

An insight into subterranean flow proposition around Alleppey mudbank coastal sector, Kerala, India: inferences from the subsurface profiles of Ground Penetrating Radar

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Abstract

The mudbank formation along south-western Indian coast has been a scintillating phenomenon during monsoon season and the source of mud is a debatable issue till now. In the midst of many hypotheses, the subterranean passage is considered a possible one but needs to have supportive scientific evidence. This present study endeavours to demonstrate the potential use of the Ground Penetrating Radar (GPR) in generating subsurface information to locate buried paleochannels in coastal zone which could act as the conduit for transport of mud from terrestrial sources to sea. The historical maps of the late 1600s show that the present day Vembanad Lake was a part of the near-shore area and the coastline was nearly 60 km inside, drained by the rivers from the Western Ghats. Due to shoreline migration towards the seaside since late-Holocene, the present day landforms came to existence while the earlier channels got buried under recent sand. Nearly 500-m long GPR subsurface (6-m depth penetration) profile was generated and various paleo-channels were traced. These buried channels were categorized based on the pattern of their occurrences. Two erosional surfaces at around 1-m and 2-m were mapped and their controls on paleo-channels were derived. During phase-I, many paleo-channels were in active condition and due to heavy deposition during phase-II, though these channels managed to maintain themselves, but the width of their courses got narrowed and, in recent times they got filled up and buried. The pre-monsoon and monsoon GPR profiles signify the high degree of wetness characteristics of these buried channels during monsoon season and their possibility of being passages for possible transport of water charged with fine clay materials through the unconsolidated in-filled material in these buried channels. This demonstrative and first-hand subsurface information through GPR studies would further support to facilitate in consolidating the subsurface evidence for strengthening the subterranean passage concept in the mudbank area of the south-western coast of India.

Keywords: *Subterranean passage, buried paleochannels, GPR, erosional surfaces, subsurface mapping*

1.0 Introduction

The formation of mudbanks has been an exceptional phenomenon occurs along the southwest coast (SW) of India, especially Kerala coast during southwest monsoon season (Silas, 1984; Philip et al. 2013). Since the 1930s, there have been many scientific studies to understand the causes, sources of mud, ecology and productivity, physical and chemical aspects of the sea, annual drift etc. (Bristow et al., 1938; Varma and Kurup 1969; Gopinath and Qasim 1974; Jacob and Qasim (1974), Ramachandran and Mallik, 1985). Similar occurrences of mud banks in few other countries such as French Guiana (Lefebvre et al. 2004, Anthony and Dolique 2004, Chevalier et al. 2008; Florida Bay, USA (Taylor and Purkis 2012), Brazil (Allison et al. 2000) etc., indicate varied characteristic in terms of its formation and spatial distribution with given geological and climatic conditions.

As far as the mudbanks along the Kerala coast is concerned, the source and origin of the mud has been one of the interesting issues among other issues such as characteristics of the mud, the process and formation of the mudbanks, ecology and fishery potentials etc., and being studied and discussed in years by various researchers. There are many hypotheses put forward to explain the source of mud, among which subterranean passage (Crawford 1860 in Bristow 1938 (cross ref.); King 1881; John Rhode (1886 in Bristow 1938)), River deposition (Ducane et al 1938), water-bearing stratum, upwelling hypothesis (Ramasatry and Myrland (1959); Ramamirtham and Rao 1973)) etc., are explained and discussed. Though all these hypotheses have their own advantages and disadvantages, they are not properly elucidated due to lack of convincing scientific / field supports holistically.

However, the consensus opinion, emerged out from all these theories, points to the subterranean passage hypothesis in terms of paleoenvironment in late Holocene and the period thereafter. In spite of the convincing explanations advocated by Crawford (1860) in Bristow (1938), Nair (1976), Gopinath et al (1983) on the theory of the subterranean passage in Alleppey mudbank coastal sector, the field evidence of buried channel system were limited. However, Balachandran (2004) explained that the subterranean flow is activated through a trending fault and the injected lake water (from Vembanad Lake) stir up with mud / clay by its thixotropic properties and transforms into flowing mud.

This present study, being substantiated with the subsurface information obtained through GPR (Ground Penetration Radar) on a demonstrative scale at Alleppey coast, attempts to

initiate an evidence-based discussion on identification of subsurface paleochannels and their possible linkages to mudbank area. This present study was initiated to understand the subsurface characteristics of the beach zone around mudbank areas as no such information was available at present. Also, this study has been carried out to generate sub subsurface information on a demonstrative scale to understand the potential use of GPR in such studies.

2.0 Study area set-up

Along the southwest coast of India and especially, Kerala coast, there are many locations of mud bank occurrences among which along the Alleppey coast is one of the best known since 1885 where the spatial spread of mud bank is significant in every year, especially in recent decades and remains for much longer period than other mud banks. For the present study, south of Alleppey (Alappuzha / Punnapara) coast was chosen (**Fig.1**). Physiographically, the study site locates at the southern periphery of the Vembanad Lake and Alleppey town. This study site is selected so as to understand the paleochannel occurrences in connection to the Vembanad Lake and this area locates at the ring of mud bank of Alleppey.

Once high degree erosion type coast, at present, it shows accretion activity as evidence by the present location of old sea wall just located 300-m from the shoreline (Parvathy et al. 2015). Due to accretion process, the beach is wide at north but during mud bank disappearing period (towards the end of the monsoon), severe erosion is observed at the southern part of the study area (Punnapara). The shelf is narrow and having a gentle gradient with paleo strandlines observed at 20-m water depth (Narayana et. 2008). Meteorological influence is dominating than that of tidal force. The SW monsoon significantly controls the formation of mudbanks. The field observation shows that during July-August, the mud bank is in the fullest function (Narayana et al. 2001). Generally, the study area has gentle but narrow foreshore and wider (150-m) backshore zone.

3.0 Methodology

Under the ongoing project on a comprehensive study around Alleppey mudbank coast, more than 9000 m long stretch of the shoreline starting from Alleppey beach has been surveyed. Survey details with respect to surface and subsurface profiling were recorded in terms of each 500-m stretch. For this present discussion, one such 500-m stretch of profiled area has been discussed in detail.

3.1 Beach profiling

Using an automatic level (Trimble), the elevation readings were recorded. Sometimes, profile line was crossed by seasonal drainages where the profiles were fragmented. The starting and ending points of each line were recorded using Ceddusor differential GPS and also few interesting locations of geomorphic interests and sample location points were marked by spatial measurements. This profile line was kept as common reference transect for GPR profiles and other seasonal fieldworks. All these observations on elevations were fed into GPR profiles to normalise the surface readings.

3.2 GPR profiling

Along the beach profile, the GPR lines were carried out (**Fig.2a**) to the entire stretch of 500-m along the shoreline. The SIR-3000 GPR system manufactured by GSSI (Geophysical Survey System Inc.), USA was used. Two seasons subsurface profiles (pre- and monsoon periods) of 6-m depth penetration (140 ns) were generated using 200 MHz antenna to understand the subsurface features along the coast. In three locations, subsurface profiles across the shoreline were collected to understand the shoreline movements, if any. In few locations, 4-m depth profiles were also generated to substantiate and recheck the findings in the other depth profile by comparisons. While initiating the subsurface survey, the GPR system was set to the field conditions by tuning with the appropriate parameters (such as dielectric constant 10; samples/scan 512;scans/s 200; scan/m 50;m/mark 100; gain mode = auto; approximate depth range 140 ns (for 6-mdepth profile) and 100 ns (for 4-m depth profile, etc.); units (m) in the header file. Parameters such as position(ns), meters/mark; scans/mark; dielectric constant, etc., could be also editable during post-processing stage. The file header was furthermore edited in the field to include location, surface material characteristic and other useful information in characterizing the survey location. The movement of the antenna along the profile lines was monitored by the measuring wheel which has been got validated by comparing the horizontal distance in the profile with the field measurements. Due care was exercised to uphold the optimum antenna towing speed along the profile line. In between, at few stretches, surveys were repeated to check the consistency of the data.

Thus, the generated time-domain geo-radar profiles were digitally processed with RADAN software (version 7) in the laboratory. By adopting the standard procedures, the subsurface profiles were normalized through low-pass filtering to remove high-frequency noises and

high-pass filtering to minimise the flat lying ringing system noises. The deconvolution and migration techniques were carried out to eliminate the ringing multiples and the diffraction, respectively. The normalised time domain data have been enhanced with Hilbert transformation algorithms through which the time domain radar data were transformed into magnitude and frequency domain data to enhance some of the subtle subsurface features. The converted information typically exhibits the significant dielectric changes and variation of some of the features based on respective dielectric constants. The verification and correlation of the GPR data with subsurface sedimentary layers were made with trial field trenches at selected locations.

3.3-Dimensional GPR survey

Based on the information on GPR profiles, a location was selected for 3D modelling of the subsurface. Separate profiles were generated in a grid pattern of 40m x 20m at an interval of 10m and 5m interval respectively (**Fig.2b**). Using 3D algorithm of RADAN software (ver.7), 3D models were constructed with slices (panels) along x, y and z directions. Various depth (time) slices were used to interpret the buried paleochannels and the subsurface flow direction.

4.0 Results

4.1 Identification of buried paleochannels

Significant differences in amplitude signals with references to the compactness of the sand layers and the refilled one by earlier streams sharply support to distinguish various bed-sets in the subsurface profiles (Slowik, 2012). Strong amplitude signals are evidenced from the compact sand layers whereas the weaker amplitudes magnify to recognise the channel filled-in deposits which are less compact and coarse grained. Likewise, reflections at different depths indicate depositional sequences of sand layers and comparative nature of moisture range in various horizontal depth layers. Many places, the radar reflections indicate a rhythmic and continuous nature of sand layers until they are intercepted by the paleochannel deposits. It is remarkably observable from the GPR profiles that periphery of the paleochannels displays evidence of dipping characters of sand layers. In many places, buried sand bars / sand dunes are remarkably traced as a strong column of vertical reflections in terms of high amplitude. Around a depth of 3-m, the water level is noticed and below which the reflections are weaker. Due to signal attenuation, the reflection amplitude

was very weak and made further interpretation difficult. Based on these signal characters, 8 paleo-channels were traced along the profile and their descriptions are presented below.

4.2 Dimensions of paleochannels

Along the entire stretch of the GPR profile of nearly 500-m, 8 paleo-channels were observed with significant radar reflection amplitudes. The width of the paleochannels varied from 5 to 26-m. Most of these identified buried channels show rhythmic refill sediments. Field investigations through trial trenches indicate a loose fine to medium grained sands with clayey propositions. The first one which is observed from 9 to 35-m in the profile has clear dipping layers at the banks and is about 26-m wide (**Fig.3**). The dipping layers are seen buried and overlain by a metre thick sand. The refilled sediments of the channel are loose and with more moisture. The second paleochannel is traced between 100 and 108-m distance in the profile and displays a distinctive cone-shaped window (**Fig.4**). Its bottom scales about 8-m in width whereas its top was found to be 3-m wide. The structure of buried channel indicates the shrinking of its width with time. It also has dipping layers at both the sides during earlier stage (while up to 2.5 m depth) and vertical cut sides in a later stage. This clearly indicates the closure of the channel in stages and that it faced burial in recent time. The third buried channel shows vertical layers at both sides up to 2.5 m depth (**Fig.5**). From the nature of the refill sedimentation, it is inferred that this 7-m wide buried channel got dried suddenly and rhythmic layers which form as a result of wind action were missing in refilled sediments. The fourth buried channel is about 18-m wide and the dipping layers at both sides are missing. It displays a partial extension of a sand dune on one side (**Fig.6**). It indicates a manual removal of sand for domestic need by local people. The buried channels 5 and 6 are complementary and could either indicate the migration of the channels or braided nature (**Fig.7**). With one meter cover of present sediments, they are seen extending up to 3.5-m depth and beyond. The paleochannel 6 looks like a tunnel having dipping layers at both sides (**Fig.7**). In this particular stretch (395-405-m), 3D subsurface GPR survey was carried out to understand the flow channel direction through 3D models which are discussed separately in section 4.6. More or less undisturbed continuation is observed from 405 to 470-m in the GPR profile (**Fig.8**). The seventh paleochannel is about 20-m wider having dipping layers on both sides (**Fig.9**). It is observed that this wider buried channel is also a deeper one. The dimension shows that there must have been comparatively a large stream draining through this channel. The

eighth buried channel is a complementary to the seventh one and is separated by only a narrow sand bar of about 2-m thickness (**Fig.9**).

4.3 Categorisation of paleochannels

Based on the geometric pattern of the buried paleochannels, there are four types identified namely (i) wider with dipping layers at both sides (ii) conical shaped (iii) composite and (iv) tunnel shaped. Each type has its processes associated with it. The wider paleochannels (1 and 4) has typical dipping layers on each side (Fig.3 and 6), indicating their existence until recent times before getting covered by the recent sediments. They show rhythmic and gradual sedimentation and becoming shallower slowly with time against sediment input. The conical (2) buried channel reveals shrinking of the channels in time and sedimentation (Fig.4). The composite paleo-channels (3, 5, 7 and 8) indicate the bifurcation (distributaries) nature of the channels and inter-channel system (Fig.5, 7 and 9). The tunnel shaped buried channel (6) indicate the cut-through capacity of the earlier drainage through the sediments and able to maintain its shape. All these types of buried paleochannels act as a conduit of subterraneous flow and support to transport mud charged water through them to the sea.

4.4 Spatial location of paleochannels with reference to present drainages

The field observations indicate two drainage channels flowing one at the northern end and another at the central portion of the study area. The presence of such drainages supports the view that the coastal area was frequently punctuated by drainages which got buried in recent times as and when sedimentation and coastal processes acted upon them. Also, the migration of shoreline as added by the regression/transgression activities cause these paleochannels to get buried. Though they got buried, still they act as media for underground passage owing to their permeable nature and loose / unconsolidated sedimentation of filled-in materials. Many of the paleochannels are seen located away from the present day streams in the study area.

4.5 3D simulation of a paleo-channel

One of the paleochannel areas (No.6) has been surveyed further to understand the flow pattern and nature of deposition in the sea front. An area of 40x20m was selected and x, y and z panel diagrams in 3D space were generated. Panels of various distances (1-m interval) to the shoreline were simulated and **Fig.10** illustrates various panel models related to paleo-channel dispositions at different distances from the sea. At 20-m model (away from the shore) (**Fig.10a**), a subsurface window / paleochannel is clearly mapped as indicated by

weaker reflection and more or less, it shows a tunnel shaped channel. It is then corroborated with a 2-m deep slice (time slice) where low amplitude reflection clearly shows the flow channel. Finally, a panel at the sea shows a narrow opening of the same channel (**Fig.10b**). The sides of the paleochannel are with strong amplitudes indicating compact sand layers representing stream banks. Likewise, other models at 15, 10 and 5-m distance from the shoreline (**Fig.10c, d and e**) illustrate the same phenomena. From these models, it is observed that the nature and dimensions of the channel vary as it approaches the shore. It clearly denotes the shoreline movements towards seaward in recent times. Until 15-m away from the sea, the buried channel was tunnel shaped. Between 15 to 10-m to the shoreline, the buried channel becomes a narrow channel with compact sand deposition at each side. This indicates a formation of a new beach and still, the paleo-stream was able to cut through. But around 10-m away from the shore, the paleo-channel was narrowed by the recent deposition and opening was minimised. However, still 5-m away from the shore, the paleo-channel get rejuvenated and connected to the sea. This clearly illustrates the active connection of the buried channel with the sea indicating dynamics of the subterranean system even at the present time.

5.0 Discussion

5.1 Inferences from the historical maps

The coast of Kerala was often visited by various travellers in historical times. Earlier historical documents and archaeological evidence indicated that Kolam, Cochin etc., were once popular ports for maritime trades with middle east countries. Due to rich maritime activities along this coast, many historical maps were available for reference (**Fig.11**). Though these old maps were prepared with minimum survey facilities, clarity in terms of spatial accuracy might be missing. However, one can visualize the general disposition and nature of the coastline in historical times. One map of 1682 indicates a highly fragmented nature of the Kerala coast especially along the Alleppey coastal area (shown as a red circle) (**Fig.11a**). There were series of islands running parallel to the shoreline. Even, Cochin was an island during that time. The Vembanad lake which is captured inland, an enclosed water at present, was a part of near shore (Padmalal et al., 2014a) and the eastern periphery of the present day lake was a real shoreline during the 1600s. If we realise the sea level changes during Holocene, especially, during high sea level stand during mid-Holocene (3200-2700 yr.BP), the islands as seen during 1600 AD could have been submerged shoals and the rivers from Western Ghats during mid-Holocene period

deposited a huge amount of sediments to the paleo sea, encouraging the shoals to grow into islands (Padmalal et al., 2014b). During that paleoenvironment and situation, all fine fluvial sediments had deposited in the nearshore region which acted as a sedimentary sink to the river sediments especially clay sediments (Limaye et al., 2014). Historical maps of 1700 and 1740 AD also witnessed to this geomorphic arrangement and paleoenvironment (**Fig.11b, c and d**). However, a map of 1760 AD reveals a huge accretion scenario wherein all these shoreline islands were started merging together and as on today, the recent survey indicates a consolidated coastal zone of depositional type and within the last 350 years, all islands were reclaimed to be a part of the mainland. This scenario could substantiate the sea level changes during mid-Holocene to recent times and heavy siltation from ancient rivers, leaving depressed portion as the Vembanad lake and recent deposition on the paleo riverine clay deposits. This geological process indicates that the Holocene clay deposits form an essential subterranean deposit in this area (Rajan, 1996). This has been confirmed by the recent studies through many boreholes studied around the Vembanad lake and surroundings (Padmalal, 2012).

5.2 Paleo-geomorphic disposition and present day coastal configuration

The present day geomorphology illustrates the migration of shorelines in recent times as evidenced from the array of beach ridges and swales in the coastal strip between the Vembanad lake and sea, around the Alleppey coast (Padmalal et al., 2014b). In fact, the lake is separated from the present day sea by a narrow strip of land of about 10-12 km. The low elevated beach ridges in this coastal strip denote the accretion activity in this area (Padmalal, 2012) and shifting the shore towards seaside in historical time. In consonance with this act, historical maps clearly reveal the regression of sea, in turn, advocates shoreline migration by progressive stages of regression since Holocene and is more rapid during the historical period. The present day rivers from the Western Ghats which flow into the lake have earlier joined the sea directly when sea level was high and Vembanad Lake was under the sea (Murthy et. al., 1984). This scenario has been significantly substantiated by the historical maps as discussed in section 4.1. Due to the migration of shoreline owing to various factors, the present day coastal strip was deposited and the lake got separated from the sea. This has been evidenced through the observation of borehole logs which shows the bedrock was encountered at 100-120-m depth but overlain by a huge thickness of clay and finer silts deposited by the earlier rivers (Brown, 1928; Silas, 1969; Padmalal et. al., 2012). These observations altogether substantiate that through the buried river

channels, due to increasing in the pressure head in the lake and present day rivers during the monsoon period, the fluid mud could get through the buried paleochannels and reach the sea. By this present study, the GPR information support to recognise few paleochannel network in the coastal zone.

5.3 Paleo-channels and buried erosional surfaces

Generally, the GPR subsurface profiles are utilised to pick-up appreciable imprints of paleochannels and its continuity in spatial dimension (Jones and Hajek, 2007; Smith et. al., 2009; Rejiba et. al., 2012; Igel et. al., 2013; Altdorff et. al., 2013). The 2D and 3D models generated clearly portrays the buried paleochannels across the shore zone in many places where present day drainages are not seen (Mallinson et. al., 2010; Loveson et. al., 2014). In the same way, through the present GPR profiles at Alleppey coast, eight paleo-channels were picked-up along the 500-m long stretch. Apart from the few buried channels which happen to be a pit for sand removal for domestic purposes, other have defined channel network characters (**Table 1**), having dipping layers at both the ends. These braided buried channels during monsoon season get saturated with water and behaves as a passage for movement of fine mud fluid into thesea. This has been further illustrated by the mud cone which appearances in coastal and paddy fields lying between lake and sea (Gopinathan et. al., 1984). Wherever along the buried paleochannels, the weak spots / crack zones exist, the mud tries to come out forming mud cones.

Based on the radar reflection as observed in the GPR profile along Alleppey coast, two erosional surfaces are traceable at around 1-m and 2-m depths. The water level is found to occur at around 3-m depth. Around 20-cm fluctuation was observed during pre-monsoon and monsoon periods. The sand layers seen up to 1-m depth from the surface have almost undisturbed lineation with dry bed sets as evidenced by the strong reflection. But, the sand horizon lying between two erosional surfaces (i.e., 1 to 2-m depth) variably displays discontinuous and disturbed disposition which is indicated by differentially weak reflections. The sand layers are highly saturated below 3-m depth as inferred by feeble reflections which were received because the signals got attenuated due to saline nature. Beside this generalised scenario, at few places, significant observations were made in respect to buried geomorphic features. At around 115 to 125-m distance (**Fig.4**), two buried sand bars are observed up to 1-m depth at where the erosional surface is seen above them. It clearly indicates that the upper 1-m sand cover is of recent origin which covers the earlier surface. Around 110-m distance, a localised slip in bedset is observed due to collapsing of nearby

paleo-channel 2. From the **Figure 5**, a distinctive appearance of sedimentary layers between 2 and 3-m is observed and indicated by the differential reflection amplitude when compared to above sand layers. These sand beds are not compact when compared to the upper layers and also they are comparatively coarse grained. These characters point to a different depositional environment. And again, these erosional surfaces are significantly distinguishable around 340 to 355-m distance (**Fig.6**). A clear demarcation of the erosional surfaces is seen in **Figures 7,8 and 9**. By analysing the occurrences of these two erosional surfaces, the following inferences are made clear (i) Above the water table (at 3-m depth), there are three sandy zones (**Fig.12**) which were deposited / formed in different environment(ii) One can also infer that the earlier surface was at 2-m below the present surface (phase-I) with sand dune topography. Thereafter, the nearly 1-m thickness of sand deposition had buried the earlier topography and subsequently, developed its own sand dune surface (phase-II). The recent processes again deposited the upper cover which conceals all the earlier surface features (phase-III) (iii) Different sets of buried sand bars are observed at 1-m and 2-m depths with respective erosional surfaces, indicating different periods of environments(iv) The upper 1-m sand cover is of recent one which conceals the earlier surface.

In the light of the above inferences, the erosional surfaces with respect to different phases can be correlated with the occurrences of paleochannels and their stages of destruction (**Fig.12**). Most of the paleochannels are developed during phase-I. During phase-II, these channels were narrowed down and subsequently got filled-up with the recent deposits (phase-III). In the case of paleo-channel 1, the dipping layers are significant with reference to erosional surfaces (**Fig.3**) and they indicate the widening of the channel at phase-II stage (refer 35-40-m distance in the profile). The paleochannel 2 was wider at phase-I stage and made narrower during the phase-II stage. Even, it was active in recent time as a narrower channel but lost its occurrence due to side wall collapse as evidenced by a slip feature nearby. In the absence of dipping layers at both sides and having vertical walls with no significant correlation with the erosional surfaces, the subsurface window 3 (**Fig.5**) may indicate anthropogenic influences rather than considered to be a buried channel. The paleochannel 4 is wider and one side has dipping layers and could be a part of a huge dune. Here, the erosional surfaces are clearly traceable with significant signatures of reflection. Braided nature of pattern is observed with respect to the paleo-channel 5. During phase-I and II, the channel was active and lost its existence in recent days. The

paleochannel 6 is tunnel shaped. During phase-I, it was about the 7-m wide channel and was in full action during the phase-II stage but subsequently closed during phase-III depositional stage. The paleochannel 7 and 8 were complimentary to each other and were active through phases-I and II and silted-up gradually in the recent times.

5.4 Paleo-channels and subterranean flow

In 1858, Heber Drury put forth the hypothesis on the probability of a subterranean flow to the sea from inland waters, especially from lagoons. Crawford (1860) illustrated the existence of subterranean channels in Alappuzha connecting inland waters and sea. After studying the mudbank formation in Alleppey coastal waters, King (1881) opined that there should be an underground discharge of water to coastal waters from the lagoon. Ancient streams and channels get buried in the coastal zone as shoreline receded. All these buried channels refilled with unconsidered materials mostly fine sediments and clays brought by the continued action of the fluvial domain. Though these buried channels were buried under the sand cover of recent origin, they have the ability to act as a passage to transport fluid through them.

This present study through GPR subsurface mapping substantiates the existence of the paleochannels which are buried and filled with less compact recent sands. These unconsolidated media has been initiating the flow through them during monsoon season. In order to understand this phenomenon in detail, a monsoon season survey (to construct subsurface 3D models) was conducted along a stretch of about 200-m within the original GPR profile line (pre-monsoon). The idea is to correlate the pre- and monsoon characteristics of the subsurface media along the coastline around the mudbank zones with particular reference to the identified buried paleochannels. In both the pre- and monsoon GPR profiles (**Fig.13 and 14**), both erosional surfaces are clearly marked out. But a few centimetres of fluctuation was observed in the water level in both the profiles. While the pre-monsoon subsurface profile indicates the dryness of the sand layers beneath, the monsoon profile reveals the wetness characteristic nature of the same sand layers through the significant reflection amplitudes. With the wetness situation during monsoon season, the extension of the paleochannel is remarkably traced (**Fig.13**). The pre-monsoon profile indicates a cone window structure whereas the monsoon profile illustrates the extension of the cone window structure as a composite buried channel. It indicates that at the phase-I stage, the channel was wider enough (nearly 40-m width) and during phase-II, it became braided due to the accretion of sediments and less supply of the water in the channel. In

addition to this information, the existence of sand bars / sand dunes is clearly traceable in the monsoon profile. Development of sand dune features in phase-I and II are also observed clearly. The reflection characters are so clear to be recorded. Even the nearby area without paleochannels are characterised significantly by the reflection amplitude of sand layers (**Fig.14**) during both the seasons. The phase-I horizon is more amenable to wetness while comparing to the phase-II horizon. It indicates that the grain size becomes finer and finer upwards. The phase-I stage buried sand dunes are well traceable (around 150-m distance in the profile). These inferences from the pre- and monsoon subsurface profiles significantly reveals that i) these buried paleochannels show a high degree of wetness during monsoon season which enabling them to fluid transport through them; ii) since they are connected with inland drainage system, even clay charged water could flow through them taking advantage of unconsolidated in-filled materials of these buried channels.

6.0 Conclusion

About 500-m stretch of Alleppey coast was surveyed using GPR and surface profile up to 6-m depth was generated. Many buried paleochannels were mapped and it is found that most of these buried channels were braided with dipping layers at both sides. Two erosional surfaces that were observed at around 1-m and 2-m have their controls on the paleochannels in terms of their existence, activeness and closure. It is observed that during phase-I period, the paleochannels were active and wider and, later on, they got silted up during phase-II and finally, filledup with sediments in recent times. These observations from the subsurface GPR profiles indicate the nature of continuous siltation and gradual sedimentation in recent years. The pre-monsoon and monsoon subsurface profiles support to establish the high degree of wetness in paleochannels and sustain the present concept of subterranean passage through these buried paleochannels to sea.

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Caption for Figures

Fig.1 Location Map and GPR plan at Allepey coastal area, Kerala, India

Fig.2a. GPR survey in the field; b) Plan for 3D survey

Fig. 3. GPR subsurface map (Part profile : 0 - 62 m) along Allepey shore

Fig.4. GPR subsurface map (Part profile : 85 - 128 m) along Allepey shore

Fig. 5. GPR subsurface map (Part profile : 225 - 263 m) along Allepey shore

Fig. 6. GPR subsurface map (Part profile : 318 - 352 m) along Allepey shore

Fig. 7. GPR subsurface map (Part profile : 368 - 410 m) along Allepey shore

Fig. 8. GPR subsurface map (Part profile : 405 - 447 m) along Allepey shore

Fig. 9. GPR subsurface map (Part profile : 460 - 502 m) along Allepey shore

Fig. 10. GPR subsurface 3D panel models; a) y-panel 20-m away from shoreline; b) y-panel is at shoreline; c) y-panel 15-m away from shoreline; d) y-panel 10-m away from shoreline; e) y-panel 5-m away from shoreline. In all models, z-panel is at 2-m depth.

Fig. 11. Historical maps showing shoreline status of the study site Red circle shows the location of present Vembanad lake.

Fig.12. Generalised schematic diagram on the occurrences of paleo-channels and depositional environment(based on GPR reflection amplitude)

Fig.13. Comparison of radar subsurface reflection (Part profile : 60 - 132 m) during a) Pre-monsoon and b) Monsoon period along the Allepey coast.

Fig.14. Comparison of radar subsurface reflection (Part profile : 130 - 210 m) during a) Pre-monsoon and b) Monsoon period along Allepey coast.

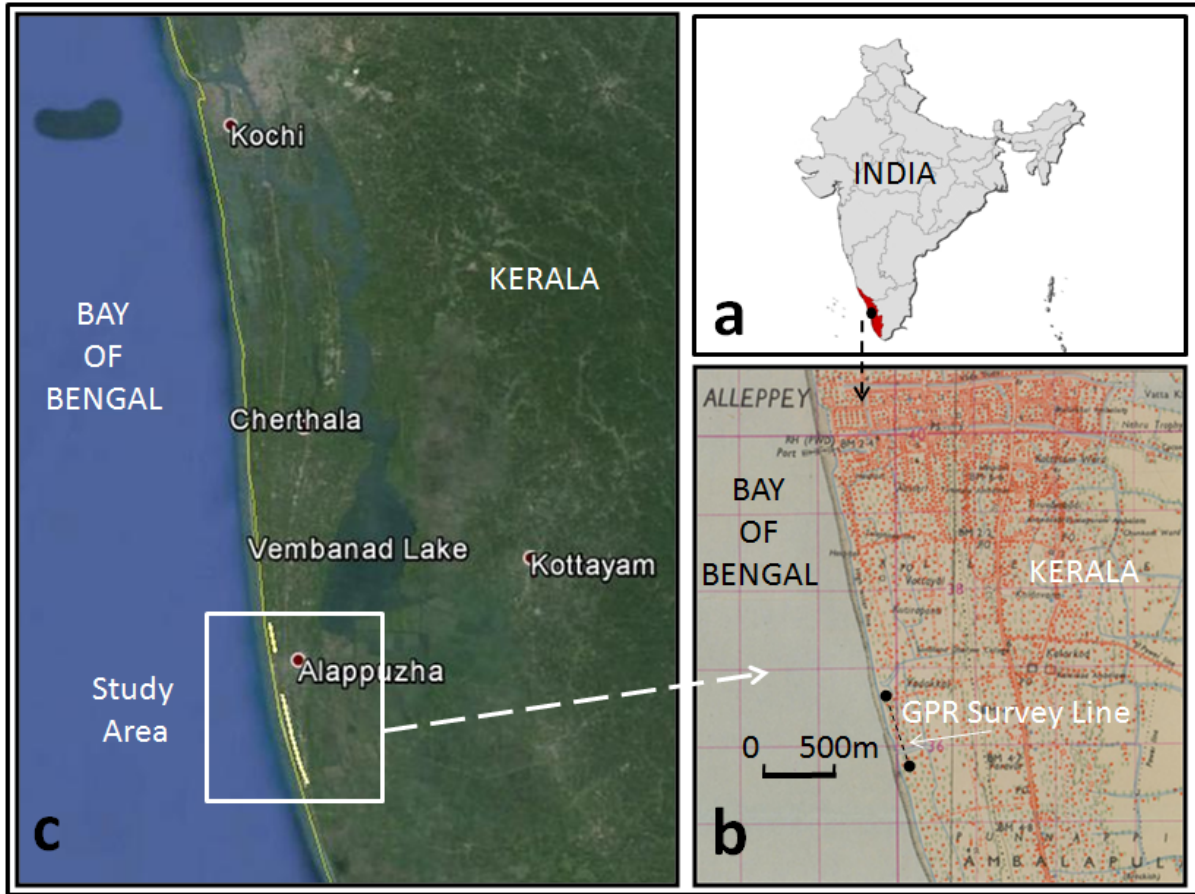


Figure 1.

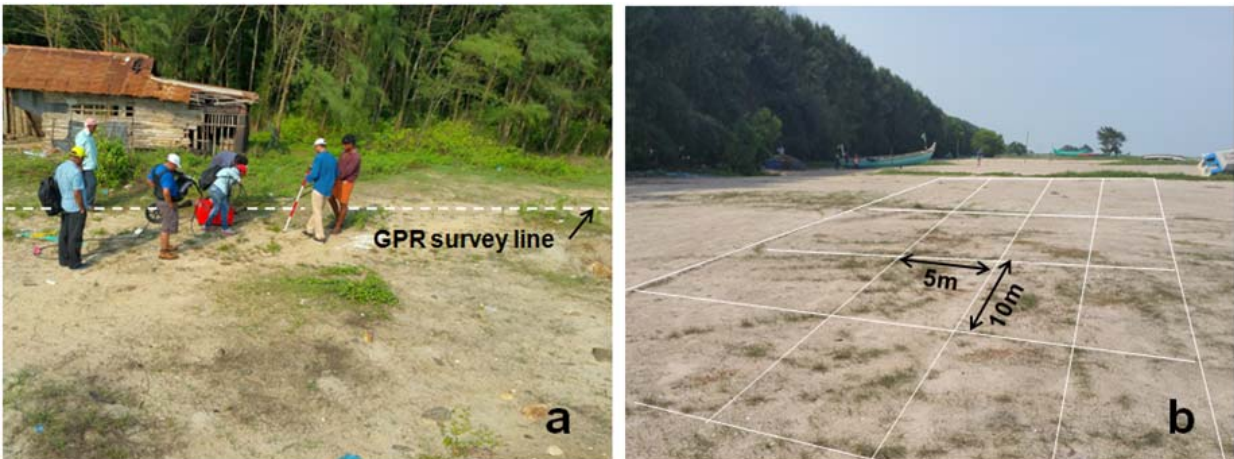


Figure 2.

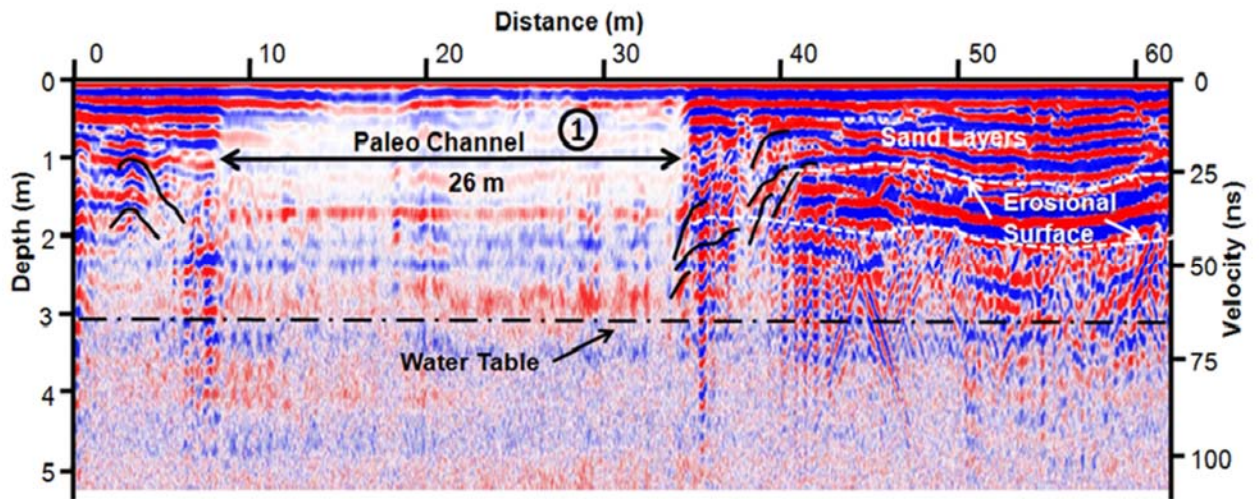


Figure 3

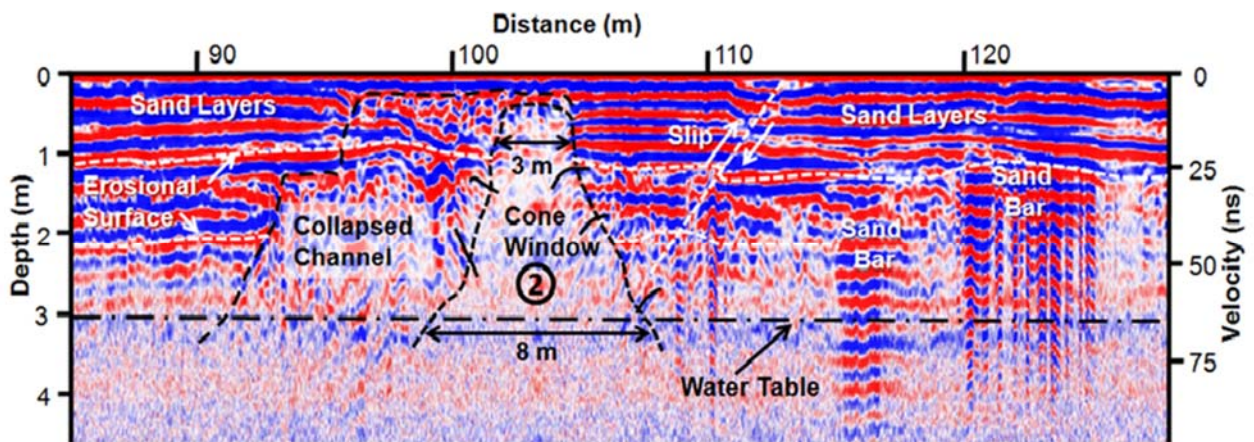


Figure 4

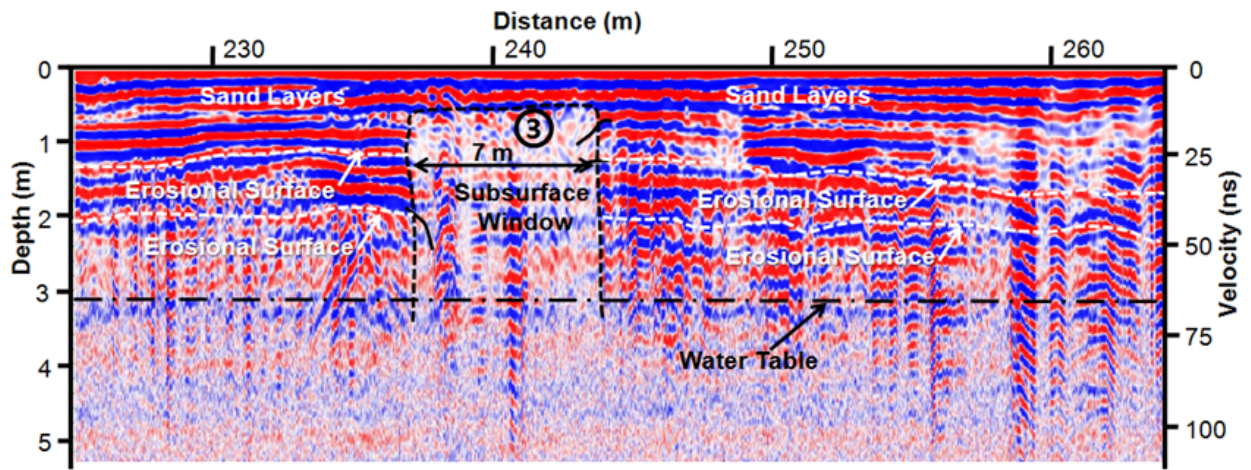


Figure 5

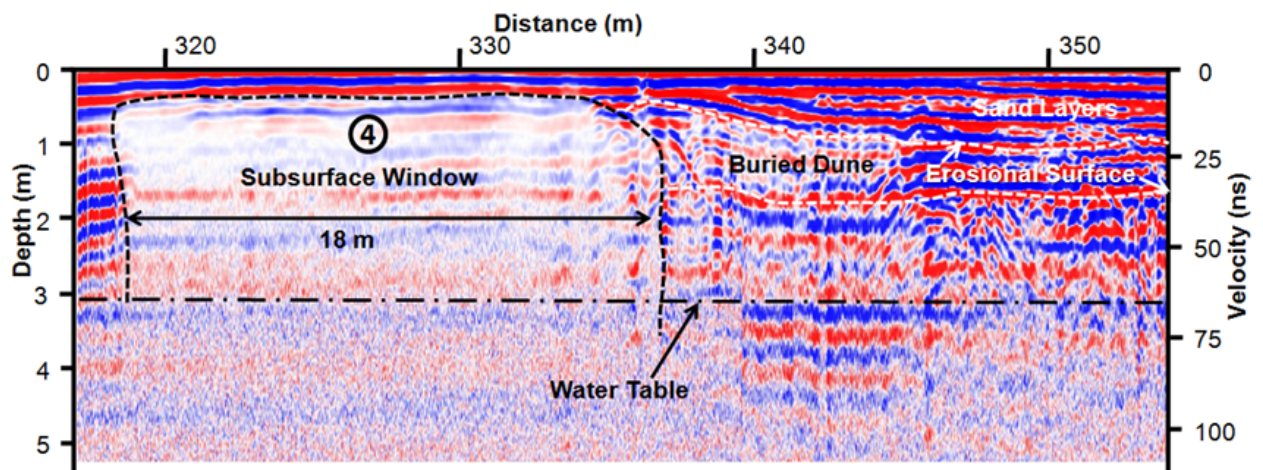


Figure 6

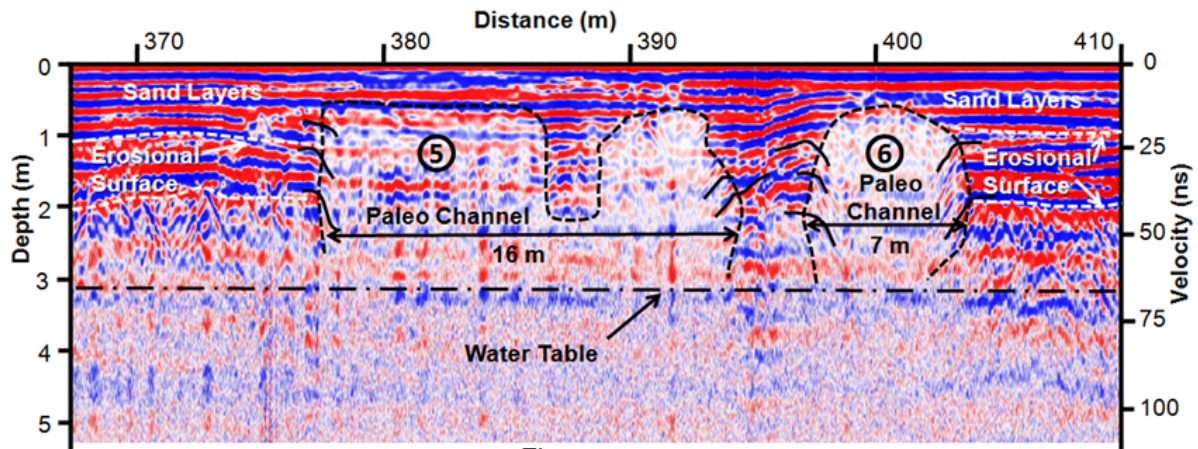


Figure 7

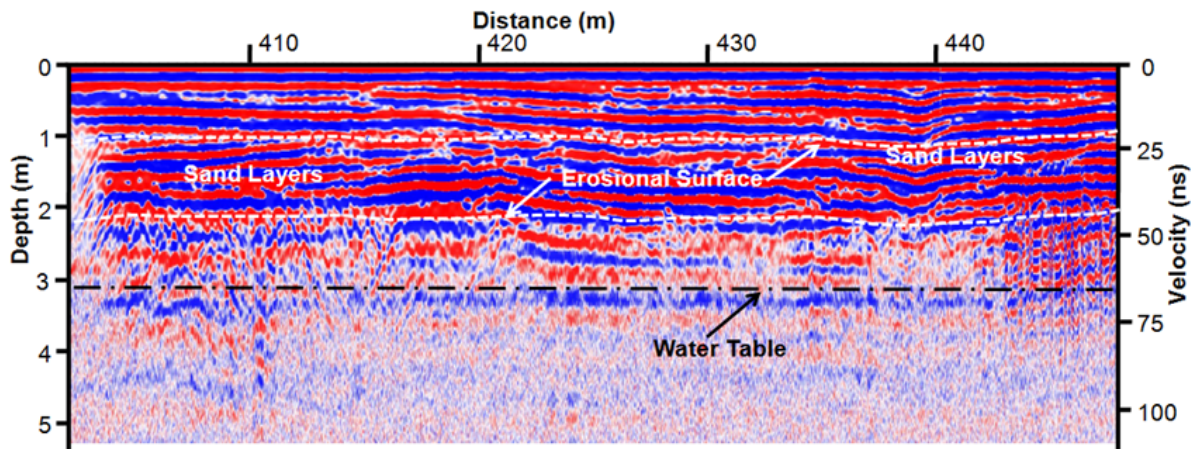


Figure 8

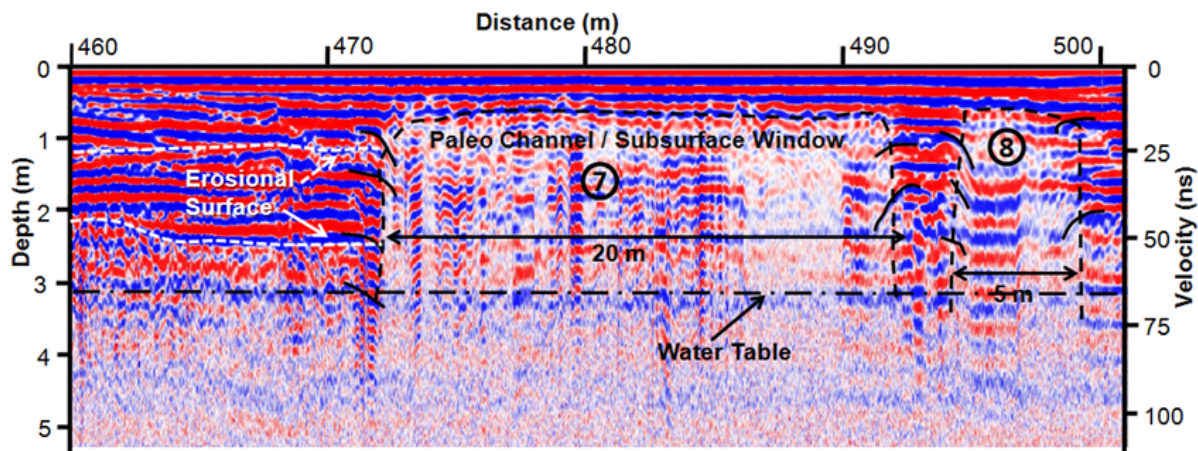


Figure 9

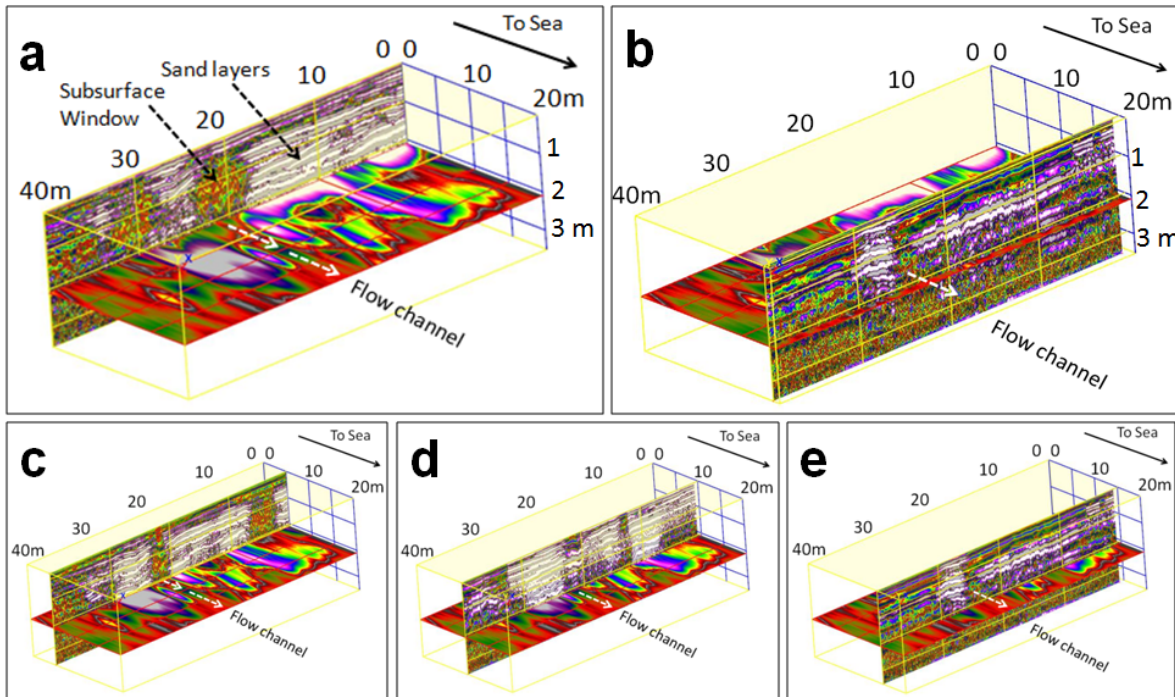


Figure 10

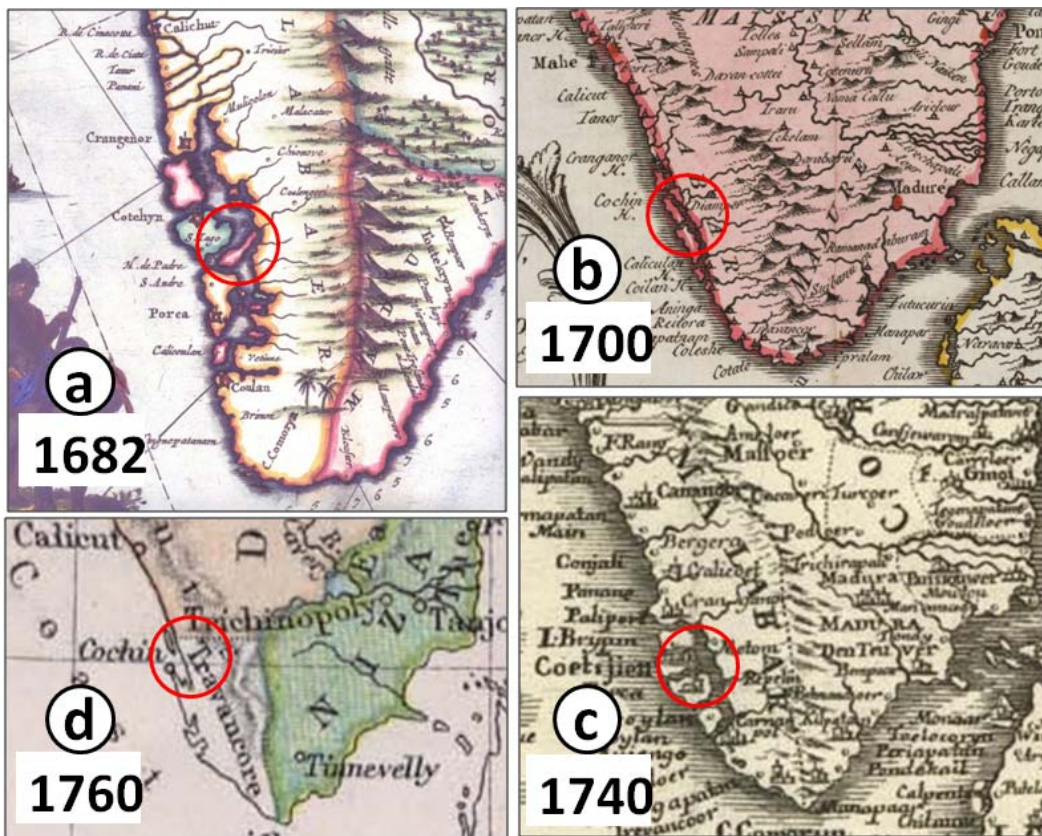


Figure 11

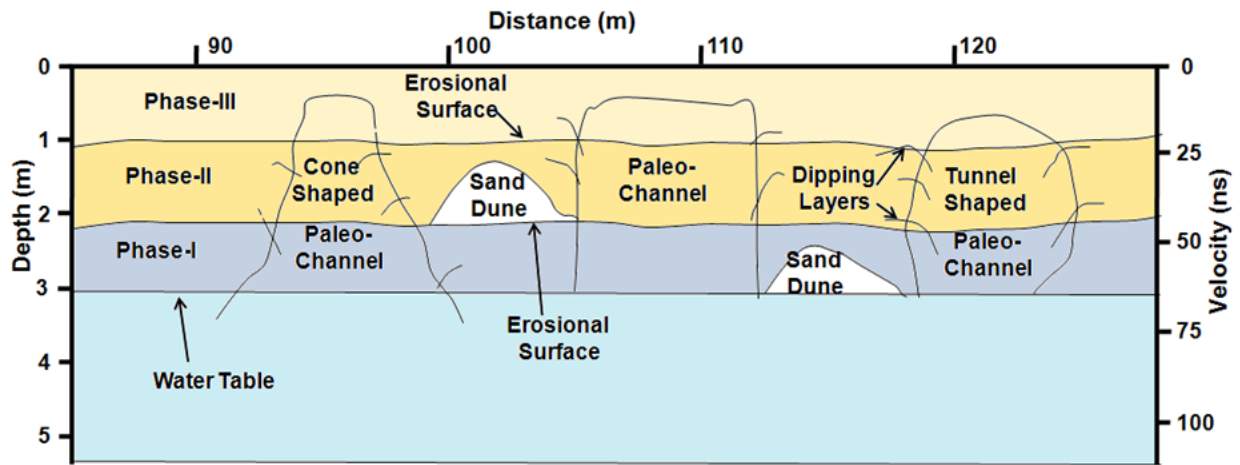


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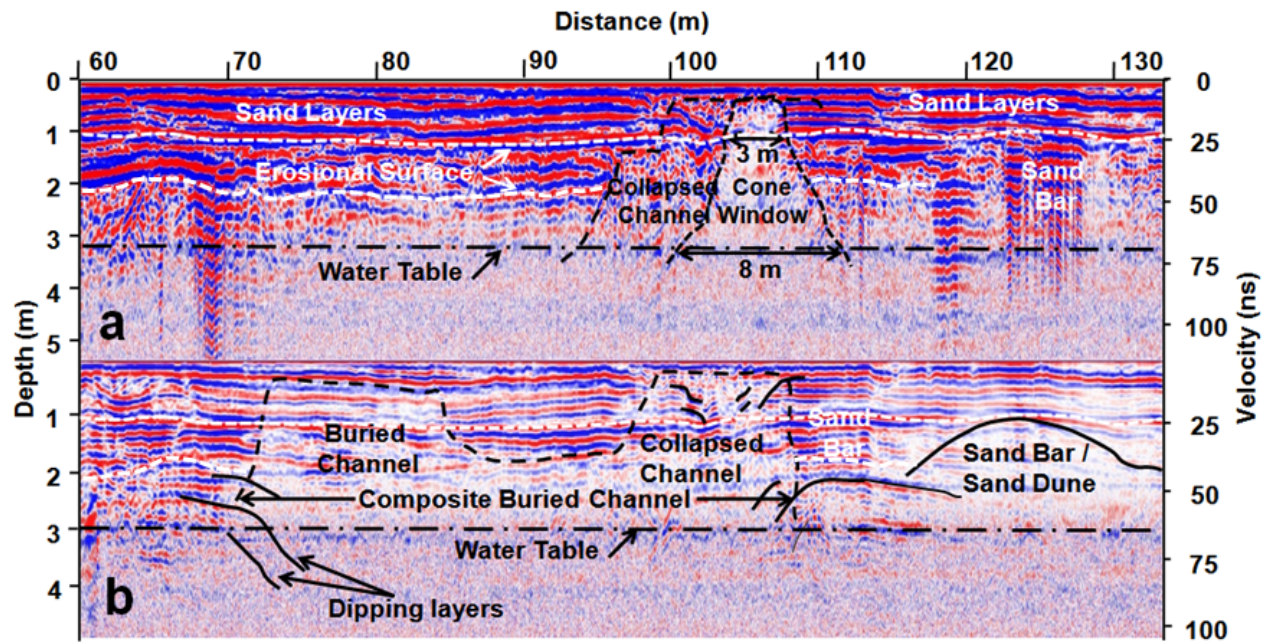


Figure 13.

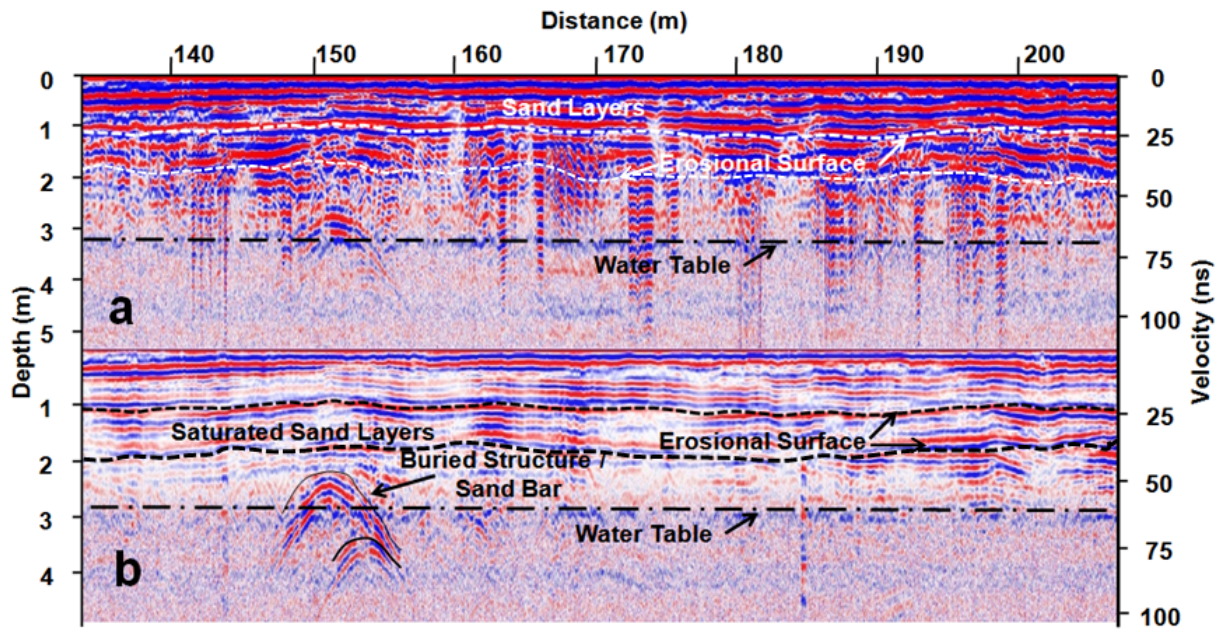


Figure 14.

Table 1. Characteristics of various paleochannels along Alleppey coast as inferred from the GPR subsurface profile

Name of the Paleo-channel	Dimension		Type of Paleo-channel	Process of sedimentation	Presence of dipping layers	Nature of filled-in sediments	Relation to present drainages	Remarks
	Width	Depth						
1	26-m	Up to 4.5-m	Wider	Rhythmic sedimentation	Seen from 1-m depth with 1-m sand cover	Undisturbed layers, deposited under water	Just after southern side of a present stream	Cutting across even present day sediments
2	8-m at bottom and 3-m at top	Up to 3.5-m	Conical shaped	Partially disturbed sedimentation	Present and seen even at near surface	Partially disturbed sedimentation, due to shrinkage of the channel.	No drainage nearby.	Conical shape indicates shrinkage of the channel in later stage.
3	7-m	Up to 3.5-m	Composite, Braided	Disturbed sedimentation	No dipping layers	Not layered	No drainage nearby.	Vertical walls. anthropogenic? Cut across a huge dune at one side; anthropogenic?
4	18-m	Up to 4.5-m	Wider	Rhythmic sedimentation	No dipping layers	Layered sedimentation	No drainage nearby.	
5	16-m	4.5-m and beyond	Composite, Braided	Rhythmic at one side and disturbed at the other side	Presence of dipping layers at both sides	Layered at one side and disturbed at the other side	No drainage nearby.	Braided nature of channel.
6	7-m	4.5-m	Tunnel shaped	Disturbed sedimentation	Dipping layers seen at both the sides	Not layered	Just after southern side of a present stream	Tunnel shaped
7	20-m	4.5-m and beyond	Composite, Braided	Rhythmic sedimentation under water	Presence of dipping layers at both sides	Layered sedimentation	No drainage nearby.	Wider and shows changes in channel width
8	5-m	4.5-m	Composite, Braided	Rhythmic sedimentation	Dipping layers seen at both sides	Layered sedimentation	No drainage nearby.	Complementary channel to 7.