Subsurface reflections of prograded paleoscarps in Avis Island, North Andaman, India

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Prominent subsurface reflections from two GPR transect marked four lithological anomalies below Avis Island coral reefs. These scarps dip 5-10° towards sea and they consist of sands with more than 30-40% heavy mineral concentrations that produce distinct subsurface reflections that make possible to locate the buried erosional scarps. Heavy minerals are considered as the indicators of erosion as well as a proxy for sediment transport of extreme wave events. Heavy minerals including magnetite have higher magnetic susceptibility values: L1a: 644.6; L1b: 556.8, L2a: 584.2 and L2b: 612×10^-5 SI units to the background magnetic susceptibility of 5-10×10^-5 SI units for quartz-rich sands suggest severe reworking process during an extreme wave event. The two profiles (L1 and L2) with four paleoscarps: L1a at a distance of 10 m from the shore, L2a approximately 15 m from the shore, L2b around 30 m from the shore and L1b nearly 35 m from the shore and the corresponding age of the dated coral above the paleoscarps increases towards land exhibiting progradation sequence. These subsurface reflections of paleoscarps were found at a depth of 1–1.5 m below the ground surface beneath the reported age of coral reefs suggesting that these coral reefs and the paleoscarps are found due to the same event.

[Keywords: Ground Penetrating Radar, Heavy minerals, Magnetic susceptibility, Paleoscarps, Avis Island, Extreme wave events]

Introduction

Buried and preserved deposits together with the event’s sedimentary signature provide a better understanding of the extreme wave events to reconstruct the historical facts1,2. Ancient extreme wave event signatures were reported to be present on the coastal beaches of India, Sri Lanka, Indonesia, and Andaman and Nicobar Islands by several researchers3,4,5. Various studies of coastal sequences are required to identify signatures of past extreme events and establish accurate regional chronologies. The composition of the beach deposits and stratigraphical studies enables us to understand the changes in the land morphology. In the past geologists studied the coastal erosion through the examination of surface features. Sediment cores and trenches alone may be insufficient to capture subsurface features and often lack sufficient continuity to describe the older part of the sequence below the water table6. To remedy these limitations, subsurface imaging technology: Ground-Penetrating Radar (GPR) has proven to be a successful tool in providing continuous high-resolution images of the buried past erosional events to a decimeter-scale resolution and penetration depth up to 10 m for coastal regions7,8,9,10. GPR allows rapid imaging of coastal stratigraphy, both above and below the water table and provides information about dip angles of deposits, paleoscarp horizons, and thickness of extreme wave event deposits and relative chronology of such event deposits11. GPR images help us to reconstruct the landscape changes12. When geophysical reflections combined with trenches and sediment cores, the information such as landward extent of erosion or inundation, thickness of eroded sediment and intensity of the intensity of extreme wave events could be obtained. The characteristics of HMCs could be used to calculate the threshold conditions of the sediment transported and deposited by these extreme wave events13.

Present study area, Avis Island, (Fig. 1) provides opportunities to study the extreme wave event deposits and their characteristic features in the beach ridges of the coastal shoreline. We took two GPR profiles (Fig. 2) on Avis Island beach to outfit ourselves with high-resolution image of the shallow subsurface. Using this we successfully mapped the morphology of the coast. The objective of the paper is to look for the evidences of subsurface signatures for
Fig. 1—Location of the study area (Avis Island, Andaman Islands) is shown in a red star with India map as inset (Source: GMT). The violet circles represent the area of upliftment and black circles comprise the subsided area (after Rajendran).

Fig. 2—Figure showing the location of the study region (A) Satellite image of study area. (Source: Google Earth 2009) (B) Photograph of Avis Island in which the arrow marks indicate the transect of the GPR profile (C) Survey area of the study region in which the blue and the green color line represents the GPR profile taken. The latitude and longitude of the profile were collected using Global Positioning System (GPS).
extreme wave events and its correlation with dated coral reefs in the Avis Island.

Materials and Methods
Andaman and Nicobar group of Island form part of the outer arch ridge of the northern segment of the Andaman-Sunda Subduction zone (Fig. 1). Curray14 discussed the basic structure of Andaman Nicobar ridges and described the incremental prism of the Subduction zone as a converging stack of eastward dipping fault slices and folds. These converging stacks are capped by younger series of rocks, termed as the Archipelago Series. These rocks are chiefly composed of limestone and formed from coral and shell sands. Of all the major earthquakes that Andaman & Nicobar region has in the past, only the 1881 (Mw 7.9) and 1941 (Mw 7.7) have historical record. These events are important in terms of their sizes, but none of them produced significant extreme wave events.15,16 In a recent review based on historical records, Dominey-Howes17 have analyzed details of all the tsunamis that occurred in the Indian Ocean since B.C. 326 but even that does not provide with any information that could suggest the occurrence of any past events closer in intensity to the 2004 tsunami. Fig. 2A shows the location of the studied area, Fig. 2B shows the GPR profiles in the site and Fig. 2C represent the exact locations of the two profile sections.

We carried out an extensive fieldwork in Avis Island, the location already surveyed by Rajendran18 during the period of April 2008, using digital high-resolution Geophysical Survey Systems Inc. SIR-2000 ground penetrating radar (GPR) with a 200 MHz monostatic antenna.19,8,20 GPR data processing was conducted using the GSSI RADAN processing software to emphasize the major subsurface reflections. Two GPR transects were taken for investigation. Due to high water saturation and the presence of coral beds, the penetration depth was limited up to 2.5 meter and spatial resolution was only few centimeters. Magnetic susceptibility measurements were carried out by Bartington MS2 system for documenting lithological differences between exposed heavy mineral concentrations and background quartz rich sands.

Results and Discussion

Ground penetrating radar signatures of extreme wave events

Ground-penetrating radar (GPR) profile shows series of prominent reflections in the sequence that can be considered as the signatures of past extreme wave events, and each reflection coincides with heavy mineral concentrations (HMCs) which are the indicators of erosion as well as a proxy for sediment transport.21,22 GPR provides the knowledge of internal structure even in the absence of exposures. Certain prominent sedimentological changes might produce distinct signal responses, and GPR proves as an exclusive device to identify and map bounding surfaces.23,7,24 Meyers25 reported the preservation of HMCs within Willappa barrier, Washington attributed to temporary co-seismic subsidence and subsequent severe erosion by tsunamis. Hayes and Boothroyds26 and Brenninkmeyer27 stated that the heavy mineral concentrations commonly take place during the waning stages of storms. The heavy mineral concentrations by extreme wave events ensure their recognition inscribed in the stratigraphic record, which is important where surface expression of past events has been marked by subsequent deposition.21,22 When geophysical images are combined with magnetic susceptibility measurements, these relict marker horizons offer information such as landward extent of erosion/inundation, long shore extent of extreme wave event impact etc. Geophysical surveys are the only means of assessing the interior architecture of the extreme wave event deposits in places where sufficient exposures are limited or lacking.11

We obtained GPR images from two profiles (Profile L1 and profile L2; Fig. 3) reveal clear subsurface signatures showing four major discontinuities. Each reflection coincides with a concentration of heavy minerals bounded between the coral reefs with an average dipping angle of 5-10°. Lithological anomalies—heavy mineral concentrations (HMCs) comprising of finer fraction are exposed on the deflation surface, which coincides with the prominent reflections attenuating the electromagnetic GPR signals.22 HMCs contain more than 30% heavy mineral fraction including magnetite in contrast to 5-10% of quartz rich sands. The GPR profiles were embedded with much noise due to the presence of coral reefs. Profile L1a that is approximately 10 m from the shore shows a dipping reflection of 10.2°; L1b nearly 35 m away from the shore shows a dip of 8.13° whereas L2a at a distance of around 15 m from the shore exhibits a dipping reflection of 5.71° and L2b at a distance of around 30 m shows a dipping reflection of 6.3°. Radar transects exhibit sharp, steeply dipping reflections towards the sea.
The subsurface reflections can be traced at a depth of 1–1.5 m below the ground surface. Based on the spectral analysis of radar data over barrier beach deposits at Waites Island, South Carolina, Guha suggested that the heavy minerals produce high-amplitude reflections in GPR profiles because of the contrast in dielectric properties between ferromagnesian minerals and background quartz rich sands. Heavy minerals can be used as a pointer for studying the sediment transport mechanisms of extreme wave events. The increased concentration of heavy minerals including magnetite in the study region might be due to the intensified wave action during the extreme wave events.

To correlate the radiocarbon dating with our geophysical data complemented by archeological record and the sedimentological signature of the extreme wave events reported by Rajendran, a graph was plotted with scarp distance vs. the ages of the respective discontinuity (Fig. 4). The scarps represented by L1a, L2a, L1b and L2b have been used to correlate with the signatures produced due to the extreme wave events. The bar diagram (Fig. 4) between scarp distances and C-14 age of coral reefs suggests the age of the dated coral reefs increases landwards indicating a prograded sequences. Scarp L1a with age of 240 years suggests of most recent extreme wave event. Rajendran reported an

Fig. 3—Ground-penetrating radar transects taken along the profile (L1 and L2). Four prominent reflections coincide with heavy mineral concentrations were marked with corresponding dip angles. The depth of the GPR transect is shown at right and time in nanoseconds at left. The location from which samples were collected for MS studies shown (black star). The correlated radiocarbon ages of coral reefs obtained by Rajendran is shown.
upliftment of the region (Avis Island) at a rate of ~2.45 mm/yr based on radiocarbon dating of the corals and also accounted the older uplift event occurred in the Avis Island yielding an age ranging from 730 ± 110 to 1200 ± 200 cal yr B.P. The oldest coral reefs (2100 years BP) dated by Rajendran18 may be correlate with the findings of sand sheets, bark and shells dated by Jankaew5 in Thailand. Jankaew5 reported the occurrence of extreme wave events in Indian Ocean in the 14th or 15th century AD, and Monecke4 reported the most recent predecessor of extreme wave event with in 13th–14th century AD in the northern Sumatra region. The dated coral reefs of 240 years were found above the paleoscarp L1a, which is at a distance of 10 m from the shore with dip 10.2° at a depth of around 1 m. Similarly, the paleoscarps L1b nearly 35 m from the shore dipping at an angle of 8.13° at a depth of around 1.5 m from the surface were obtained below the 2100-year-old coral reefs. The paleoscarp L2a at an approximate distance of 15 m from the shore with dip of 5.71° at a depth of nearly 1 m from the surface were found below the 540 years old coral reefs. Finally the paleoscarp L2b were found beneath the 1500 year old coral reefs, at a distance of 30 m from the shore with dip of 6.3° at around 1 m depth from the surface.

Buynevich11 obtained prograded sequences of erosional scarps in Western Gulf of Maine based on GPR observations. The observed GPR revealed series of prominent reflections with concentration of heavy mineral which is further confirmed by optical dating showing ages of S4 (153 ± 17); S3 (287 ± 27); S2 (391 ± 36); S1 (1545 ± 170). Similarly the Holocene barrier sequences using GPR and sedimentological data reveal that imaged scarps formed in the past 1.5–2.0 ka BP indicating of prograded erosional sequences21.

The magnetic susceptibility measurement of HMCs in presence of 300 A/m magnetic field shows values of L1a -°644.6°; L1b-556.8; L2a-584.2 and L2b 612×10\(^{-5}\) SI units to the background magnetic susceptibility of 5-10×10\(^{-5}\) SI units for quartz-rich sands, where 8 cm\(^3\) sample is used for analysis. Magnetic susceptibility measurement of HMCs and quartz rich sands demonstrates clear distinction between the two lithologies30. Shankar31 accounted that this lithological difference is mainly because magnetic susceptibility is principally a function of magnetite content. Such high concentration of magnetite percentage indicates the
severe reworking process in the offshore as well as the large-scale transportation of sediments, and also the magnetite presence indicates that they are transported by extreme wave event, as normal waves and current are not capable of transporting such high density mineral (5.2).12

Conclusions

Present study addresses the use of coastal sequences for high-resolution reconstruction of ancient extreme wave events along the Avis Island. Erosional features buried as paleoscarps produce prominent reflections due to their dielectric properties, distinct geometry with the dipping angle of 5-10°, complemented with HMCs recording major erosional events. High concentration of HMCs including magnetite indicates their transportation due to the extreme wave energy conditions. The youngest extreme wave event deposits accounted by Rajendran18 (240 years BP) of coral reefs in Avis Island provide age estimation and terrace history were obtained at an average distance of 10 m and oldest at a distance of around 35 m (2100 years BP). Magnetic susceptibility analysis from the profile L1 and L2 show the MS values of L1a: 644.6; L1b:556.8; L2a: 584.2 and L2b: 612×10^-5°SI units to the background magnetic susceptibility of 5-10×10^-5°SI units for quartz-rich sands, reveals the severe reworking processes as well as the large-scale transportation of the sediments. Presence of magnetite derived from MS measurements suggests that they have been transported by extreme wave events because of their high density (5.2).

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References


