The Images of Subsurface Tertiary – Quartenary Deposits Based on Ground Penetrating Radar Records of Subi Kecil Island Coast, Natuna District, Riau Archipelago Province

Pencitraan Endapan Bawah Permukaan Tersier – Kuarter Berdasarkan Rekaman Ground Penetrating Radar, Pantai Pulau Subi Kecil, Kabupaten Natuna Provinsi Kepulauan Riau

Kris Budiono

Marine Geological Institute, Jl. Dr. Junjunan No. 236, Bandung, 40174

Email : kris_budiono@yahoo.com

(Received 31 January 2013; in revised form 29 April 2013; accepted 17 May 2013)

ABSTRACT: Subsurface Tertiary to Quaternary deposits from coast of Subi Kecil Island, Natuna Distric, Riau Archipelago Province, were imaged with Ground Penetrating Radar (GPR). The GPR survey was carried out by using GSSI Surveyor III/20 with 270 MHz and 40 MHz of 3200 MLF antennas. GPR data were processed using software GSSI's RADAN for Windows NT™. The interpretation were done by using the radar facies as a groups of radar reflections. The GPR images of study area can be recoqnized in to several facies such as parallel, sub parallel, chaotic, oblique, mound and reflection-free. The calibration were done with geological data along the coast (cliff and outcrop). Unit A is the uppermost layer which is characterized by continous to non continous pararel reflection, srong reflector and high amplitude and is interpreted as alluvium deposits. Below the unit A is unit B which is characterized by non continous sub parallel, chaotic and mound reflector, strong reflector and high amplitude.

Unit C and D (Mio-Oligocene) are overlain by unit A and B include chaotic, reflection-free and, locally, discontinuous parallel, oblique mound reflector radar facies, correlatable at the cliff face to massive sands, mostly representing near coastal deposits. These units are bounded by continuous, high amplitude reflections that can be easily correlatable throughout the GPR profiles, serving as important stratigraphic markers. The GPR survey may improve the reconstruction of the depositional environments through the recognition of massive and unconsolidated sand deposits within unit A and B (Holocene). The stratigraphic framework was also improved through the recognition of the discontinuity surface between Units C and D.

Keywords: radar facies, stratigraphy, Tertiary to Quatenary, Subi Kecil Island

ABSTRAK : *Pencitraan endapan bawah permukaan Tersier sampai Kuarter di pantai Pulau Subi Kecil, Natuna, Propinsi Riau Kepulauan, telah dilakukan dengan "Ground Penetrating Radar (GPR). Survey GPR dilakukan menggunakan SIR 20 GSSI dengan antenna 200 MHz, 40 MHz da MLF 3200. Data GPR diproses mengunakan perangkat lunak Radan GSSI untuk Window NT™. Citra Radar di daerah penelitian dapat dibagi menjadi reflektor paralel, sub paralel, chaotik, oblik, undulasi dan bebas refleksi. Kalibrasi telah dilakukan dengan kondisi geologi sepanjang pantai (tebing dan singkapan batuan). Unit A merupakan lapisan paling atas, dicirikan oleh reflektor parallel yang menerus dan tidak menerus, reflektor kuat, amplitudo tinggi dan ditafsirkan sebagai endapan alluvium. Di bawah unit A adalah unit B yang dicirikan oleh reflektor sub paralel yang menerus sampai tidak menerus, chaotic, hiperbolik, dengan reflektor kuat dan amplitudo tinggi. Unit C dan D (Mio-Oligosen) ditutupi oleh unit B yang dicirikan oleh fasies reflektor chaotic, bebas reflektor, dan secara lokal pararel tidak menerus, miring dan hiperbolik, dapat dikorelasikan dengan pasir padat pada tebing sebagai endapan dekat pantai. Citra GPR memperlihatkan rekonstruksi lingkungan pengendapan melalui pengenalan pasir padat dan pasir lepas pada unit A dan B (Holosen). Kerangka stratigrafi akan lebih baik melalui pengenalan ketidak menerusan lapisan antara unit C dan D.*

Kata kunci: *fasies radar, stratigrafi, Tersier sampai Kuarter, Pulau Subi Kecil*

INTRODUCTION

The application of ground penetrating radar (GPR) is mostly focused on environmental, groundwater and geotechnical studies (Rosssetti 2001, Beres and Haeni, 1991). Recently, many publications have discussed usefulness of GPR in sedimentary facies and stratigraphic analysis (Jol and Bristow, 2003; Heteren et al;1998 Rossetti, 2001).

Administrativelly the study area is located at Subi Kecil Island, Natuna Distric, Riau Archipelago Province and geographically between 108.822^o – 108.895^o E, and 2.996$^{o\,-}$ 3.069^o N (Figure 1)

The main purpose of the study is to collect and to analysis of the GPR image performed in shallow subsurface Tertiary and Quartenary deposits from coast of Subi Kecil Island.

Generally, the geological condition of study area is a part of Natuna arch which is located between West and East Natuna Basins. The Subi waters and adjacent area are shallow marine with the maximum depth about 70 meters and is characterized by coral reef.

The Subi Islands consist of Subi Besar and Subi Kecil Islands that are separated by Nasi Strait (150 m width). The area of Subi Besar is 129 km^2 where as Subi Kecil Island is about 11 km^2. In general, the mophology of Subi Besar Island is characerized by hilly undulation with elevation between 40 – 70 m, where as Subi Kecil Island has elevation between 0 – 70 m above sea level.

Based on the geological map of South Natuna Sheet (Harahap et al, 1995), the geology of survey area can be explained as folow (Figure 2) :

Alluvium deposits

Alluvium deposits are dominated by coastal deposits and coral reef. Coastal deposits consist of sand, gravel and plant remains that are distributed in the Subi Besar, Subi Kecil, Panjang and Serasan Islands. Coral reef is characterized by reef limestone which are still growing or eroded and talus. They are mainly found in the island of Tebeian Besar and small islands on the north east of Subi Kecil Island.

Teraya Formation

Teraya Formation is characterized by interbeded medium grained calcareous and fine grained non calcareous sandstones, brownish to greenish grey, 10 to 20 cm in beds, composed of quartz, chert, muscovite, carbonaceous material and pyrite. The foraminifera fosils such as *Cibicides* sp, *Eponides* sp, *Astegerina* sp, *Elpidium* sp and *Nonionella* sp were also found. Most of this sedimentary rock is classified as shallow water

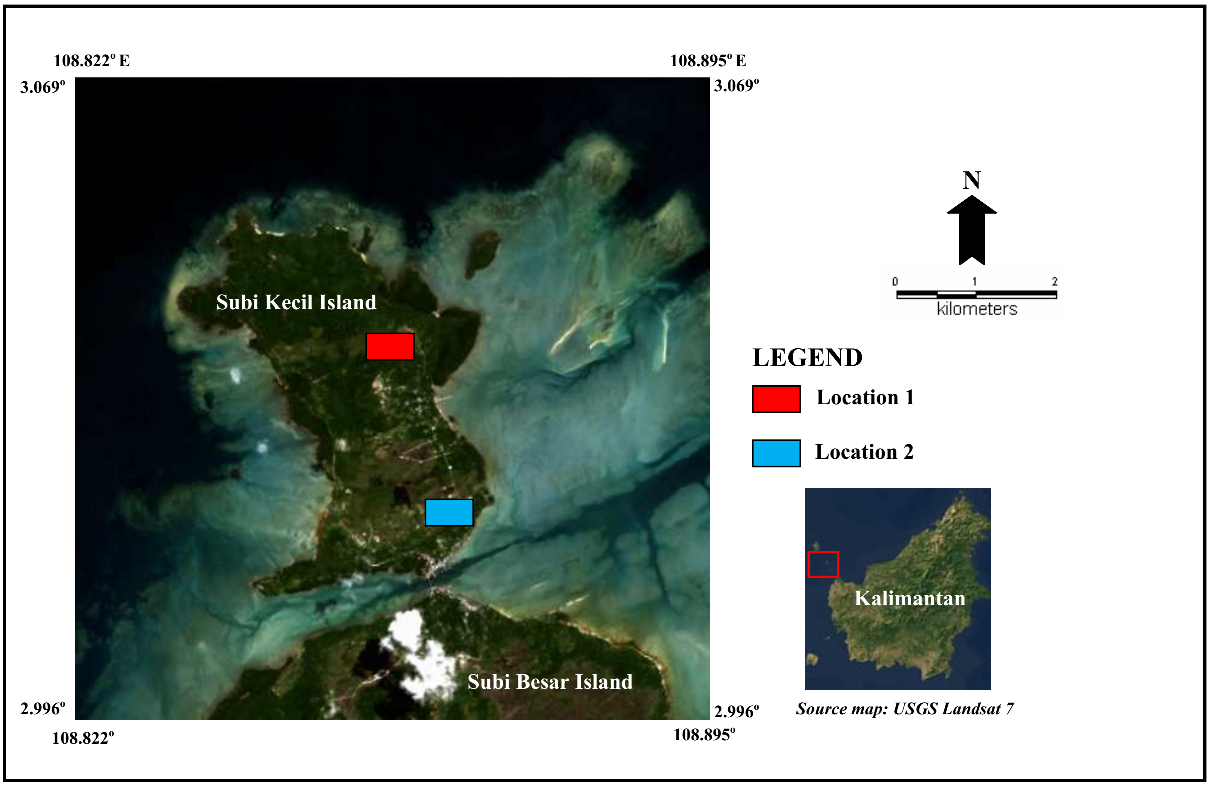

Figure 1. Location of GPR survey

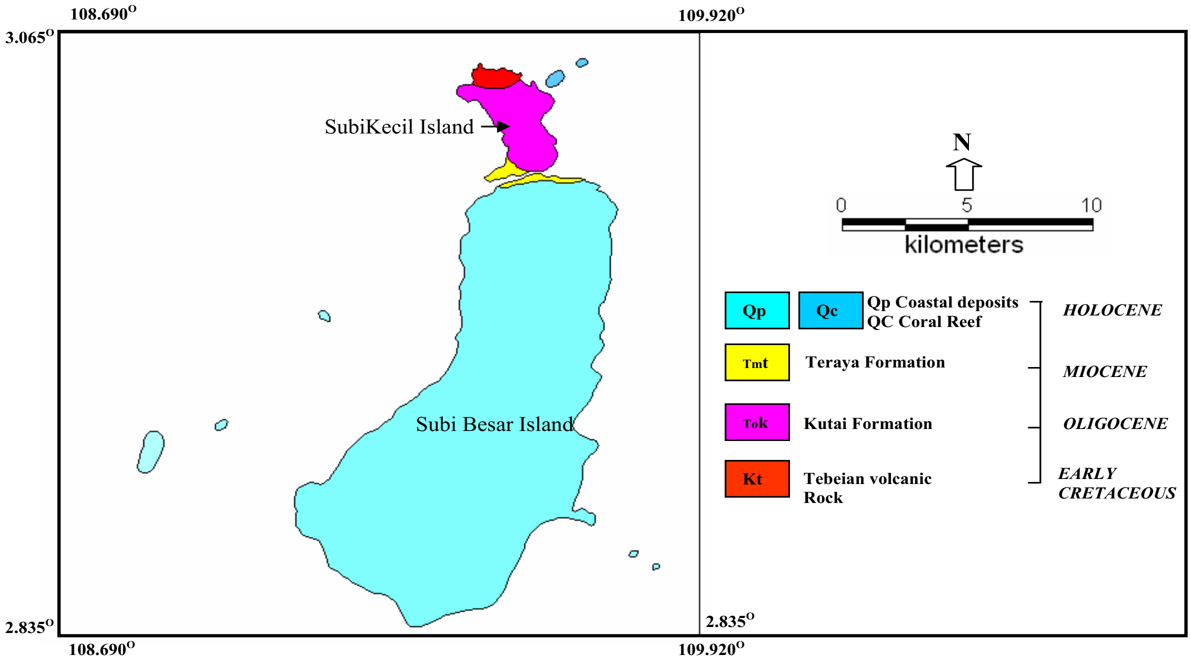

Figure 2. Geological map of Subi Island, Natuna (modified from Harahap et al, 1995)

environment deposition. It was reported that there is no key fossil for the age in this formation. The distribution of this formation is in the north coast of Subi Besar Island and the south coast of Subi Kecil Island. They overly conformably the Kutai Formation. The formation is corelated to the Miocene Arang Formation in the East Natuna and West Natuna Basins.

Kutai Formation

Kutai Formation is dominated by river deposit which is characterized by poor to moderately bedded and greenish grey to yellowish grey. This formation consists of conglomerate and sandstone. Conglomerate is characterized by moderately sorted, well rounded, comprise of chert, granite, silicified rock, chalsedon, quartz, kaolinite clay, with a sand matrix. Sandstone is characterized by medium to coarse grained, well sorted, composition same as conglomerate with matrix of kaolinitic clay. The distribution is in the western part of Serasan and Subi Kecil Islands. They overly unconformably the Tebeian Volcanics and Serasan Pluton. This formation is might be correlated to the Oligocene Gabus Formation in the East Natuna and West Natuna Basins.

Tebeian Volcanic Rock

Tebeian volcanic rocks consit of dacite and andesite holocrystaline, porphyritic, locally altered to chlorite, sericite and epidote.The volcanic forms dyke and extrusion, a subduction related forming the magmatic belt as Serasan Pluton. The distribution is in the islands of Subi Kecil, Tebeian, Nangka and Perayun. The Tebeian volcanic rock intrudes Balau Formation and overlain unconformably by Kutai Formation. The age of this volcanic is definitely unkown.

METHODS

The geological and geophysical survey of Subi Kecil Island was done and funded by Marine Geological Institute. The surface geological setting of the study area was observed through the recognition of the rock outcroup which is exposed along the coast line and coastal cliff. The sub surface geology of the study area was recorded by Geophysical Survey Systems Inc SIR- 20 Ground Penetrating Radar (GPR). The GPR operation was arranged according to pre-exiting flat area and the line was done pararel and perpendicular to the coast line.

In many contamination problems, the sub bottom soil, and stratigraphic sub surface information is sparse and drill core, outcrop description only gives a limited geometry picture of inhomogeneties (Saarenketo and Scullion, 2000). The method of GPR is a promising tool for resolving changes of physical properties in burial stratigraphic condition at the scale of natural inhomogeneties arising from changing physical and engineering properties composition (Carrivick, 2007). The GPR record demonstrates that reflection image of the basic geometry forms in subsurface geological

Fugure 3.Operating of Ground Penetrating Radar with 3200 MLF antenna

condition might be distinguished (Budiono at all, 1996).

The GPR uses antennas placed near or in contact with the surface of the ground to probe the shallow subsurface (Figure 3).

The technique is known as Electromagnetic Subsurface Profiling (ESP) and is the electrical analog of seismic sub-bottom profiling technique used in marine geology.

The techniques are also based on the principle that high-frequency of electromagnetic waves may be reflected at boundaries separating heterogeneous regions of the subsurface. They are best suited for high-resolution geophysical and subsurface concrete block investigation. The system is capable of detecting and graphically displaying subsurface interface in shallow depth (Beres and Haeni, 1991).

The system is also capable of identifying subsurface materials by analyzing the reflected pulses. The shapes of these pulses depend only on the effective dielectric constant and conductivity of the material. Ranges of values of dielectric constant and conductivity for different materials are taken from the literature (Budiono, 1999).

A reflection may also be generated by a gradual change in dielectric constant caused by variable moist, dry and very dry subsurface lithology. Capillary force produce a continous change is moisture content over a thin depth interval for sediment or soil. If the two types of reflectors-one a transition zone and the other a layer boundary are closely spaced, then their reflections may be superimposed in a radar section. Neither feature will be easily recognized, and interpretation would be difficult (Rossetti and Goes, 2001).

The GPR system is composed of video pulse transmitter, a receiver and an antenna and note boks computer.

Once an area for subsurface investigation has been established, the lightweight antenna unit is towed over the ground by hand. A portion of the radar signals that have been reflected from the interface of surface and subsurface objects is received by the antenna.

Radar reflections from the interface are governed by the differential in the dielectric constant and conductivity of the materials (Van Dam and Schlager, 2000)

The system receives reflections of these pulses from interfaces between materials that have different electrical properties. This digital data is stored on computer and is printed out graphically after area has been scanned, processes and analysis (Beres and Haeni, 1991).

The equipment which was used are: GSSI SIR-20, Note book and GSSI Software Radan, Transducer 400 MHz, 270 MHz and Multy Frequency 3200 MLF.

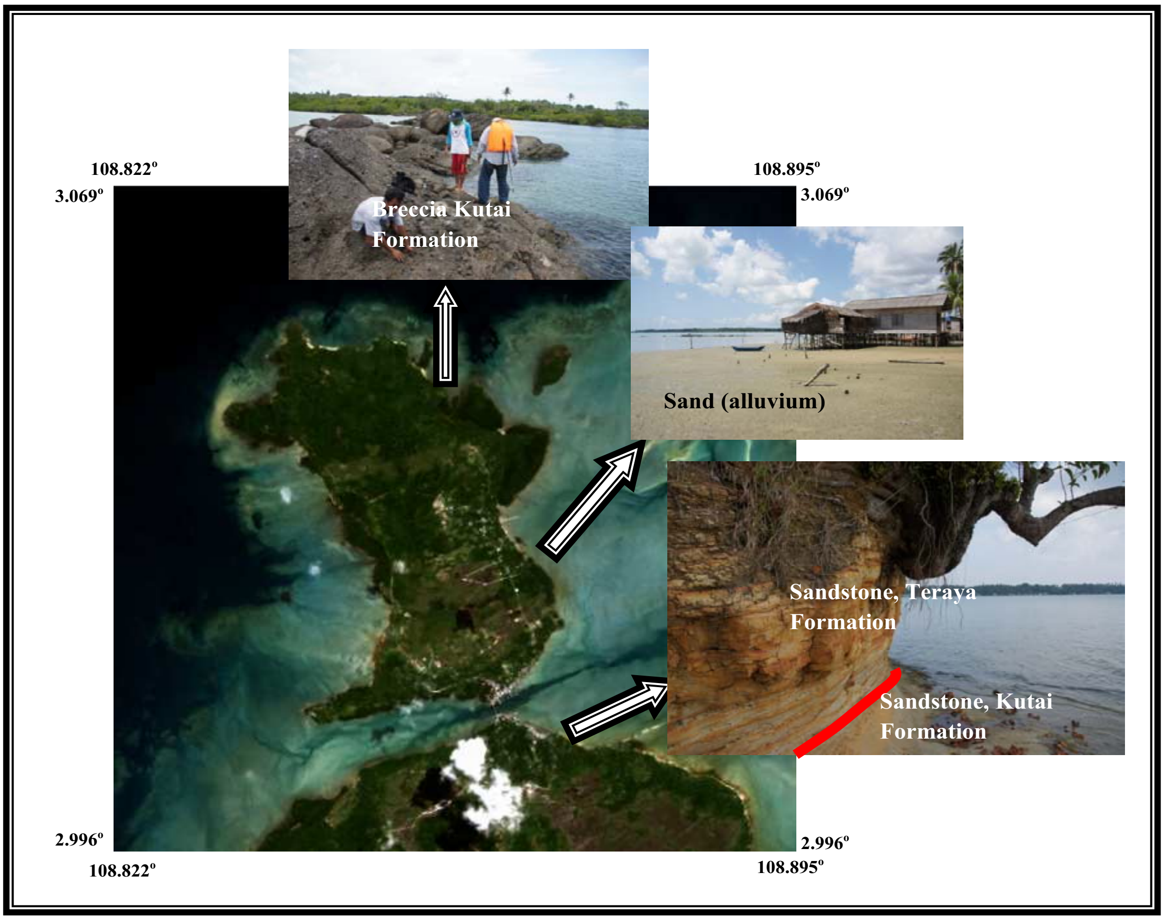

Figure 4. The exposed rock around the Subi Kecil Island

Processing of GPR data involves some modification that can be more easily visualized and interpreted. Since data obtained from GPR surveys is similar to data obtained from seismic reflection surveys, many of the same techniques used to process seismic data can be used to process GPR data. In many cases, very little processing of the data is required to locate the target of interest .Normally, the data processing involves the following steps: (Beres and Haeni, 1991).

Converting the data to a usable digital format, removal or minimization of direct and air waves from the data, amplitude, gain, filtering the data, migration, decompulation, and stacking.In many cases, it is possible to use the results from a GPR survey with very little processing. In these cases, the only adjustments that need to be made are to convert the data to a usable digital format, to make gain adjustments to the data, and to determine the depth to each reflector (such as the water table) in the subsurface (Johnson, 1987).

The interpretation of GPR-image in this paper is based on correlation of GPR reflector with the rock outcroup which is exposed along the coast line and cliff.

The GPR signal can be affected by rock type and pore-water/clay content and chemistry, and its facies interpretation relies on the principles of seismic stratigraphy, which mostly include the identification of reflection configuration and external geometry (Rossetti and Goes, 2001; Heteren et al, 1998; Beres and Haeni, 1991).

Radar stratigraphic procedure identifies radar sequences which are defined by packeges genetically related strata bounded by unconformities and their correlative conformities, as well as to analyze the sedimentary facies and facies architecture in order to understand the lithology, depositional environments and stratigraphic evolution (Rossetti and Goes, 2001).

RESULTS

The interpretation of Ground Penetrating Radar image was correlated with the lithology that distributed along the coast and cliff of Subi Kecil Island.

Surface Lithology

The lithology which is exposed around the study area can be summarized as follow:

Sand and clay

Sand and clay can be found along the east coast and characterized by grey to yellow, fine to coarse grained, consists of shell remains, unconsolidated sediments that are classified as Quartenary alluvium deposit (Figure 4)

Sandstone and breccias

Sandstone and breccias are also very good exposure at south and northern coasts of Subi Kecil Island. Sandstone are grey to yellowish grey coloured, fine to medium grained, consists of quartz and feldspar mineral, massive and consolidated density, medium to high hardness.

Breccia has a component which derived from rock fragments of sandstone, silica, basalt, sub angular to angular form and deposited at the northern part of the coast.

Based on the correlation with the geological map of Subi Kecil Island, these lithology are parts of Teraya and Kutai Formations.

Analysis of Radar Facies

The procedure to analize the radar facies is similar to the sedimentological facies analysis. The radar facies is resulted by analizing the GPR data set, which is consisted in the identification of individual radar facies. These facies were grouped into radar unit and will resulted the interpretation of depositional environments (Budiono at all, 1996).

Based on distinctive reflection configuration, there are three groups of radar facies which can be recognized in study area and the description of each group can be explained as follow:

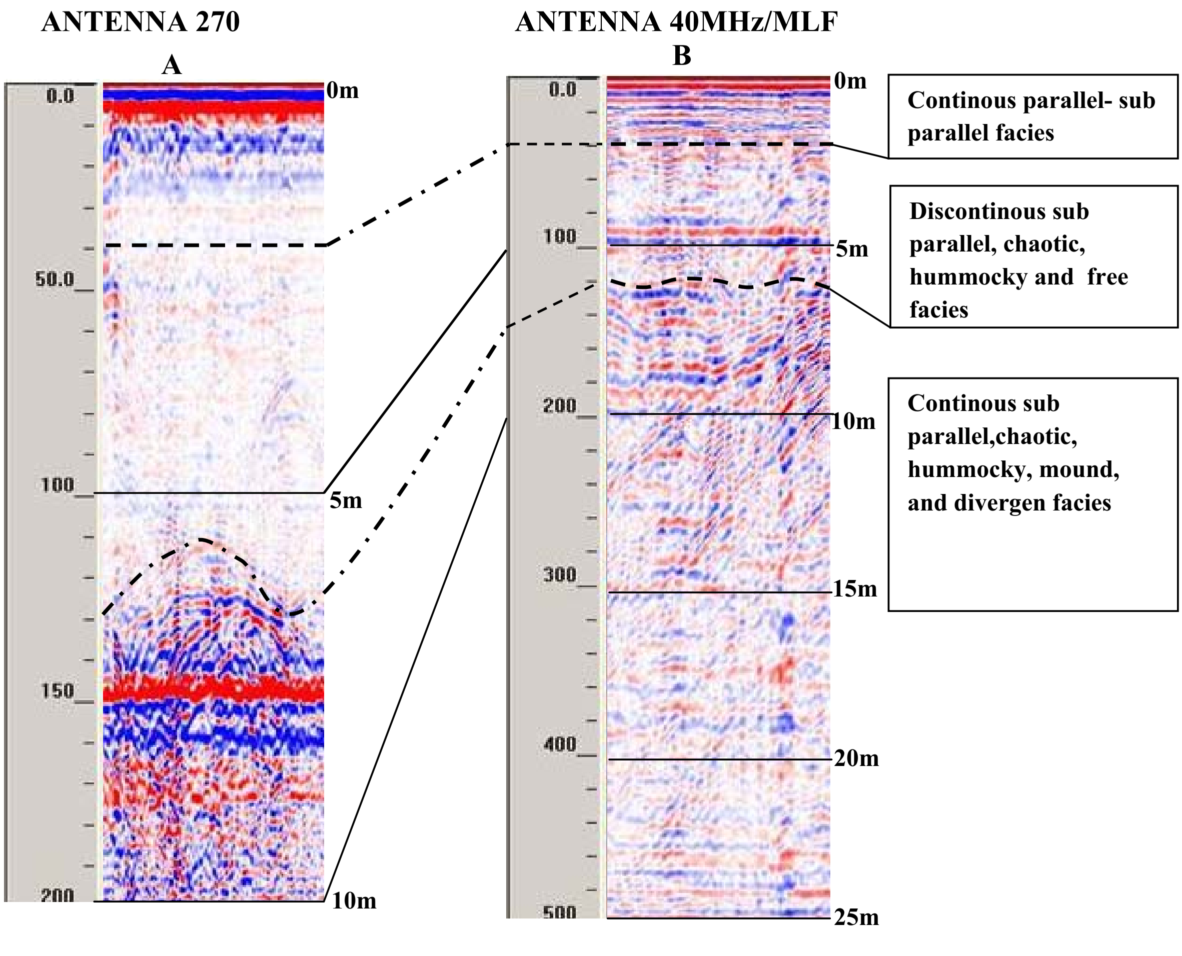

Figure 5. The group of radar facies (A. reflector by antenna 270 MHz., B. reflector by antenna 40MHz/MLF 3200)

Continous parallel – sub parallel facies

This radar facies is characterized by closely-spaced, continous, strong reflector, high-amplitude (Figure 5A and B) with a contant thickness about 2 m. There are two types of parallel reflection which can be identified in the study area: even and wavy parallel. Even to transparant – parallel and subparallel is shown by GPR image which is recorded by antenna 270 MHz, consists of series horizontal layered, underlying by tranparent parallel facies (Figure 5A). The wavy parallel – sub parallel facies is dominated by undulating reflector, strong reflector and high amplitude, with the thickness about 2 m (Figure 5B). Most of this facies is shown by GPR image that was recorded by 40 MHz of MLF 3200 antenna.

Discontinous- sub parallel, hummocky, chaotic and free facies

Most of these facies are characterized by weak to medium reflector and low to moderately amplitude. The image of this facies is recorded by 270 MHz antenna, that is shown more transparent, weak reflector and low amplitude (Figure 5A). This condition is different with the record that resulted by 40 MHz antenna, where the facies is characterized by more strong reflector and high amplitude (Figure 5B). The thin layer of continous parallel facies is also shown in GPR image that resulted by 40 MHz antenna.

Continous sub parallel, chaotic, hummocky, hypherbolic and divergent facies

These facies occur in packages that are up to 10 m thick. It consists of medium to strong reflector, moderately to high amplitude. Sub parallel, divergent and hummocky facies is very clear in GPR image that was resulted by 40 MHz antenna, whereas hyperbolic and chaotic facies is clear enough both in recorded of 270 MHz and 40 MHz antenna (Figure 5A and 5B).

Radar unit and interpretation

Radar discontinuities were recognized by the analysis of different styles of reflection terminations. These discontinuities show good correlation with the surface geological condition of Subi Kecil Island. Four radar units from top to bottom were recognized in the study area and each unit is characterized by one or more facies which have been discussed previously.

Location 1

Location 1 was imaged by using 40 MHz antenna and the radar unit can be divided into 4 units mainly unit A, B, C and D, with maximum penetration about 25 m depth.

Unit A is the uppermost layer, characterized by continous parallel-sub parallel facies, strong reflector and high amplitude. The thickness of this unit approximately 2 m depth and was interpreted as alluvium deposit

Based on the surface lithology observation, alluvium deposits consists of sand, fine to coarse grained and clay. Continous parallel facies indicate that most of layer dominated by fine fraction material (clay, silt and fine sand). Strong reflector and high amplitude.

Below the unit A is unit B. On line 1A, it shows that this unit is characterized by discontinuous sub parallel, free and chaotic facies, medium to high reflector and high amplitude. On line 2A the facies is dominated by discontinuous sub parallel and chaotic, low to medium reflector and moderately amplitude. On this line, unit A sometimes is directly underlain by unit C. On line 3 A, unit B is dominated by continous sub pararel facies and wavy, medium reflector and moderately amplitude. The thickness of this unit is about 3 m and in some places it can reach until 5 m (Figure 6). This unit is corelable with alluvium deposit.

Unit C is underlain unit B. On line 1A, is dominated by chaotic, free and discontinuous parallel facies in bottom part, strong reflector and high amplitude. This condition indicate that this facies is very influenced by ground water. On line 2A, the reflector is characterized by discontinuous sub parallel, chaotic, hummocky, divergen, strong reflector and high amplitude. It is very clear that in this line the unit C is already deformed and indicated by devergen facies. On line 3A, this unit is dominated by chaotic and continous devergen parallel facies, strong reflector and high amplitude. It is interpreted that this unit has been deformed and created structur geology such as fold and fault (Figure 7). Based on the outcrop which is exposed around the GPR survey area, this unit is corelable with the sandstone of Miocene Teraya Formation.

Unit D is the lowest layer, it is characterized by discontinuous parallel – subparallel, chaotic, hummocky, hyperbolic, medium reflector and moderately amplitude. The parallel – subparallel and chaotic facies indicate the sandstone facies whereas hummocky, chaotic, and hyperbolic can be interpreted as sandstone and breccias of Oligocene Kutai Formation.

Location 2

The GPR survey which have been carried out at location 2 were recorded by using 270 MHz antenna and maximum penetration is about 200 nano second or about 10 m depth (Figure 7).

There are 3 radar units that can be recognized from location 2 mainly unit A, B and C.

Unit A is uppermost layer, characterized by continous parallel facies, strong reflector and high amplitude. This unit has an approximate thickness

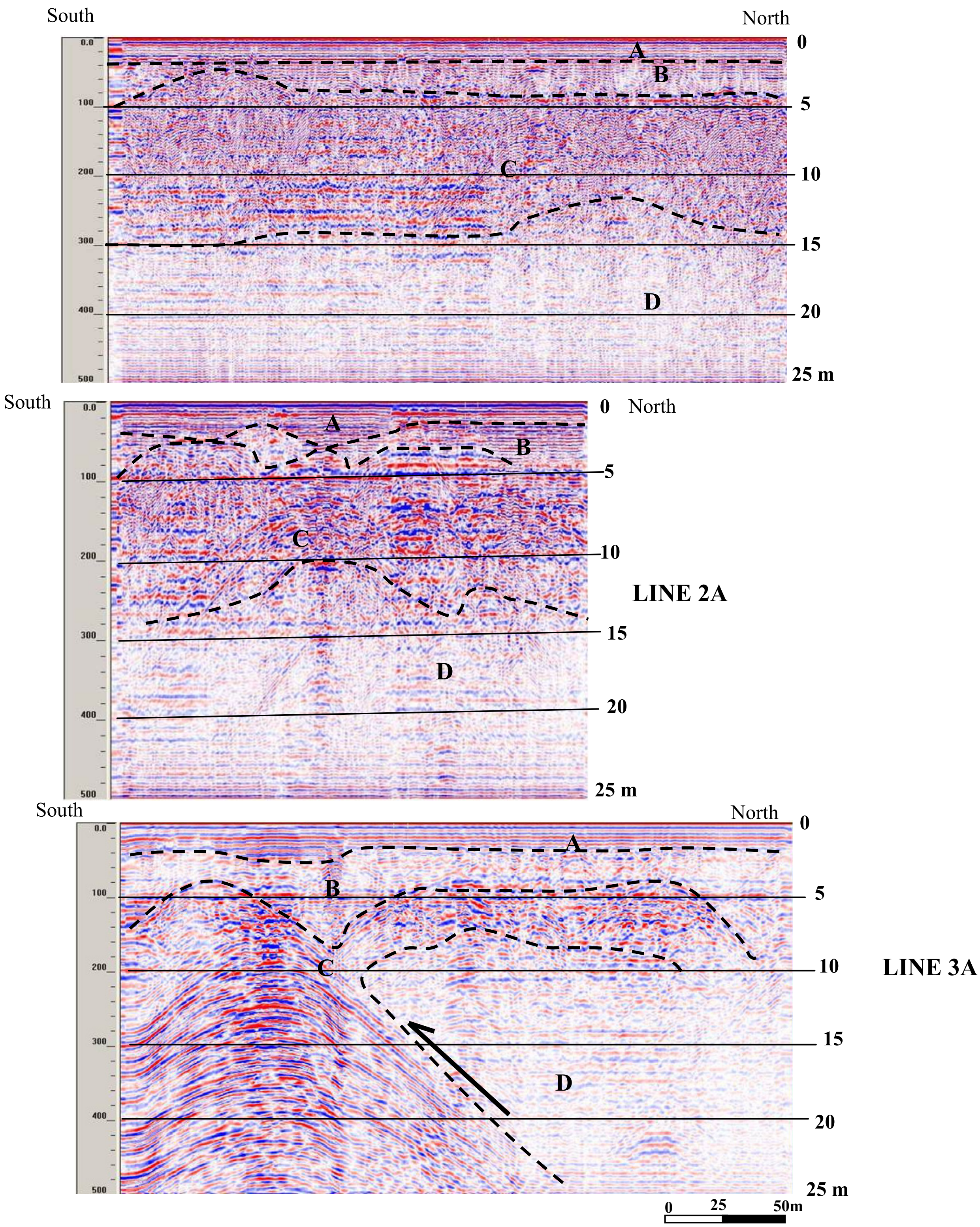

Figure 6. The radar unit of location 1, recorded by 40 MHz - 3200 MLF antenna

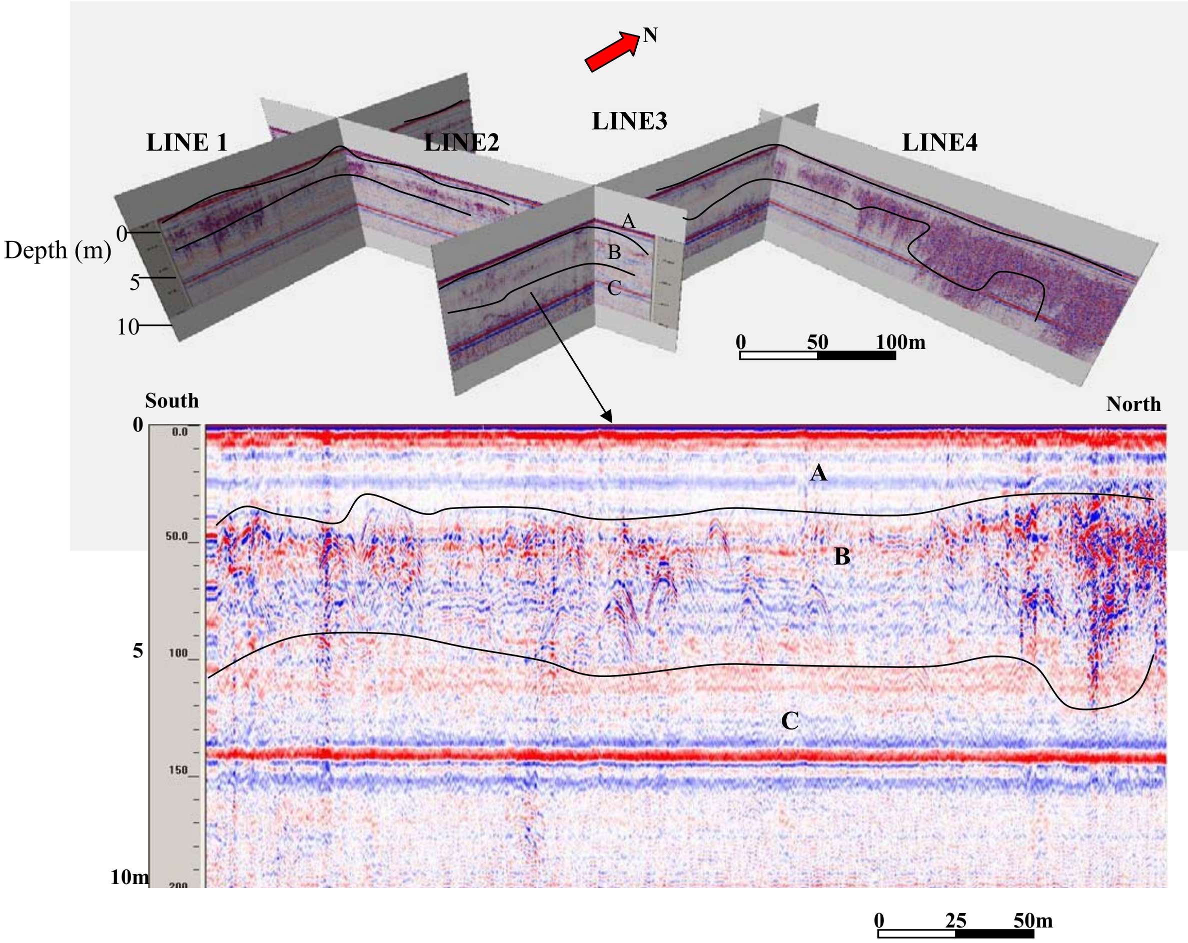

Figure 7. The fence diagram of radar unit of location 2, recorded by 270 MHz antenna

ranging from 2 to 5 m and interpreted as alluvium which consists of sand and clay. Compared to the sediments facies, the continous parallel facies indicate that the texture of sediment deposits probably is characterized by fine to medium grained sediments that was deposited through low energy. Below unit A is unit B which is dominated by discontinuous sub parallel, hummocky, hyperbolic and free facies.

All of these facies are dominated by medium reflector and moderately amplitude. The thicknes of this unit is about 2.5 m. Further more each of radar facies probably can be interpreted as follow:

Sub parallel facies with strong reflector represent sand and clay which is influenced by salt water. Between this facies there is hyperbolic facies and mix with chaotic and hummocky facies. This facies can be interpreted as sand, clay and reef. All of these deposits are part of alluvium deposit.

Unit C is the lowest layer, characterized by transparent continous parallel and chaotic facies. Most of these facies is dominated by weak to medium reflector and low amplitude. The thickness of this unit is about 5 m and can be found from 5 m depth (Figure 8). By compairing to the lithology which is exposed around the study area, this unit can be interpreted as sandstone from Teraya Formation.

DISCCUSSIONS

The radar images from GPR survey, have shown the radar facies which can be correlated with sediment facies. In many contamination problems, the sub bottom stratigraphy information of study area is spare and surface geological mapping description only give a limited picture of geometry of inhomogeneties. The result of GPR survey allowed the studies of subsurface stratigraphy to be subdivided into several units. They have good correlations with the stratigraphy unit along the coast of Subi Kecil Island. Comparisons between radar facies and exsposed sediment along the coastline and cliff, will give more information about the horizontal and vertical geometry of the stratigraphy of the study area.

In general, the GPR image of the study area is the key of defining radar facies. Bares and Haeni (1991) stated that the generality of the radar facies result is confirmed by the large number of qualitative studies.

They have catallogued radar facies based solely on the geometric description of reflections in the data, e.g., parallel, sub parallel, continous, discontinuous, poor reflection, oblique etc. The result of correlation between radar facies and the sedimentary rock around the study area shows that unit A is a uppermost layer which is interpreted as alluvium deposits. The dominance of sheet packages with continous sub-parallel and parallel facies corresponds in coast line to sand and muddy, laminated deposits which is formed in low energy. Holocene Alluvium deposits correspond also to unit B until 5 m depth. The characteristic of radar facies of unit B correspond to package of unconsolidated sand, boulder of reff and massive sandstone. Unit C corresponds to Miocene sandstone of Teraya Formation with the thickness about 10 – 15 m. The structure geology such as fold and fault is also found in unit C and it is characterized by discontinuity of horizontal layer between unit C and D especially on line 3A.Unit D is the lowermost layer and correspond to sand and breccias of Oligocene Kutai Formation.

The link between sedimentary facies and radar reflection implies that different radar facies represent spatially varying geologic setting in the subsurface. How ever Jol and Bristow (2003) in Moysey et al (2006) caution that many different geologic scenarios can produce similar reflection patterns in a GPR image. Similarly, based on our experience that the dependence of GPR resolution on frequency means that a single facies or depositional environments could produce many different interpretation.

CONCLUSSIONS

Generally, the GPR facies can be used to extend the sedimentologic information from the outcroup. Although the GPR method has been applied as a tool for reconstruction of subsurface sediments deposition and environment, most of studies experiences were concerned with Holocene sedimentation.

Based on the GPR survey, the subsurface lithology of study area can be summarized as follow: The uppermost layer is unit A which corresponds to Holocene alluvium deposits. This unit is underlain by unit B and still represent the alluvium deposit. Bellow unit B is unit C which corresponds to massive sand of Miocene Teraya Formation. The structure geology such as fold and fault can also be recognized from this unit. Unit D is the lowermost layer which represent the sandstone and breccias of Oligocene Kutai Formation.

The GPR investigations provided more information, to be better reconstruction of deposition and the development of the external structure of the study area, particularly within unit C.

GPR can distinguish reliably between unconsolidated alluvium deposits and consolidated massive sedimentary rock. There is a clear separation between Holocene unconsolidated alluvium deposits and underlying Miocene massive sedimentary rock.

ACKNOWLEDGMENT

The author thanks to Susilohadi the Director of Marine Geological Institute for his support and encouragement to publish this paper. Very special thanks is also to my best friend Godwin Latuputty to his support for using the data. Thanks are also to my colleagues who were helping during preparing the draft paper.

REFERENCES

[1] Beres Jr. M., and Haeni F.P., 1991. Application of Ground Penetrating Radar Methods in Hydrogeologic Studies, *Ground Water,* 29,(3), 375-386.

[2] Budiono K., Raharjo P., dan Yosi M., 1996., Penggunaan Georadar Untuk Penelitian Geologi Bawah Permukaan, Proceeeding's of The 25th Annual Convention of The Indonesia Association of Geologist

[3] Budiono,K., 1999. Ground Probing Radar as a tool for heterogeneity estimation in Quartenary sediment: Proceeding of Indonesian Association of geologist,

[4] Carrivick, J.L, 2007. GPR-Derived Sedimentary Architecture and Stratigraphy of Outburst Flood Sedimentation Within a Bedrock Valley System, Hraundalur, Iceland, *Journal of Environmental and Engineering Geophysics.* 12, (1), 127-143.

[5] Harahap, BH., Mangga, S.A., and Wiryosujono, S., 1995. Geological map of Natuna Sheet, *Geological Research and Development Centre*

[6] Johnson, D.G. (1987). *Use of Ground Penetrating Radar for Determining Depth to The Water Tableon Cape Cod, Massachusetts.* [Online]. http://info.ngwa.org/gwol/pdf/870143801.PDF [25 Juni 2011]

[7] Jol, H.M., and Bristow, C.S., 2003, GPR in sediment: Advise on data collection, basic processing and interpretation, a good practice guide, in Bristow ,C.S., and Jol, H.M., Ground penetrating in sediments, *Geological Society of London*, 9 – 27

[8] Moysey, S., Rosemary, J.K., and Hary, M., 2006, Texture – based on classification of ground-penetrating radar images, *Geophysics* 71, k111-k118

[9] Rossetti., D.D.F., and Goes, M. A., 2001, Imaging Upper Tertiary to Quarternary Deposits from Northern Brazil Applying Ground Penetrating Radar, *Journal of Geoscience.* 31 (2), 195-202.

[10] Saarenketo,T., and Scullion, T., (2000). Road Evaluation with Ground Penetrating Radar, *Journal of Applied Geophysics.* 43, 119–138.

[11] Van Dam R.L. & Schlager W. 2000. Identifying Causes of Ground Penetrating Radar Reflection Using Time- Domain Reflectometry and Sedimentological Analyses. *Sedimentology,* 47- 435-449.