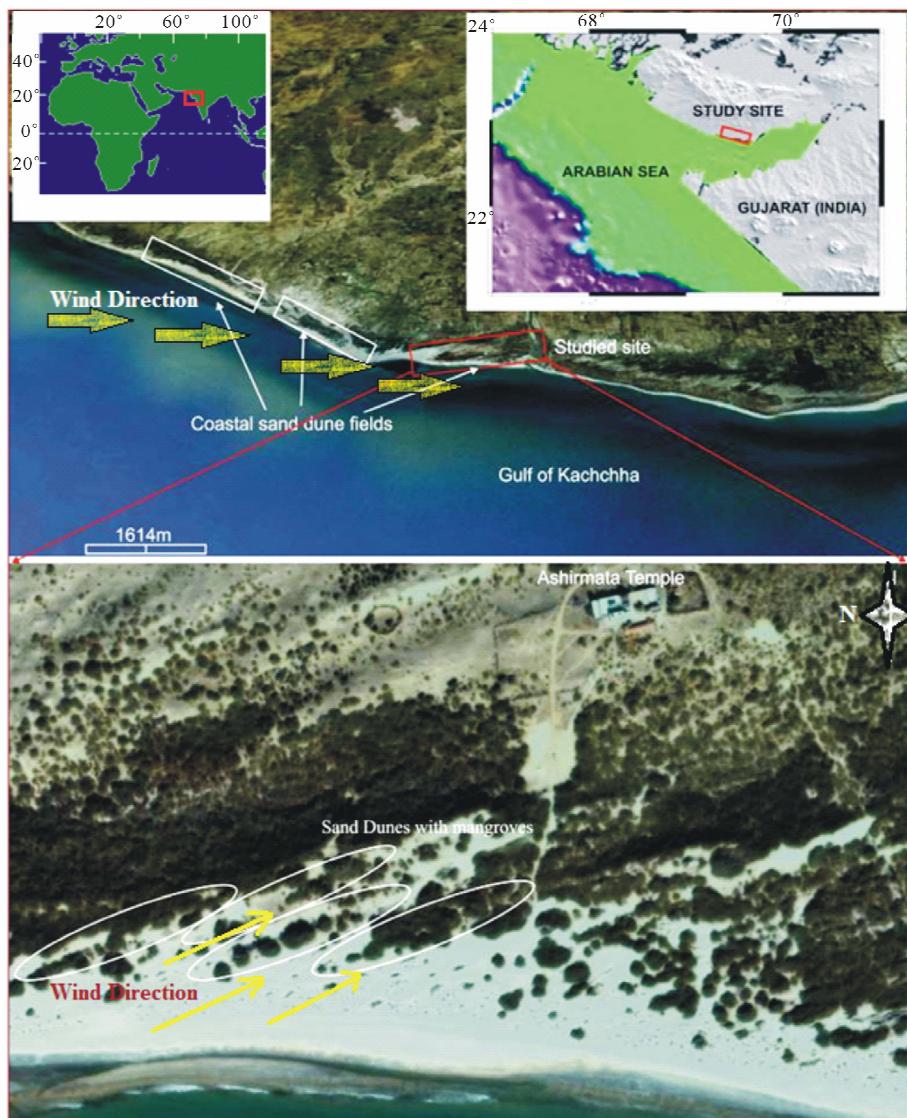


Figure 1. Location map of study site in Ashirmata dune fields near Mandvi beach in Gujarat. Yellow arrows indicate NW direction of wind pattern and circles and rectangles denotes the dune fields in the study area and nearby areas, mangrove vegetations are seen associated with these dunes.

The North West part of the Gujarat, southern border of Thar Desert is extremely arid in case the location of the state near to Tropic of Cancer. The complex Cenozoic tectonic processes and associated sea level changes impart the coastal area results the present geological and geomorphological set up. Gujarat is largely underline by the flat alluvial fans, originated from structurally controlled rivers of eastern highlands of Deccan Trap and flowing through the tectonic slopes towards the Arabian Sea. The coast line of Kutch comprises Quaternary and Tertiary sediments which are mainly comprises friable sandstone, sand and silty sand along with tidal clay [24]. In the study area, the orientations of longitudinal dunes are generally along NNW to SSE direction, parallel to the prevailing winds and occur in the form of parallel or sub-parallel to the coast. Almost straight sand ridges with partial vegetation cover (**Figures 2(A) and (B)**), backed by sand hills with mangrove swamps and fronted by sand banks are characteristic of the study in dry season.

3. Methodology

The study area lies under the geographical coordinates $22^{\circ}50.230'N$, $69^{\circ}13.057'E$ and $22^{\circ}50.246'N$, $69^{\circ}13.062'E$, as acquired from the Global Positioning System (GPS). Sand samples were collected from three pits which are excavated in three dunes (D1, D2 and D3) (**Figure 3**) (after the primary investigation of GPR data, ground truthing have done for cross checking) and representative samples were collected from top and bottom of each pits, those samples were subjected to sedimentological analysis by using Malvern particle size analyzer. The statistical parameters such as mean, median, standard deviation, skewness and kurtosis were estimated by using standard statistical techniques for studying the textural characteristics (**Table 1**).

The GPR data collected by using Subsurface Interface Radar (SIR) 3000 system mode developed by Geophysical Survey System, Inc. (GSSI) with shielded monostatic



Figure 2. (A) Shows the orientation of sand dune fields (red line) sub parallel to the coast; (B) Demonstrates the transection of GPR profile from coast to land indicated by dotted arrow means the direction of data collection; (C) Denotes the schematic presentation of dune height, distance from top to base of the dune indicated by solid arrow line.

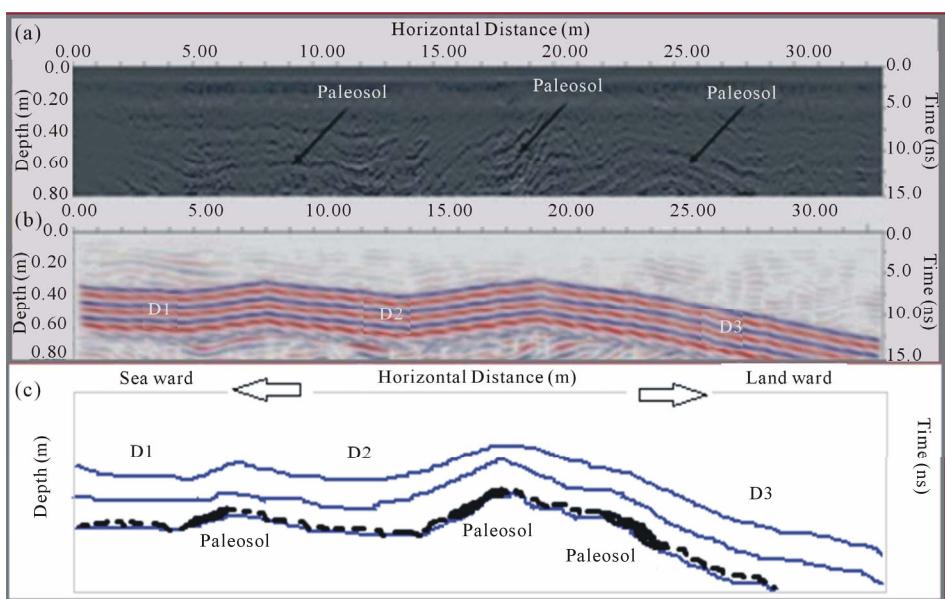


Figure 3. GPR signatures have shown in grey scale (a) and colour (b) images, paleosols can be clearly visible in (a) and dune morphology can be seen in (b). The schematic representation of GPR image, (c) showing the three dunes with continuous, homogenous sand layer and interpolation of paleosol layer.

Table 1. Grain size distribution parameters shows textural group and sediment type of three dunes, samples were collected from top and bottom of each dunes (Mean-x, Sorting- σ , Skewness-Sk and Kurtosis-K).

Samples	x	σ	Sk	K	Sample description
D1 (Top)	2.949	0.454	0.110	0.936	Fine sand, well sorted, symmetrical, unimodal
D1 (Bottom)	2.636	0.460	0.006	0.935	Fine sand, well sorted, symmetrical, unimodal
D2 (Top)	2.934	0.451	0.005	0.937	Fine sand, well sorted, symmetrical, unimodal
D2 (Bottom)	2.652	0.481	-0.016	0.947	Fine sand, well sorted, symmetrical, unimodal
D3 (Top)	2.883	0.410	0.003	0.948	Fine sand, well sorted, symmetrical, unimodal
D3 (Bottom)	2.658	0.464	0.003	0.936	Fine sand, well sorted, symmetrical, unimodal

antenna of 900 MHz center frequency of maximum signal penetration was about 15 ns (0.80 m). Several continuous profiles were collected along three dunes of 30 m length, NNW-SSE profile and the topographic survey was carried out using a Global Positioning System. The Radan 6.5 software is used to process the data and to correct the topography; the radargram undergoes basic and advanced processing such as surface normalization, filtering and migration.

4. Results and Discussion

4.1. Morphology of the Dunes

The interpretation from satellite imagery indicates that dune fields are distributed along the coastal plain, oblique to the present straight coast with mangrove vegetations growing associated with dunes and their density ceases towards land (**Figure 1**, **Figure 2(A)**). Dunes are oriented NNW to SSE and with increasing height towards land; dune 1 (D1) has 0.45 m, dune 2 (D2) and dune 3 (D3) have 0.65 m and 1.3 m heights respectively (**Figure 4**, **Figure 2(C)**); in Ashirmata temple region height of the sand hill is approximately 30 m. **Figure 4** demonstrates the bar diagram showing distance versus dune height, signifies the gradual increase in dune height from sea to landward. The vigorously growing vegetation increases the residence time of deposited sediments in the dunes and act as shelter to prevent erosion [25], may be the reason of increase in dune height towards land. The lee and stoss angles generally increases from coast to land, such as leeward angle varies from 11.07° in D1, 22.11° in D2 and 15.78° in D3 whereas the stoss angle varies from 7.76°, 11.30° and 13.30° respectively (**Table 2**). The gentle slopes on both windward and leeward side mostly by deposition by wind rather than erosion. The morphology of the dunes and paleosols dipping direction indicates the wind direction, probably from NW to SE and the fine grained sediments of the dune formation may be transported by the strong E-W currents. Distinct ripple marks, shifting continuously, are found associated with the sand dunes. The Indus delta is composed of

Quaternary and Holocene sediments and during south west monsoon, sediments in sea water receding to inlands through the creeks and the deltaic sediments accumulated along the coastal area. The long shore currents and tides transported these sediments towards Gulf of Kutch region [26]. Tidal currents and local winds carried the grains onto the beach and landwards like the Colorado River delta sediments carrying sediments to El Pinacate dune fields [27]. The coastal segment between

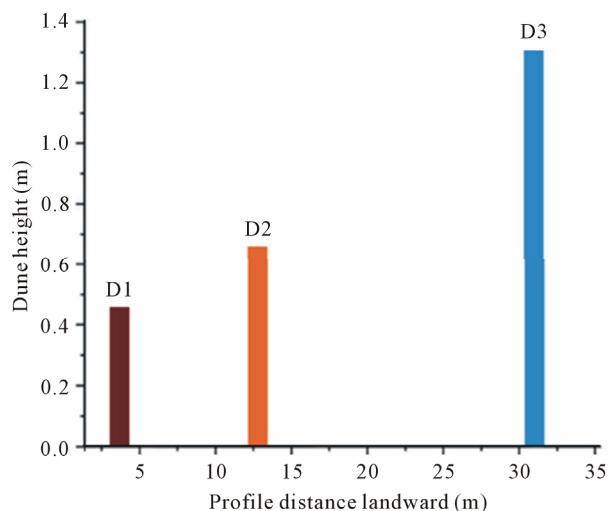


Figure 4. Bar diagram of dune height versus dune distance, dune height shows a gradual increase towards land. Dune 1 indicated by dark red with 0.35 m height, Dune 2 has 0.65 m and Dune 3 has 1.35 m heights, indicates by orange and blue respectively.

Table 2. Lee and stoss angles of the three dunes (D1, D2 and D3) along the GPR profile, estimated from GPR signature.

Dune	Dune height (m)	Stoss angle (in degrees)	Leeangle (in degrees)
Dune 1	0.45	7.76	11.07
Dune 2	0.65	11.30	22.11
Dune 3	1.3	13.3	15.78

Jakhau and Mandvi constitute sediments with terrestrial composition, which are reworked and redistributed by littoral drift, onshore winds and cyclonic events [28].

The vegetation-free backshore act as an important role for the sediment supply and dune formation [29,30]; the higher the longshore accumulation of sand the higher will be the growth of the foredune and more sediments will be transported towards inland causes a non vegetative backshore [31]. Mostly vegetation stabilizes the dunes but in some conditions vegetated dunes may eroded and mobilized, and they act as a nucleus for the accumulation of aeolian sediments and give a larger area of stability, under suitable conditions small dunes join together and form a continuous dune ridge system [5]. The mangrove vegetation associated with the dunes far from coast shows increase in height than dunes nearby coasts, illustrate the dune stability in relation to the vegetation.

4.2. Grain Size Analysis Interpretation

The grain size analysis results mean grain size varies from 2.636ϕ to 2.949ϕ in phi scale falls under fine sand category, there is no much variation in grain size of top and bottom sediments indicate the same source of origin.

The sorting varies from 0.410 to 0.481 implies well sorted sand, mostly originated from windblown sediments, the general trend shows that bottom sediments are more sorted than top. The grain sorting usually improves with decrease in grain size [32,33]. The better sorted and fine-grained dune sands are the results of longer aeolian transport [34,35]. The skewness values in between -0.016 to 0.110 indicate symmetrically skewed unimodal grain distribution evidenced by single source origin of sediments and kurtosis varies from 0.948 to 0.935 represents mesokurtic nature [36] (**Table 1**). Compared to top layers, the fine and medium sand proportion is higher in bottom layer, and on the top of dune 1 and dune 2, negligible amount of silt is found along with the sand (**Figure 5**). The percentage of medium sand is insignificant compared to the fine sand.

The particle size analysis of older dunes crests in Jaisalmer area perceived that coarser sand seen at top of the units indicated stabilized part of the crest due to the slow creeping of coarser sand for an extend period of time and finer sands generally seen on the mobile part [32,37,38]. Dunes of present study area is devoid of coarse grained sediments hence it is mostly younger dune complex and finer grain size implies the mobility of the dune to the

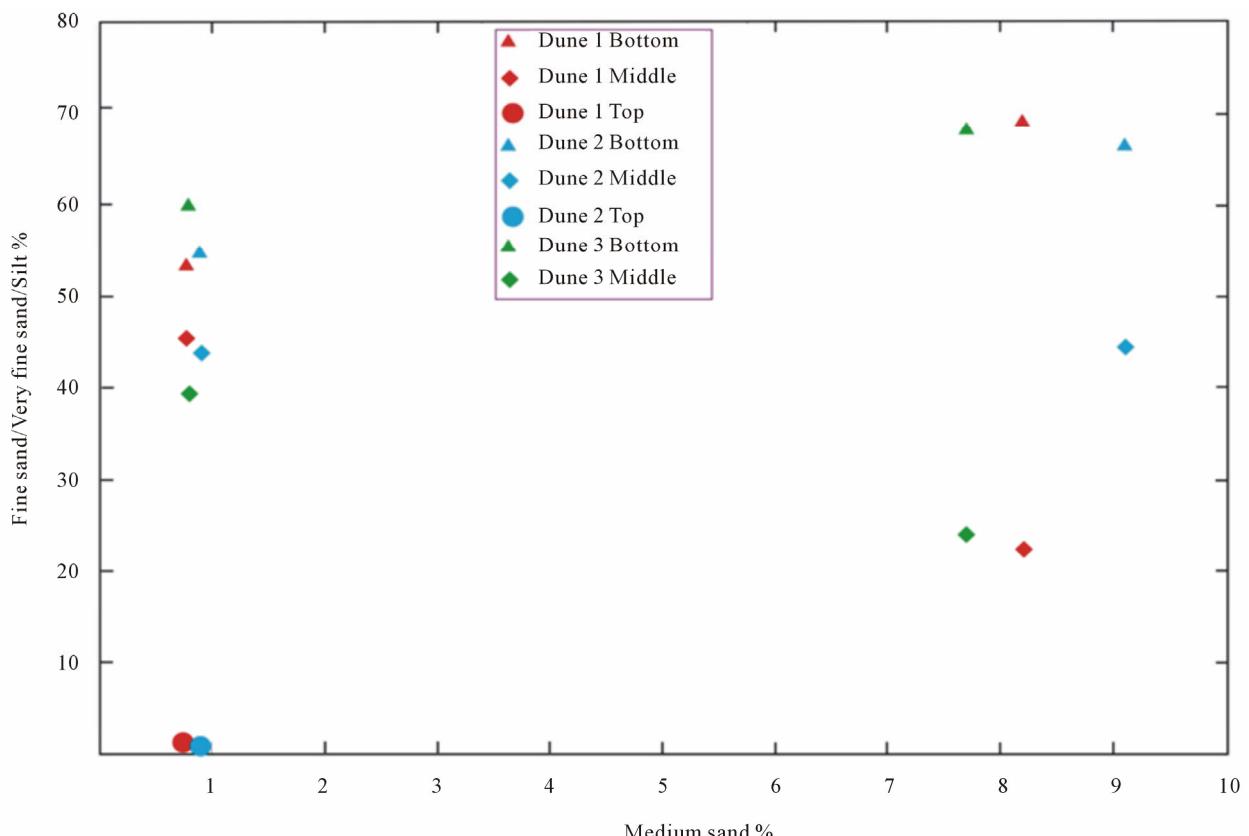


Figure 5. Plot showing the total fine, very fine sand and very coarse silt content of transverse dune types of Ashirmata Region Mandvi.

prevailing wind direction. The mean grain size of older dunes has finer and better sorting than the dunes with reactivated crest and has a large difference in grain size and sorting [29].

4.3. GPR Interpretation

The resolution of the radargrams is sufficient for the identification of sedimentary structures and stratigraphic markers within the dune structure. The depth of penetration limited to 0.8 m prevents the detailed analysis of the dunes, but continues, homogeneous sand layers with dune 1 (D1), dune 2 (D2) and part of dune 3 (D3) can be observed with high resolution (**Figure 3(a)**). Paleosols are noticeable along the dune slip faces characterizes the erosional and/or depositional surface (**Figure 3(b)**), might be formed by extreme storm activity, which are common along Gujarat coast. Buynevich [39] described the paleosols formation in dune slip faces and associated heavy mineral concentrations are clearly recognized in high amplitude GPR reflections. The extend and thickness of the paleosols have long been used as the indicators of dune stability in coastal dune fields [40-46]. The undisturbed planar bedding planes are better preserved at shallow depth may be signifies the recent aeolian origin of sand deposits. The uniform thickness of sand layers indicates a continuous wind at constant rate and direction with steady supply of fine sand. [47,48] reported plains of north Gujarat evidenced by reddened paleosol related to aeolian deposits indicated pedogenesis and the formation of paleosol was strong in Gujarat plains [49,50]. In Thar Desert, Punjab and Haryana plains, weakly developed paleosol horizon noticed in near surface sediments of the dunes [51,52]. The paleosols in ancient dunes of Geelbek in the Western Cape of South Africa have the age of Late Pleistocene and Holocene related to the last glacial maximum [22].

Patel and Desai [53] attributed that strong aeolian activity and dune formation in Northern part of Gujarat related to regression pursuing the Flandrian sea level rise. The evidences from aeolian sediments implied that arid condition in Gujarat mainland prevailed up to at least 10 ka [54]. In northern Great Plains lakes, several periods of paleosol formation took place about 2300 - 2000, 1400 - 1000 and 600 - 500 cal years B.P. and aeolian activities occurred between these periods, may correspond to droughts [55]. According to Shukla [24] the coastal dunes and sand beaches in between Jhakau to Modwa segment (study area falls under this coastal region) is the result of waves, currents and tide dominated processes. These processes may continuously or intermittently influenced by the deposition of sands along the coastal regions, onshore wind promoted the accumulation of sand near to an obstacle and consequently dune results.

Thus, the dune formation of present study, point out Recent origin of the dunes by aeolian activity.

5. Conclusion

The present study utilized GPR signatures and statistical data from sedimentological analysis to determine the internal structure of the dunes and their formation. The conclusions from the present work indicates that the dunes are NNW-SSE oriented and non parallel to the coast is aligned parallel to the prevailing NW-SE wind direction and there is a general trend of increase dune height towards landward side. The origin of sediments may be from Indus deltaic sediments; transported and deposited to southward by long shore currents and tides. Winds carried these sediments to inland for further deposition. The sedimentological analysis results in fine grained, well sorted, unimodal sand derived from wind-blown sediments of single source of origin formed during Recent Age. The undisturbed, homogenous sand layers in the GPR signature symbolizes a constant, unidirectional wind that may resulted the dunes. Paleosols noticed in the shallow depth of GPR profile indicates that the erosional or depositional surface may be formed by extreme storm action, frequent in Gujarat coast.

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