Ground Penetrating Radar (GPR) Survey of Formerly Mined Coastal Sand in Central Vietnam: A Rapid, Non-Invasive Method for Investigating the Extent and Impact of Mined Areas

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***Abstract*— Ground Penetrating Radar (GPR) offers a non-invasive, high-resolution subsurface imaging method that can be used to investigate and characterise the sedimentary features and depositional history of various coastal deposits. GPR utilises the electromagnetic wave properties in the megahertz frequency range and can generate 2D and 3D images of the subsurface to identify coastal depositional features to a depth in excess of 20m. In this study we use a series of GPR surveys to identify the depth and physical characteristics of an infilled site formerly subject to sand mining for heavy mineral sands. We outline a fast non-invasive technique that allows large areas of coastal dunes to be imaged for the purposes of delineating past land uses. The technique is likely to be particularly applicable to developing coasts where the historical record is incomplete or fragmentary or there has been a history of poorly constrained or illegal sand mining.**

***Index Terms*— Ground penetrating radar, coastal dunes, sand mining, mine rehabilitation, Vietnam**

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I. Introduction

THE concept of applying radio waves to image the subsurface dates from the 1920s with the use of radio echo sounders to profile ice thickness in the polar regions (e.g. [1]). Although the instrumentation varies, all Ground Penetrating Radar (GPR) systems use a burst of electromagnetic energy, which is radiated from a transmitter at frequencies ranging from 10 MHz to over 1 GHz, depending on the transmitting antenna. The energy propagates through the ground and reflects off geological interfaces, returning to the surface to be detected by a receiving antenna [2;3]. As the emitted energy travels through the subsurface at rates approaching the speed of light, each transmission/reflection/detection sequence requires less than a second [4]. A two-dimensional 'slice' of the subsurface is acquired as the transmitter/receiver is moved along the survey profile and the lateral and vertical variations in geological interfaces are revealed. Basic processing (e.g. signal-enhancing stacking) may be performed at each station in a fraction of a second and facilitates interpretation of the GPR signal.

GPR works if there are dielectric differences in the subsurface media. In earth-science and environmental applications, these differences cause reflections that are primarily a function of the electrical conductivity of the soil/rock matrix and pore fluids. The penetration range of GPR is primarily governed by the electrical conductivity of the ground, the transmitting frequency and the transmitted power [5]. GPR systems that utilise lower frequencies allow deeper penetration of the sediment, but return low resolution images, and higher frequency systems produce detailed images, but with limited penetration. Optimal penetration is achieved in electrically-resistive soils, such as, sands and gravels, whereas saturated clays generally limit penetration to decimeters. Saline ground and pore waters result in signal attenuation [6].

Field experiments have found that GPR functions effectively in materials, such as gravel, sand, limestone and peat, which

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have a high electrical resistivity [4;7]. Of interest in this study, is that quartz sands found in coastal environments have high resistivity, and thus, have good GPR penetration (>10m) [4;;8;9;10;11]. The utility of GPR in these environments is augmented when the coastal environment is subject to high rainfall regimes that flush salt water from the sediments.

GPR images of structures like cross-stratification, prograding beds and bounding surfaces in dunes can be imaged at high resolution with reflection characteristics, termed radar facies. These radar facies can be used to characterise sedimentary environments [3;2;10;12]. The relatively high resolution imaging of sedimentary features along with the relative ease and speed that GPR can be used, mean large areas of the coastal landscape can be characterised rapidly.

Unfortunately, many coastal environments are currently subject or have been subjected to both legal and illegal sand mining processes [13]. In many countries, these practices are not regulated and so little information exists concerning the area and volume mined, the minerals removed and the material subsequently used to rehabilitate the area.

In central Vietnam, sand mining practices can have one of two purposes, for:

1. the construction industry, e.g. cement for houses, as loose sediment for fish/shrimp pond walls, road foundations and land reclamation, and
2. heavy mineral mining;

and little information or documentation is supplied to local governing authorities concerning the nature of the mining activities and the rehabilitation of mined areas.

In this example, we use GPR to image an infilled site formerly subject to sand mining for heavy mineral sands. We also outline a fast non-invasive technique that allows large areas of coastal sands to be imaged for the purposes of delineating past land uses. In particular, we focus on how to identify previously mined areas and discerning mining radar facies from typical coastal radar facies produced by normal coastal and environmental processes. The technique is likely to be particularly applicable along developing coasts where the historical record (historical maps or satellite images or historical written records) is incomplete or fragmentary or there has been a history of poorly constrained or illegal sand mining.

II. STUDY SITE

The study site is located near the sandy coastline of the northward facing Chan May embayment, approximately 35 km north-northwest of Danang, central Vietnam (Figure 1a). Danang, and by extension the Chan May region, has a tropical climate with average maximum daytime temperatures ranging from 24.8 to 34.3ºC in January and July, respectively. The minimum nighttime temperatures range from 18.5 to 25.5ºC in January and June/August, respectively. Annual average rainfall at Danang is ~2500mm, with average minimum (22.4 mm) and maximum (612 mm) monthly rainfall occurring in March and October, respectively[14]. The high rainfall regime and clean sandy sediments makes this region an ideal location to apply GPR techniques.

A GPR profile (Line 7) was collected from the modern Chan May shoreline and extended southward for 588 meters starting at 16°18’53.3”N and 107°59’20.7”E. The location of this study is in the modern, but now removed, sandy dune system which onlaps a large sequence of older beach ridges (Figure 1b). This profile passed from the modern prograding shoreface through a vegetated backshore environment and over an extensively rehabilitated sand-mined area (Figure 1). At the time the GPR profile was carried out (November 2011), small trees had been planted to rehabilitate the site. On a subsequent visit (January 2013), many of these trees had died.

III. DATA AND METHODOLOGY

The GPR profile was obtained using the Sensors and Software® PulseEKKO PRO radar system using the 250MHz antennas. This system utilises an odometer attached to the transmitter and receiver to consistently collect data at 10 cm increments along the line following the methodology outlined in [5;15]. The transmitter and receiver are 38cm apart, the time window for data collection was set at 300ns and the data obtained from each pulse was stacked 16 times.

The GPR profiles were processed using the EKKO View2 software®. Automatic Gain Control was applied using a maximum gain of 200 and then topographically corrected using the differential elevation data from dGPS data collected at 10m increments along the profile combined with the calculated sediment velocity (0.06m/ns) derived from curve-matching hyperbola velocity estimation. The differential elevation data from the dGPS was corrected to real height by referencing the dGPS heights to local benchmarks with known elevation. These corrected dGPS heights were used as the topographic correction and applied to the GPR profile [5;16].

A sediment sample from the sand-mined area along the GPR profile, and a sample from the unmined area were collected and visually inspected for heavy mineral concentrations. Microscopic photos of these two samples were taken using Leica L2 binocular microscope (Figure 5).

IV. RESULTS

The processed GPR profile of Line07 is shown in Figure 2. Five topographic features are evident:

1. the modern beachface displaying a shallow rise from the modern high tide mark to the tree line from 0 to 75 m (Figure 2b),
2. a relatively flat, vegetated back beach from 75 to 178 m (Figure 2d),
3. two small rises on either side of the gravel road from 178 to 200 m (Figure 2c,d - note that the powerlines on the northern side of the road do not affect the GPR profile generated by the shielded antennas),

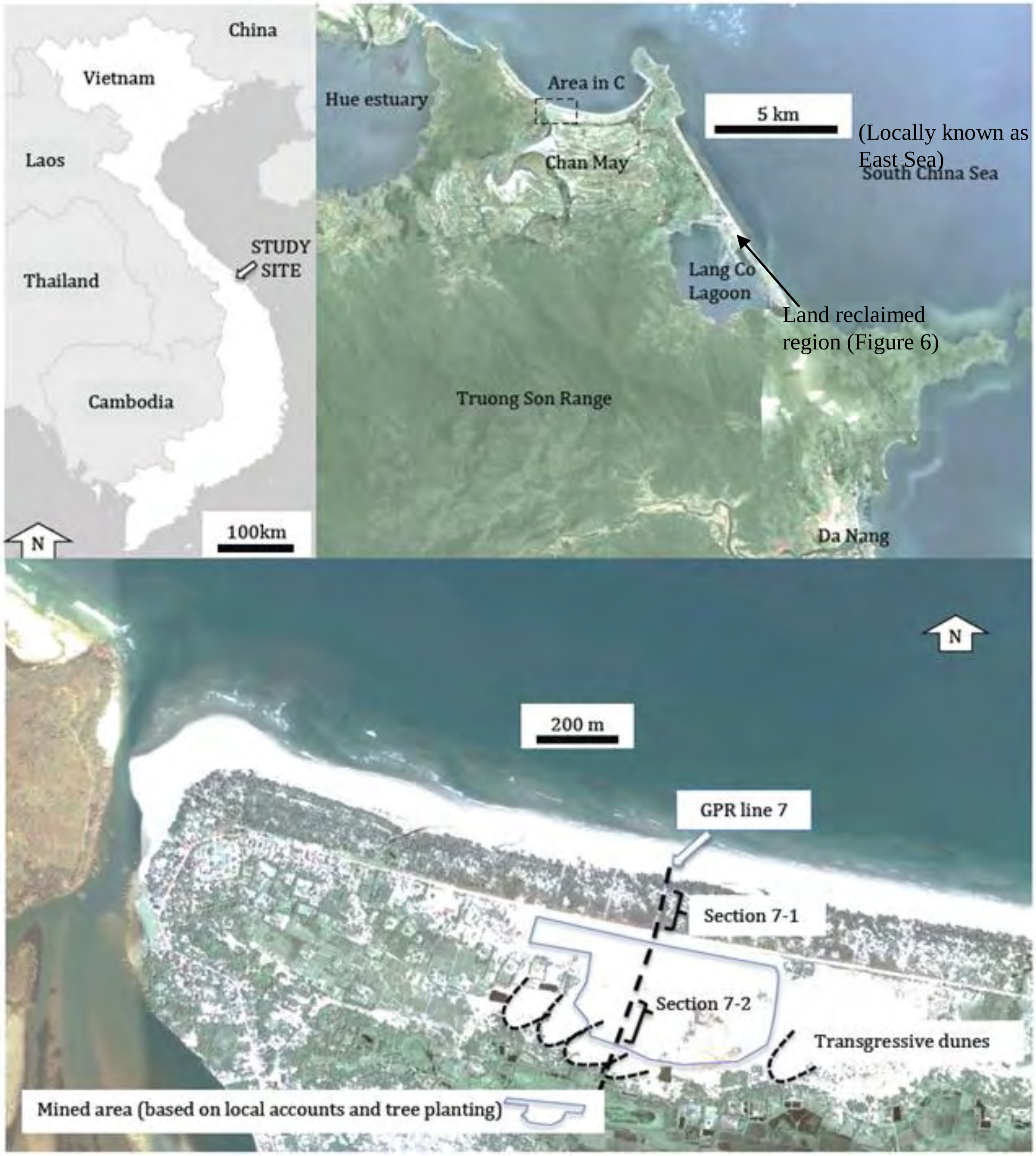

Figure 1. Study site in Chan May embayment, approximately 35 km north-northwest of Danang, central Vietnam. A GPR profile (Line07) was collected from modern shoreline to a trangressive dune across a sand-mined area. Section 7-1 and 7-2 shown are figure 2 and 3 respectively, distinguishing the difference between prograding beach radar facies and sand-mined radar facies.

4. a relatively flat featureless plain where sand-mine rehabilitation and replantation has occurred from 200 to 530 m (Figure 2f)
5. a 6 m high modern transgressive dune from 530 to 588 m (Figure 2g,h).

With the exception of the modern beachface environment, the GPR achieved a maximum penetration depth of 3 to 4 metres. On the beachface GPR penetration ranges from <0.5 m at the high tide mark to 2 m at the tree line due to salt groundwater intrusion causing the electromagnetic signal to attenuate.

Two detailed sections of this profile are shown highlighting the different radar facies along parts of this line. Section 7-1 (Figure 3), extending from 125m to 150m along the profile, is dominated by one main radar facies consisting of uniformly-dipping (apparent seaward dip of 6 to 7° (Figure 3)), long, parallel reflectors, interpreted as a prograding beach facies. This radar facies is apparent from just below the ground surface (approximately 1.4 m depth) and extends to the total depth of the radar profile. Above this prograding beach facies is

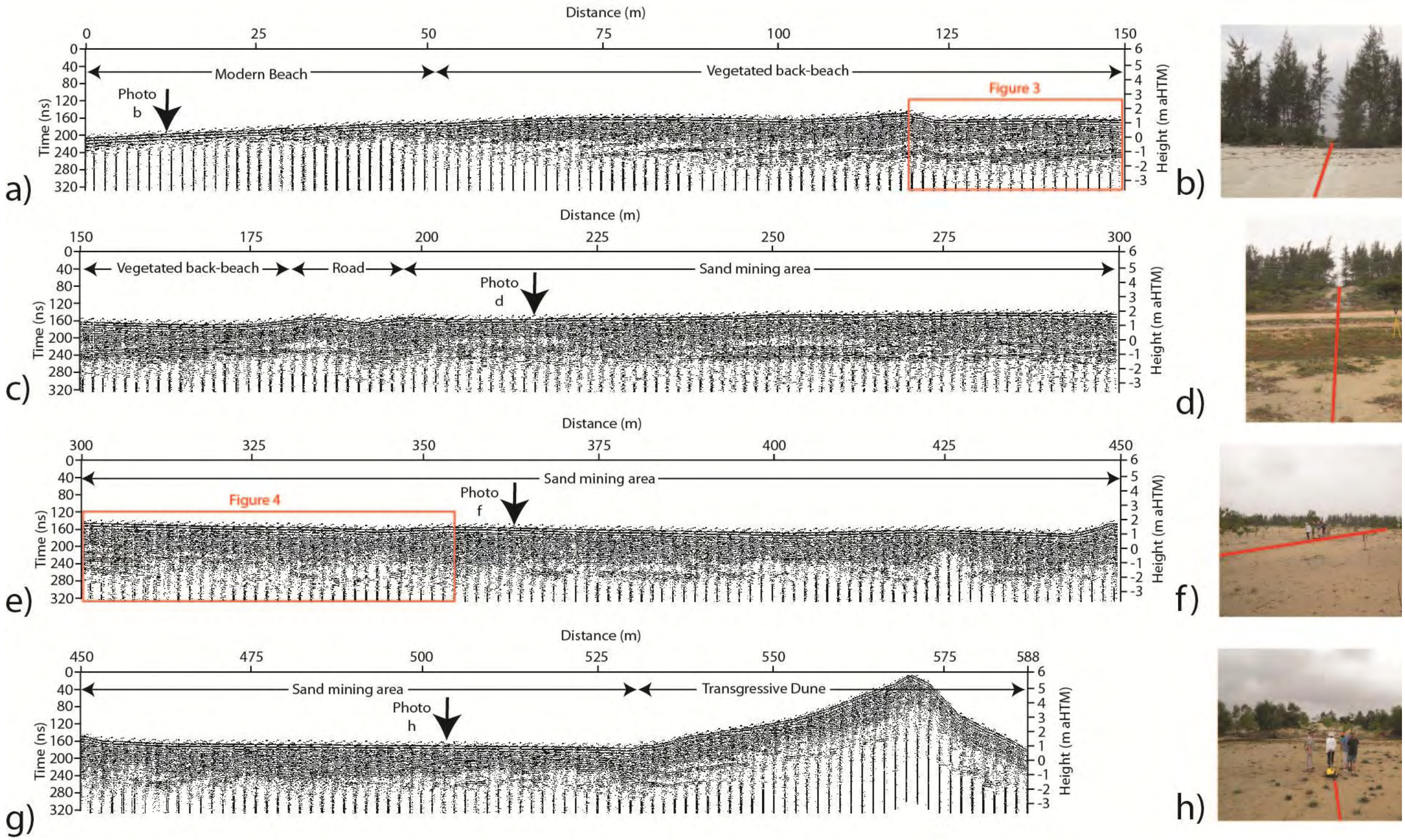

Figure 2. Ground Penetrating Radar (GPR) profile of Line07, extending north to south from the modern beach, vegetated backshore environment, rehabilitated sand-mined area and transgressive dune in the Chan May embayment, central Vietnam (Figure 1). The line is 588m long and is cut into four sequential slices for viewing ease (a,c,e and g). The red boxes in a and e show the location of the GPR profiles presented in Figures 3 and 4 that highlight the radar facies recorded in this profile (see text). The arrows in a,c,e and g are the approximate position from where the photos (b,d,f and g) were taken. Note that the red line in the photos shows the location of the GPR profile. Photo b (facing south) is of the modern beach environment extending to the tree line at the start of the vegetated back-beach environment. Photo d (facing north) shows the transition from sand-mined area in the foreground to the back-beach environment in the background; the middle shows powerlines to the north of a gravel road that is perpendicular to the GPR profile. Note that the trees in the background of this phot are the same as the trees in Photo b. Photo f (facing west) shows the rehabilitated sand-mined region with small shrubs, many of which have since died . Photo g (facing south) shows the transition from sand-mined area to the ~6m high transgressive dune at the end of the profile. Heights are measured in meters above high tide mark (m aHTM).

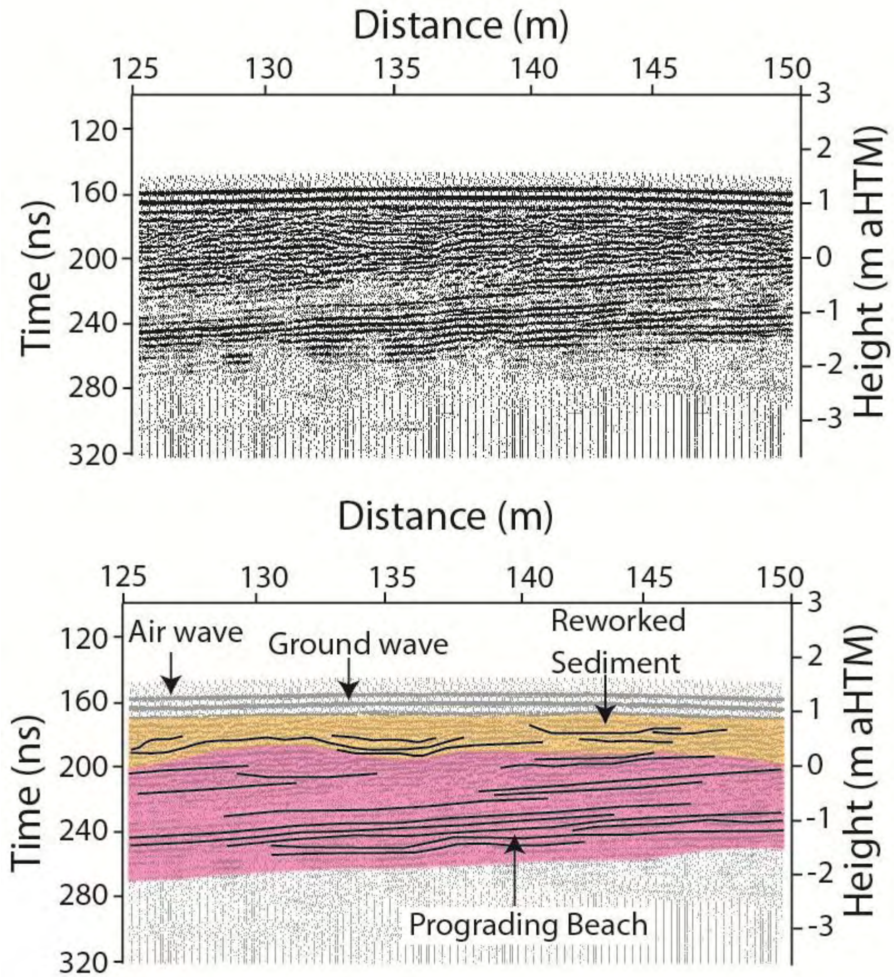

Figure 3. Detailed image of Section 7-1 from GPR profile Line07 with an upper panel showing the post-processed GPR profile and lower panel showing the environmental interpretations derived from the GPR reflectors. Pink zones show uniformly dipping reflectors, interpretated as a prograding beach facies, and the orange section is interpreted as reworked sediment and vegetated foredune.

a thin veneer (1 to 1.5m thick) of shallow, discontinuous, seaward-dipping reflectors that are flat or concave upward. These first two reflector types are interpreted to be formed by foreslope accretion during dune growth in conjunction with vegetation growth as the coastline progrades. The third reflector type is interpreted to be scour and fill structures (e.g. the water filled depression in Fig. 2d). Both of these radar facies were originally described from a prograding beach sequence from Norfolk, England [11].

Section 7-2 (Figure 4), extends from 300 to 354m along the profile in an area that has been mined for heavy minerals (Figure 1; Figure 5), has three main radar facies with distinct boundaries. The oldest radar facies recognized occurs between 300 to 312m and at a depth of -1 to -2m and consists of long and continuous reflectors dipping (apparent dip of 14 to 18°) landward that we interpret to be either a:

1. transgressive aeolian dune cross bedding similar to the dune that now exists further inland (Figure 2);
2. scroll bars associated with a buried tidal or river channel system that are similar to GPR profiles of modern scroll bars and buried channel structures from elsewhere in the Chan May embayment (Gouramanis unpublished data); or,
3. a washover deposit.

Interpretation 1 or 2 above seem the most likely explanation as GPR profiles of storm washover deposits recorded from other parts of the Chan May embayment show reflectors with a much steeper dip and are constrained longitudinally to only a few meters (Gouramanis unpublished data), much less than the 10 to 15m observed for this facies.

Overlying this transgressive aeolian or scroll bar radar facies at a depth of -0.2 to -1m is a continuation of the shallow, seaward dipping (apparent dip of 4 to 5°), strong and continuous reflectors that characterize the prograding beach radar facies.

Between 308 and 312m in Section 7-2 (Figure 4), is a distinct termination in both of the landward-dipping reflector facies and the seaward-dipping prograding beach radar facies caused by the removal of these sediments during sand mining.

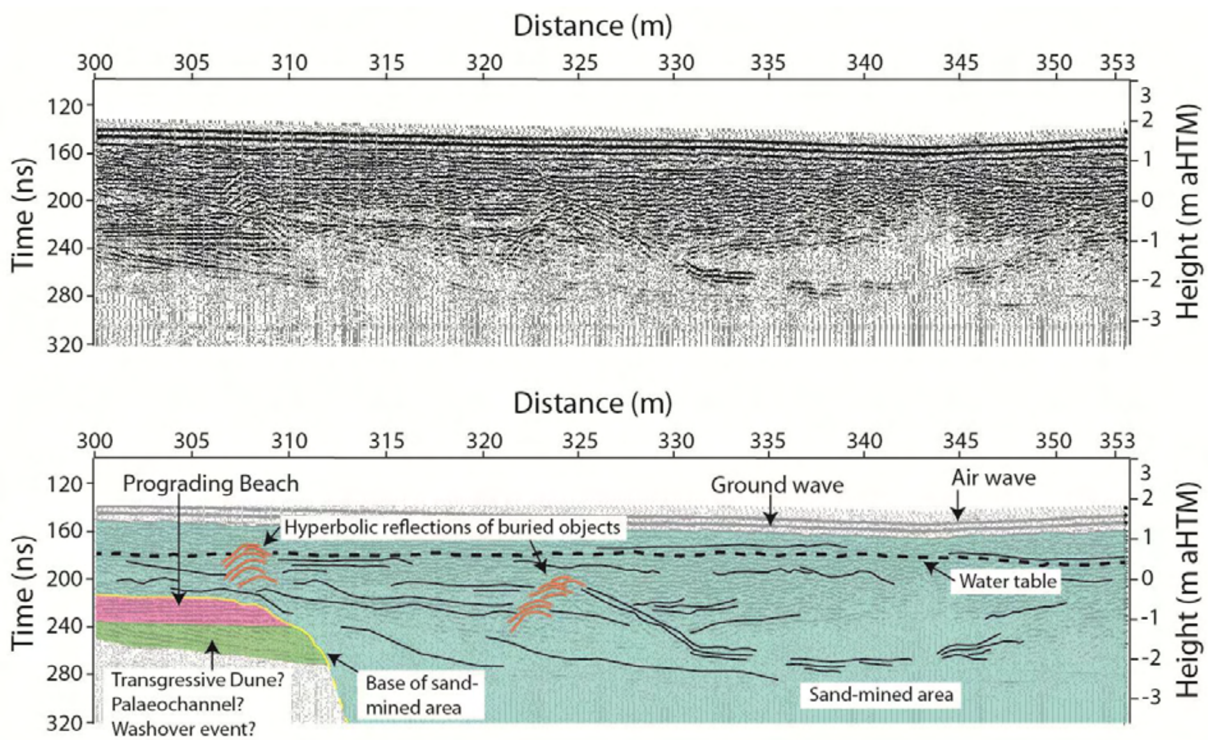

Figure 4. Detailed image of Section 7-2 from GPR profile Line07 with an upper panel showing the post-processed GPR profile and lower panel showing the environmental interpretations derived from the GPR reflections. The three main radar facies recognized in this section are 1. either a transgressive dune, channel scour or washover deposit (green) underlying 2. a prograding beach facies (pink), and, 3. the sand-mined facies (blue). The base of the sand-mined region is evident where the reflections of radar facies 1 and 2 are truncated (yellow solid line), but becomes ambiguous below these truncated reflections (yellow dashed line). Note also two regions of stacked hyperbolae which are indicative of objects buried when the sand-mined region was infilled with sediment.

Landward of this termination are a series of landward-dipping reflectors continuous with the clearly younger radar facies overlying the prograding beach radar facies. These reflectors dip steeply close to the termination, but become shallower up-sequence and landward. This is indicative of sediment slumping downslope and is inferred to be the result of sediment infill following heavy mineral extraction. Between 328 and 348m, at a depth of -0.5 to -2m, are a series of strong concave-upward reflectors that are overlain by reflection-free packages. The concave up reflections are interpreted as scars from an excavator or bucket dredge and the overlying reflection-free packages are interpreted as apparently structureless, possibly fluidised sands from backfill beneath the watertable. Above about -0.5m in the remainder of the profile are a series of short, discontinuous, convoluted, horizontal, randomly dipping or wavy reflectors that are clearly the effect of sediment infill during land rehabilitation following the completion of mining activities.

Outcrop examination of the unmined prograding beach facies (not shown) shows rich concentrations of heavy minerals (Figure 5a) parallel to the gently dipping beds. This suggests that the gently dipping reflectors of the prograding beach facies are probably caused by variation in the dielectric properties of the heavy minerals and the quartz sand. The sand-mined facies does not have gently-dipping reflectors due to the disturbance of the beds during mining as well as extraction of the heavy minerals (Figure 5b). Thus the reflectors within the sand-mined GPR profile may result from differences in water content, grain size, mineralogy and compaction following mine rehabilitation [5].

V. DISCUSSION

Reference [5] and [15] urge caution in interpreting GPR profiles, claiming that radar facies of different sedimentary structures and environments can give similar radar signatures. Here we extend this cautionary note to include a requisite understanding of the historical anthropogenic signatures that are frequently superimposed upon sedimentary environments. The characteristics of the prograding beach radar facies collected from the Chan May embayment (Figure 3) are similar to other prograding beach radar facies from Guichen Bay, South Australia [17], Batemans Bay, eastern Australia [18] and the Kujukuri strand plain, eastern Japan [19]. However, prior knowledge that the site examined from the Chan May embayment has been minimally affected anthropogenically reinforces this interpretation. Conversely, the strong concave-upward reflectors in Figure 4, could easily be interpreted as a shallow subsurface buried river channel structure, similar to those interpreted in Niobrara River, Nebraska, USA [20], Maple Creek, Guyana [21] and eastern Japan [19], or inlet channels, such as those recognized in Massachusetts [22]. The prior knowledge of the mining practices in the Chan May region, in conjunction with the cross-cutting relationship of the radar facies produced by sand

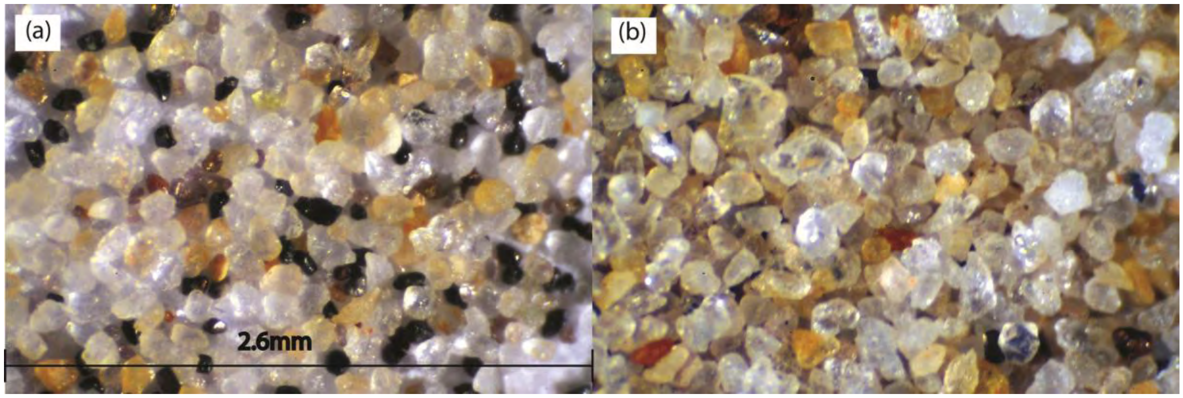

Figure 5. Microscopic view of (a) sand prior to heavy mineral extraction which collected from unmined area, and (b) sand after heavy mineral extraction from mined area (Figure 1). The removal of heavy minerals is clearly evident. Field of view is 2.6 mm.

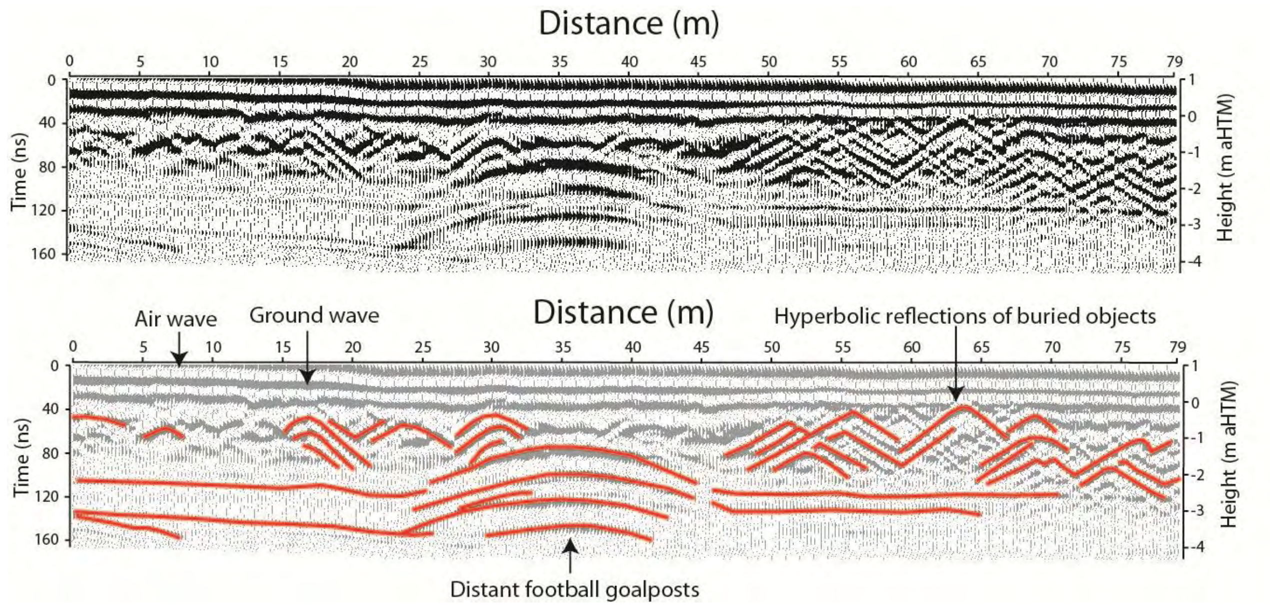

Figure 6. GPR profile of Line02 extending north-east to south-west along a football field in Lang Co, approximately 15 km south-east of the Chan May GPR profile. This profile demonstrates the very noisy GPR reflections (many hyperbolae of varying curvature) in areas where variously-sized objects have been buried during land reclamation activities. This can be used as an analogy to the fill evident in the sand-mined region of the Chan May embayment where sand was used to infill and rehabilitate the sand-mined region.

mining on the older radar facies, definitively defines the processes that generated this facies.

As well as being a tool to identify areas that have been subject to sand mining, the extent of the sand mining operation and volume of sediments removed can be estimated if multiple parallel and perpendicular profiles are generated. This could give a three dimensional estimate of the volume of sediment removed. Although not a true reflection of the mined volume, this can give valuable minimum estimates, especially in areas where illegal mining or where mining records are poorly documented. This is of particular importance in evaluating the success of rehabilitation practices. Unfortunately this cannot be applied to regions where modern dunes have been excavated for construction sand as it is impossible to reconstruct the former dune profile.

GPR examination of rehabilitated sand-mined areas can also indicate what materials were used to refill the mine. In the Chan May example presented here, it is clear that the infilling material is similar to the material extracted, that is, the sand removed was reused as mine fill. Where less scrupulous mine-filling practices occur and junk or trash is used to fill in the depression and a veneer of sand overlain, GPR can be used to rapidly identify such practices. In these cases, the GPR profiles will be much noisier, with many hyperbolae of differing curvature throughout the mined area. These hyperbolae are generated from a difference in size of the buried object and a difference in the resistivity of the buried objects (23). An example of this practice is evident from a land reclamation GPR profile of an area 15 km southeast of the Chan May GPR profile (Figure 6) which clearly shows heterogeneous materials used as land fill. Saline water has penetrated the land reclamation zone, similar to that demonstrated in the leachate detection and mapping example in [24], whereas there does not appear to be any saline water intrusion in the Chan May sand-mined area.

Although GPR has been used extensively as a tool in mineral exploration, its use in sand-mining operations is not well documented in the literature [25, 26]. In central Java, Indonesia, [27] used 100 MHz GPR antennas to map the contacts between surficial fine sediments, intermediate iron mineral sands and lower bedrock units in a coastal environment.

Similarly, GPR has also been largely neglected as a tool in mine rehabilitation condition assessment. The exception to this are the studies of [28] and [29], who successfully used GPR to map the depth to spoil in shallow rehabilitated coal mining deposits in Mpumalanga, South Africa. These studies demonstrated that it was faster and more cost-effective to use GPR than conventional invasive techniques, such as augering.

VI. CONCLUSIONS

Our study has shown that ground penetrating radar can be a rapid, non-invasive and cost-effective method used for delineating past-land uses in coastal environments and this tool is especially useful for those developing coasts that do not have historical maps or satellite images or historical written records. Many legal and illegal sand-mining activities and their subsequent rehabilitation have occurred along the coastlines of many countries. These activities have caused a great deal of damage to the coastal environment resulting in coastal erosion and biodiversity loss through monoculture plantations [30]. Thus, for those coasts that have been environmentally affected by sand-mining practices, knowing the historical record of a coast is important for future planning.

Our study further recognises that similar radar facies can be created by different sedimentary environments both natural and anthropogenic. Thus, prior knowledge of the history of a region is important in the interpretation of GPR profiles and can improve the interpretation of the radar facies.

To complement our examination of the rehabilitation of shallow sand-mined regions in the Chan May embayment of central Vietnam, we aim to investigate the heavy mineral properties of the sediments from regions yet to be mined. Trenching of the rehabilitated area in the vicinity of Section 2 will also enhance our understanding of anthropogenic sedimentary structures and allow the refinement of GPR radar facies in rehabilitated regions.

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