

**Ground Penetrating Radar Response to Thin Layers:
Examples from Waites Island, South Carolina**

by

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of the requirements for the degree of
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models

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Ground Penetrating Radar Response to Thin Layers: Examples from Waites Island, South Carolina

Swagata Guha

ABSTRACT

Thin layers (layers that are not resolvable in terms of GPR wavelengths) are very common in sedimentary deposits. To better understand ground penetrating radar (GPR) wave behavior in sequences of thin layers with contrasting electromagnetic parameters, 1D FDTD simulations are run for simple layer distributions. Laminated (mm-scale) sequences can produce reflected energy with 10-20% of the amplitude of reflections from equivalent isolated contacts. Amplitude spectra from laminae packages are shifted toward higher frequencies. Such spectral shifts in radar profiles may potentially be used as indicators of fine-scale laminations. A comparative study of GPR records and models generated from core data from Waites Island, South Carolina, a Holocene barrier island, suggest that magnetite-rich laminae contribute significantly to radar profiles, but that some features in the radar traces cannot be associated with lithologic changes seen in vibracores.

Introduction

Geophysical methods can aid stratigraphic interpretation of sedimentary depositional environments by providing information on bed geometry and internal structures within the deposits. The stratigraphic interpretation depends on the resolution capabilities of the geophysical technique being employed. Ground penetrating radar (GPR) is one such non-invasive, portable device that can provide relatively high-resolution, near-continuous shallow subsurface profiles. GPR is similar to seismic exploration in its approach, except that it utilizes electromagnetic waves rather than acoustic waves. Radar reflections produced are due primarily to variations in the dielectric properties of the ground; GPR wavelengths, and hence spatial resolution, are on the order of centimeters to meters.

Because of the wavelength dimensions, GPR can be used to delineate subsurface geology in various sedimentary environments. Facies analysis of deltaic and coastal deposits, and recognition of internal structures of braided-river deposits, boundaries of ancient channel fills and river courses are some of the examples of radar stratigraphic applications for the reconstruction of depositional environments (Jol and Smith, 1991, 1992, 1997, Heinz et al, 2003, Woodward et al, 2003). Coastal studies have incorporated this geophysical technique for various purposes, including demarcation of ancient and modern shorelines (Neal et al, 2003), sediment budget estimation (Van Heteren et al 1996), description of facies (Baker, 1991, Gawthorpe et al, 1993), mapping of internal structures of sand dunes (Harari, 1996), and understanding the development of coastal landforms (Jol et al, 1996, 2003, Nishikawa et al, 2000, Daly et al, 2002, Neal et al, 2002, 2003, Smith et al, 2003). GPR has also proved to be a useful tool for estimation of water content in soils (Greaves et al, 1996, Hagrey et al, 2000, Schmalz et al, 2002) and detection of the water table in different environments (Van Overmeeren, 1998).

Most of the above-mentioned investigations have involved the stratigraphic interpretation of GPR profiles combined with field observations. Fewer studies have

been devoted to understanding the physical causes of reflections in sediments. Among these, Olhoeft (1980s), Knoll and Knight (1994), Van Dam (2002 and more), and Moore et al. (2004) have addressed the relationships between sedimentary and electromagnetic properties that are responsible for reflection patterns in sands and aeolian sediments.

There remain many settings where radar responses to sediments are poorly understood. In particular, in many, if not most, sedimentary environments, bed thicknesses are much smaller than the radar wavelengths used. For reflecting strata whose thicknesses are $\geq 1/4^{\text{th}}$ or $1/3^{\text{rd}}$ of the radar wavelength, identification of reflections off the top of the strata and off the bottom as separate events in the GPR record is plausible (Fig. 1a). However, for thinner layers it is impossible to assign a single reflection event to each contact (Fig. 1b). The GPR response acquired from a sequence of thin beds is an interference pattern produced by a complex interaction of the propagating radar wave with these layers.

In this thesis an attempt is made to better understand the nature of GPR responses to thin sedimentary layers, and to determine whether more information about thin layers can be derived from the frequency and attenuation characteristics of radar traces. The relationship between sedimentary layer patterns and radar response is examined through several suites of simple numerical models. The numerical models are aimed at answering the following questions:

1. What sort of thin-layer patterns typical of sedimentary environments will yield radar returns of significant amplitude?
2. What are the effects of very thin beds (laminae) on radar returns? Can any information regarding the nature of thin beds be derived from the frequency and attenuation patterns of radar records?

Finally, a comparative study of radar records and cores from a sandy barrier island setting has been conducted, adding to the relatively small volume of literature on the physical causes of radar reflections in sediments.

Ground Penetrating Radar in Sediments

Ground penetrating radar (GPR) systems emit electromagnetic waves from a transmitting antenna. Part of this electromagnetic energy is scattered when the incident waves encounter an inhomogeneity in the subsurface, and wave energy reflected back up to the surface is detected by a receiving antenna. Radar wave velocities are determined largely by the permittivity (dielectric constant) and magnetic permeability of the medium; wave attenuation primarily by the electrical conductivity of the medium and the wave frequency; and reflection coefficients at contacts by the contrast in the three electromagnetic properties—permittivity, magnetic permeability, and conductivity. Both vertical and horizontal resolution limits in radar profiling are function of the radar wavelength, which is primarily controlled by antenna frequency and ground permittivity. Higher frequency antennas generate shorter wavelength radar pulses, from which finer-scale features can be resolved. However, stronger attenuation of high frequency pulses means that their depth of penetration is more limited. Ground penetrating radar wave propagation is discussed in greater detail in Appendix 1.

In sediments in general, the petrophysical relationships between electromagnetic properties and the geologic and hydrogeological properties of strata are complex and relatively poorly understood. Laboratory studies (e.g. Olhoeft, 1994, Knoll and Knight, 1994, van Dam and Schlager, 2002, Schon, 1996), theoretical models (e.g. Topp, 1985), and comparisons of radar records with cores and outcrops (e.g. Jol and Smith, 1991, 1996, Baker, 1991, Wood, 1990, van Heteren, 1998, Vandenberghe and van Overmeeren, 1999, Harari, 1996, van Dam and Schlager, 2002) show that reflections in sediments are primarily controlled by changes in i) porosity, ii) mineralogy and iii) pore water content. Appendix 2 gives an overview of the physical causes of radar reflections encountered in different sedimentary environments.

In many settings, the contacts between sedimentary strata (e.g. sands, muds, peat, organic-rich zones with variations in porosity, mineralogy, and/or water content) are often very closely spaced. Sedimentary layers, designated as beds (thickness > 1 cm) or laminations (thickness < 1 cm) (McKee and Weir, 1953) show a wide range of variability in their mode of occurrences (given in Appendix 3) in coastal, lacustrine, fluvial, and

aeolian environments. Imaging the depths of interest in geologic applications (meters to tens of meters), however, typically requires antenna frequencies low enough that the radar wavelengths are on the order of tens of cms or more. Thus, it is common in sedimentary studies that GPR wavelengths are considerably greater than the thickness of many layers. Commonly, the radar record represents the combined response to many thin layers (e.g. van Dam, 2003), and there is difficulty in identifying a one-to-one correspondence between an event in a radar profile and a contact observed in core or nearby outcrop.

Wave response to thin layers (thin beds)

Thin bed is a term widely associated with seismic exploration, especially for reservoir characteristics. By definition, reflections obtained from the top and bottom of a thick bed are distinguishable in time, whereas, for an isolated thin bed separate responses from the top and bottom interfaces are not resolvable since the reflections overlap in time (e. g. Knapp, 1990). The resultant waveform from a thin bed is a single pulse which is an approximate time derivative of the source pulse (e g Widess, 1973). For a bed of thickness Δt , $w(t)$ and $-w(t + \Delta t)$ are the wavelets of reflection from the top and bottom interfaces of the bed, the composite wavelet is given by (e. g. Knapp, 1990):

$$w(t) - w(t + \Delta t) \approx \Delta t \, dw/dt$$

Widess (1973) showed for a Ricker wavelet incident upon thin beds, the amplitude of the composite reflection is linearly proportional to bed thickness and inversely proportional to the wavelength. The relation is given by:

$$A_d \cong 4\pi A b / \lambda_b$$

where A_d is the amplitude of the composite wavelet, A is the amplitude of reflection for a thick bed, b is bed thickness, λ_b is the dominant wavelength in the bed.

Widess (1973) demonstrated with the above expression, that for a bed in a homogeneous medium, the practical thick vs. thin resolution limit is attained when bed thickness is approximately $1/8^{\text{th}}$ of the dominant wavelength (λ) i.e. the top and bottom of beds with thicknesses less than $\lambda/8^{\text{th}}$ cannot be distinguished as separate events (fig.1c).

Clearly, GPR studies in sedimentary settings often deal with bed thicknesses that fall in the thin bed category. Furthermore, in most settings thin beds are not isolated, but

contained within strata composed of multiple thin beds or laminae. The wave response to such a package will be an interference pattern determined by the spacing of the individual lamina and their reflection coefficients. Examples of marine seismic investigations of sequences of thinly bedded show that strong reflections may be recorded even when individual layers are indistinguishable and reflected energy is a resultant interference pattern. Mayer (1980) showed that seismic reflectors observed in profiles of pelagic carbonate sediments did not corresponding to individual layers but a composite outcome of interferences from several small layers. Knapp (1990) studied seismic wave response to Upper Pennsylvanian cyclothems (alternating thin layers of limestone and shale) and arrived at the conclusion that a high frequency (> 500 Hz and a wavelength of 6m) would be required for better resolution of thin beds

Radar waves are expected to behave in similar way, in which one-to-one correlation of geologic horizons to GPR reflectors is not expected in many settings. There are relatively few examples, however, that examine radar wave response and the nature of the waveforms generated from a sequence of thin beds. Van Dam (2002) showed for an aeolian deposit, with 100 and 200 MHz antennas radar responses were largely interference patterns. Kruse and Jol (2003) modeled GPR interactions to large (1-2 m) and small-scale (cm) strata in a deltaic depositional setting, and found that graded sequences could not be distinguished from ones bounded by thin beds.

To determine whether information on thin beds could be extracted from radar records in sedimentary environments, several hypothetical scenarios are examined with the aid of numerical modeling.

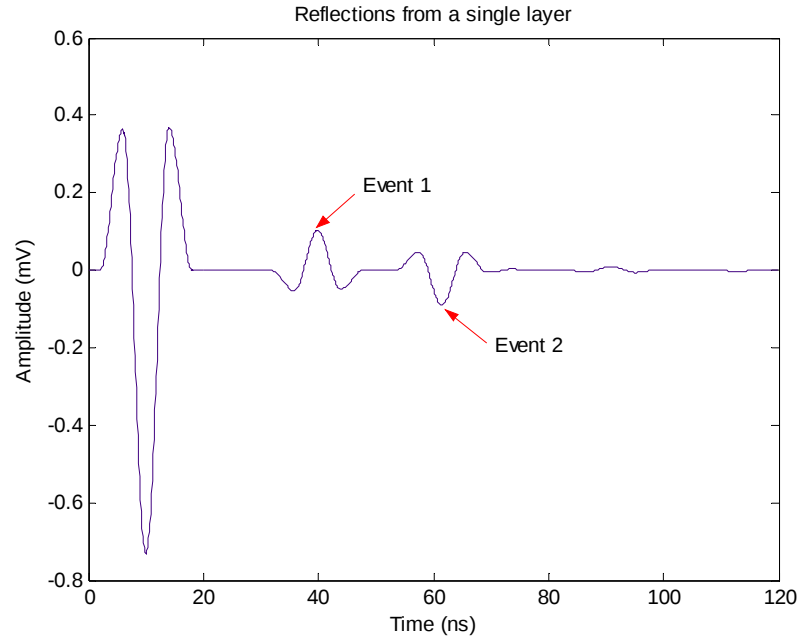


Fig. 1a Reflection Event 1 is from top and reflection Event 2 is from the bottom of a 50 cm thick layer.

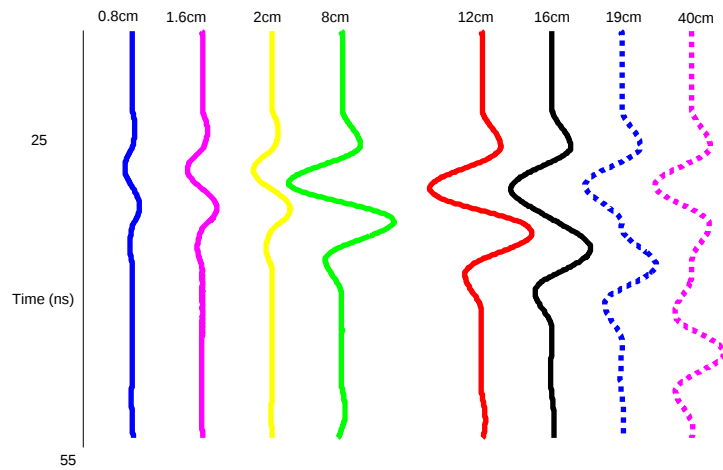


Fig. 1b Reflection events distinguishable for thick layer (e. g. 40 cm) and indistinguishable for thin layer (e.g. 8 cm) in synthetic GPR traces.

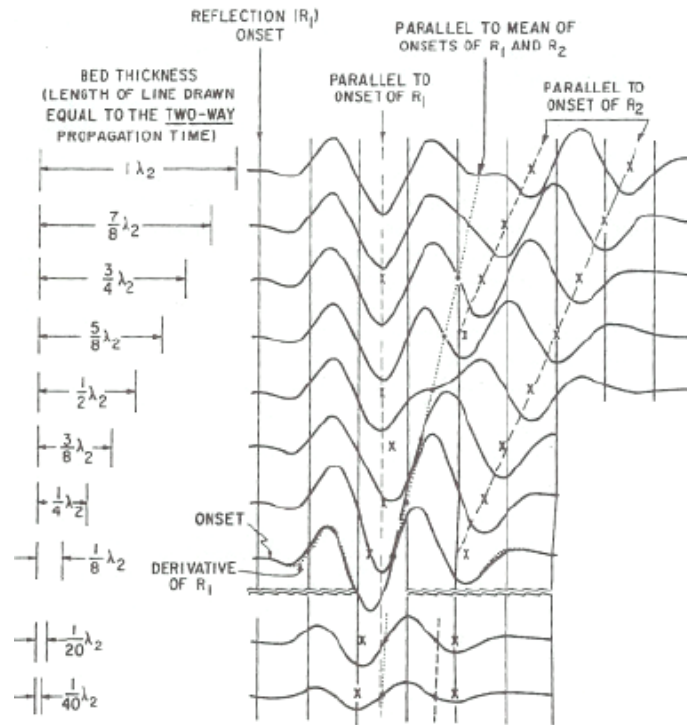


Fig.1c Reflections from beds with decreasing thickness with respect to dominant wavelength, λ (Widess, 1973)

Models of GPR response to thin layers

Method

Radar wave propagation through thin layers is simulated with finite-difference time-domain (FDTD) codes. These techniques are commonly used for GPR data analysis (e.g. Cassidy and Murdie, 2000, Wang and Mc Mechan, 2002, Teixeira et al, 1998, Kruse and Jol, 2003). FDTD methods allow the user to simulate radar propagation through strata and features with variable permittivity, magnetic permeability, and conductivity. The signal recorded at a hypothetical receiving antenna can be compared against those observed in the field.

The FDTD methods propagate electromagnetic waves through a grid, solving a finite difference approximation to Maxwell's equations for electric and magnetic fields. The codes used here follow the classic staggered grid formulation of Yee (1966). All models described in this study are one-dimensional (1D), and hence contain the following implicit assumptions: (1) the transmitted energy is a vertically-traveling plane wave normally incident on the surface; (2) there is no offset between the transmitter and receiver positions; (3) subsurface layers are horizontal, smooth, and laterally homogeneous. Furthermore it is assumed that there is no lateral or vertical anisotropy of physical parameters (electrical conductivity (σ), relative permittivity/dielectric constant, (ϵ_r), relative magnetic permeability, (μ_r), which are further defined in Appendix 1). The 1D approximation fails to account for the dipole nature of typical commercial GPR antennas and attendant radiation pattern, geometrical spreading, effects associated with non-vertical incidence on interfaces, as well as any 3D complexities in the subsurface. Despite the obvious shortcomings, 1D modeling offers the advantages of rapid computations and a basic understanding of radar wave propagation behavior from studying simple scenarios, and is often used as a first step in GPR data interpretation (Bano, 1996, Kruse and Jol, 2003). For the purposes of this study—to examine the first-order characteristics of GPR returns from finely laminated sequences of thin layers—1D

modeling is adequate, and the benefits of 1D speed and simplicity outweigh the shortcomings. 2D and 3D modeling, beyond the scope of this study, are needed to fully address the limitations associated with the 1D approximation in this context.

As the models developed here are aimed at interpretation of GPR response to beds as thin as 1 mm scale, the cell size in the finite difference grid (dx) used in the runs in this study is set to 0.25 mm and the time interval (dt) is 0.5 ns. These grid parameters satisfy the Courant stability criteria and the recommendation that cells be smaller than 1/10 the wavelength (Kunz and Luebbers 1993). As the thinnest layers in our models are 1 mm, a cell dimension of 0.25 means that individual layers are comprised of at least 4 Yee cells.

All models assume a tri-lobed pulse similar to the one transmitted by the pulseEKKO 100 GPR systems (Sensors & Software Inc.).

Models and results

Two suites of layered models have been analyzed to better understand the response of radar waves of frequencies typically used in geological studies (50-400 MHz) to thin (mm-decimeter scale) layers of dimensions observed in sedimentary settings. In each suite, alternating layers with different relative permittivity, magnetic permeability and conductivity values form the layered models.

Prior to discussion of multi-layered models, the resolution of isolated layers under conditions potentially observed in coastal deposits is addressed. For example, Figure 2 shows a 50 cm thick layer of $\epsilon_r = 35$, $\mu_r = 1.2$ and $\sigma = 4\text{mS/s}$ sandwiched between layers of lower ϵ_r values of 20, $\mu_r = 1$ and $\sigma = 1\text{mS/s}$. This could represent, for instance, a magnetite-enriched layer or a lower porosity layer within a package of saturated sand. The radar wave velocities are ~ 0.05 m/ns through the slower and more conductive central layer and 0.06 m/ns through the surrounding sand. Figure 3 shows a pulse with center frequency 100 MHz traveling through the package. The pulse on the left is the downgoing pulse as it crosses the air-ground boundary in the model. As the wave front encounters the top of layer 2, a fraction of the energy is reflected back and the reflection is recorded as Event 1. Energy reflected back from the bottom of layer 2 appears as

Event 2. Because events 1 and 2 can be distinguished from one another, this layer is not considered a thin layer.

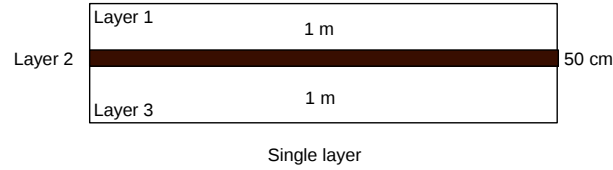


Fig. 2 Single-layer model

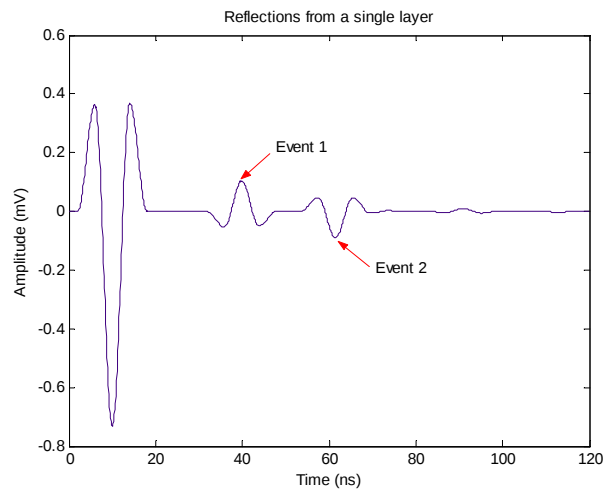
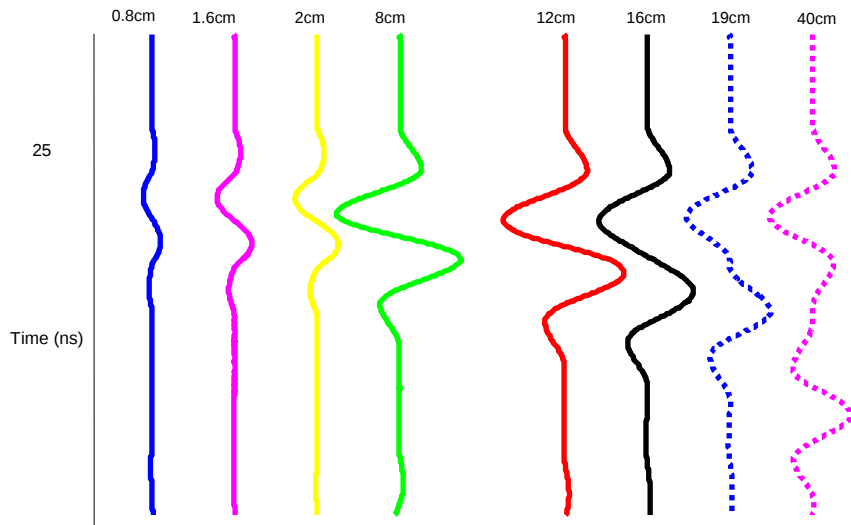


Fig. 3 Reflections from a single layer

For the case where layer 2 is thin enough that the two events cannot be distinguished, the amplitude and form of the composite reflection follow the thin bed description of Widess (1973); reflection amplitude decreases with layer thickness. Figure 4 shows that for the hypothetical magnetite-enriched layer within saturated sand, the thick-thin bed transition occurs at ~ 20 cm thickness for a 100 MHz pulse. In this case, the wavelength of the radar wave within layer 2 is ~ 50 cm, so the thick-to-thin bed transition for this radar scenario occurs where layer thickness is $2/5$ central wavelength, slightly greater than the $1/8$ wavelength criteria described by Widess (1973).

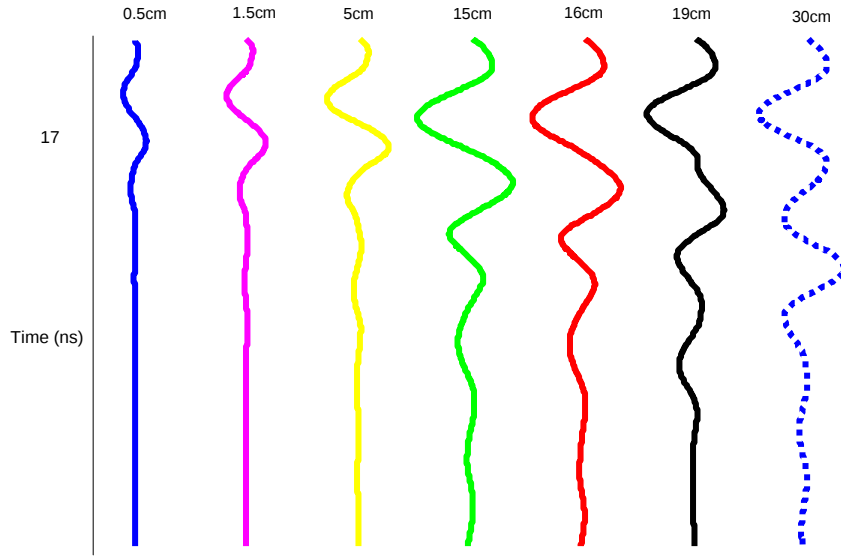
It is worth noting that it is the wavelength and hence velocity in layer 2, rather than the surrounding medium, that determines its resolution. Figure 5 shows, for example, a scenario identical to figure 4 excepting a faster ($\epsilon_r = 4$) surrounding medium. The thin-thick bed transition thickness occurs again at ~ 20 cm.

As the thin layer threshold is based on the ratio of the layer thickness to pulse wavelength, the thin layer resolution limit will decrease with increasing antenna frequency (decreasing wavelength). For the magnetite-rich layer sandy layer considered here, Figure 6 shows the thin bed resolution limits versus antenna frequency for those frequencies commonly used in geologic surveys. Even at 500 MHz, mm-scale laminae commonly seen in sedimentary environments fall well below the thin-bed limit.



55

Fig. 4 Change in trace form with increasing layer thickness (surrounding medium with $\epsilon_r = 20$)



60

Fig. 5 Change in trace form with increasing layer thickness (surrounding medium with $\epsilon_r = 4$)

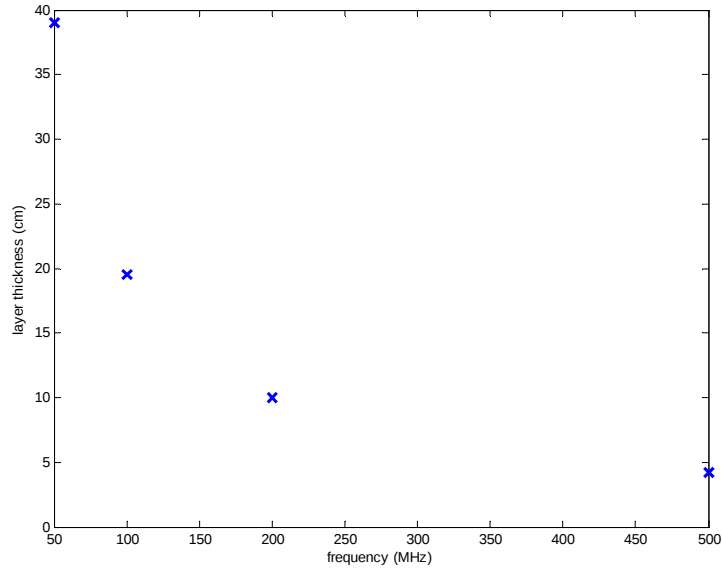


Fig.6 Change in reflection form of different layer thicknesses at different frequencies. A transition thickness is observed at 39 cm for 50 MHz, 19.5 cm for 100 MHz, 10 cm for 200 MHz and 4.2cm for 500 MHz

Internal layering within packages

In practice in many sedimentary settings, thin layers are not found in isolation, but within packages whose total thickness may itself be on the scale of the radar wavelength. The first suite of multi-layer models addresses the conditions under which internal layering within packages could be resolved from radar records. Figure 7 shows such a multiple layered model. Radar returns are modeled for a 30 cm thick package imaged with 100, 200, and 500 MHz pulses. The internal layers (dark zones on Fig 7) have the properties of the isolated layer in the case considered above: $\epsilon_r = 35$, $\mu_r = 1.2$ and $\sigma = 4$ mS/s. The interlayer spacing and background has $\epsilon_r = 20$, $\mu_r = 1$ and $\sigma = 1$ mS/s. In the models, the interlayer spacing is kept fixed at 1 cm while the layer thicknesses are varied from 1 cm to 6 cm, 9 cm and 14.5 cm.

For 100 MHz pulses incident on the package, (Figure 8a), the 30 cm package itself constitutes a thin layer, and the presence of internal layering produces no additional signature in the overall reflection pattern; the trace appears similar in form to that of a single 30 cm thick layer. The amplitude of the returns from the package decreases somewhat with decreasing internal layer thickness. This is presumably due to increasingly destructive interference as layer thickness decreases, as well as a reduction in the bulk difference in material properties between the package and the surrounding medium for models with thinner layers. The net result is that packages with finer internal structure will have lower amplitude returns. For the model scenario here, however, these differences are subtle enough that they might be difficult to resolve in practice.

For higher frequency pulses, e.g. 200 MHz (fig. 8b) and 500 MHz (fig. 8c) incident on the same model packages, the total package itself does not constitute a thin layer (reflections from top and bottom can be distinguished), and some information about internal structure can clearly be resolved. In both cases, energy returns from within the "thick bed" package are significant (i.e. returns from within the package have amplitudes $\sim 50\%$ or more of the package boundary reflections) for all models except the uniform (30 cm) layer and the models in which both layers and interlayers are 1 cm in thickness. Only the 500 MHz returns from packages with thicker internal layers show peaks that can be correlated with individual interlayers. In summary, for the velocities considered here,

layering on scales of a few cm to 10s of cms can yield interference patterns with amplitudes of 50% or more of those from thick bed contacts. For layering on 1-cm scale, returns from within the package are much smaller ($\sim 2.1\%$ of the return from the top of the bed).

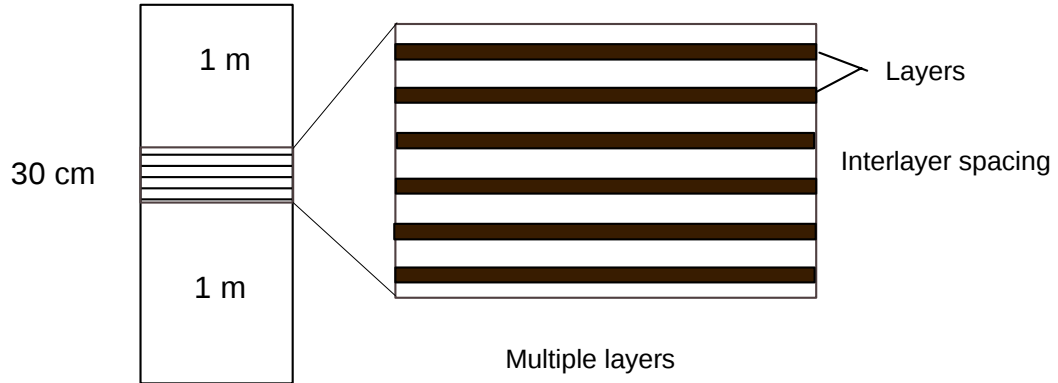


Fig. 7 Model with internal layerings with 30 cm package

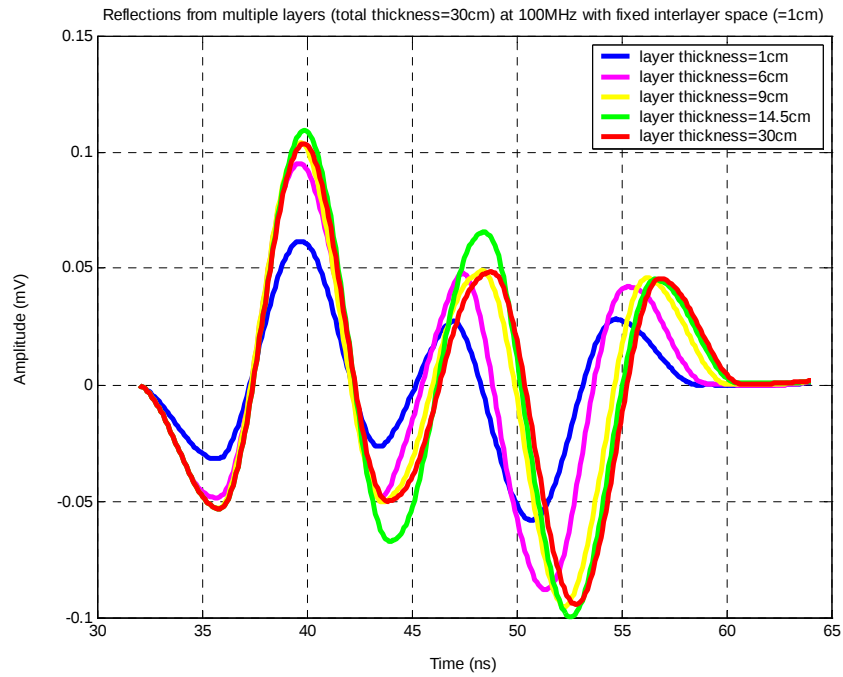


Fig. 8a

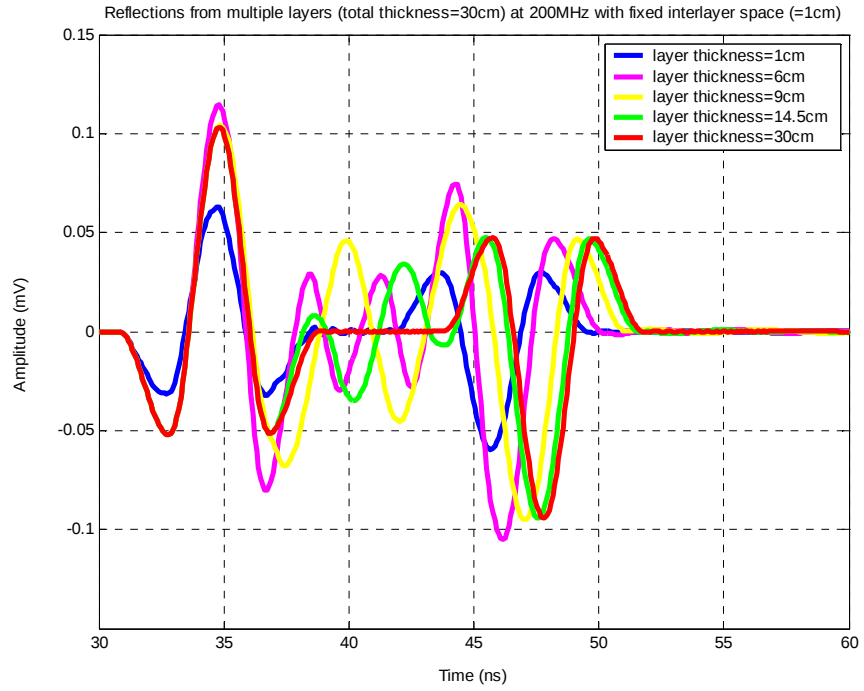


Fig 8b

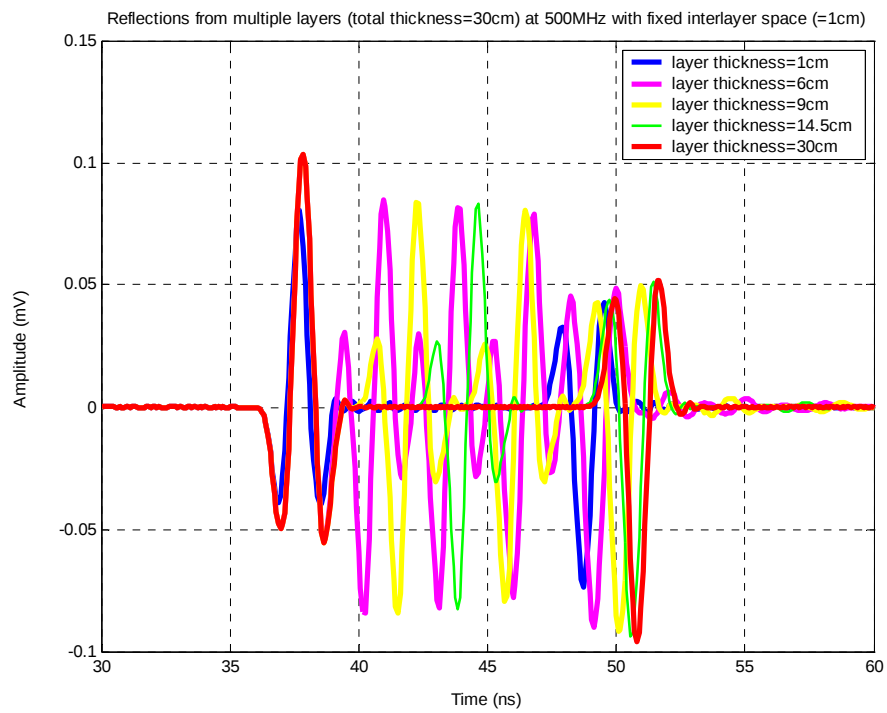


Fig. 8c

Laminae

The models above indicate that for the "saturated sand" scenario returns from cm-scale layering should be low in amplitude, an order of magnitude smaller than returns from equivalent thick bed contacts. We note, however, that in the above models, the low-amplitude response in the 1-cm layer stems in part from geologically implausible assumption that all layers are exactly 1 cm thick. In fact, GPR surveys in sandy coastal environments in many cases do yield coherent returns in settings where only mm-thick laminae, separated by mms or cms, are visible in cores or trenches (e.g. Hand, 1998, Dog Island thesis; Moore et al. (2004).

To better understand conditions under which laminae could generate a significant radar response, a suite of layered models simulating sedimentary laminations is generated. In this suite the "magnetite-rich" (dielectric constant = 35, relative magnetic permeability = 1.2 and conductivity of 4 mS/m) layer thickness is kept constant at 1mm and the "saturated sand" (20, 1 and 1mS/m) interlayer spacings are varied. In each model, the interlayer thicknesses are set to a Gaussian distribution about a fixed mean. Models were run with means of 2 mm, 5 mm, and 50 mm, with standard deviations set to half of the means (1 mm, 2.5 mm and 25 mm respectively). To satisfy model constraints the Gaussian interlayer thickness distributions were then rounded to the nearest 0.25 mm, and set no thinner than 1 mm (fig. 9).

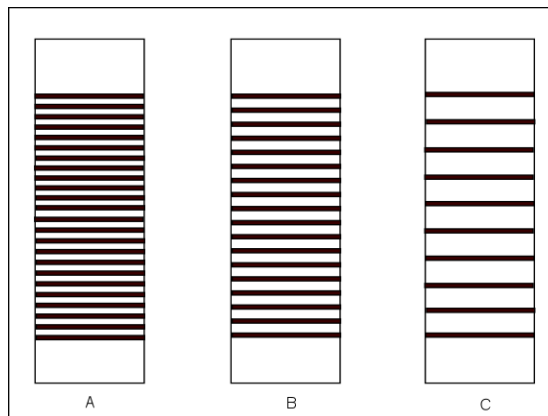


Fig.9 Schematic representation of model suites A –2 mm interlayer space; B – 5 mm interlayer space; C –50 mm interlayer space. Dark zones represent layers. The interlayer spaces follow a Gaussian distribution and are not constants as shown in figure.

The amplitudes and frequency characteristics of the returns from the layered models are examined for pulses with center frequencies of 100, 200 and 500 MHz. Sample traces are shown in fig 10a, 10b and 10c. Peak amplitudes of the interference patterns returns from the laminated zones are on the order of or greater than the amplitudes of the 1cm models of the suite above, despite the fact that the amplitude of the return from each single lamina would be an order of magnitude smaller. The Gaussian distribution of laminae generates periods of constructive interference not simulated with fixed spacing cm-scale models, and it is clear that the assumed distribution of interlayer (in this case interlaminar) thicknesses influences the interference patterns.

The frequency spectra of the traces are computed using a standard Fast Fourier Transform (fft) algorithm in Matlab. The ffts were run in each case for a time window of 22ns that spans energy returning from the layered package. The spectra, shown in Figure 11, have been averaged for three realizations of each model.

A spectral shift towards higher frequencies is observed in the returns for all three models (Figure 11a, 11b, 11c). When compared with the original input pulse, more energy is being returned to the surface at higher frequencies. This can possibly be correlated with the fact that reflected energy is being generated in response to the multiple thin layers. The higher frequency components of the pulse correspond to shorter wavelengths. Since wavelength is inversely proportional to the reflection amplitude (following the equation $A_d \cong 4\pi A_b / \lambda_b$, Widess, 1973), the higher frequency components should perceive correspondingly greater reflection coefficients.

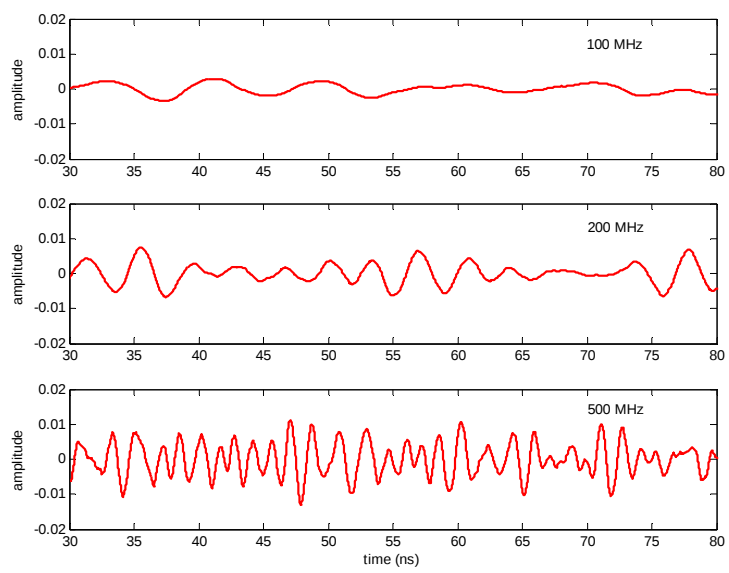


Fig 10a

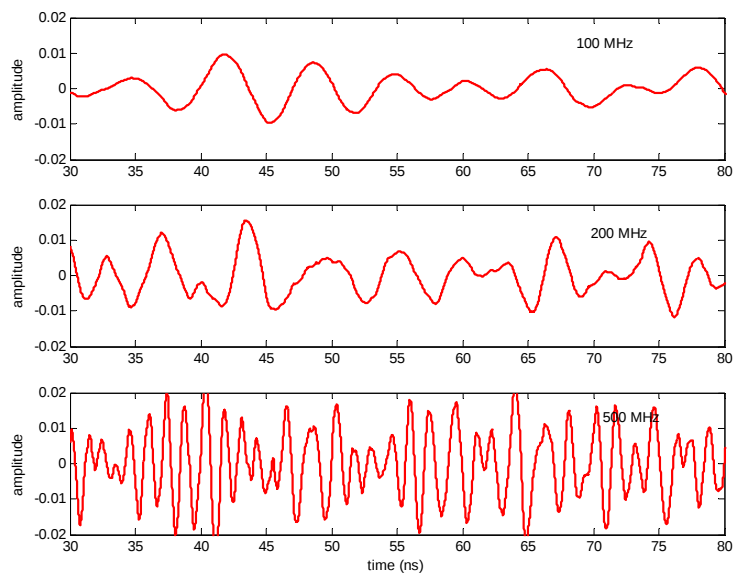


Fig.10b

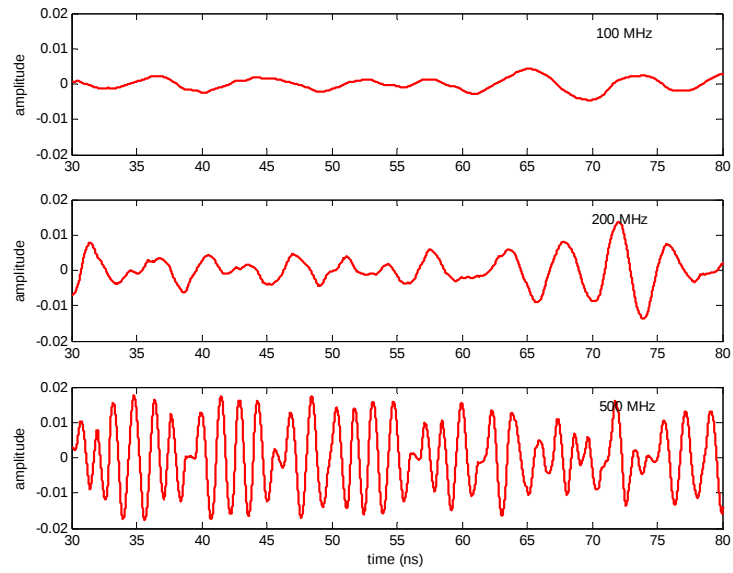


Fig.10c

Fig. 10 Reflections from a sequence of layers with fixed layer thickness (1mm) and varying interlayer spaces at different frequencies. 10a – interlayer space =2 mm (mean), 10b – interlayer space = 5 mm (mean), 10c – interlayer space =50 mm (mean)

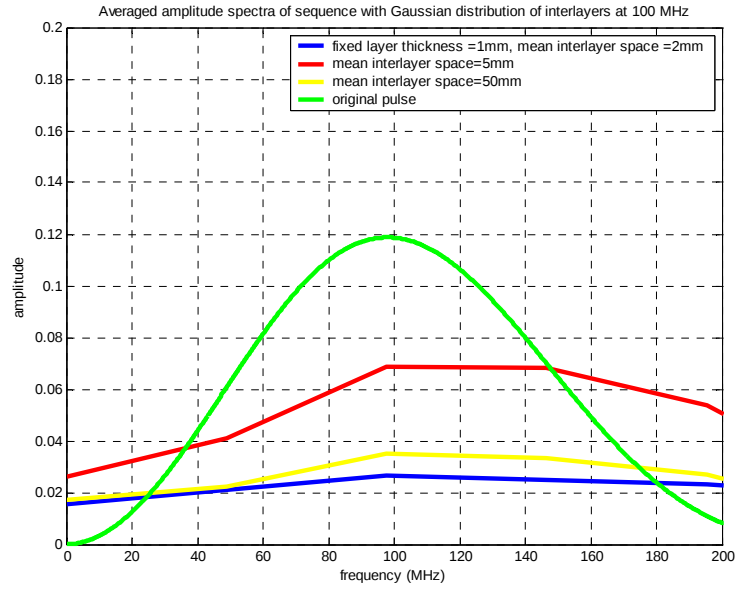


Fig.11a

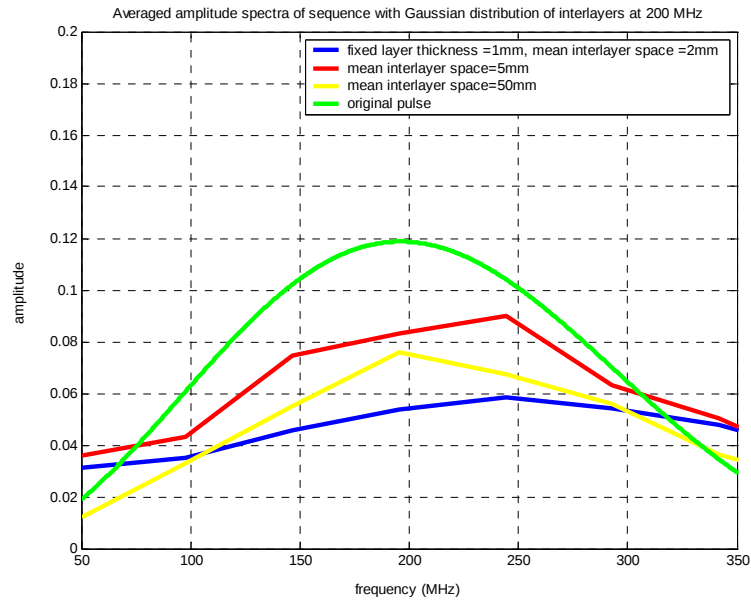


Fig. 11b

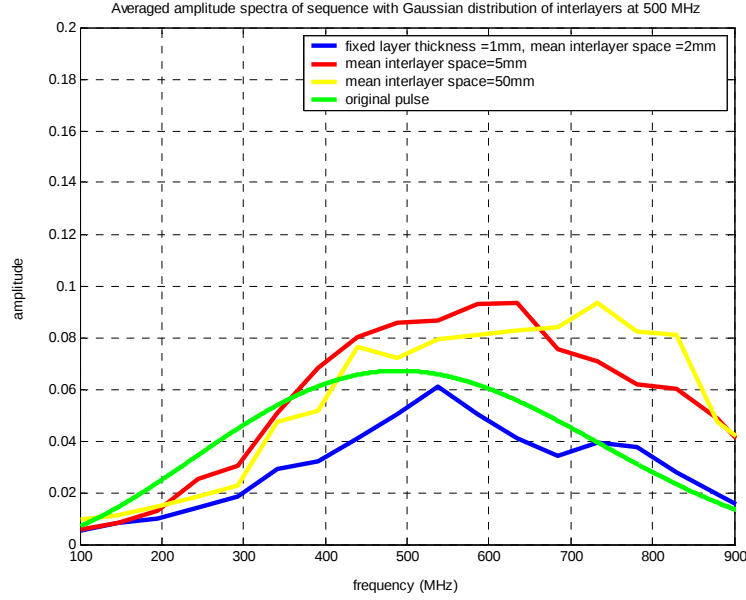


Fig.11c

Fig.11 Averaged amplitude spectra for different models at 100 MHz (fig.11a), 200 MHz (fig.11b) and 500 MHz (fig.11c).

Summary and discussion of model results

Single layer models: The GPR resolution limit for isolated thin, $K=35$ beds within saturated sands ($K=20$) is examined, following the form of the seismic analysis of Widess (1973). Considering antennas typically employed in geologic studies, resolution limits decrease from ~40 cm (50 MHz) to 4 cm (500 MHz).

Package with internal layering (30 cm package, cm-scale layering): When the package thickness itself is at the thin bed resolution limit (100 MHz case), finer-scale internal layering tends to simply reduce overall reflection amplitude. When the package is thick (200 and 500 MHz examples) internal layers may be directly resolved or appear as an interference pattern. Returns from internal layering drop off dramatically in amplitude when interlayer and layers are both thin and similar in dimension, in this case on the order of 1 cm. This suggests that for significant amplitude returns in an

environment characterized by the velocities assumed here, there must be variability in the layering, or layering on scales of ~5 cm or more.

Fine laminae (separated by mm to cm): These sets of models deal with multiple thin layers, 1 mm in thickness, with mean interlayer spaces of 2 mm, 5 mm, and 50 mm. Reflection amplitudes from packages of laminae, can be as high as 10 or 20% of the equivalent thick bed reflection. Amplitudes are higher for the models with mean interlaminar spacing 5 and 50 times the lamina thickness, than for mean interlaminar spacing two times the lamina thickness. Thus, irregularity in laminar and interlaminar thicknesses tends to increase amplitudes.

Models of returns from lamina packages show spectral shifts toward higher frequencies. Such a spectral shift in portions of a trace may thus perhaps be an indicator of fine-scale (mm to cm scale) layering within a unit.

The models show, as expected, that higher frequency waves have stronger amplitude returns from lamina packages. Thus in theory, criterion for identification of the presence of laminations in a sequence calls for a comparative analysis at both low and high frequencies. This may be difficult in practice, however, as intrinsic attenuation increases with increasing frequency, and this effect will probably outweigh lamina effects.

Case study: Waites Island, South Carolina

Geologic setting

Waites Island is located on the northeastern coast of South Carolina and forms a part of the Grand Strand barrier island system (fig.12). This 5 km long and 0.5 km wide Holocene island (Wright et al, 2001) has a seaward beach and dune system. Moving from the shore toward the mainland, it has five distinctive depositional environments: namely, washover / barrier island, salt marsh, back-barrier intertidal, back-barrier subtidal and fresh water peat (Adam et al, 2001), (fig.13). As part of a larger study of the stratigraphic development of Waites Island, extensive subsurface imaging was done using GPR. In this thesis, we examine profiles across two sites in the northern part of the island, where cores were taken.

Data collection and processing

Two sets of GPR profiles were collected using a PulseEKKO 100 system manufactured by Sensors and Software Inc. The first, in May 2002, was a long transect (LINE 1) run across the island, perpendicular to the shoreline, with 100 MHz antennas (Fig.12). Readings were collected at fixed time intervals, and traces were correlated with position every 5 meters. Trace positions were then linearly interpolated between the known values, and the profiles resampled to a uniform spacing of 0.25 m.

The same core sites (fig. 12) were then revisited in February, 2003 when shorter profiles and CMPs centered over the two core sites were collected, both parallel and perpendicular to the shoreline, with 50 MHz, 100 MHz and 200 MHz antennas. Transmitters with voltages of 400 V (200 MHz and 100 MHz) and 1000 V (50 MHz) were used.

Data processing was done with the aid of PulseEKKO version 4.22 software to remove noisy traces from the original records. Other processing steps involved merging data files and applying dewow filters and AGC gains to the data.

Conversion of the two-way travel time to depth was done by the conventional CMP velocity analysis (Appendix 1). The best-fitting velocities were found to be 0.12 m/ns for the unsaturated zone and 0.07 m/ns was obtained for the saturated zone. The saturated and unsaturated zones are demarcated on the GPR reflection profiles on the basis of the position of the water table (fig. 14)

The GPR profiles span locations where vibracores were collected in August, 2002 at sites WI1 and WI2 (on fig.12). Detailed descriptions of cores are given in Appendix 4. Site WI1 is located in the dunes of a ridge/dune system formed parallel to the shore and WI2 is located in a low in the dunes on the landward side of the barrier island (Eric Wright, personal communication). Further coring was done at the same sites in August, 2003. These cores were acquired for analysis in a Multi-Sensor Core Logger (MSCL) to determine sediment bulk density. Lengths of core sections were approximately 1m.

A Schlumberger resistivity survey was conducted at site WI2 to obtain the ground apparent resistivity and hence conductivity information.

Reflection profiles and CMPs

Reflection profiles at site WI1 (fig. 14) show two prominent reflectors, R1 and R2, at depths of 2.5 m and 5 m respectively. R1 represents the water table whereas R2 is interpreted as reflections from a marsh layer, correlatable with the top of the marsh layer in core section WI1 (D) in fig.18. At site WI2, profiles show the water table as the single strong reflector (fig.15). These reflection events are also identified in the CMPs (fig.16 and fig17). The presence of reflections other than those mentioned above is noticeable in profiles at both sections. These additional reflection events cannot be associated with any conspicuous lithologic changes in the core sediments.

To better understand the nature and characteristics of the radar reflections at Waites Island, the vibracore sediments were analyzed in the laboratory.

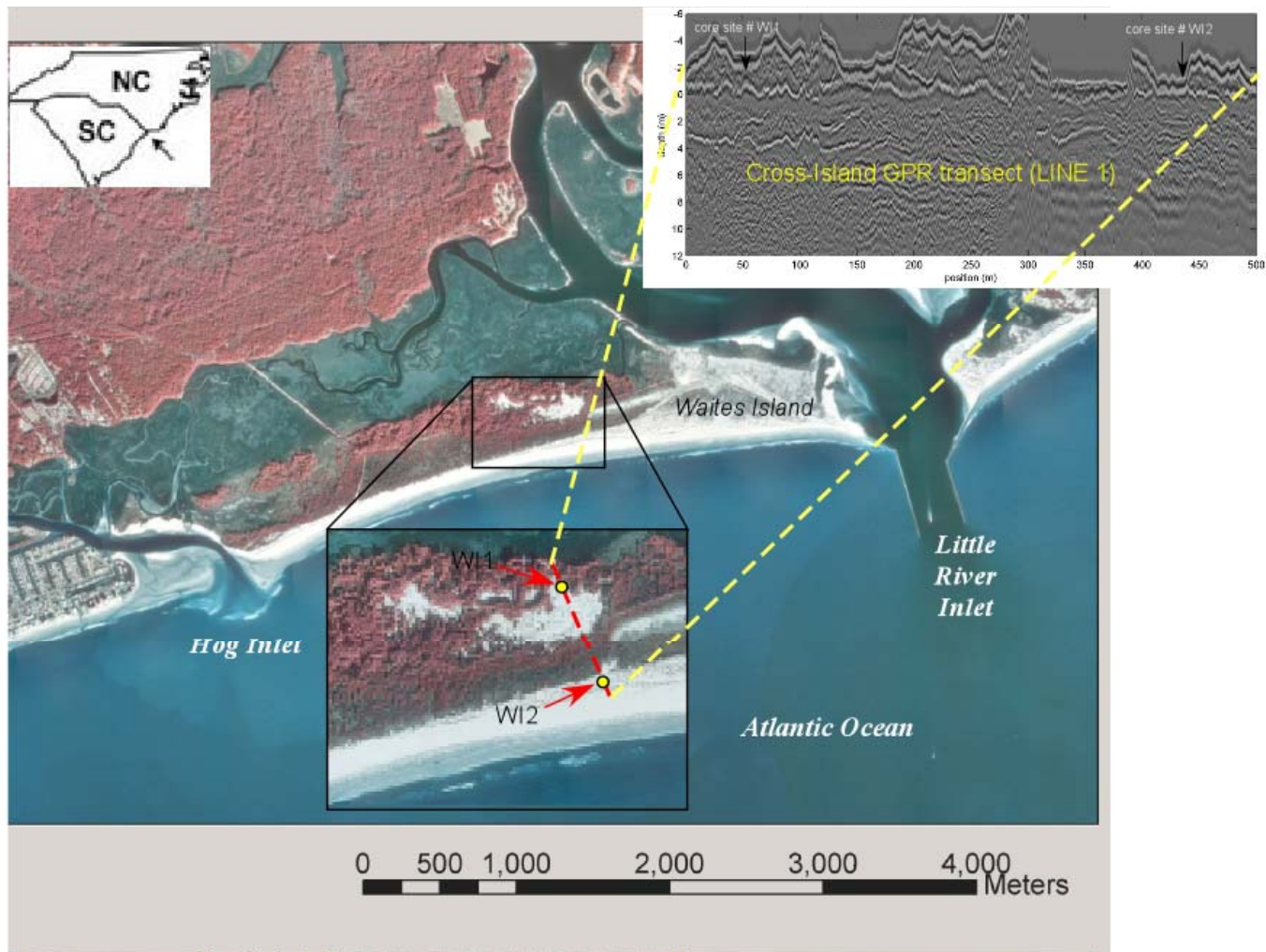


Fig. 12 Infrared aerial photo of Waite's Island showing cross-island GPR transect (LINE 1) and core sites WI1 and WI2 on LINE 1.

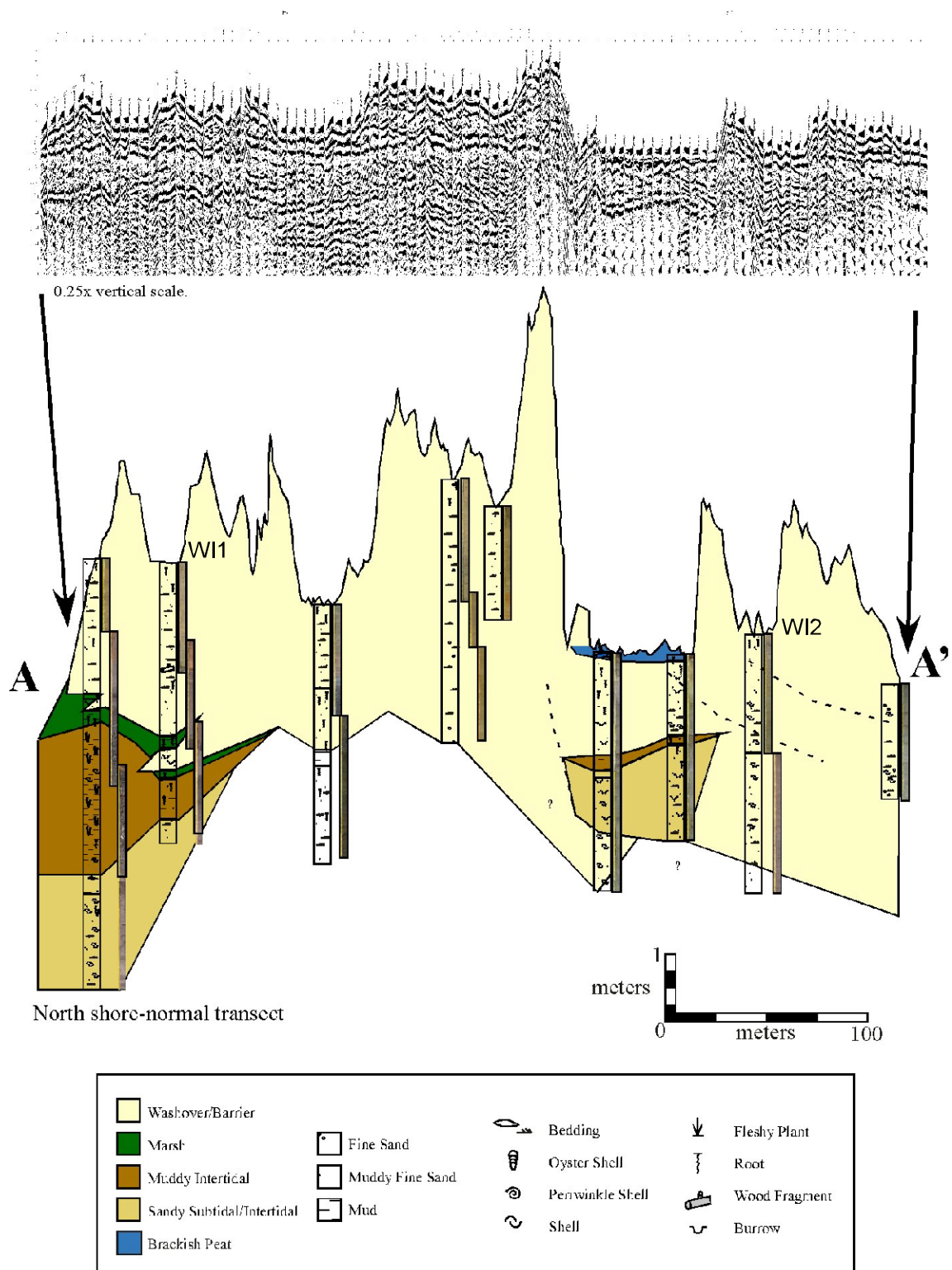


Fig.13 Waite Island cross section along LINE 1 showing different depositional environments as interpreted from vibracores and GPR data (Eric Wright, personal communication)

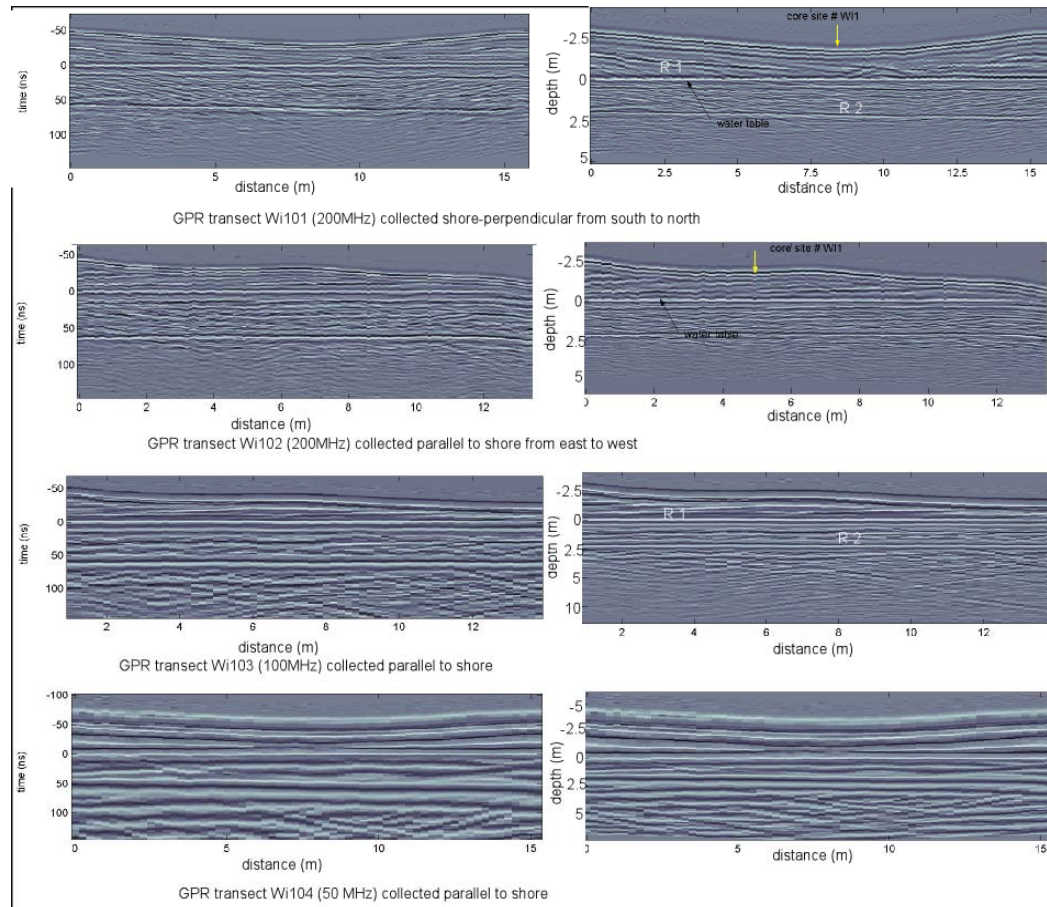


Fig. 14 Reflection profiles at core site WI1

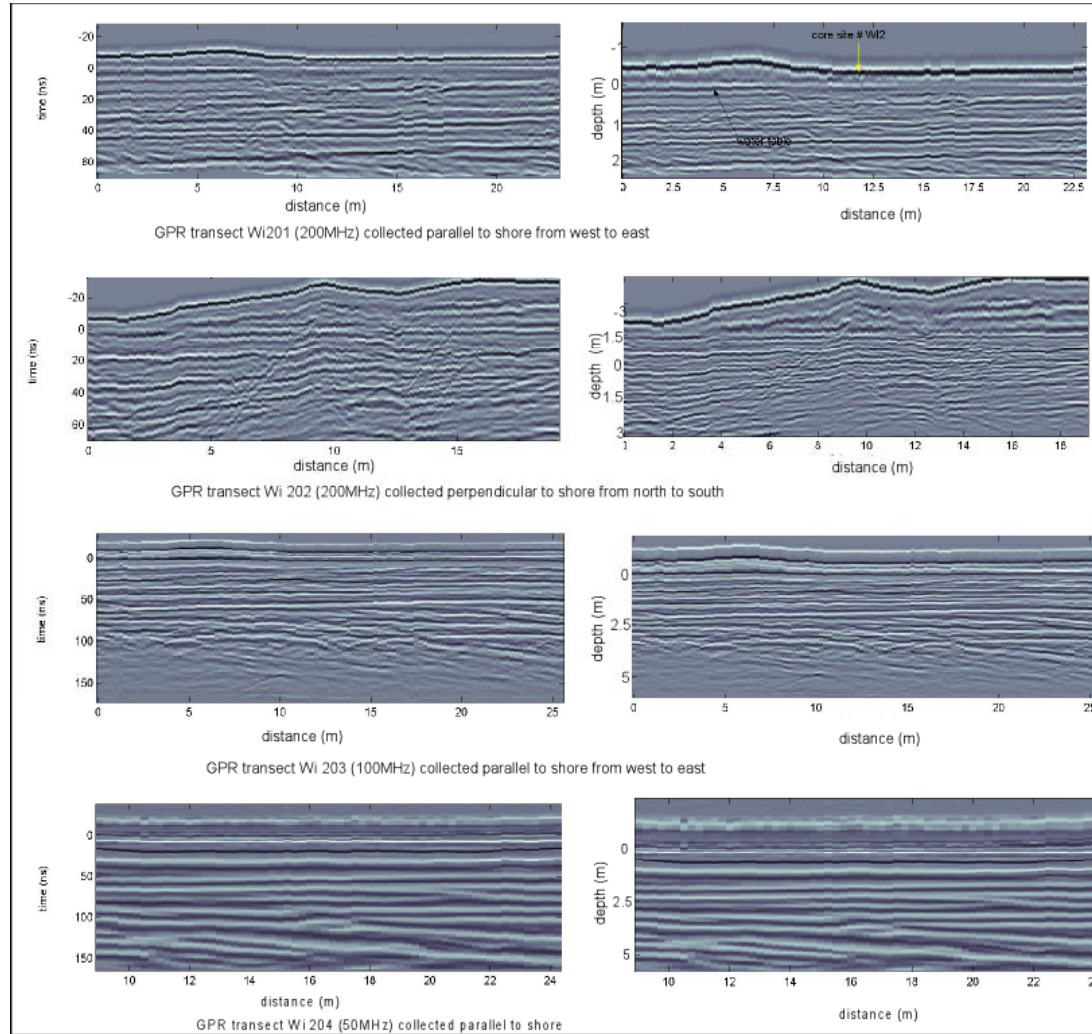
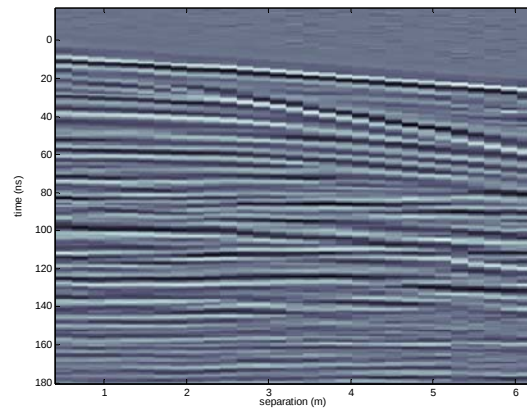
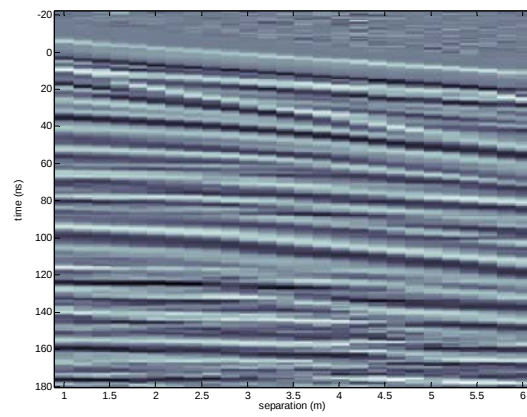


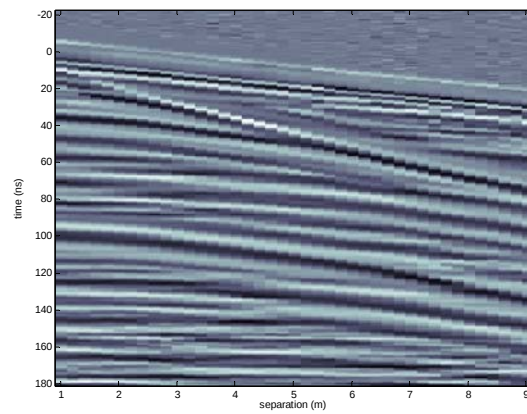
Fig.15 Reflections profiles from core site WI2



(a)

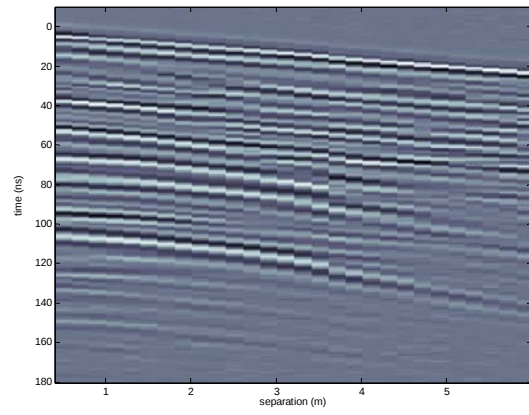


(b)

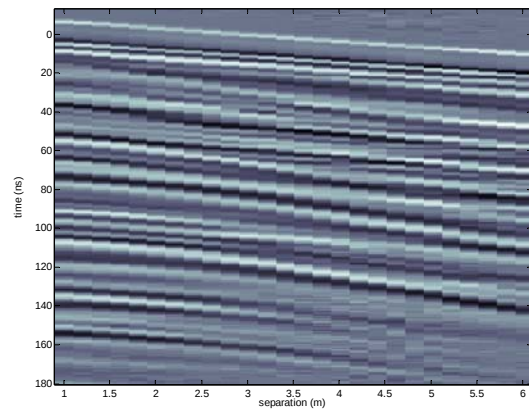


(c)

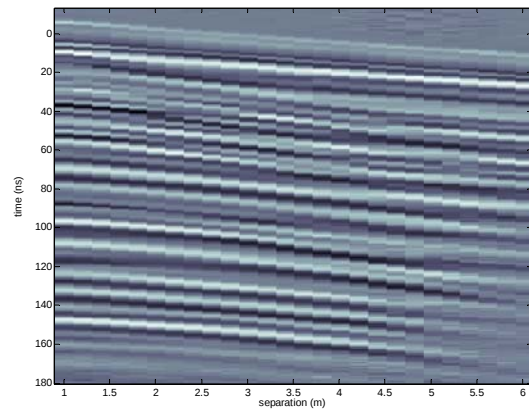
Fig. 16. CMP at site WI1. (a) at 200 MHz, (b) at 100 MHz and (c) at 50 MHz



(a)



(b)



(c)

Fig.17 CMP at WI2 (a) at 200 MHz, (b) at 100 MHz and (c) at 50 MHz

Laboratory Methods

Core sediment analysis

The split sections of cores (WI1 and WI2) were photographed (photos obtained from Marine Science at Coastal Carolina University, E. Wright, personal communication). Figures 18 and 19 show the split-core sections. The presence of finer layers of heavy minerals or beach laminations (e.g. Komar, 1974), in different portions of each of the cores is the most noticeable heterogeneity in the sediment. Section WI1 (A) of WI1 (collected in August, 2003) contains extensive layers (mm scale) of heavy minerals alternating with fine sand from a depth of 45 cm to 110 cm (fig. 18b).

Sediments of core section WI1 (A) were analyzed for bulk density and porosity information by running it in the Multi-Sensor Core Logger at the University of Florida, Gainesville. Data sampled had a sampling interval of 0.5 cm. The gamma bulk density has a slightly high value from 50 cm to 80 cm of the core and a gradual drop is seen for core sediments after 80 cm (fig. 20). However, no other significant change is observed in the overall data. The corresponding porosity values increase from 80 cm to the base of the core (fig. 20).

Grain-size analysis was done for samples of core section WI2 (A) using the sieve analysis method. Grain size distribution patterns are the same for all samples (fig.22). Heavy minerals formed the finer particles in all samples.

To obtain a better image of the lamination patterns in WI1 (A), a lacquer peel was made from which the layer thicknesses were measured. The individual heavy mineral enriched layers are approximately 1 mm in thickness. At places they are very closely spaced forming a zone with a thickness of 2-5 cm (18b). The lacquer peel helped in the measurement of individual thin heavy mineral layer and their interspaces which would otherwise be difficult to discern from the split core.

A Bartington susceptibility meter was used to acquire the magnetic susceptibility of sediment samples from 40 cm to 110 cm of the core where the heavy mineral laminations are in abundance. A sample volume of 8 cc was taken from the central portion of the core starting from 40 cm and ranging to 110 cm for measuring the susceptibility. Samples were collected every 2 cm.

The susceptibility data as given in figure 22 shows an appreciable match with the lamination patterns obtained from the lacquer peel.

Some samples of the concentrated heavy minerals from WI1 (A) at depths of 65-70 cm and 105-110 cm were separated using non-toxic heavy mineral separation liquid, Sodium Polytungstate. The primary objective of this separation was the identification of iron-oxide-bearing minerals such as magnetite from other heavy minerals (e.g. zircon, apatite). The presence of magnetite (dielectric constant value of 33.7 (Schon,1996) can serve as a prominent reflecting surface when forming a lamina. Deposition of magnetite along lamination boundaries in dune sands causing GPR reflections has been noted by Harari (1996). Baker (1991) also correlated GPR reflections from heavy mineral layers in a barrier island sand deposit.

On the WI1 (A) core, samples taken from 55-60 cm and 85-90 cm from the same core were treated with a strong bar magnet which resulted in separation of magnetite particles (fig. 23). Thus GPR returns from this setting are likely generated by the magnetite-bearing laminae, in addition to the water table, marsh contact, and other variations not seen by eye or in the porosity structure.

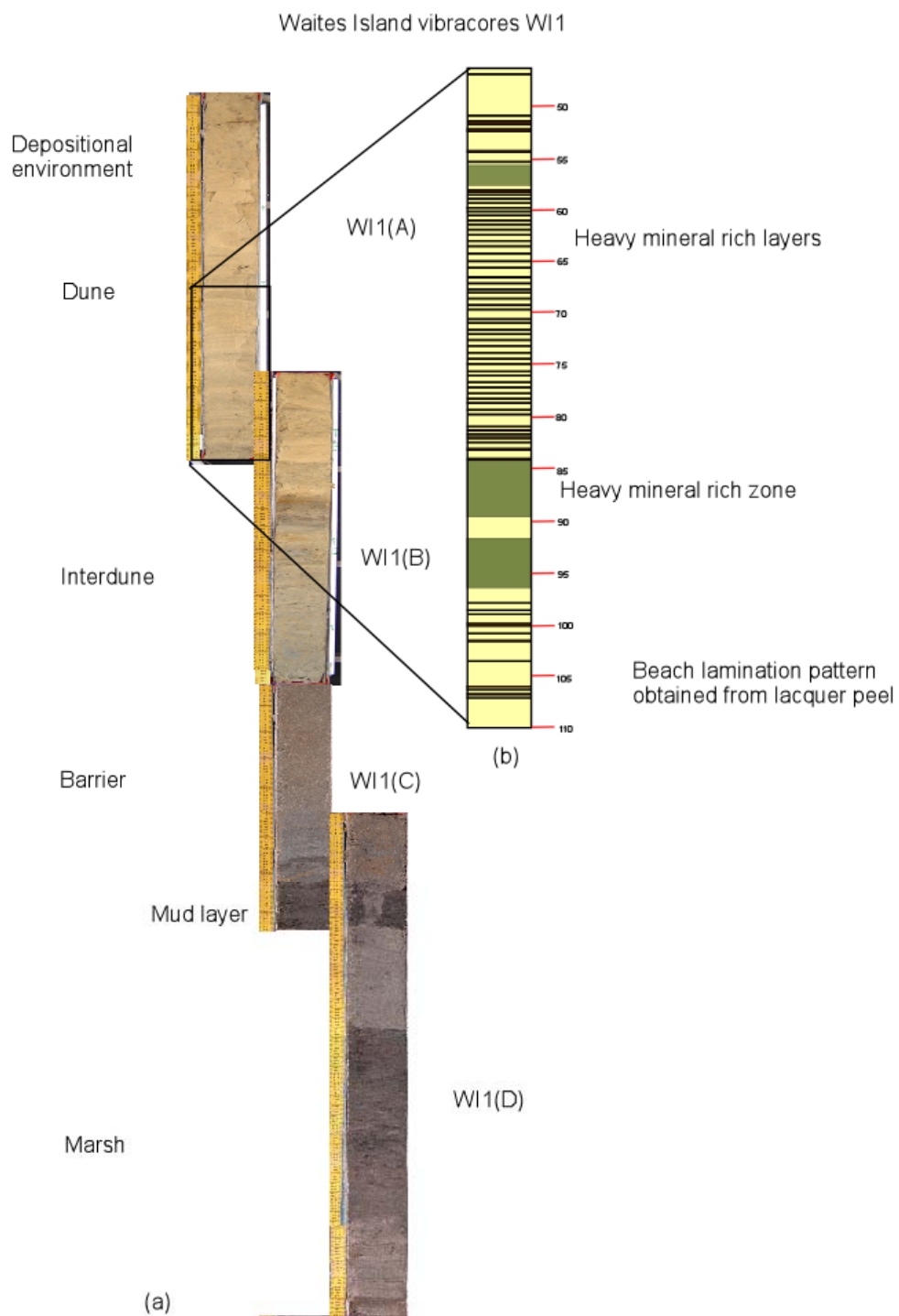
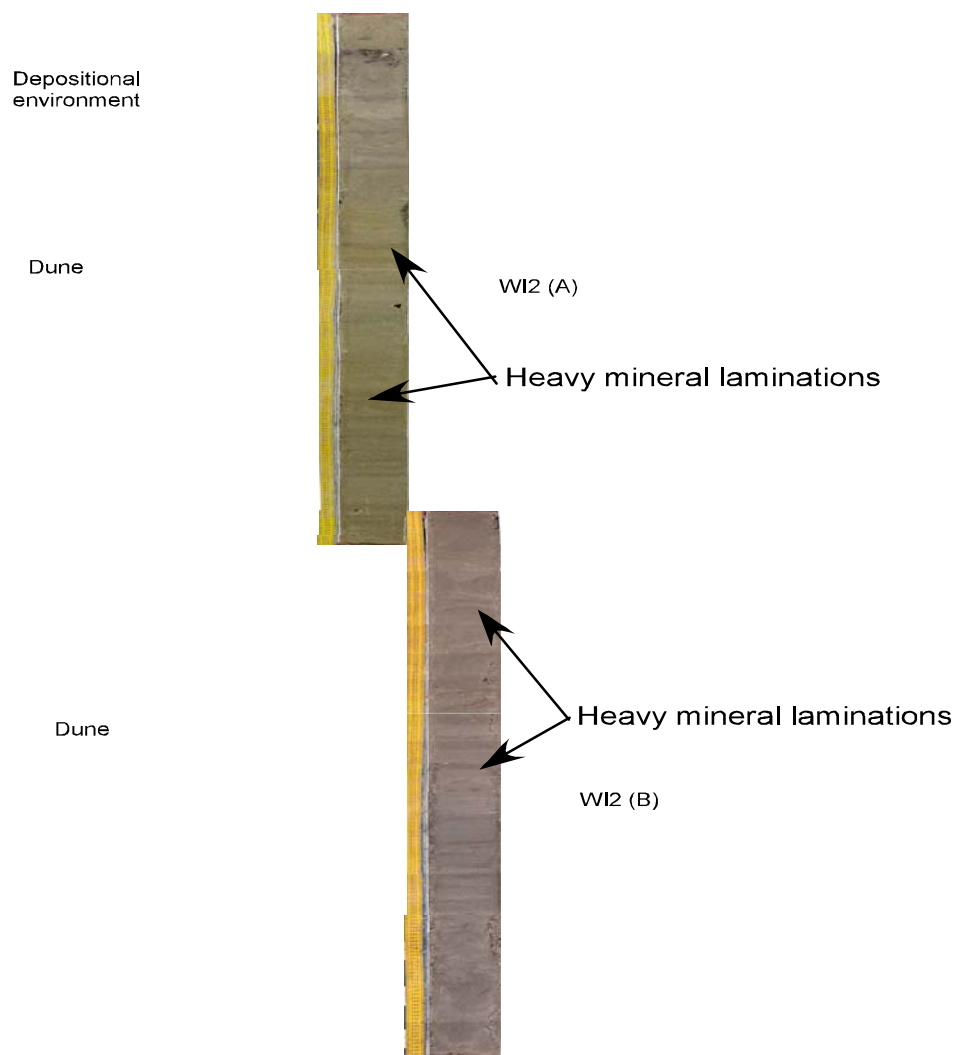


Fig. 18 (a) Core sections of WI1, (b) layer patterns obtained from lacquer peel of WI1 (A). Core description given in Appendix 4.

Waites Island vibracores from site WI2



Core section length -- WI2(A)--2.02m

WI2 (B)--2.41m

Core description given in Appendix 4

Fig. 19 Core sections at site WI2

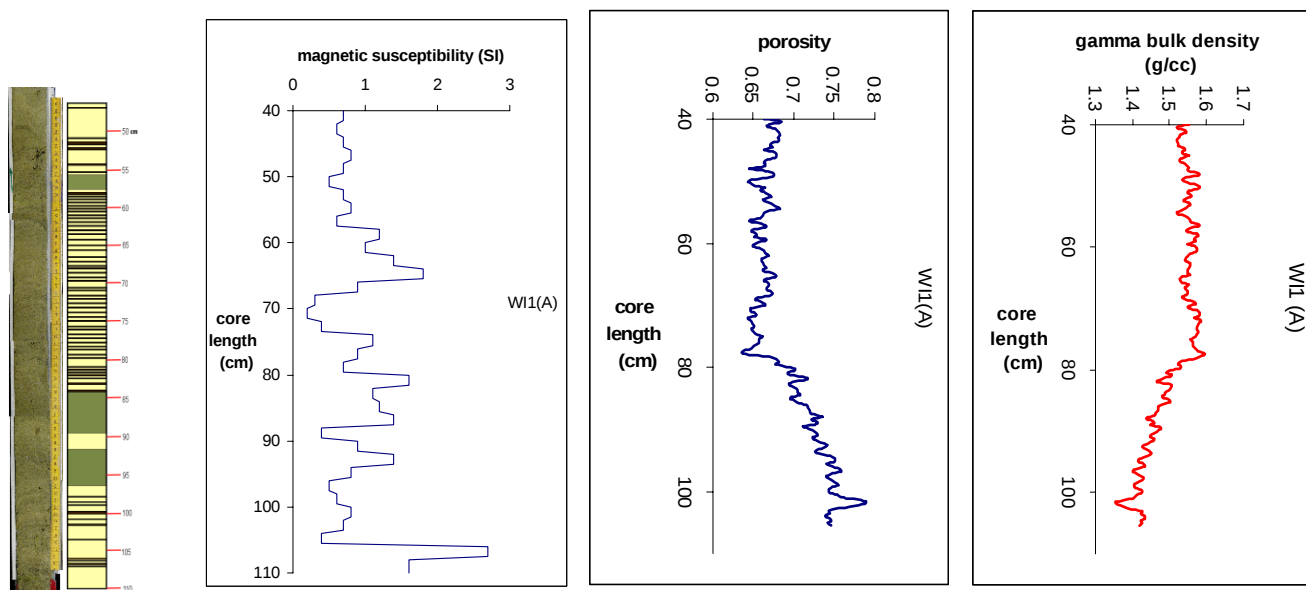


Fig. 20 Magnetic susceptibility, gamma bulk density and porosity values for core section WI1 (A)

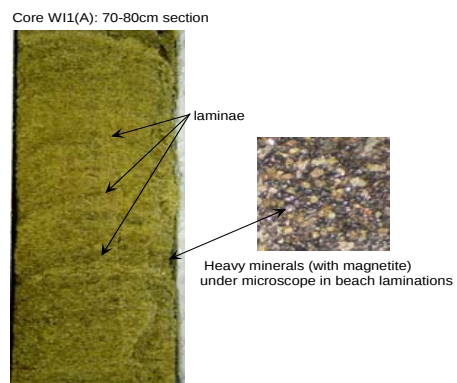


Fig. 21 Heavy mineral layers containing magnetite in core section WI1 (A)

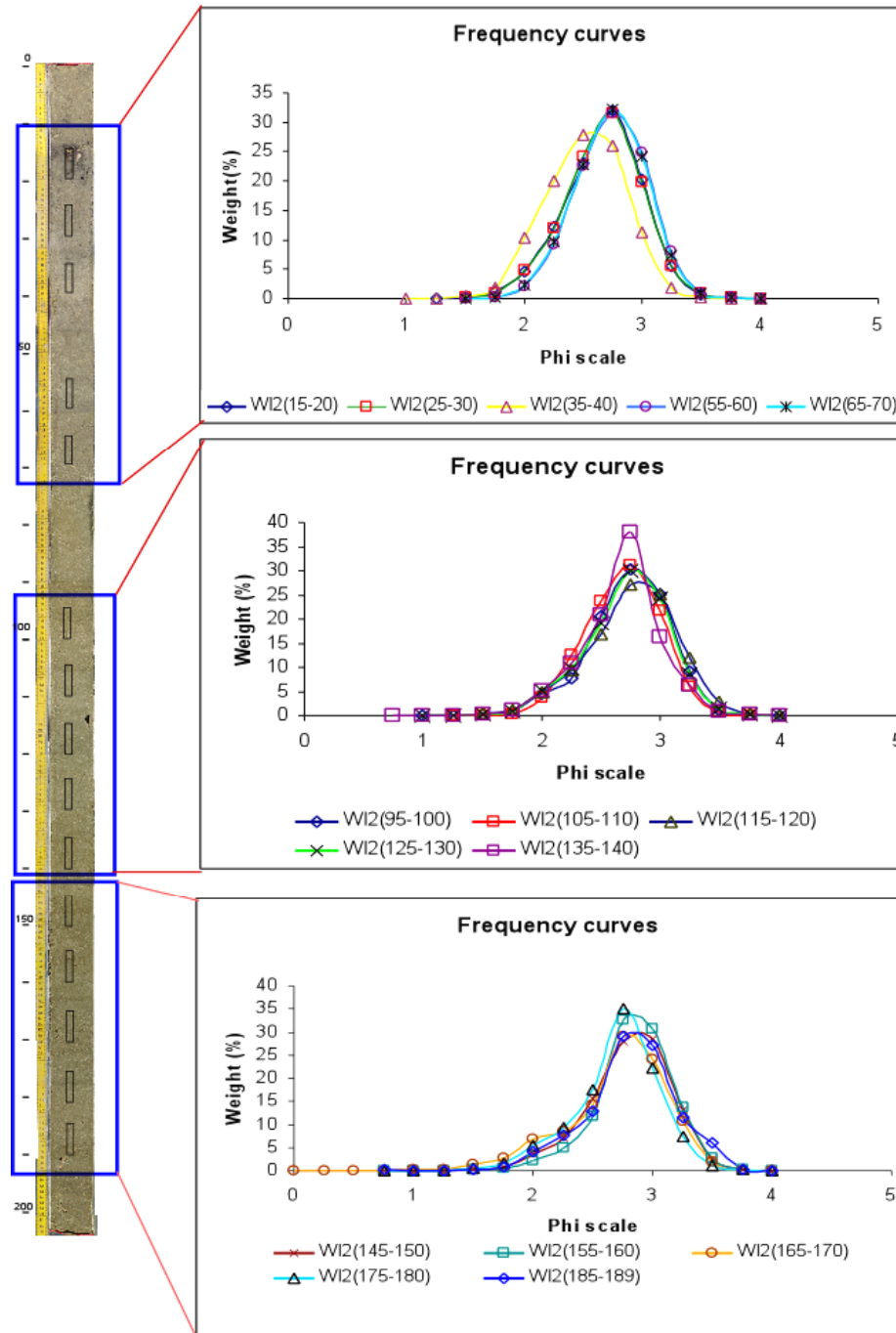


Fig. 22 Grain size distribution for core section WI2 (A). Samples collected at intervals of 5 cm as represented by rectangles on core diagram.

Layered models simulating core laminations

To test the hypothesis that the Waites Island radar profiles could in fact be produced by the fine-scale layering and other contacts seen in the cores (as well as the water table), two sets of models have been designed. Model 1 simulates the lamination patterns as obtained from the lacquer peel and photographs for core WI1, and model 2 the core WI2 based on descriptions of core photos.

Fig. 23 gives the schematic presentations of the layered models. Models were required to (1) assume geologically plausible values of permittivity, magnetic permeability, and conductivity; (2) have contacts at observed depths; (3) fit the observed average saturated and unsaturated zone velocities; and (4) have bulk conductivity on the order of 1-5 mS/m (as observed in the field).

Since the 1D model does not account for attenuation of energy due to geometric spreading, a factor of $1/r^2$, where r is the distance traveled and $r = \int v(t)dt$, has been applied to the model traces.

Model parameters

Model parameters that satisfy the constraints are given in Table 1. As most petrophysical parameters (e.g. moisture content, organic content, iron-oxide content, grain shape and orientation) of the Waites core are unknown, these models are non-unique in the sense that many models could be generated that yield equivalent or better fits to the observations. Without better knowledge of core characteristics, fine-tuning of the models to better fit observed traces is not warranted. Here discussion is focused simply on the quality of these simple models, and addressing the question: can the basic features of the radar traces be explained from contacts and layer patterns visible in cores?

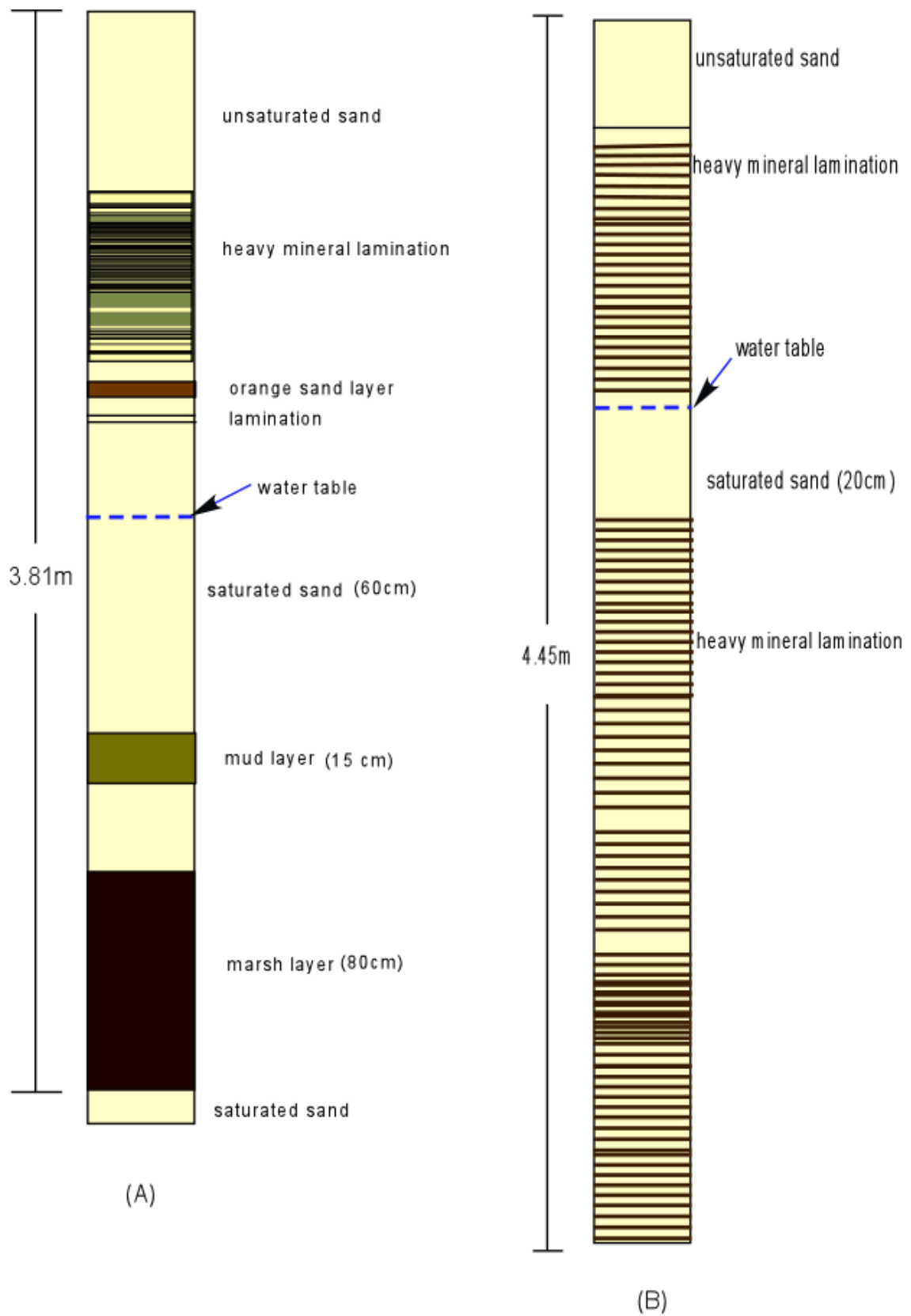


Fig. 23 Schematic representation of Model 1 (A) and Model 2 (B)

Table 1. Physical parameters used in model simulations

Model 1	K (dielectric constant)	μ_r (relative magnetic permeability)	σ S/m (conductivity)
unsaturated sand	3	1	0.001
saturated sand	20	1	0.001
magnetite	15	1.1	0.004
mud	17	1	0.002
marsh	6	1	0.003

Model 2	K	μ	σ S/m
unsaturated sand	6	1	0.001
saturated sand	20	1	0.004
magnetite	15	1.1	0.003

Analysis of models

GPR traces were selected from the records at the two study sites. Plots of individual traces at different frequencies are compared to traces produced by the models as given in fig. 24 and fig. 25. Analysis focuses on the saturated zone, for which the water table reflection provides a convenient reference signal. In these models the water table is simulated as a 20 cm-thick contact across which electromagnetic properties change linearly.

Pattern of returns: The 60 cm package of laminations present above the water table does not yield significant distinctive returns in either observed or model records. Radar wavelengths are longer in the faster unsaturated zone, and detectable returns would

be confined to a short time window between direct arrivals and the water table reflections. Reflections from within the saturated zone for require the presence of changes that are not incorporated in Model 1. (Some of the observed returns may represent diffractions). The saturated zone of WI1 lacks heavy mineral laminations, but the mud and marsh layers include sporadic mud lenses and organic materials. Perhaps the muds lenses and organics are part of coherent layers on a larger scale.

Model 2 is a laminated section (laminations present above and below water table) consisting of sand and magnetite layers (mm and cm scale). The 200 MHz model result shows reflection patterns similar to the GPR record (Figure 25a). The presence of thin magnetite layers is sufficient to explain the reflections seen in the 200 MHz record. However, comparing the lower frequency GPR responses at 100 MHz and 50 MHz at this site points out that lithologic changes on a larger scale than the laminations exist that are not perceptible in the core data, particularly in the deeper parts of the record.

Attenuation: For both sites, exponential decay curve fits of the observed and model trace envelopes yield higher attenuation coefficients for the models. This discrepancy may be due to: (a) unrealistically high conductivities in the models; (b) poor modeling of the water table reflector; (c) underestimation of the true attenuation due to noise late in the record; and/or (d) underestimating contrasts (reflection coefficients) between layer types. Better estimates of the layer contrasts could be derived from amplitude-versus-offset analysis of the data (e.g. Kruse and Jol, 2003), which is beyond the scope of this work. Explanation (a) is unlikely, as the Schlumberger resistivity survey at site WI2 (fig. 28) shows a conductivity of 5 mS/m; at radar frequencies the effective terrain conductivity should be higher, rather than lower.

Spectra: Comparison of spectra from models and data are of little utility, as there is not a good constraint on the spectra of the downgoing pulse in the observations. However, one can compare spectra of 100 MHz traces from sites with known laminations (near WI2) with those from sites without (near WI1). From model results of the previous section, it is inferred that an upward shift in the amplitude spectrum should be associated with returns from fine layered packages will result with increasing frequencies. Traces from the 100 MHz (LINE 1) cross-island transect have been selected. Amplitude spectrum of traces consisting of reflections from fine layers in the saturated zone at site

WI2 (Figure 29b) show a spectral shift relate to that from the saturated non-laminated zone of WI1 (Figure 29a). Thus, spectral analysis of traces may be a useful measure to identify presence of thin layers in coastal deposits.

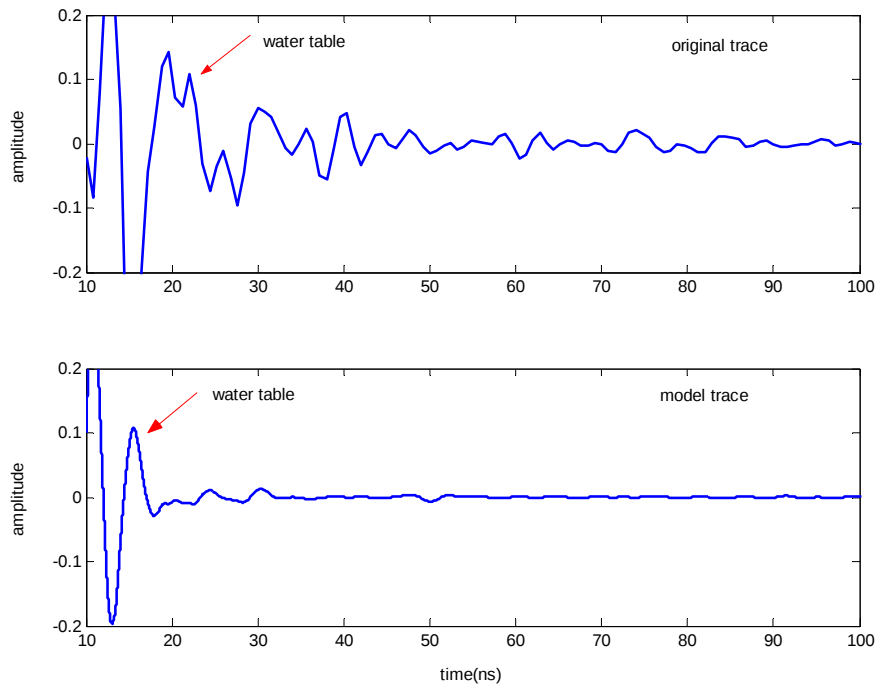


Fig.24a

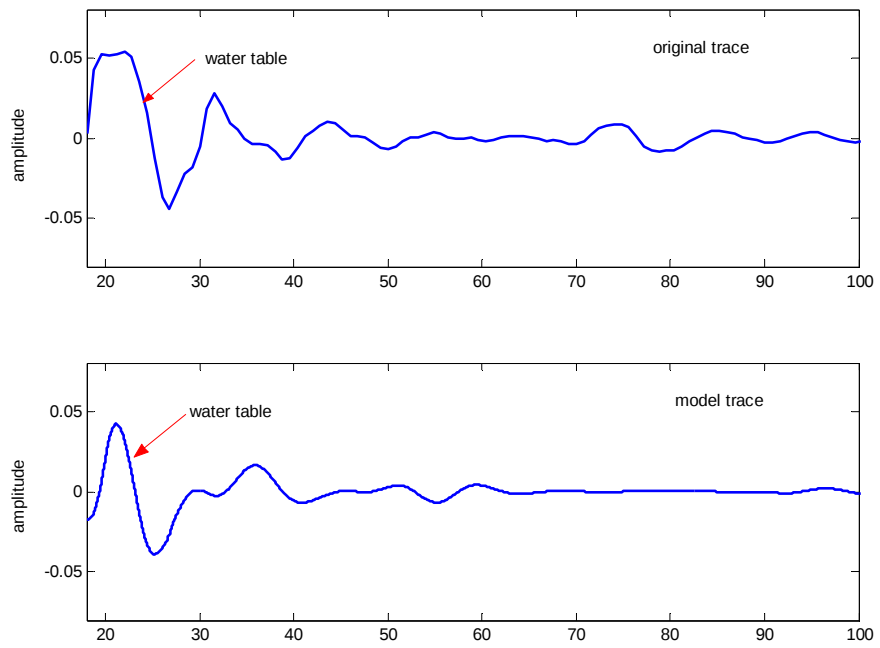


Fig.24b

Fig.24 Comparison of real and model traces for site W11. 24a—200MHz, 24b – 100MHz

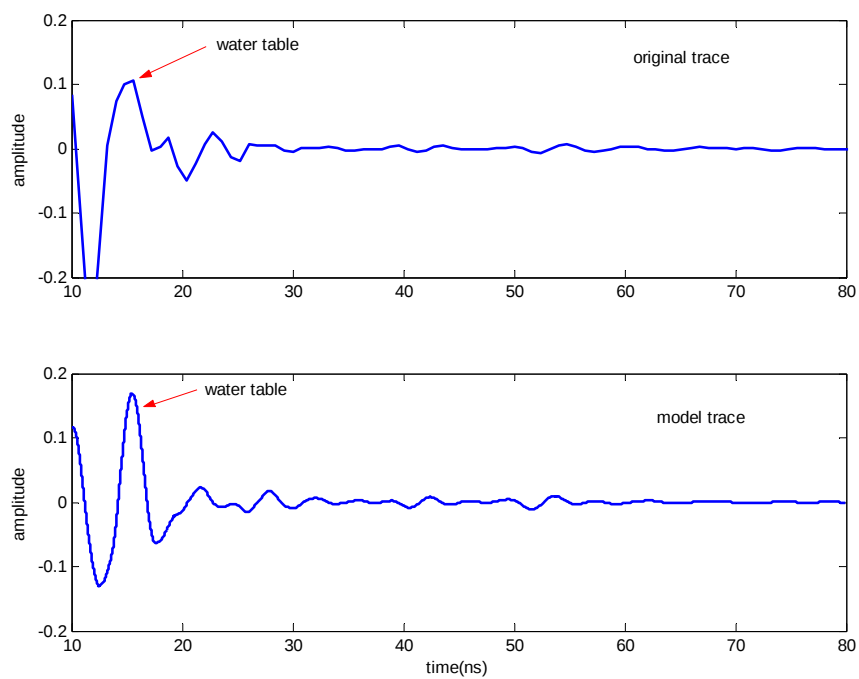


Fig. 25a

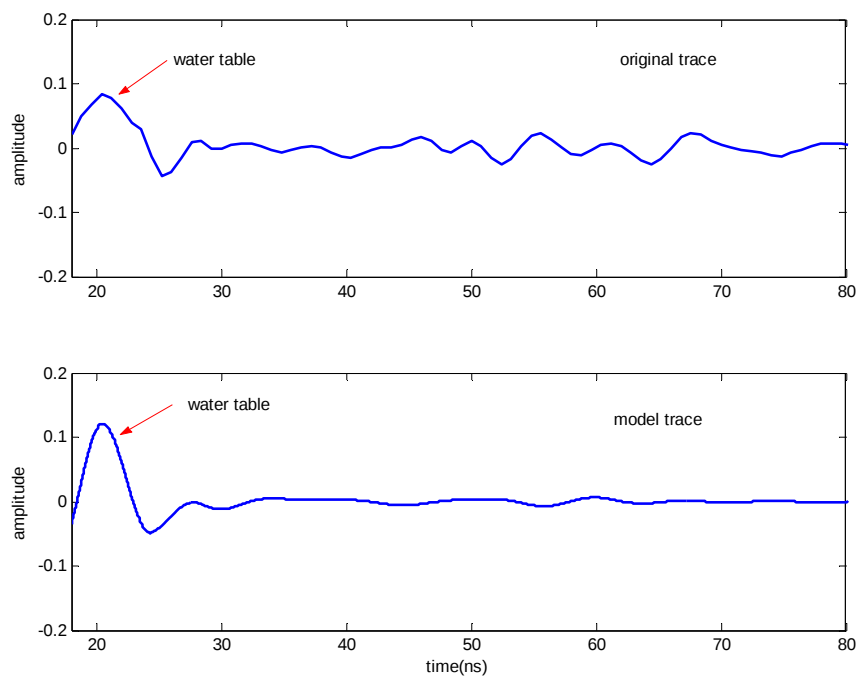


Fig. 25b

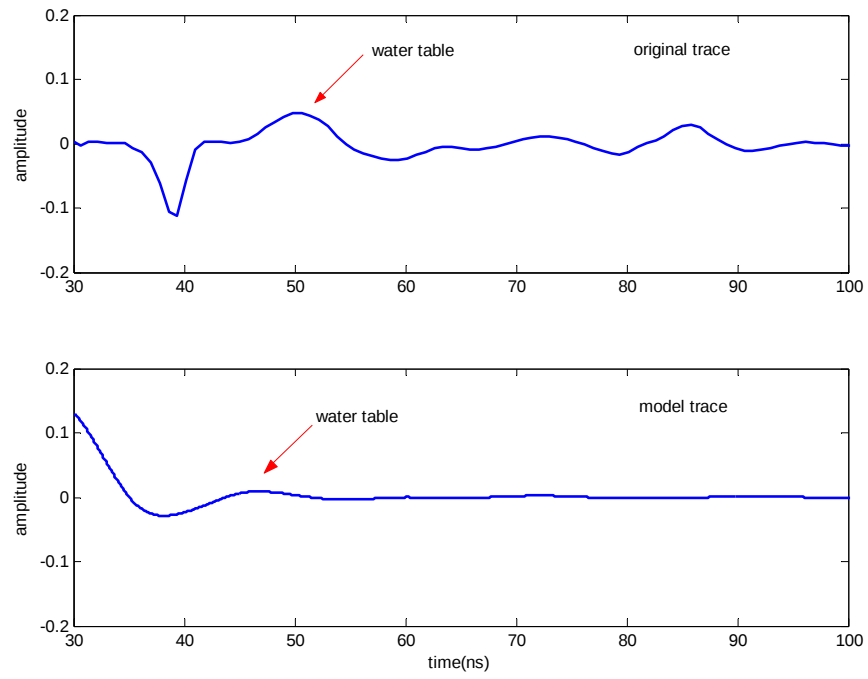


Fig.25c

Fig. 25 Comparison of real and model traces for site W11. 25a—200 MHz, 25b – 100 MHz, 25c – 50 MHz

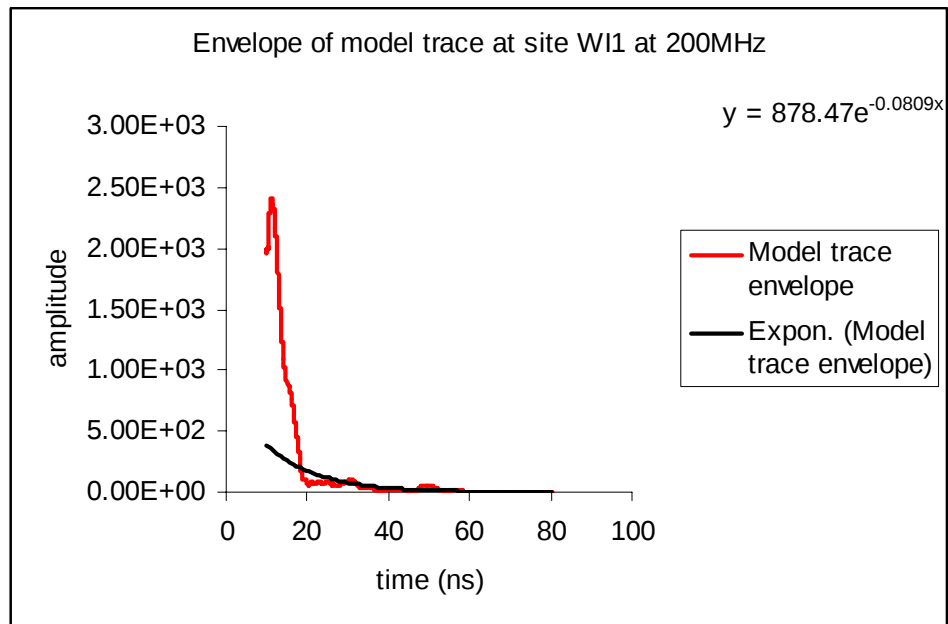
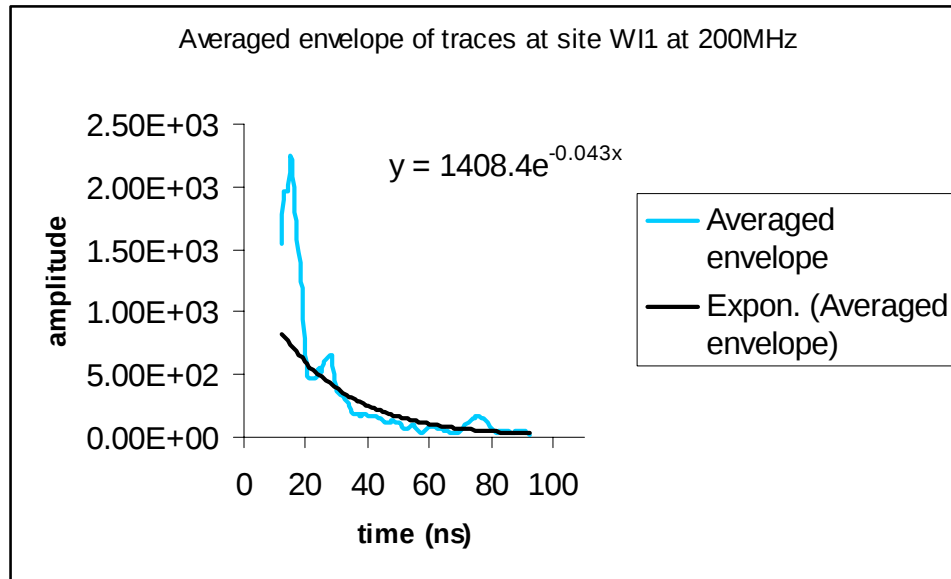


Fig.26a

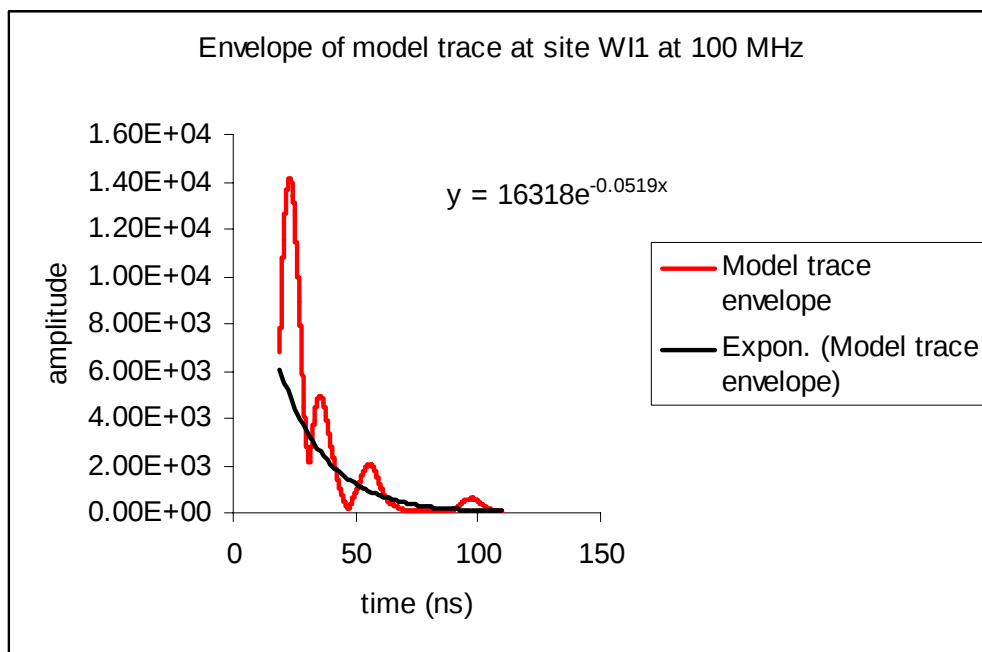
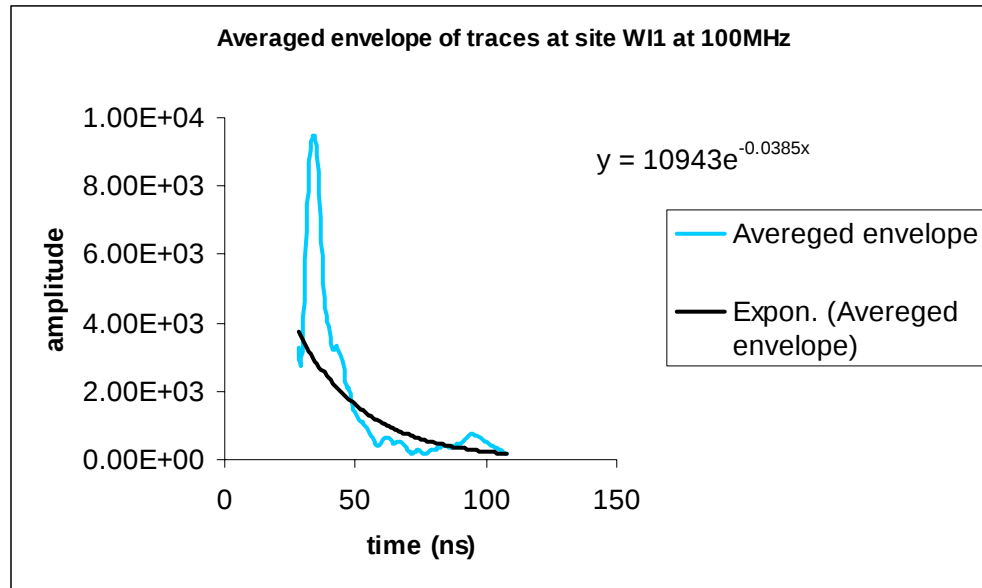


Fig.26b

Fig. 26 Exponential trend of attenuation in real and model data for site W11 at different frequencies.

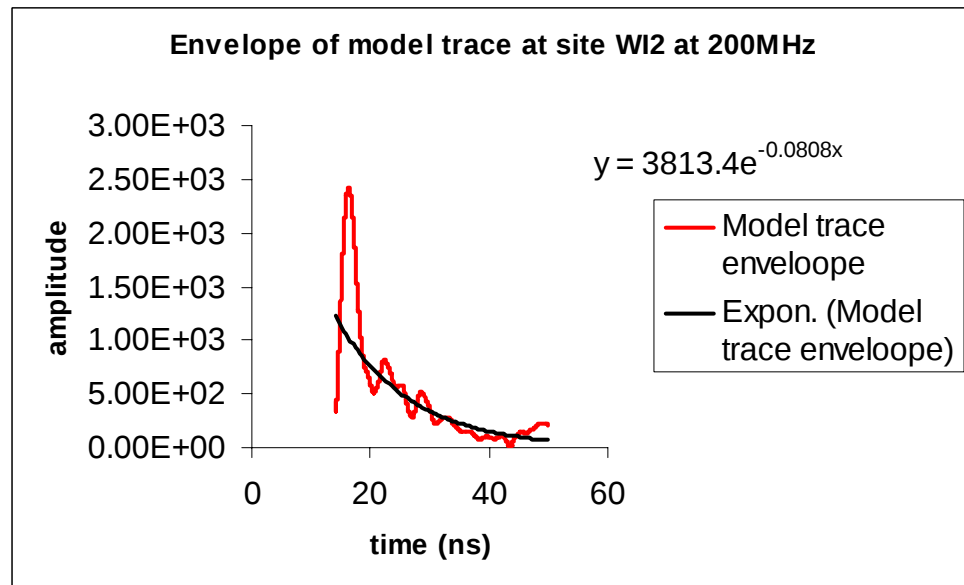
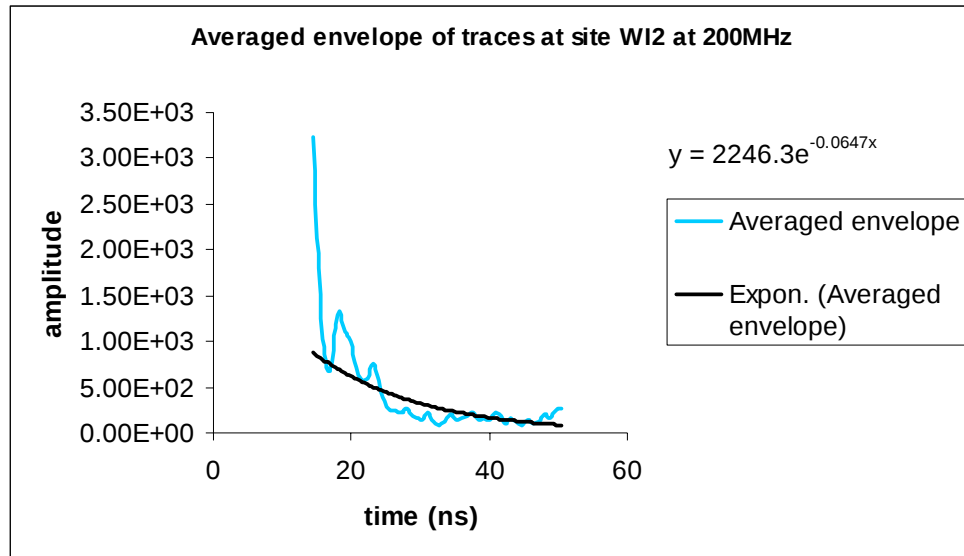


Fig.27a

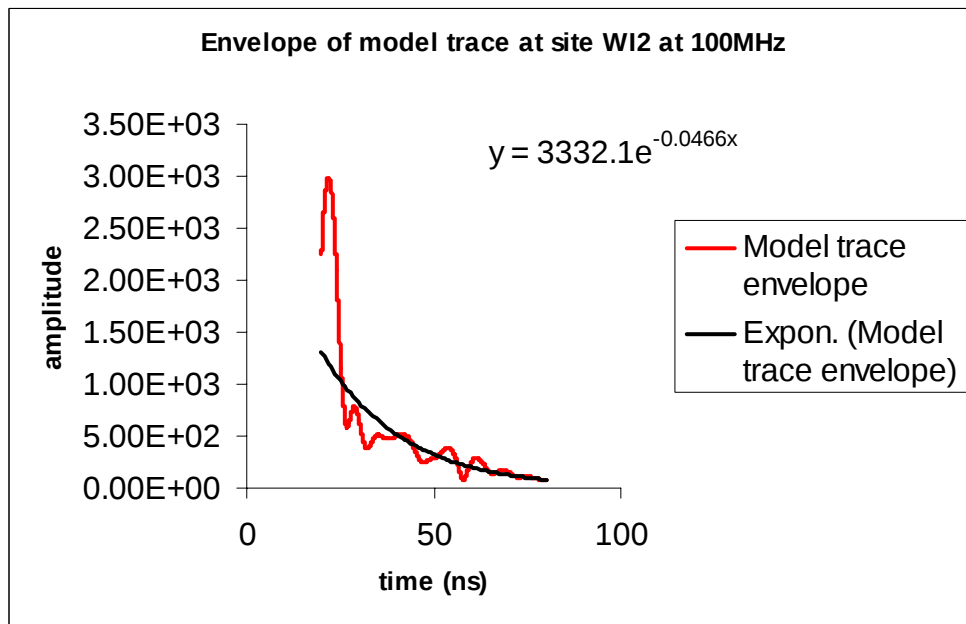
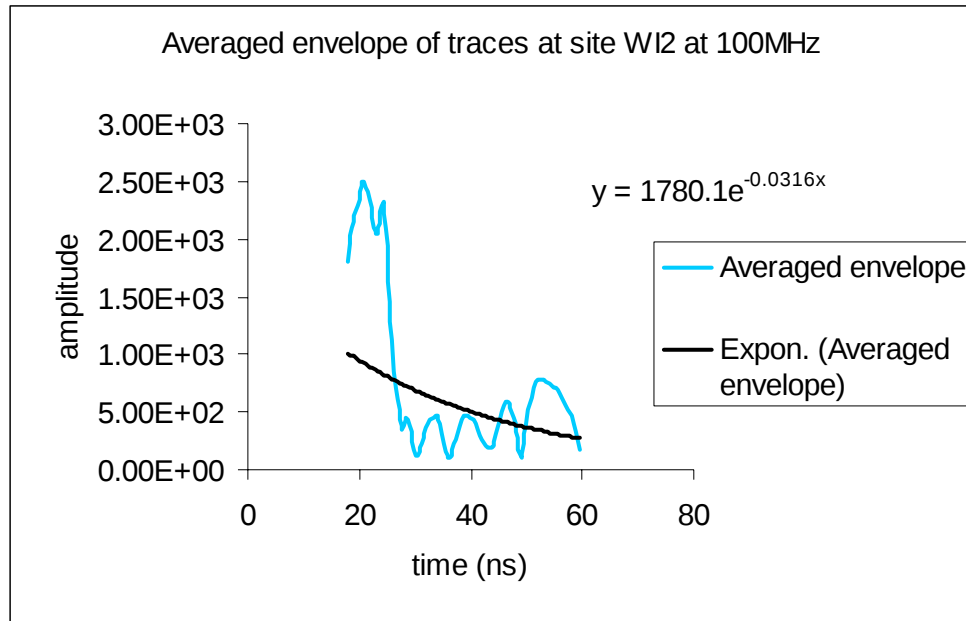


Fig. 27b

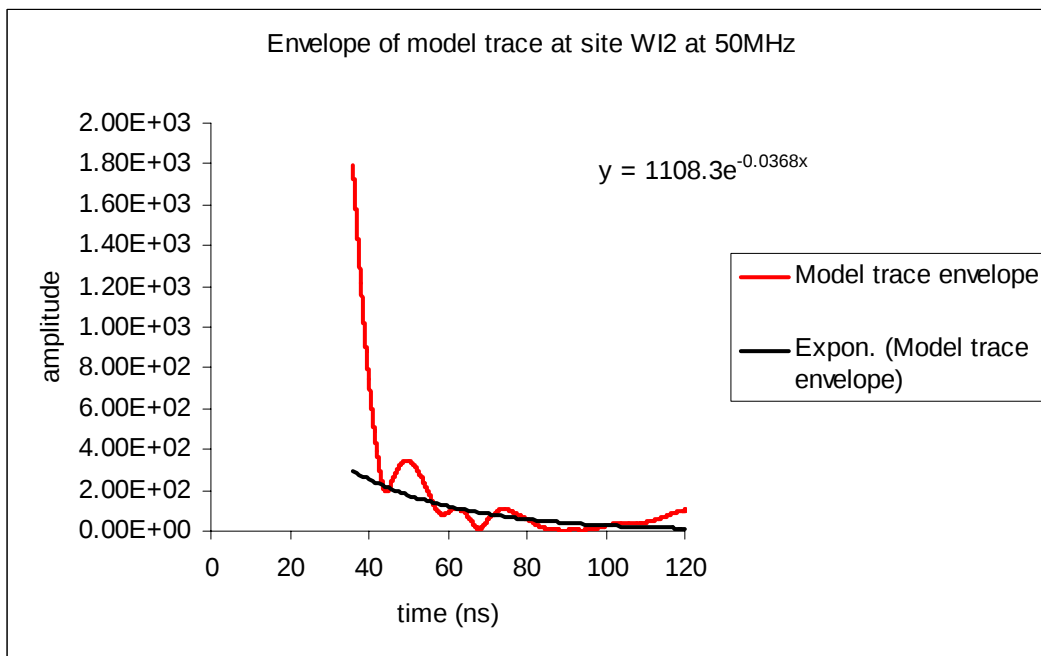
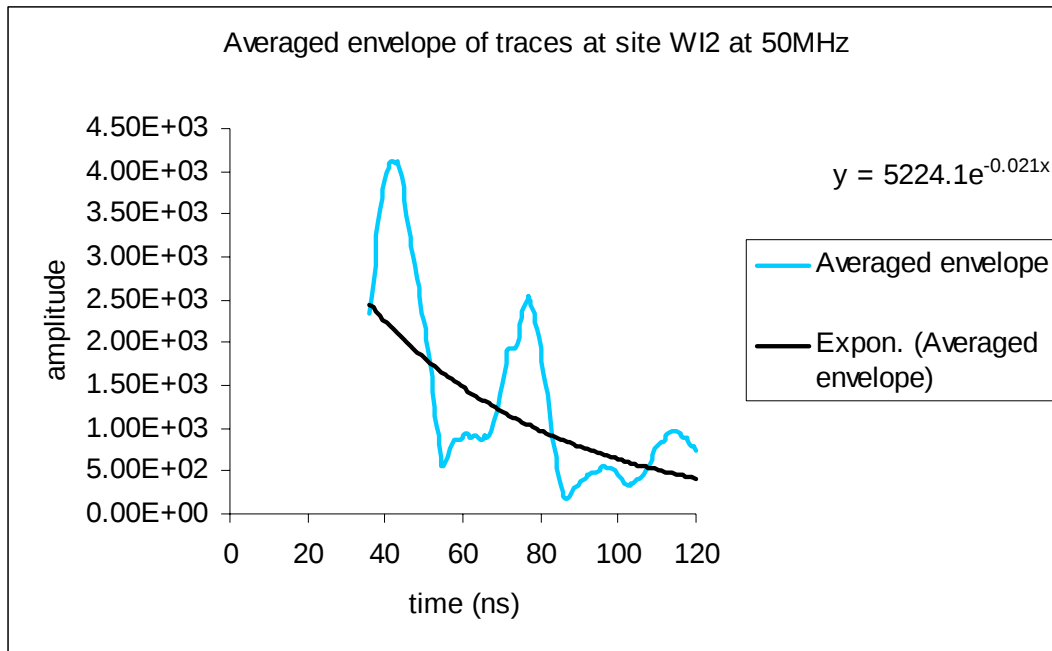
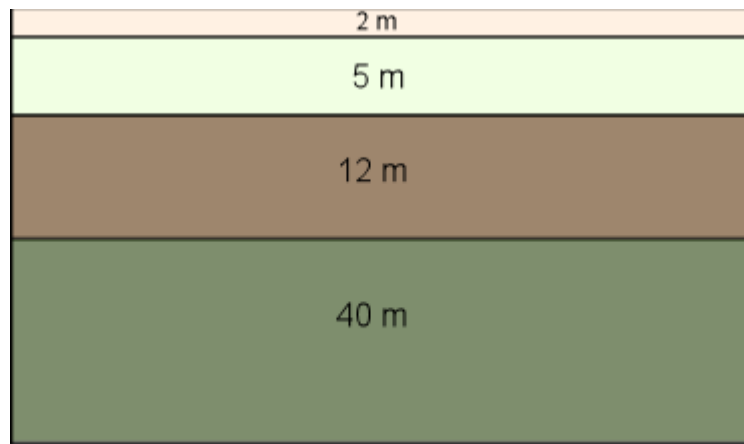
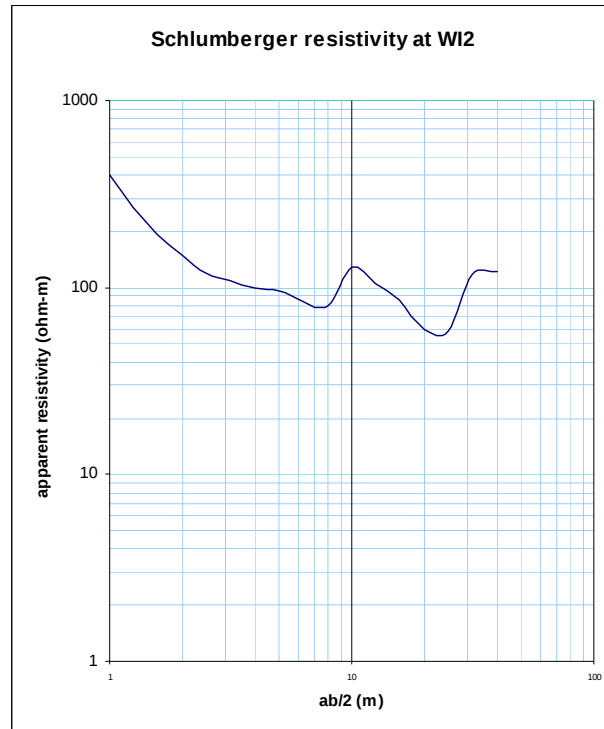


Fig.27c

Fig. 27 Exponential trend of attenuation in real and model data for site WI2 at different frequencies.



Apparent resistivity: 195.15 ohm-m (layer1)
 64.382 ohm-m (layer 2)
 74.812 ohm-m (layer 3)
 198.5 ohm-m (layer 4)

Fig 28 Layer model apparent resistivity and layer thicknesses estimation (program used ENVIRT6).

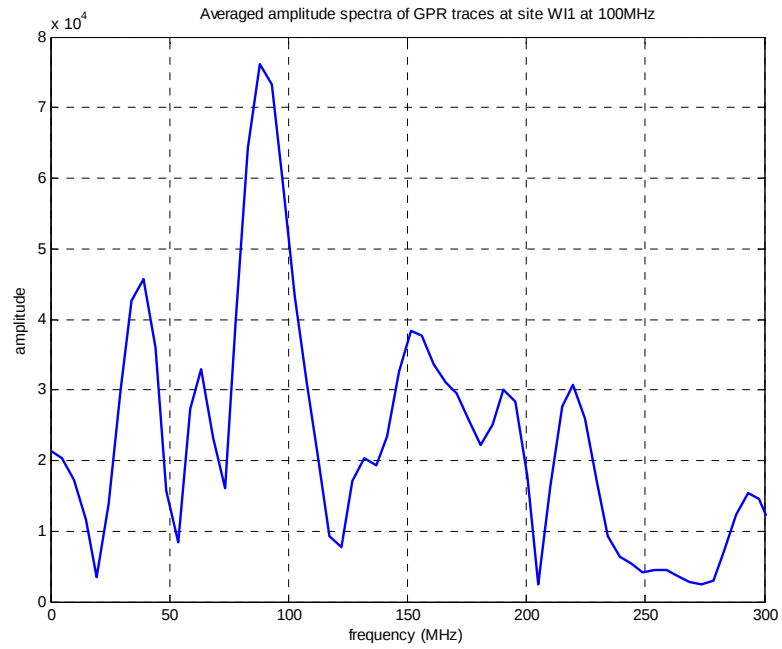


Fig.29a

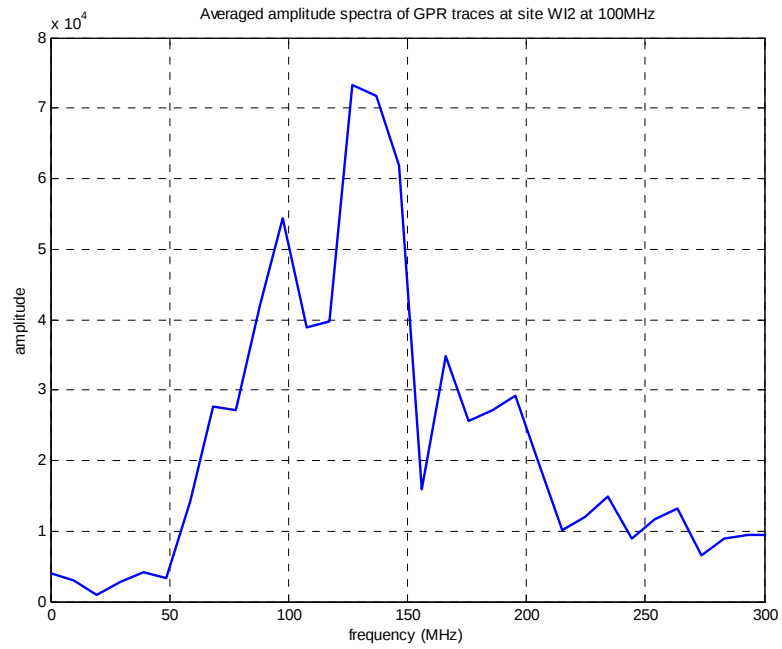


Fig.29b

Fig. 29 Averaged amplitude spectra of GPR traces at two different sites (close to WI1 and WI2) along LINE1.

Conclusions

Thin beds are common in GPR surveys in sediments, but extracting information on thin beds from GPR profiles has not been widely discussed. From simple models of radar wave propagation, and comparative analysis of GPR records and core sediment records from a sandy barrier island, the following conclusions are drawn:

1) The presence of multiple thin beds, such as magnetite-enriched laminae in coastal sedimentary deposits, can produce low-amplitude but detectable GPR returns at the commonly-used frequencies of 100 to 500 MHz. The returns cannot be directly correlated with individual laminations. Return amplitudes will depend on the distribution of layer and "background interlayer" thicknesses, and as the difference between layer and interlayer thickness increases. Layering within packages with package thickness near the thin bed limit would be difficult to detect.

2) Spectral analysis of both model and real traces indicate that the presence of mm-scale laminations is accompanied by a spectral shift towards higher frequencies. Spectral shifts may serve as an indicator of local zones of thin laminations.

3) Comparison of observations with models based on contacts seen in cores in Waites Island, SC, suggests that thin magnetite-rich layers are important contributors to the radar signal, especially at 200 MHz, but do not in themselves explain all the major features of the radar record. Contacts not noted in cores, perhaps subtle variations in porosity, are required to explain the basic pattern of returns and attenuation characteristics of the Waites GPR profiles.

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Appendices

Appendix 1

Radar wave propagation

The properties of the ground determine the key aspects of the radar wave propagation, namely (1) its velocity and (2) its attenuation.

For high frequencies or very low conductivity, the above equation becomes $v = c / \sqrt{\mu\epsilon}$.

where c = electromagnetic wave velocity in vacuum (3×10^8 m/s) and the properties of the medium the wave travels through are μ = magnetic permeability and ϵ = dielectric permittivity. So both permittivity and magnetic permeability play important roles in determining the velocity.

Electromagnetic waves attenuate with increasing distance from the transmitter due to spherical spreading of energy, scattering from heterogeneities and dissipation of energy into subsurface materials (Annan and Davis, 1989). The attenuation of the downgoing pulse due to the latter can be expressed by

$A = A_0 e^{-\alpha z}$ where A is the amplitude of the pulse at some distance z from the source, A_0 is the pulse amplitude at a given distance z_0 , and $\alpha = 0.5\sigma\sqrt{\mu/\epsilon}$ (Van Dam, 2000).

Reflection coefficient, resolution, depth of penetration

Reflection coefficient determines the amplitude response of the reflected signal from layers of different dielectric properties. For normal incidence, reflection coefficient

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1}, \text{ } Z_1 \text{ and } Z_2 \text{ are impedances of lower layer and upper layer respectively.}$$

(Impedance, $Z = \sqrt{j\omega\mu/(\sigma + j\omega\epsilon)}$ where $j = \sqrt{-1}$, $\omega = 2\pi f$, angular frequency, expressed in radians/s).

Physical parameters influencing radar wave propagation

Dielectric constant, electric conductivity and magnetic permeability are three parameters influencing radar wave propagation.

Dielectric constant:

Of the greatest significance among the three, is relative permittivity. Relative permittivity (ϵ_r), also referred to as dielectric constant (K), is defined as the ratio of material permittivity (ϵ), to that of vacuum ($\epsilon_0 = 8.85 \times 10^{-12}$ F/m).

Appendix 1 (continued)

Dielectric constants for earth materials are strongly influenced by water content, and hence by both degree of saturation and porosity of the material. Table 1 shows dielectric constant values for some geologic materials. While air has a K value of 1, water has $K \approx 80$. So an increase in water content is associated with a corresponding increase in permittivity. A porous material with greater water content than a nonporous substance will show a greater K value. Experiments show that bulk dielectric constant is also influenced by the pore internal geometry and pore fluid configuration (Endres and Knight, 1992), and thus mixing formulas that account for these effects are required for full understanding of dielectric constants. Clay content, which influences water retention capacity, also governs dielectric properties (Schon, 1996).

Electrical conductivity

According to Archie's equation (Archie, 1942), bulk conductivity (σ) of porous materials varies with water content.

$$\sigma = a\phi^m s^n \sigma_w + \sigma_c$$

where ϕ = porosity, σ_w = pore water conductivity, σ_c = soil grain surface conductivity,

a = constant between 0.4 to 2, m=constant between 1.3 to 2.5, s= degree of saturation, and n = constant ~ 2

Archie's Law shows that high conductivities in geologic materials may be due to both grain size effects (e.g. clays) or pore water influence (e.g. saline water). For most materials, the conductivity is assumed to be isotropic although it may vary in anisotropic materials such as along bedding planes in stratified rocks (Telford, 1984).

Magnetic permeability

It is given by $\mu = \mu_0(1 + k)$ where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability for vacuum and k is magnetic susceptibility.

For most GPR purposes, magnetic permeability does not hold a major influence as compared to the electrical effects. However, the presence of iron oxides e.g magnetite in soils or rocks will result in changes in magnetic susceptibility.

Appendix 1 (continued)

Table 1. Dielectric constant, conductivity, velocity and attenuation of some geologic material (from Annan and Davis, 2002)

Material	K	σ (mS/m)	v (m/ns)	a (dB/m)
Air	1	0	0.30	0
Fresh water	80	0.5	0.033	0.1
Sea water	80	3×10^3	0.01	10^3
Dry sand	3-5	0.01	0.15	0.01
Saturated sand	20-30	0.1-1.0	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shales	5-15	1-100	0.09	1-100
Silts	5-30	1-100	0.07	1-100
Clays	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

GPR resolution and depth of penetration

Resolution involves the detection of reflection events separately from one another in temporal and/or spatial domains and needs to be considered in both the vertical and horizontal directions.

Vertical resolution

Vertical resolution implies distinction between reflections from closely spaced contacts, one overlying the other, e.g. reflections occurring from the top and bottom surfaces of a sedimentary layer. It depends on the pulse width and is generally considered to be $\frac{1}{4}$ of the dominant wavelength (Kearey and Brooks, 1991). Because resolution increases with decreasing dominant wavelength, it increases with increasing frequency. However, with increasing depth higher frequencies undergo greater attenuation due to energy loss and hence vertical resolution generally decreases with increasing depth (Irving and Knight, 2003).

Appendix 1 (continued)

Horizontal resolution

Horizontal resolution expresses GPR's ability to distinguish reflection events from closely spaced targets at equal depths. It depends on the Fresnel zone, which is the interface from where the reflected energy within half the transmitted wavelength undergoes constructive interference to enhance the resultant reflection. The Fresnel zone width is given by the following equation:

$w \approx \sqrt{(2z\lambda)}$, for $z \gg \lambda$ where w = width, λ = wavelength of source and z = reflector depth (Kearey and Brooks, 1991).

The Fresnel equation governs horizontal resolution because reflectors separated by a distance less than the Fresnel zone width cannot be distinguished as separate events in the reflection records (Kearey and Brooks, 1991). Horizontal resolution decreases with depth as the Fresnel zone width increases with depth, but also decreases with increasing depth of investigation due to the dispersion effects (loss of higher frequencies) discussed for vertical resolution.

Depth of penetration

Because terrain conductivities are frequency-dependent, and generally increase with increasing frequency, as discussed above, depth of penetration is largely dependent on the transmitter frequency. There is thus a tradeoff--higher frequency will limit the depth of investigation but will result in a better resolution. Fig.1 gives a relationship between different antenna frequencies and probable depth of penetration in unconsolidated sediments (Smith and Jol, 1995).

Appendix 1 (continued)

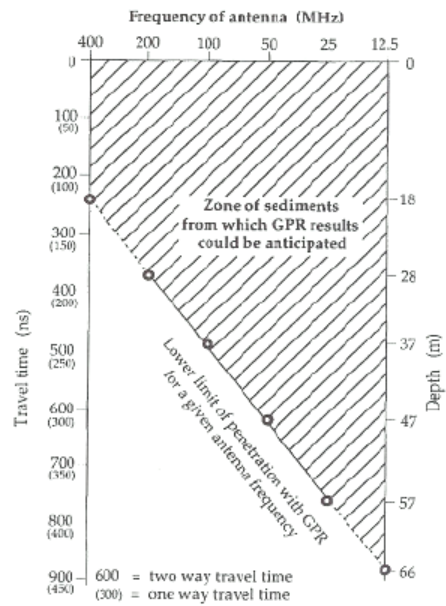


Fig.1 Comparison of different antenna frequencies with maximum probable depths of penetration in Quaternary unconsolidated sediments. Interpolation of points along best fit line indicates maximum probable depths of investigation of 66m and 18m for 12.5 MHz and 400MHz respectively (Smith and Jol, 1995).

Appendix 2

Sedimentary Environment	Reflectors	Reference
Coastal	Sand-silt contact	Jol et al, 1996
Barrier Island	Freshwater-brackish water contact	
	Peat, heavy mineral layers	Baker, 1991
Spit	Sand-mud interface, lag deposits	Van Heteren et al, 1998 Daly et al, 2002
Beach ridge	Cheneir deposit (sand-shell, sand-silt contacts)	Neal et al, 2002
Lacustrine deltas	Mud-peat contact	Jol and Smith, 1991
	Sand-peat contact	Van Heteren, 1997
	Peat-clay contact	Wood, 1990
Fluvial deposits	Silt, gravel, peat, water table	Vandenberghe and van Overmeeren, 1999
Aeolian deposits	Heavy minerals	Harari, 1996
	Sand-silt contacts, organic content, iron-oxide (goethite with high water retention capacity) content	van Dam and Schlager, 2002
	Soil lamellae	Tomer et al, 1996

Appendix 3

Layer patterns in sedimentary environments

Delineation of sedimentary features has been a prime objective of stratigraphic research. Due to its efficiency as a high-resolution subsurface exploring tool, GPR has been greatly employed to these studies. In this section, sedimentary bed geometry in some depositional settings is discussed as a prelude to the following sections that will deal with GPR response to diverse layer patterns.

Beds and laminations

A primary depositional feature of sedimentary succession is layers or stratification which is defined by mineralogical and textural differences of a layer from its adjacent ones. Classified on the basis of their morphology, sedimentary layers are designated as beds (thickness > 1cm) or laminations (thickness < 1cm). McKee and Weir (1953) proposed further subdivision of beds and laminations on the basis of their thickness.

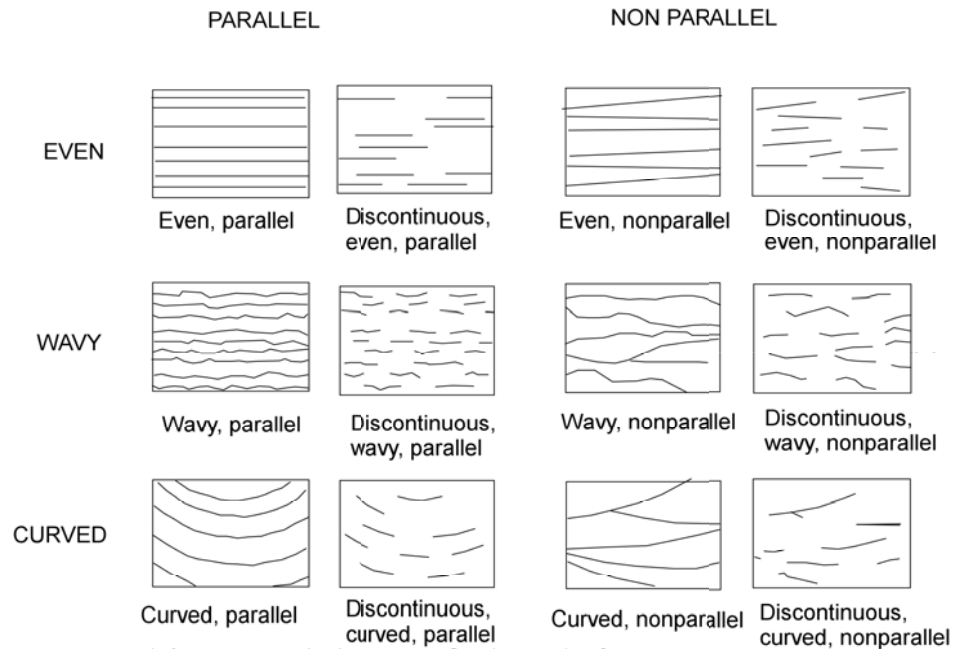
A bedded sequence itself may be composed of several beds that are defined by bedding planes. Pettijohn (1984) described the following four classes of such sequences in terms of uniformity of bed thickness and their lateral continuity:

1. “Beds equal or subequal in thickness, laterally uniform in thickness and continuous
2. Beds unequal in thickness, laterally uniform and continuous,
3. Beds unequal in thickness, laterally variable in thickness but still continuous
4. Beds unequal in thickness, laterally variable and discontinuous”.

Excluding the rarely occurring massive bed, most beds are characterized by their internal structures and their orientation. The most common internal structure within beds is laminations. These interlaminations, formed by mineralogical and textural heterogeneity of components, can be repetitive in nature. They often display either a parallelism or non-parallelism to the bounding surfaces, forming cross-laminations in the latter case. These laminations, found mostly in fine grained sands and silts, show thickness of 0.5 mm to 1.0 mm (Pettijohn, 1984). Gradational changes within a bedded sequence result in graded bedding as seen in Bouma cycle of turbidites.

Appendix 3 (continued)

Figure (from Collinson and Thompson, 1989) below shows different layer patterns encountered in sedimentary environments.



Beds and laminations in different sedimentary environments

Layer thickness is largely a function of the grain size, which in turn, is controlled by the nature of the depositional processes responsible for the formation of layered sequences. Hence it is expected that the pattern of layers deposited by different processes will exhibit some uniqueness depending on the depositional settings. An overview of the mode of occurrence of sedimentary layers is given below.

Aeolian deposits:

Sand dunes of aeolian origin are often internally characterized by sets of cross-beds. These cross-beds can be of several types e.g. tabular-planar, wedge-planar, and convex upwards, depending on their geometry and orientation. Associated with the beddings are small scale (cm

Appendix 3 (continued)

scale) internal stratifications which, in many cases, are defined by the presence of heavy minerals. Bounding surfaces, foresets, bottomsets, onlap and overlap features in aeolian sand dunes have been well documented with ground penetrating radar.

Fluvial deposits:

Cross-bedding and laminations are the dominant internal structures in fluvially deposited sandstones. Sandstone units can extend vertically for meters forming successive sequences of thick beds.

Parallel laminations, defined by the grain diameter, occurring parallel to flat bed surfaces also occur in both aqueous and aeolian sand deposits. Fine laminations in shale with thicknesses in the range of 0.5mm to 1mm occur as alternations of 1) coarse and fine grains e.g. silt and clay, 2) light and dark of organic layers, 3) calcium carbonate and silt (Pettijohn, 1984).

Glacio-lacustrine deposits:

The most significant layered sequence of glacio-lacustrine deposits is that of varves. Formed on glacial lake bottoms, varves show a typical couplet structure and can attribute to extensive laminated sequences when deposited for a long duration of time. These cyclic layers, representing seasonal changes, show very consistent layer configuration, the individual layer thicknesses varying from mm scale in most instances to cm scale and forming parallel laminations.

Coastal deposits:

Dunes and ripple marks are the primary sedimentary structures in coastal environments. Coastal sand dunes, like aeolian sand dunes, also show internal cross-stratification. Fine-scale layering is observed in beach laminations formed by alternating laminae of light (quartz and feldspar) and dark minerals (heavy minerals). Best seen in cross-sections, beach laminations are 1 to 20mm thick (Komar, 1976) and may extend laterally upto 25m (Thompson, 1937).

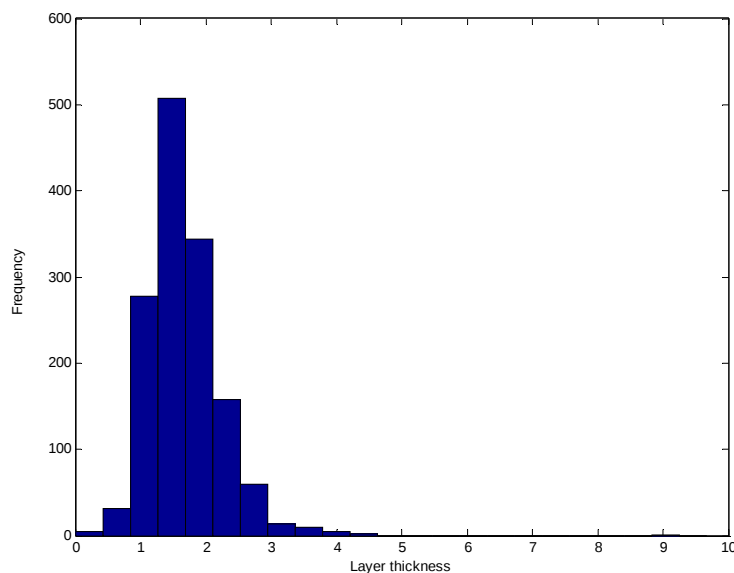
Appendix 3 (continued)

Volcaniclastic deposits:

Among the pyroclastic/volcaniclastic deposits, accumulation in layered sequence takes place in case of ash falls and base surges. Ash falls, with well-defined bedding, show a decreasing trend of bed thickness away from its source. Base-surge deposits show internal laminations and cross-laminations.

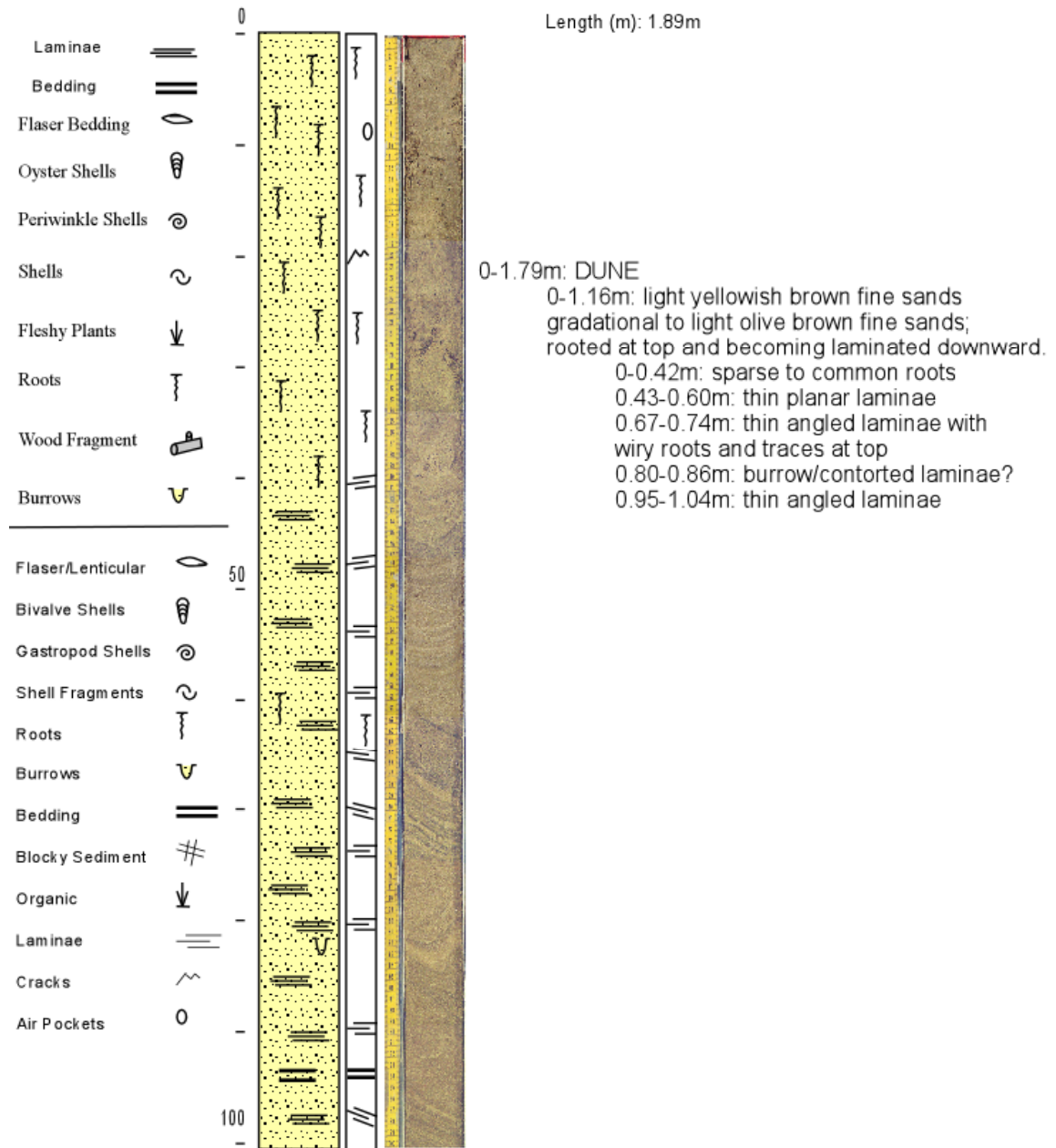
Statistical analysis of layered sedimentary sequence

Stratigraphic sequences defined by rhythmic or repetitive lithounits is not an infrequent occurrence in nature. These units follow a definite pattern of spatial distribution e.g. they may be of equivalent thicknesses or may be equally spaced. A statistical approach is often taken to describe this lithostratigraphy. Mutual dependence of layers in vertical sequences has been studied in details by applying Markov chain analysis. Statistical study of layer thickness has been sparse. In recent years varve thickness analysis and time series analysis of cyclic lithounits have been carried out. A Gaussian distribution pattern of layer thickness can be expected as in the histogram below showing frequency of varve layer thickness (mm scale) from Lake Elk (data obtained from Eric Oches (personal communication)).



Appendix 4

WI1



Above core section is equivalent to core WI1 (A).

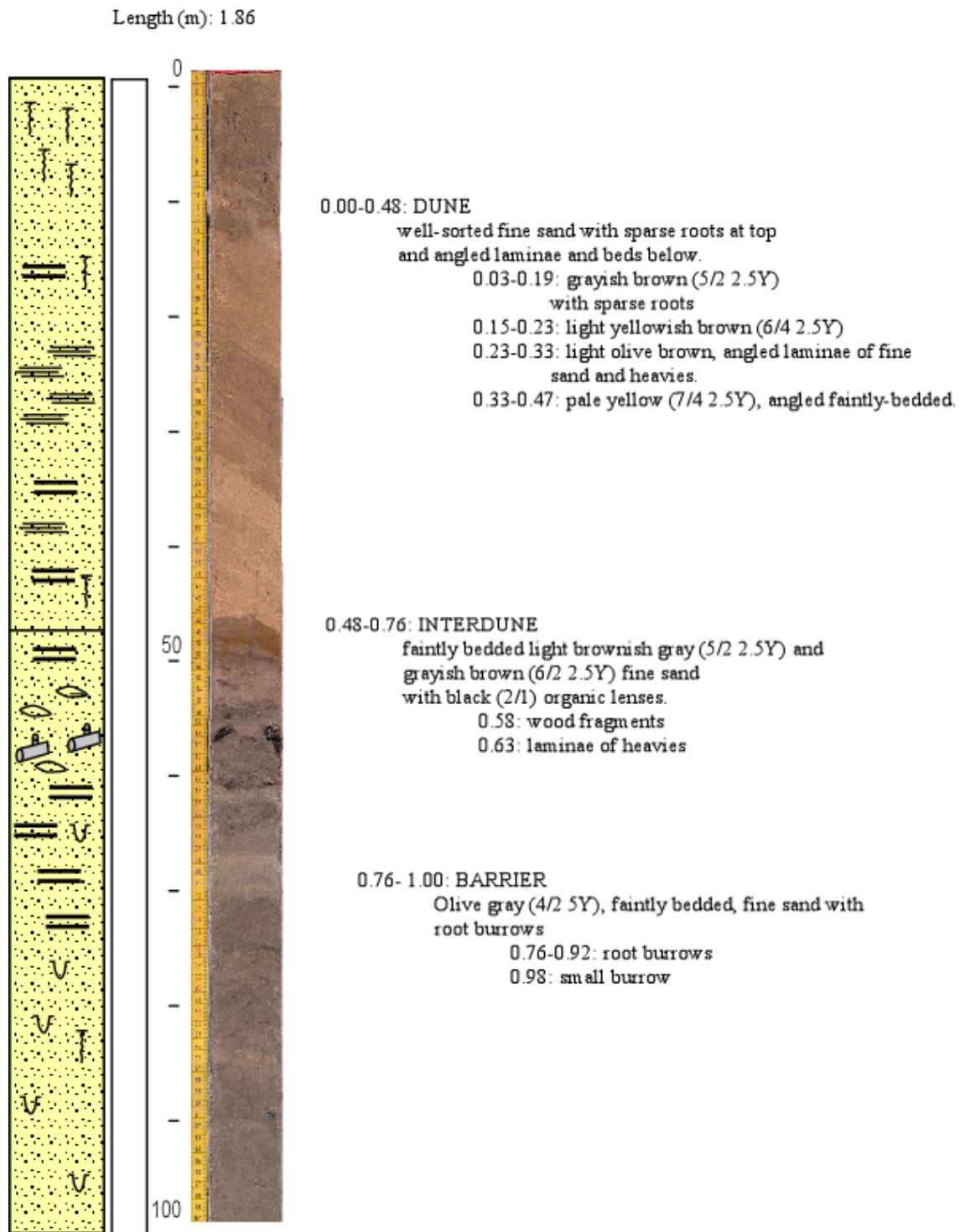
Core descriptions obtained from Eric Wright, (personal communication), Coastal Carolina University.

W11 contd.



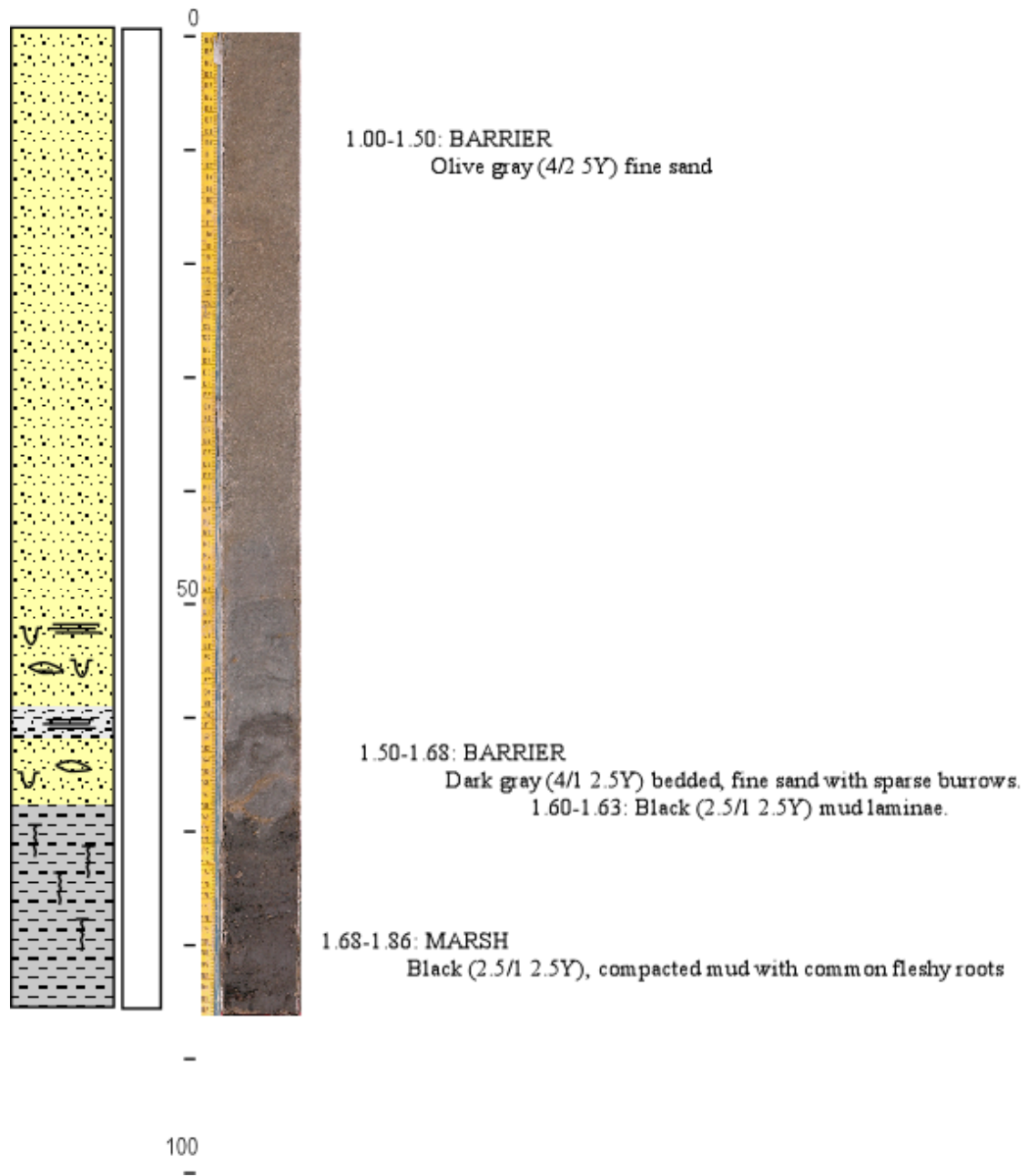
Appendix 4 (continued)

WI 1 contd.



Appendix 4 (continued)

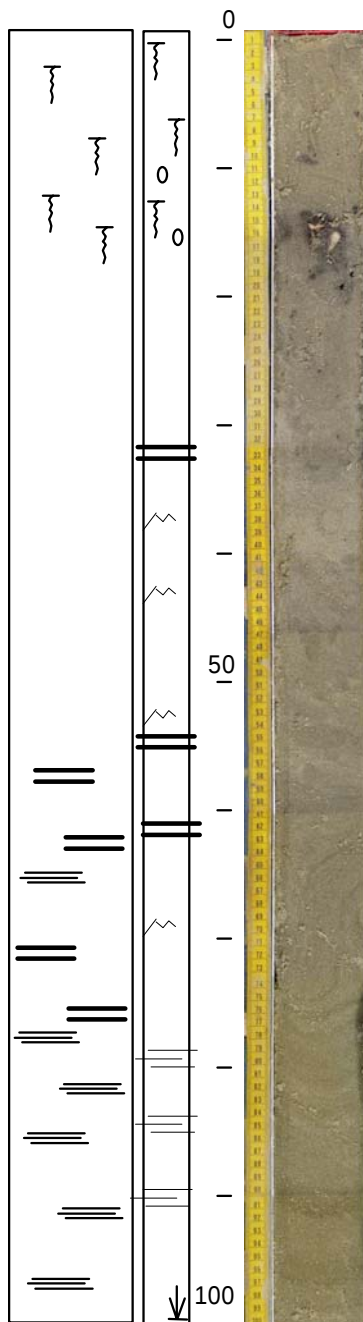
WI1 contd.



Appendix 4 (continued)

WI2

Length (m): 2.02m



0-0.34m: dark olive gray very fine sand with common very fine heavies

0-0.15m: few wiry roots/root pieces

0.15-0.18m: large fleshy roots, smaller roots

0.34-0.40m: light gray fine sand

with common very fine heavies

0.40-1.00m: dark olive gray very fine sand

with common very fine heavies

0.52m: burrow (lens) of different colored sand

0.57-0.75m: contorted bedding

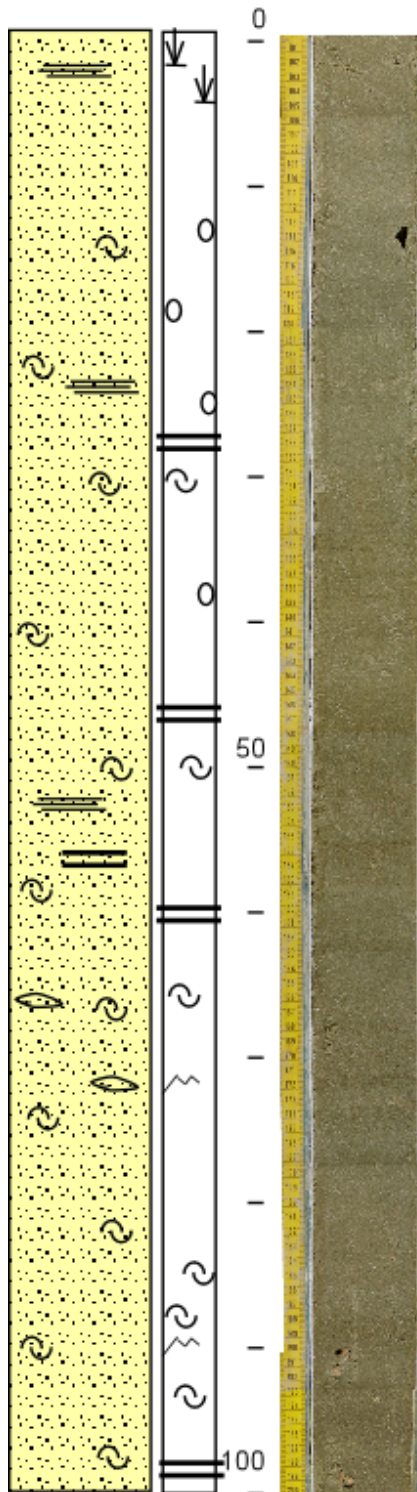
0.63m: sharply angled laminae

0.75-0.85m: prominent curved laminae

0.75-2.02m: laminae (laminations mostly faint)

0.90-0.92m: bed of heavies

Appendix 4 (continued)



1.00-2.00m: dark olive gray very fine sand transitions to fine sand (no distinct boundary)

0.75-2.02m: laminae

1.15-2.02m: very small shell pieces

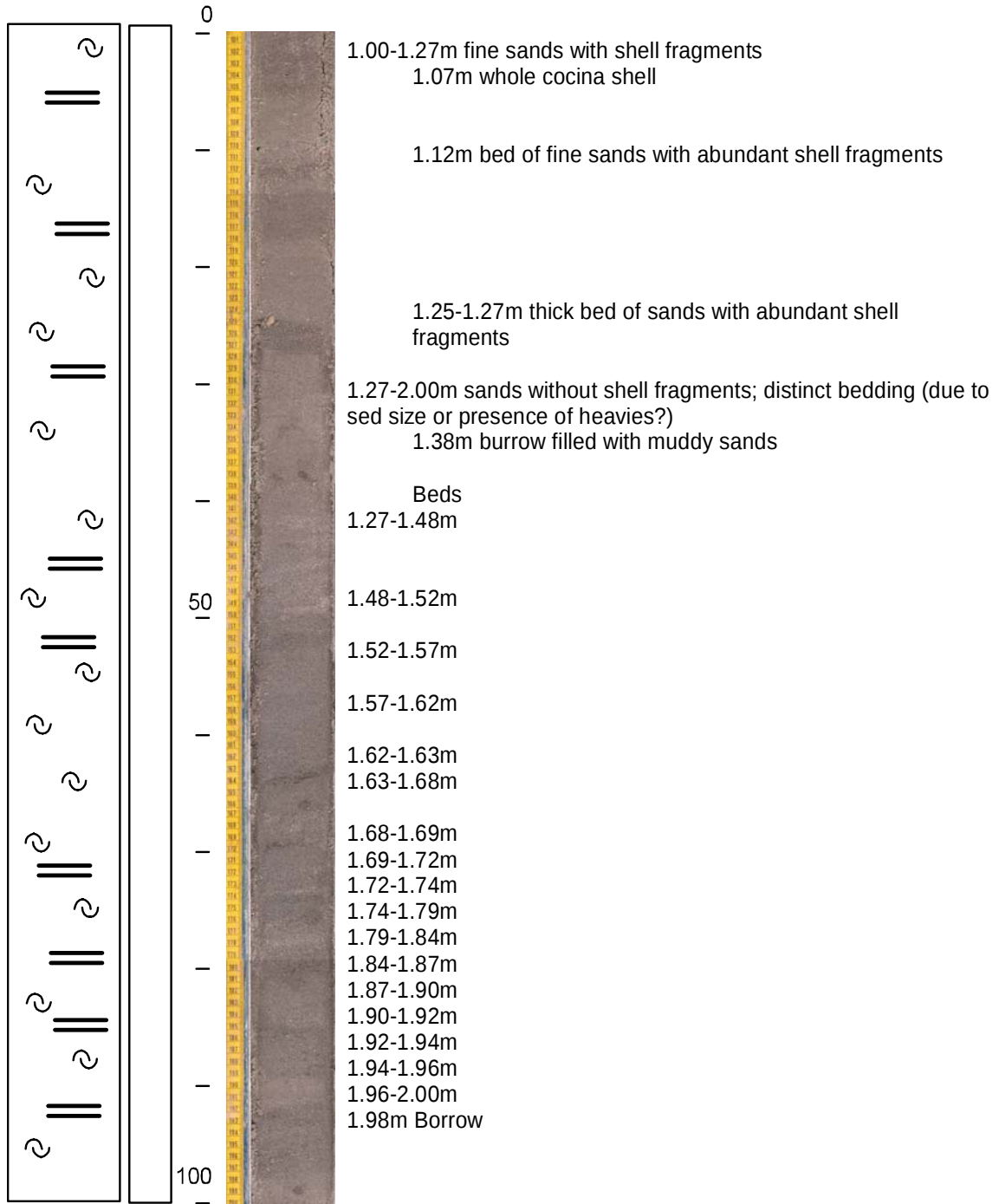
1.23m, 1.53m: shell laminae

1.55m: thick bed of heavies

1.67m, 1.71m: lens

1.83-2.02m: coarser shells, .5-1 cm shell fragments

Appendix 4 (continued)



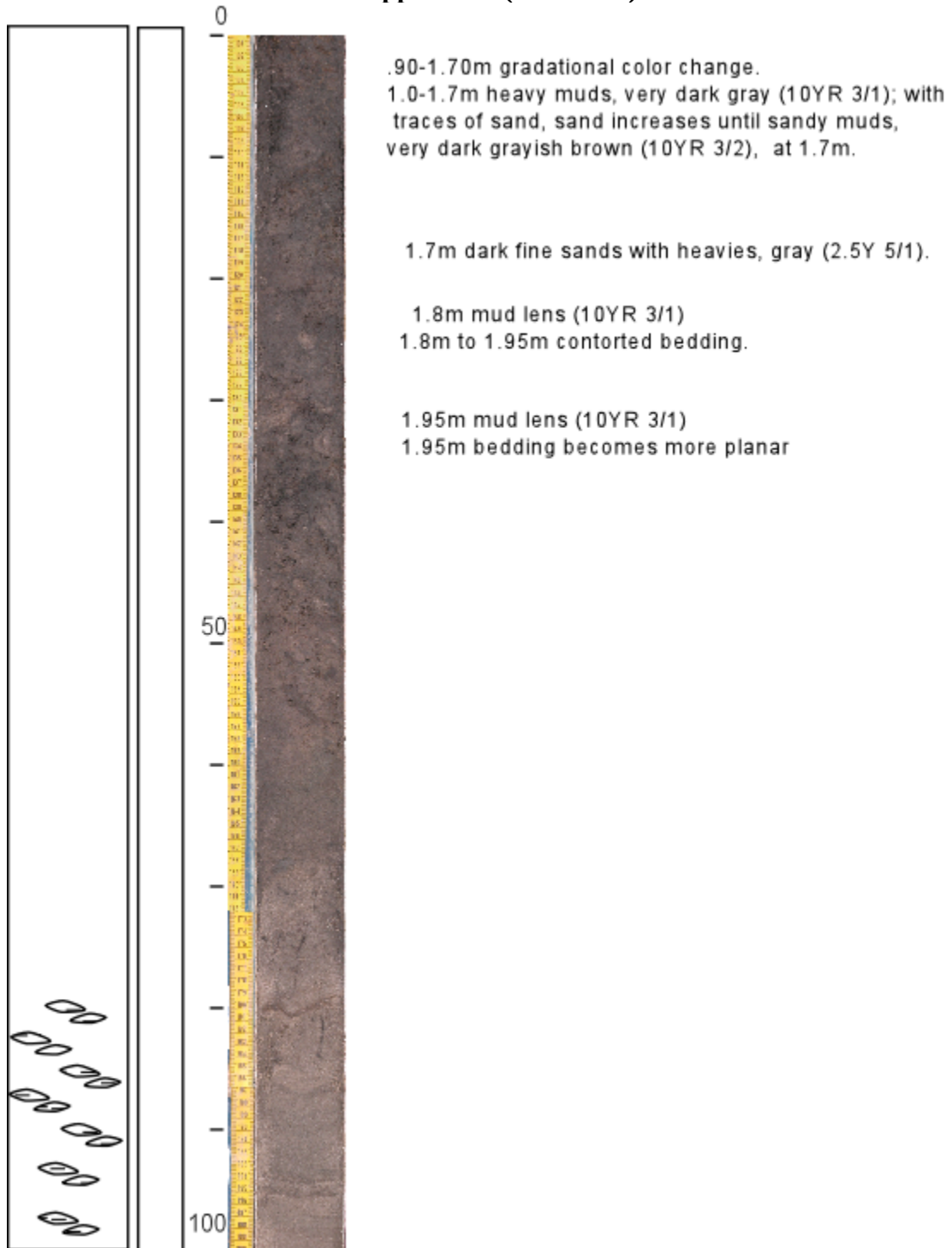
Appendix 4 (continued)



2.00-2.41m fine dark sands lots of heavies throughout
no shells or shell fragments
(distorted bedding or burrows)

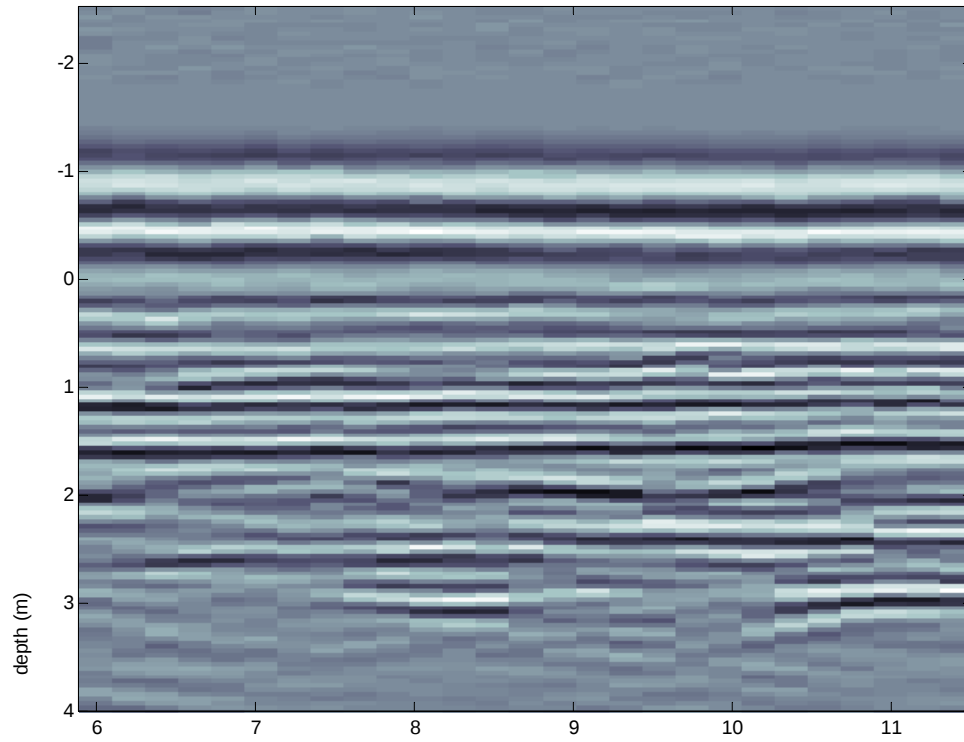
2.39-2.41m roots and filler from the surface
(if needed the core catcher seds are in a plastic bag marked
0208 wi 19, in the warehouse)

Appendix 4 (continued)



Appendix 4 (continued)

Reflection profile at site WI 2 at 200MHz

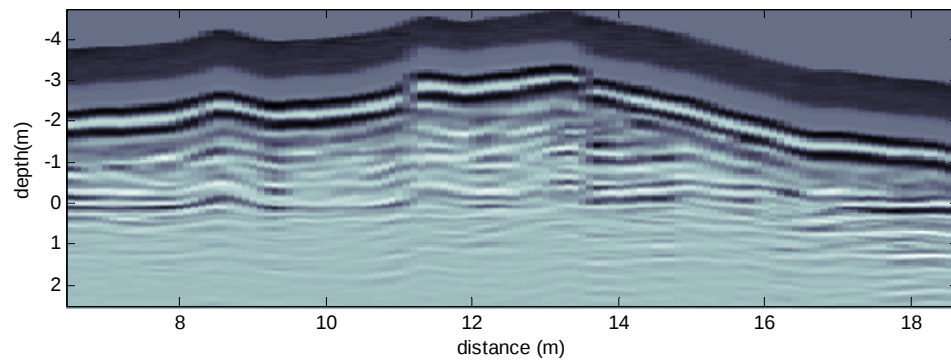


Reflection profile at site WI2 (August, 2003)

Appendix 4 (continued)

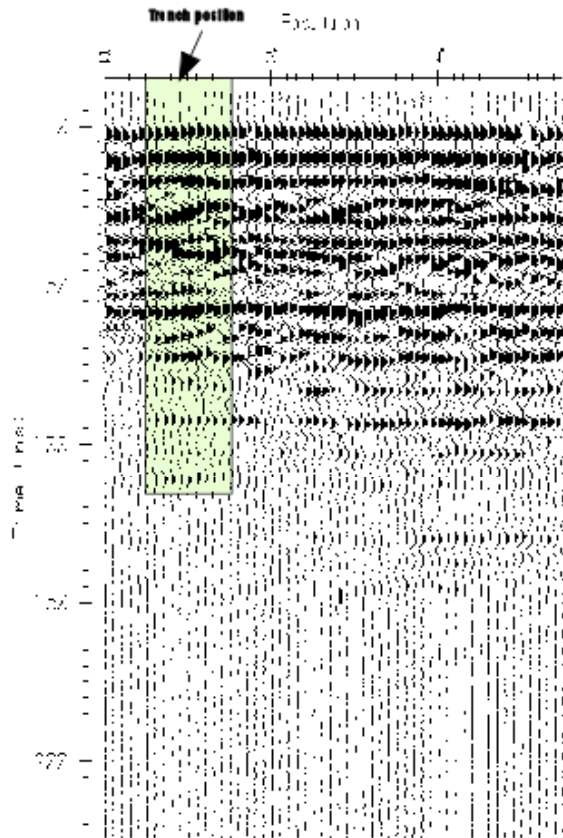


Beach lamination in dune outcrop at Waites Island.



Reflection profile of dune outcrop in Waites Island

Appendix 4 (continued)



GPR reflection profile at 200MHz
over trench in beach, Jekyll Island



Heavy mineral laminations
in trench, Jekyll Island, Georgia

Interference patterns observed in reflection profile over a heavy mineral enriched trench,
in the beach in Jekyll Island, Georgia