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Imaging Stratigraphy of Pontian Peatland, Johor Malaysia with Ground Penetrating Radar

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ABSTRACT

Peat's stratigraphic sequence contains information related to humification, hydrology, nutrient content and formation history of the bog. These are vital information needed for effective assessment of the deposit's economic potentialities and environmental impact. This research is aimed at developing a model for delineating stratigraphic sequences of Pontian Peatland with ground penetrating radar. The study involves imaging of prominent reflection layers within the subsurface of the deposit and laboratory determination of organic content of the soil samples collected at various depth intervals on the study area. Four Ground Penetrating Radar (GPR) transects were scanned at regular interval spacing. Comparison of the processed radar image with the experimental data leads to the identification of three prominent stratigraphic layers: Top soil fabric with high ash content (low organic content), hemic layer of low ash content (high organic content) and kaolinitic clay with moderate organic content. The study could therefore serve as a means of assessing and monitoring fertility level and hydrological pattern of the deposit.

Key words: Peatland, ground penetrating radar, organic content, stratigraphy, humification

INTRODUCTION

Southeast Asian peatland constitutes about one-tenth of the entire extent of the global peat resources and occupies about 60% of the tropical peatland (Global Environment Centre Secretariat, 2005). The largest deposit of peat soil in Southeast Asia is found in Indonesia. Malaysia also has significant deposit of peatland which is more extensive in the low lying poorly drained depression basin of the coastal areas. Peatland in Malaysia covers a total area of approximately 2.4 million hectares, about 8% of the total land mass of the country (Mamit, 2009). The distribution of the deposit according the country's three major regions is shown in Fig. 1.

The state of Johor has the largest deposit of the resource in peninsular Malaysia (Wetland International, 2010). The peatland of western coast of Johor is described as highly extensive with a thickness up to about 6 m mainly underlain with marine clay and silt (ASEAN/US CRMP, 1991).

Peat is a product of partial and gradual decomposition of plant materials in marshy areas under waterlogged condition (Huat *et al.*, 2009). It is an organic soil with excessively high proportion of organic matter. The formation process involves consequences of the development of an ecosystem where accumulation rate of organic matter exceeds decomposition rate (Huat *et al.*, 2011).

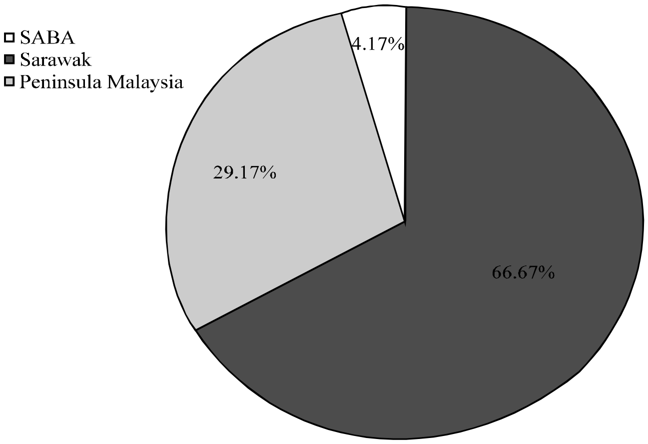

Fig. 1: Regional distribution of peat soil in Malaysia

Thus, peat production is a continuous process so long as bog plants continue to grow and die. It can therefore be distinguished from organic soil by its higher organic content.

Owing to the variation in decompositional resistance of plant materials, there is high degree of spatial variability in the rate of decomposition of peat. This variation in degree of decomposition of the accumulated organic matter is represented as stratigraphic layers in the peat core (Xuehui and Jinnming, 2009). The stratigraphic sequence is a representation of distinctive physical and chemical properties within the deposit. Although climatic factors such as temperature and precipitation also play a significant role in decomposition process (Ratnayake *et al.*, 2011), the microbial activities is principally a physicochemical transformation process that determine the spatial and temporal variation in the nutrient content of the deposit.

Various efforts were made to classify peat based on the variation in the physical and chemical composition of its constituent deposit. The most generally acceptable classification technique is based on the degree of humification known as Von post classification scale (Klavins *et al.*, 2008). The Von post scale classified peat into ten successive degrees of decomposition ranging from H1 as undecomposed to H10 as completely decomposed. The degree of decomposition usually increases with depth up to about H7 (Huat *et al.*, 2011). The American Society for testing and Material (ASTM) however, approaches peat on two bases: Degree of humification and degree of acidity. On the bases of the degree of humification, ASTM narrowed down the peat classification of the Von post scale into three categories: least decomposed fabric with more than 67% fibre content, moderately decomposed hemic with fibre content between 33-67% and highly decomposed sapric with more than 33% fibre content (ASTM D4427-07, 2007).

Fibrous peat is characterized by high organic and fibre content, low degree of humification (undecomposed) and highly acidic. The sapric peat on the other hand is highly decomposed with comparatively low water retention capacity. Hemic peat is characterized by moderate organic and fibre content (ASTM D4427-07, 2007). ASTM D4427-07 (2007) also classified peat according to pH scale into highly acidic (pH <4.5), moderately acidic (pH between 4.5 and 5.5), slightly acidic (pH between 5.5 and 7.0) and basic pH≥7).

There is however, great difference between humid temperate peat deposit upon which the above classifications are based and the tropical peat deposit. Wust *et al.* (2003) observed that various existing peat classification schemes failed to adequately characterize tropical peat deposit due to the great variability in both texture and composition of the deposits. A classification scheme uniquely for tropical organic soil was therefore developed by Wust *et al.* (2003) based on ash content with particular reference to Tasek Bera Basin peatland in the central part of Peninsular Malaysia. According to ash based classification scheme, peat is defined as organic soil with ash content below 35% and is classified into five classes as follows: Very low ash (ash content between 0-5%), low ash (ash content between 5-15%), medium ash (ash content between 15-25%), high ash (ash content 25-40%) and very high ash (ash content between 40-55%) These can correspondingly be described in terms of organic content as very high organic content (organic content between 95-100%), high organic content (organic content 85-95%), medium ash content (organic content 75-85%) and low organic content (organic content 45-60%).

In view of the relevance of peat deposit to the socioeconomic development of the communities within the study area, this study is designed to develop a model for noninvasive delineation of the stratigraphic sequence of the deposit by calibrating geophysical radar image with geotechnical data. The study involves field GPR survey and laboratory analysis for the purpose of charactering detected layers on the bases of organic content in accordance with Wust's classification. The overall goal of the study was to develop a model for the assessment of fertility level of the deposit for effective utilization and sustainable management of the resource.

MATERIALS AND METHODS

Theoretical background: Ground Penetrating Radar (GPR) is a near surface geophysical tool that record the back scattered signal of the subsurface reflected due to contrast in the electrical properties of the earth composition. The suitability of GPR as a geophysical survey tool is strongly influenced by the electrical and hydrogeological properties of the subsurface. Peat is characterized by relatively low magnitude of electrical conductivity due to the presence of highly concentrated inactive and strongly bound organic compounds. This property enables GPR to be suitable as a subsurface surveying tool on peat deposit. The electrical and hydrogeological properties of peat are functions of the effective properties of various components of the aggregate deposit. There are four main components of Southeast Asian peat namely water, air, mineral and organic contents (Wetland International, 2010). Each of these exercises significant influence on the electrical properties of the aggregate deposit. For instance radar signal velocity through a material is directly related to the apparent (measured) component of dielectric permittivity ε_0 of the material according to the equation:

$$v = \frac{C}{\sqrt{\varepsilon_0}} \tag{1}$$

where, C is the radar velocity in free space. This complex frequency-dependent electrical property of materials is a measure of polarizability of the molecular structure of materials due to the influence of external electromagnetic fields.

Being a dipolar in nature, water molecules are highly polarizable. Dielectric permittivity of water within GPR frequency range is about 81 whereas dielectric permittivity of most soils and materials within the same frequency range is between 4 and 7 (Daniels, 2004). The dielectric permittivity of air is 1. Thus the presence of water highly influenced the magnitude of this property. Based on Eq. 1 above, higher magnitude of dielectric permittivity implies lower radar signal velocity (Idi and Kamarudin, 2011). On the other hand, the presence of free-phase biogenic gas, a product of anaerobic decomposition of organic materials that are mostly trapped within the peat deposit, having same dielectric properties as air, reduces the overall magnitude of the dielectric permittivity and therefore enhances the radar signal velocity (Benedetto, 2010). Thus variation in signal velocity could be used as diagnostic for characterizing various components of the deposit.

The range of radar signal through a material medium is governed by the total path loss which is a function of the material loss, the spreading loss and the target reflection or scattering loss (Daniels, 2004). These are functions of characteristic impedance of the medium. The radar energy attenuation rate α through a medium is related to the electrical conductivity of the medium by the equation (Annan, 2001):

$$\alpha = \frac{\sqrt{\omega\mu\sigma}}{2} \tag{2}$$

where, ω is the radar signal frequency, μ is the magnetic permeability and σ the electric conductivity of the medium.

In most materials with the exception of metallic (ferromagnetic) materials, the magnitude of the magnetic permeability is close to that of free space. Thus the attenuation rate of electromagnetic waves in a medium at a given frequency depends on the electrical conductivity of the medium.

Electrical conductivity of peat deposit is greatly influenced by the chemical properties of the deposit such as the chemical composition, Cation Exchange Capacity (CEC) and acidity. These properties vary with the degree of humification. The CEC of a peat increases with increase in pH value and fibrous peat has the largest CEC (Huat *et al*., 2011). The most common exchange cations in the peat are Ca^{2+}, Mg^{3+}, Al^{3+}, K^{+}, Na^{+} $(NH_4)^{+}$. The concentration of these cations provides pathways for electrical conduction. Electrical conductivity is directly related to the concentration and mobility of the cations on the peat particles. Hence microbial activities enhance electrical conductivity which in turn increases radar signal attenuation (McGlashan *et al*., 2012).

The chemistry of the water content due to the presence of mineral ions boosts the conductivity of the pore water, causing the radar signal to be more strongly attenuated based on Eq. 2. High concentration of these exchangeable cations in fresh peat deposit enhances the dissipation of electrical energy. Thus, signal attenuation in peat deposit decreases with increase in the level of decomposition. Variation in EM wave parameters are therefore associated with changes in the electrical properties and bulk density of the medium at the stratigraphic interfaces (Gomez-Ortiz *et al*., 2010). Radar parameter variation with changes in subsurface formation was used by Pati *et al*. (2011) in interpreting GPR radargram for the sedimentary study of the Indo-Gangetic plain of the Himalayas in which concealed thrust sheet beneath the thick sediment cover of the middle Gangetic plain of India was revealed to a maximum depth of 15 m. The radar image was acquired with GSSI model 620 GPR shielded antenna at a central frequency of 100 MHz.

Data acquisition and interpretation: The study area is a plot of peatland located along Pontian-Pekan Nanas highway, near Kampung Batu Dua Puluh Sambian, at Pontian district, in the state of Johor, Malaysia. The area is geographically located at longitude 103°27'49.94"E-103°27'38.88"E and latitude 1°35'15.16"N-1°35'08.14"N (Fig. 2). The area is a portion of the coastal plain of southwestern Johor described by ASEAN/US CRMP (1991) as largely underlain with marine clay, silt and the paludal peat deposit of Holocene age.

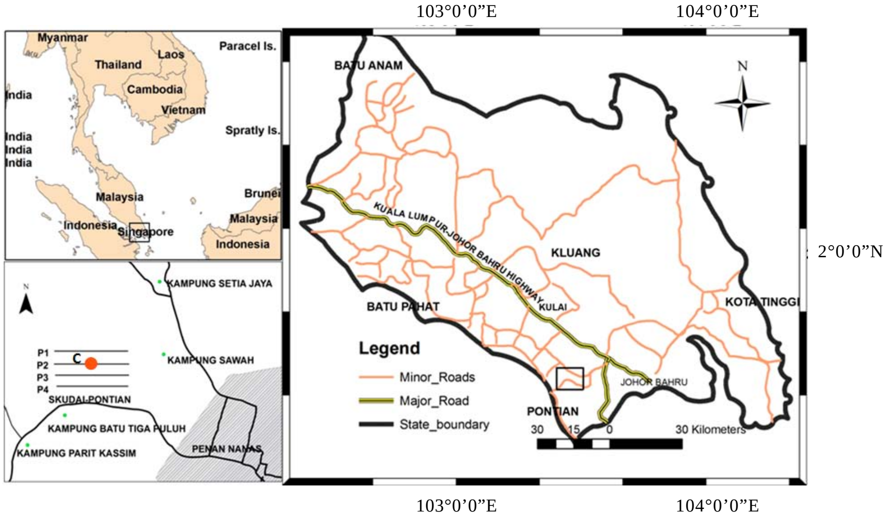

Fig. 2: Study area with the four scanned transects shown

A common offset single fold reflection profiling was used to obtain GPR cross sections along four equidistance profiles of lengths 20 m shown in Fig. 2. The profiles are 4 m apart and run in the east-west direction. The equipment used for the survey is IDS DAD fast wave radar acquisition unit at a central frequency of 200 MHz. a perpendicular polarized antenna orientation was used to scan the profile at a trace increment of 0.025.

Undisturbed peat samples were collected at depth intervals of 0.5 m from the surface to a maximum depth of 2.5 m using a 30 cm diameter cylindrical sampler. The sampled core was collected at a 10 m horizontal distance of profile 2 so that it coincides with the centre of the profile as shown in Fig. 2. The samples were carefully, sealed and parked in an appropriate container that minimize the effect of vibration during transportation.

The acquired radar image was processed with Reflexw radar image processing software (Sandmeier, 2010). The software has the advantage of compatibility with different GPR radar image formats and user-friendly interface for the import, display, processing and interpretation of radar and seismic images. The following processing steps were applied in order to enhance the signal-to-noise ratio and improve the image quality: Subtract mean (dewow), static correction, amplitude gain and background removal.

The performances of the applied processing techniques were evaluated by computing the normalized root mean square error NRMSE between the raw and the processed images. The NRMSE between a raw data f (k) and its corresponding processed data r (k) is given by Baili *et al.* (2009):

$$\text{NRMSE} = \frac{\sqrt{[f(k) - r(k)]^2}}{[f(k) - \mu f]^2} \qquad (3)$$

where, μf is the mean value of f (k) (amplitude of the raw data at a given scale level from k to N) and r (k) is the corresponding amplitude of the de-noised image. The amplitudes of the raw and

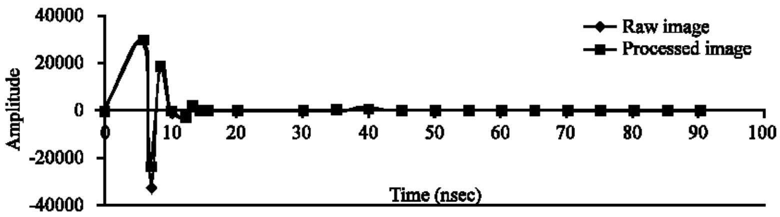

Fig. 3: Plots of the raw and correspondent processed radargrams of profile 1

Table 1: Statistics and computed normalized root-means square error of the processed radargrams

	Profile 1		Profile 2		Profile 3		Profile 4	
	Raw	Processed	Raw	Processed	Raw	Processed	Raw	Processed
Mean	128.461	185.817	128.972	189.461	129.582	189.526	131.413	210.904
SD	37.461	63.928	41.831	65.596	42.217	68.858	38.109	57.246
NRMSE	0.1908		0.5502		0.3305		1.1787	

correspondent processed radargrams were recorded with respect to each of the four profiles at grid intervals over a selected point using the wiggle plot window of the processing tool. Figure 3 is the plots of the raw and processed amplitudes with respect to profile 1.

Thus, with relatively lower values of NRMSE in all the profiles, the processing techniques are effective in preserving the quality of information in the images. The performance is however relatively higher with respect to profile 1 in which the lowest value of NRMSE is recorded. Based on the descriptive statistics of the raw and processed images shown in Table 1, the mean of the raw and corresponding processed images are fairly closed while the standard deviations are relatively small in magnitudes. These imply that the images were fairly recovered after processing. There is however slight variation in both cases with the standard deviations recording greater variation. Based on the obtained statistics however, the overall performance of the processing techniques is adequately satisfactory.

The processed radar images are shown in Fig. 4a-d. Physical observation of the collected samples shows that the top layer to a depth of 0.7 m consist of water saturated high fibre content peat overlaying the water table. The water table was encountered at a depth of 0.7 m. At 2.5 m depth, a highly saturated whitish clay, identified as kaolinite clay was encountered. Comparison of the sampled core data collected with the control radargram (Fig. 4b) shows that the top layer above the water table corresponds the region of strong signal activity that remains after time-shifting the data to ground level. Water table encountered at the depth of 0.7 m corresponds to the end of this strong signal on the radargram. This implies that the signals encountered strong attenuation at the water interface due to higher electrical conductivity of the water: soil mixture. The whitish clay layer at 2.5 m depth corresponds to a strong nearly-horizontal signal activity in the radargram. It is therefore believed that the near-horizontal activity at this point, which roughly appears in all the radargrams around the central portion, is associated with the kaolinite clay content.

Radar signal velocities were estimated using hyperbolic velocity analysis. Various reflection hyperbolas present within the radargram were fit with a mathematical velocity model and the value of the best fitting hyperbola was recorded as the respective layer velocity. Figure 5 is shows the adopted hyperbolas and velocity values with respect to profile 1.

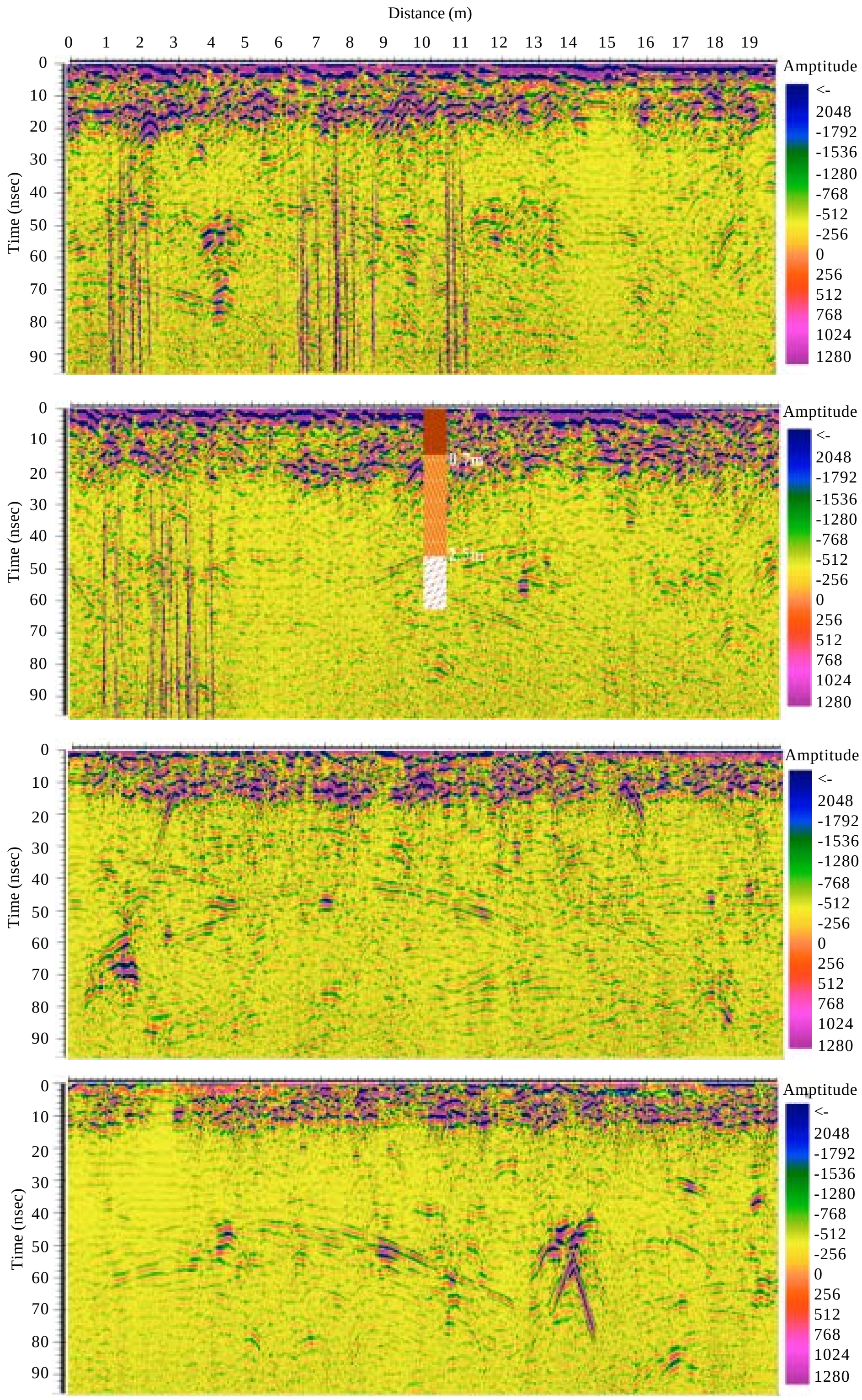

Fig. 4(a-d): Processed radar image of GPR cross section acquired along profile (a) 1, (b) 2 with sampled core data interpolated, (c) 3 and (d) 4

Variation in the subsurface stratigraphy of the peat is detected from the processed radargrams based on the strength of the phase and velocity changes at the layer interfaces. The layer interfaces in the subsurface are detectable by the virtue of significant contrast in velocity and attenuation rate of the radar signal. The interfaces are therefore picked using layer picking procedure which leads to the extraction of the depth and topography of the layer interface. Arrivals are picked based on significant variation in layer velocity and attenuation rate. The picking option utilizes the velocity information saved on the 2-D velocity adaptation file to create a cross sectional profile.

There are three layer picking options: manual, continuous and semi automatic (phase follower) pickings. After several trials with both options, it has been observed that the three could be used to complement each other for optimality. Thus semi automatic picking was initially used to trace all possible layers. Manual picking was then used to trace the most significant layer(s). Figure 6 is a window snapshot of the layer picking interface with respect to profile 1. Frequency-wave number (f-k) migration was next applied to the picked layers on the bases of the velocity information. f-k migration collapses the reflection energies to the location of their sources. These reposition events to their true spatial locations.

Laboratory determination of sampled organic content: Loss on Ignition (LOI) experiment was conducted to determine the ash content (and hence organic content) of the representative

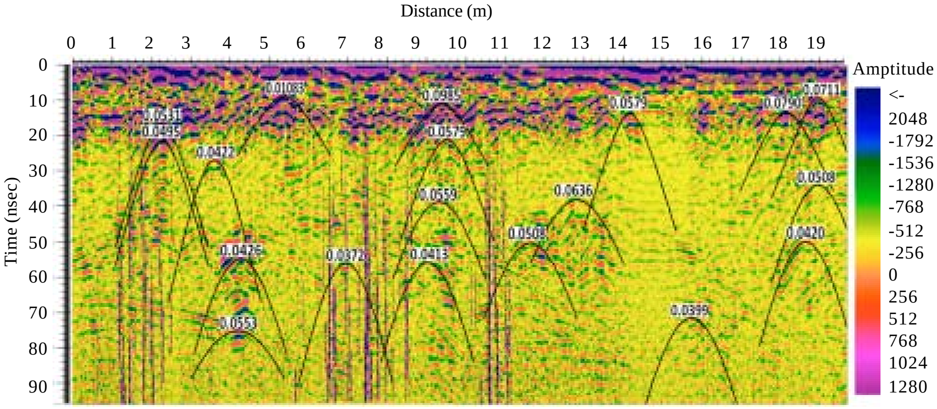

Fig. 5: Adapted reflection hyperbolas of profile 1 showing the adopted velocities (m nsec^{-1})

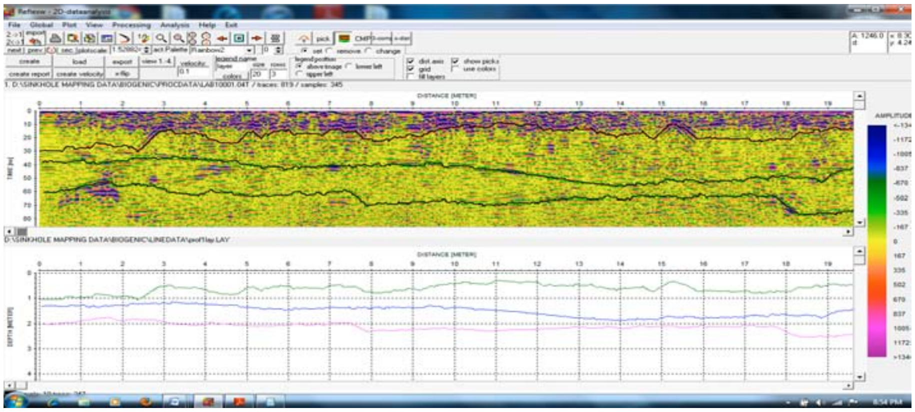

Fig. 6: Profile 1 layer picking interface

samples in order to estimate the organic content of the various detected layers. The LOI technique was used by Handayani *et al.* (2010) in estimating the organic content of soil in a study for the evaluation of the influence of tall fescue management on soil organic matter fraction. The technique was also used by Gasim *et al.* (2011) in estimating the organic content of four selected soil series in Tasik Chini, Pahang, Malaysia with the aim of analyzing their physicochemical properties.

American Society for Testing and Materials (ASTM) standard procedure for the LOI determination was used (ASTM D2974-07, 2007). According to the standard, the fractional organic content OC of peat sample is given as:

$$OC = 1 - \frac{M_a}{M_d} \tag{4}$$

where, M_a is the mass of ash remains after subjecting the sample to excessive heating and M_d is the mass of oven dried specimen. The ratio M_a/M_d is the measure of the samples' ash content. The experimental procedure involves oven drying and measurement of the mass of the oven dried specimen. The specimen was then ashed in a furnace at a temperature of 440°C to a constant mass. Two sets of specimens from each of the six depth samples were prepared for the experiment.

RESULTS

Based on the layer picking output, four stratigraphic layers were detected in all the profiles within the depth of coverage. Figure 7 shows the detected layers picked with respect to profile 1 after the application of f-k migration. The layer cross sections' are given in terms of velocity variation obtained from the hyperbolic fitting as shown in the scale bar. It has been observed that the top layer is detected as high velocity layer compared to underlying layer in all the cross sections. This could not be unrelated to the fact that the layer is associated with relatively low water content owing to its position. The layer is overlaying a relatively lower velocity zones whose upper level coincides with the water table.

The zone is made up of two layers of slightly varying signal velocity as shown. The upper layer has relatively higher signal velocity than the underlying layer in all the profiles. Below this horizon is a continuous layer of maximum velocity at all the profiles. This implies that the stratigraphic sequences are nearly consistent in all the scanned profiles. Table 2 gives the computed values of

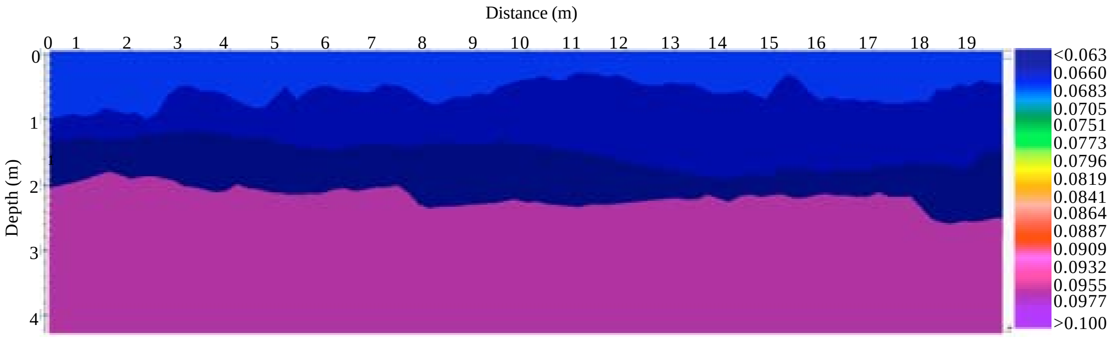

Fig. 7: Cross sectional transect showing the stratigraphic reflection events of profile 1. Four layers of varying reflection strengths are detected as shown. The second and third layers have minimal variation in signal strength

Table 2: Experimental results of the obtained ash and organic contents

Depth (m)	Ash content	Organic content
0.0	0.3334	0.6666
0.5	0.0903	0.9097
1.0	0.0228	0.9772
1.5	0.0244	0.9756
2.0	0.0122	0.9878
2.5	0.2027	0.7973

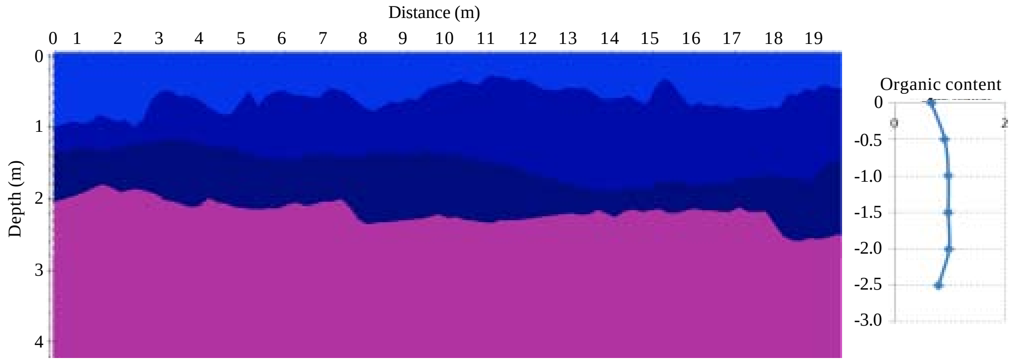

Fig. 8: Comparison of the measured organic content with detected subsurface layers

the ash and organic contents obtained from the six sampled depths. The results show that the top soil has the least organic content. The two underlying layers under waterlogged condition have nearly the same organic content with values ranging from 0.9097-0.9878. Thus there is no significant variation in the level of decomposition between the two layers. Underlying these layers is however, a significantly lower organic content layer (0.7973) which corresponds to highest velocity layer (Fig. 8) from a depth of 2.5 m at the point of coring. The layer appears in all the profiles at varying depths and extents to the maximum depth limit of the signal. The layer is also characterized by relatively lower organic content. Thus, the whitish kaolinite clay which begins at a depth of 2.5 m is associated with less fibre and water content.

DISCUSSION

Comparison of the velocity-based stratigraphic layers in all the profiles with the results of the laboratory measurement of organic content shows that the top soil, having the least organic is characterized by high ash content. The two underlying layers have nearly the same constituents they are therefore interpreted as single stratigraphic unit. The underlying layer that appears in all the profiles as high velocity layer characterized by relatively lower organic content corresponds to the kaolinite clay deposit, which is abundant in tropical peat soil (Wust *et al.*, 2002). Even though it is also organic soil, the kaolinite clay at this point is considered to be at a transition point between the peat deposit and a kaolinite clay because of its low organic and fiber content and comparatively higher signal velocity. A numerical organic content of 0.797311 (79.7311%) was recorded at this interface. This implies that the peat deposit in the entre study area has a maximum thickness of about 2.5 m.

Peatland deposit of western state of Johor was generally categorized in terms of depth, into three categories (Wetland International, 2010): Shallow (less than 1.5 m deep), moderate (1.5- 3.0 m deep) and deep (more than 3.0 m deep). Although, the deep deposit has the largest land coverage (about 62%) according to Wetland International, a maximum depth of 2.5 m recorded in this study showed that the area under study is within the moderate depth category. The findings of this study is also fairly within the thickness range of Johor state peat deposit given by ASEAN/US CRMP (1991) where the variation in the deposit's thickness was given as 6-2.5 m from the west to the south-eastern coast of the state, respectively.

According to Wust's ash content-based classification system, the top layer with an average ash content of 33.34% is classified as high ash content. The ash content reduces to about 9.0256% at a depth level of 0.5 m probably on transition to lesser ash content peat. This is in line with Wust *et al.* (2003)'s observation of upward trend increase in ash content toward the surface in a laboratory analysis of peat samples collected at Tasek Bera basin, central part of Peninsula Malaysia. A mean ash content of 0.0374 (3.74%) was recorded between the depth of 0.5-2.0 m with a standard deviation of 0.035643. The two layers within this depth range are therefore considered to be of the same constituent and interpreted as very low ash content peat. Underlain this deposit is the kaolinite organic clay soil with ash content of about 20.2689%.

Analyzing the ash classification scale relative to ASTM humification in accordance to Wust *et al.* (2003)'s comparison indicates that the top layer corresponds to fabric-to-hemic decomposition levels. This implies that the deposit at this horizon ranges from very slight to moderately decompose with a von post scale ranges from H1-H6. The results of the organic content analysis indicates that the two underlying layers within the depth range of 0.5-2.0 m are fairly homogeneous since the variation in both water content (signal velocity) and the organic content do not exceed 7.9%. The ash content range of 1.22-9.03% on the Wust's scale also corresponds to the range of fibric-to-hemic with a von post scale range of H1-H6. Based on the relative positions of the layers however, the top layer is considered fibric while the underlain layer is hemic under waterlogged condition (Wust *et al.*, 2002). The lower layer ranges from 2.5 m depths downward interpreted as kaolinite clay may not continue as peat because of the abrupt loss of organic and fiber contents with depth. The layer interface is therefore considered to have marked the end of peat deposit at the study area. This finding is fairly similar to the result of several tests conducted by Zainorabidin and Bakar (2003) which revealed that the entire Johor peat deposit is generally hemic with organic content range of 80-96% (ash content range of 4-20%). The variation between the two results could be attributed to the great spatial variability in physical properties of peat. It has been observed that peat soil is highly variable on its physical properties not only from region to region but also from point to point within a region.

The interpreted stratigraphic sequences for the four profiles are depicted in three 3-D fence plot of profiles shown in Fig. 9. Three major stratigraphic layers are identified within the depth range of the study. The first two are interpreted as fibrous and hemic peats. The layers are found to be fairly undulating but they all approximate horizontal beddings. Horizontal bedding peat deposit usually occur when peat is accumulated in still water environment (Xuehui and Jinnming, 2009). This implies that the hydrology of the environment was initially characterized by still water. Being least decomposed, the upper layer also has the highest concentration of cation exchange capacity

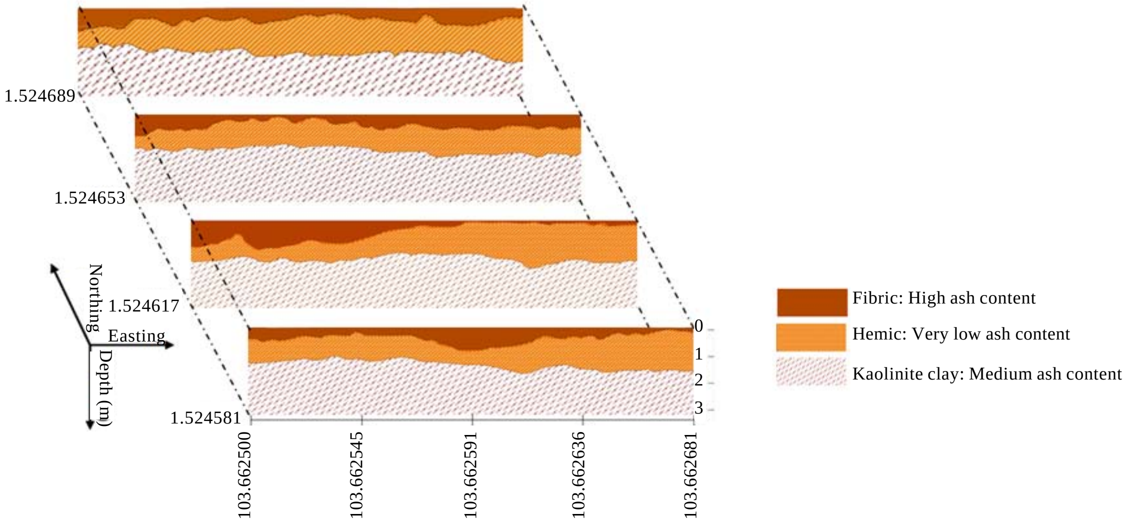

Fig. 9: 3-D fence plot of the stratigraphic sequence of the four profiles based on the interpretation of the reflection events. All the four profiles show high ash content fabric peat overlaying lower ash content hemic peat. Beneath is the kaolinite clay

(Huat *et al.*, 2011) and is therefore the richest in acidity and nutrient content. Thus stratigraphic and humification data provide vital information needed for effective utilization and management of peat resources.

CONCLUSION

Stratigraphic sequences of peat deposit is controlled by a number of factors such as climate and availability of nutrients. Availability of nutrients on one hand depends on the type and part of the peat-forming plant material at given location. Plant species differ in decomposition rate depending on the physiological properties of the species. On the other hand, different parts of plant materials also decompose at different rate due to the variation in fiber content. These factors inhibit linear decomposition of undisturbed peat deposit with depth especially in a larger peatland. Thus each of the stratigraphic unit is considered a unique horizon of nearly the same constituent and interpreted as stratigraphic layers of varying levels of humification and nutrient content based on the laboratory analysis of core samples collected within the depth range.

The stratigraphic sequence of peat is similar to sedimentary series of earth layers in which each layer provides information about the prevailing condition of the deposit at the time of its formation. Qualitative interpretation of the detected layers in terms of subsurface composition however requires experimental calibration. In this study, we developed the calibration data experimentally and used it to interpret GPR radar images. The study therefore provides a model for the qualitative interpretation of the southwest Malaysian peatland on the bases of the organic content of the detected layers. Thus, GPR could serve as a tool for the monitoring and assessment of nutrient level and hydrological history of the peat deposit. It is therefore hoped that the results of this study will serve as a reference for surface radar surveying of the peatland for the effective monitoring of the fertility level and hydrological pattern of the deposit.

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