The Characteristic of Coastal Subsurface Quartenary Sediment Based on Ground Probing Radar (GPR) Interpretation and Core Drilling Result of Anyer Coast, Banten Province

Karakteristik Sedimen Pantai Kuarter Bawah Permukaan Berdasarkan Penafsiran "Ground Probing Radar" (GPR) dan Hasil Pemboran Inti, Pantai Anyer, Provinsi Banten

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ABSTRACT: The study of characteristic of subsurfase Quatenary sediment of Anyer coast have been done by using the data of Ground Probing Radar (GPR) image, Surfacial Geological map around the coast and the result of core drilling. The GPR equipment which was used are GSSI SIR 20 system and GSSI Sub Echo 40 MHz antennas. The GPR data image have been processed by using Radan GSSI software, Window NT^{IM} version. The processing including Stacking, Spatial Filter, Migration and Decompolution. The interpretation of GPR image was done by using the principle of GPR stratigraphy through recoqnize to the internal and external reflector such as reflector configuration, continoutas, reflection, amplitude, etc, Furthermore the interpretation result of GPR image are correlated with the surfacial geological map and core drilling result that have been done by previous researscher. Besed on that correlation result, the characteristic of subsurface Quatenary deposits of study area can be divided into 5 unit mainly unit A, B, C, D and E. Unit A is the uppermost layer which is charactized by clay layer and coral reff fragments. Below the unit A they are unit B, C, and D wich were characterized by intercalation between sand and clay, sand deposit or sandstone, loose to dense. This condition is shown by the SPT (Standard Penetration Test) which have range between 10 to 50 blows per 15 Cm. Based on the characteristic of GPR image and sediment deposits of core drilling, these sediment deposits are interpreted as coastal and shallow water sediment deposits. Unit E is the lowermost layer which is interpreted as volcanic deposit.

Key Word : subsurface quatenary sediment, ground propbing radar, core drilling, Anyer coast.

ABSTRAK: *Penelitian karakteristik sedimen bawah permukaan Kuarter di kawasan pantai Anyer telah dilakukan dengan mempergunakan data citra " Ground Probing Radar", geologi permukaan di sekitar kawasan pantai dan data hasil pemboran inti. Peralatan GPR yang dipergunakan adalah sistim SIR 20 GSSI dan antenna MLF 3200 GSSI.Data citra GPR telah diproses dengan mempergunakan perangkat lunak RADAN GSSI versi window NT^{IM}. Pemrosesan terdiri dari "Stacking", "Spatial Filter", "Migration" dan "Decompolution". Penafsiran Citra GPR dilakukan dengan mempergunakan prinsip Stratigrafi GPR melalui pengamatan terhadap internal dan eksternal reflector seperti konfigurasi reflector, kontinuitas, refleksi, amplitude dan lain-lain. Selanjutnya hasil penefsiran citra GPR ini dikorelasikan dengan peta geologi permukaan dan hasil pemboran inti yang telah dilakukan oleh peneliti terdahulu. Berdasarkan hasil korelasi tersebut karakteristik endapan Kuarter bawah permukaan daerah penelitian dapat dibagi menjadi 5 unit yaitu Unit A, B, C, D dan E. Unit A merupakan unit paling atas yang dicirikan lapisan lempung dan kerakal kerikil hasil rombakan koral. Unit B, C dan D berada di bawah ubit A yang merupakan endapan selang seling pasir dan lempung serta endapan pasir atau batu pasir bersifat urai sampai padat. Kondisi ini ditunjukan oleh hasil pengujian SPT ("Standard Penetration Test") yang berkisar antara 10 sampai lebih dari 50 tumbukan per 15 Cm.Berdasarkan karakteristik fasies citra GPR dan endapan sedimen dari hasil pemboran inti, endapan sedimen tersebut ditafsirkan sebagai endapan pantai dan endapan laut dangkal Unit E merupakan lapisan paling bawah yang ditafsirkan sebagai endapan gunung api.*

Kata kunci :*Sedimen Kuarter bawah permukaan,"Ground Probing Radar", pemboran inti, pantai Anyer*

INTRODUCTION

The analysis of Ground Probing Radar (GPR) stratigraphic provides the framework for assessing both lateral and vertical geometries and the stratification of coastal deposits (Beres and Haeni,1991; Jol and Smith, 1991; Gawthorpe et al., 1993; Huggenberger, 1993).

The analysis is based on well-developed principles of seismic stratigraphy and provides a systematic methodology to objectively describe and interpret GPR reflection profiles for geologic applications. The development of radar stratigraphic analysis has allowed for the delineation and mapping of genetically related stratigraphic units within sedimentary deposits (van Heteren et al., 1998). In addition to stratigraphic applications, recent studies demonstrate the use of reflection geometry as a sea level indicator (e.g., upper contacts between oblique beach/shoreface and dune reflections; van Heteren and van de Plassche, 1997; van Heteren et al., 1998.

The main purpose of the study is to collect and to analysis of the GPR image performed in shallow subsurface Quartenary deposits from coast of Anyer both horizontally and vertically.

Administrativelly the study area is located at Anyer coast, Anyer Distric, Banten Province and geographically between 105.90^{o} – 106.05^{o} longitude, and -5.95 $^{-}$ -6.10 Latitude (Figure 1).

In general the geological condition around the GPR survey area is based on to the geological map of Anyer Quadrangle which have been made by Santosa et all 1982. From the old to the younger rock units which are found in the area of Anyer, consists : Marikangen volcanic rock, Produc of Gede volcano, Banten tuf, Gede volcanic rock, Pinang Mt Basalt and alluvium deposits (Figure 2)

Concerning to the location of GPR survey area, the rock unit that will influent the result of GPR survey are Banten tuf and alluvium deposits.

Banten tuff is divided into lower Banten tuff and upper Banten tuff. Lower Banten tuff consist of tuff breccias, agglomerate, pumiceous tuff, lapilli tuf and sandy tuff.

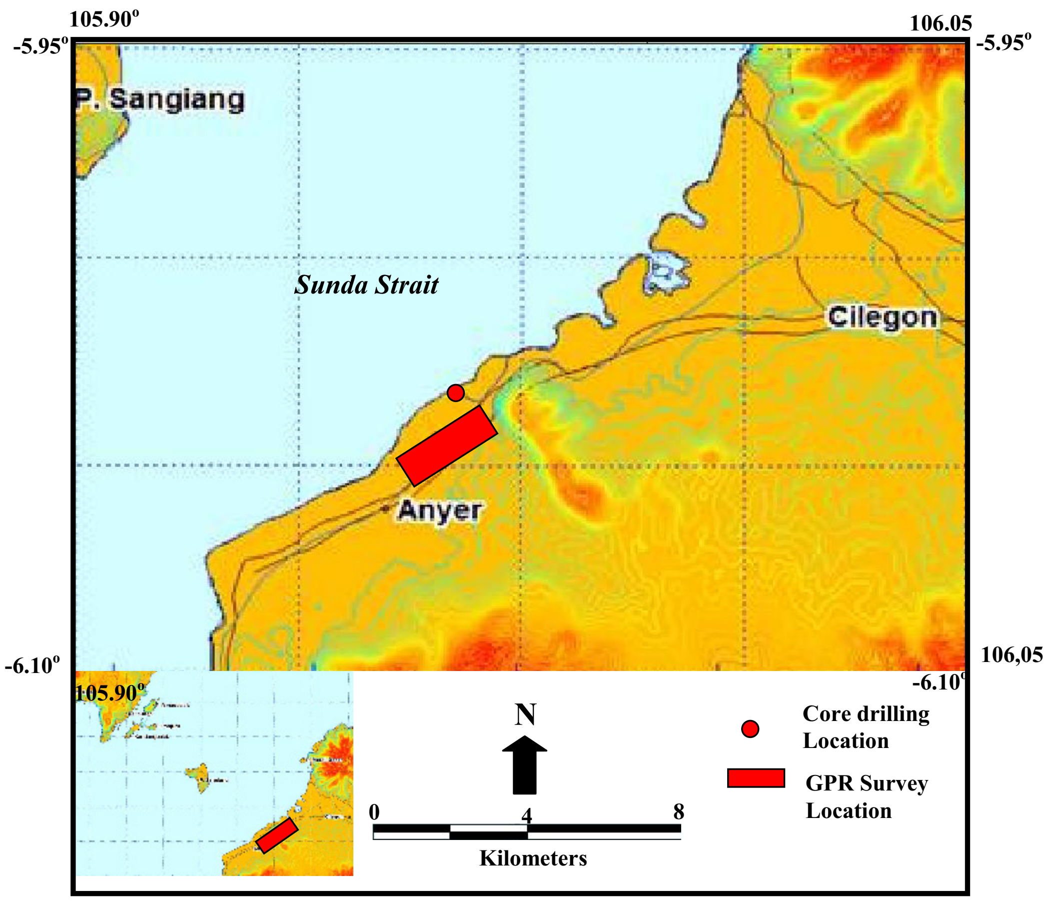


Figure 1. The study area location

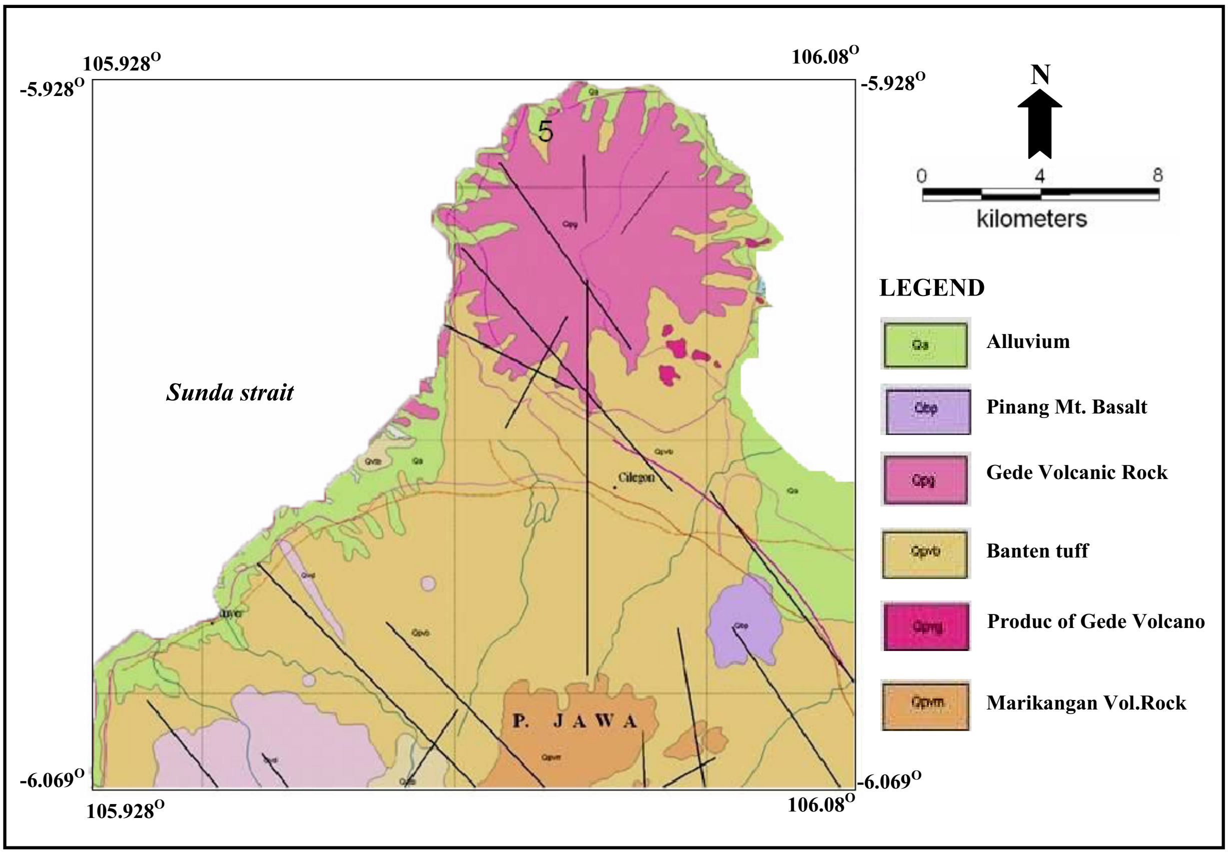


Figure 2. The geological map of Anyer Quadrangle (modified from Santosa et all, 1982)

Tuff breccias, of intermediate tos basic composition, the clats make up of sand to bomb size, subangular to subrounded; composed of basalt, andesite, pumice, obsidian with very fine pyroclastic groundmass, thickness is several meters. The bomb clasts are scattered and at limited numbers (Santosa et all, 1982).

Agglomerate, clast make up of lapilli to bomb size, well rounded to subrounded; composes of basalt, andesite, pumice with sandy or fine clastic tuff matrix; as small intercalations in the volcanic breccias, the thickness is about several meters. The exposes are found at the upper course of the Anyer River and on the the northeastern escarpment of Danau Caldera (Santosa et all, 1982)

Pumiceous tuff, dirty white to gray, clasts make up gravel to sand size, sub rounded; composes of dominantly pumice, basalt, andesite and obsidian; loose and weathered; the thickness of the layer is about several centimeters.

Lapilli tuff, clast size range in less than 1 mm to gravel; acid to basic composition; composes of basalts, andesite, dacito-andesite and pumice; and the thickness is about several meters (Santosa et all, 1982)

Sandy tuff, clasts size range in coarse to medium, acid to intermediate in composition; contain minor of light mica, biotite, mafic minerals and glass; and as intercalation or alternation in the other tuffs. The thickness is more or less than 10 Cm.

The Lower Banten Tuff was deposited on a terrestrial environment, and the age was estimated at Early Pleistocene to Midle Pleistocene (Alzwar and Akbar, 1975).

Alluvium deposits are consists of coastal and river deposits : pebble, gravel, sand, clay, mud and pumice pebbles (Santosa et all, 1982).

Coastal deposit, locally mixes with shell and molusc fragments; and occupies along the west coastal plain. River deposit commonly occupies along the lower course area of the river : Cilemer, Ciliman Labuhan and Anyer (Santosa et all, 1982).

Pumice, gray to dirty white ; light, vesicular; and between 5 to 30 cm in grained size, subrounded; rough surface. Locally, the distribution is as small accumulation along the west coastal plain (Santosa et all, 1982).

The core drilling (Figure 3) was excecuted by Marine Geological Institute in 2004 (Mustafa, 2004).

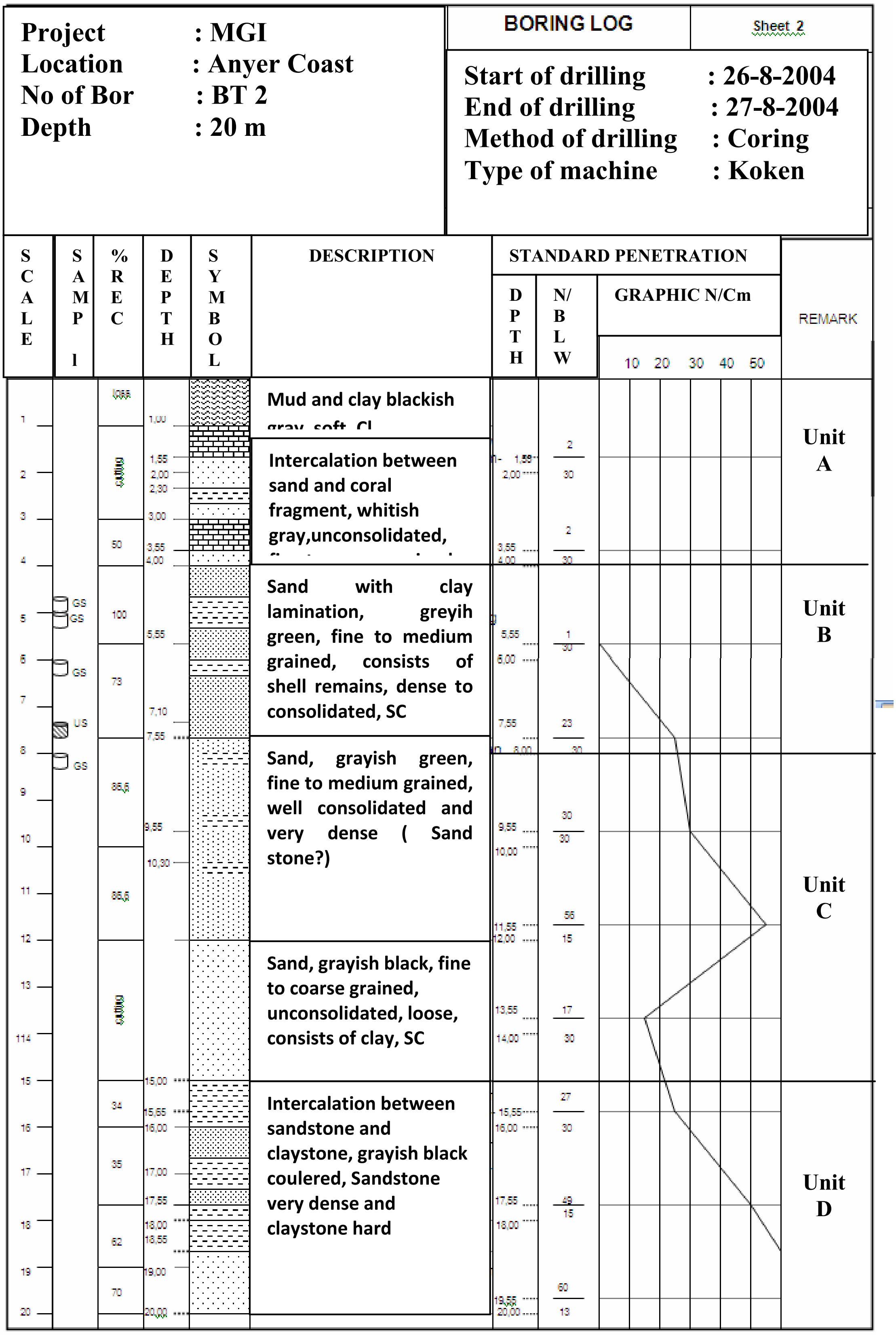


Figure 3. Core drilling result (Modifid from Akrom, 2004)

The results of core description can be summarized as follow:

Form 0.00 to 1.00 meters is characterized by mud or clay, blackish gray, very soft, low plasticity. Below mud until 4.00 meter depth, is intercalation between sand and coral fragment, whitish gray,unconsolidated, fine to coarse grained. From 4.00 to 7.50 meter depth is occupaid by sand wich is laminated by clay, grayish green, fine to medium grained, consists of shell remain, medium dense to well consolidated. Below sand, from 7.50 to 12 meter depth is characterized by sand grayish green,fine to medium grained,well consolidated and very dense. From 12.00 to about 15 meters depth is sand, grayish black, fine to coarse grained, lose to medium dense and consist small of clay. From 15.00 to 20.00 meters is characterized by intercalation between sandstone and claystone, grayish black coulered, Sandstone very dense and claystone is hard.

METHOD

The area was studied using 2D and 3D GPR sections (location of the sections in Fig.1). GPR is a powerful, non-intrusive electromagnetic profiling technique for revealing sedimentary structures in a shallow subsurface (Pasanen, 2008)

Using this method, pulses of electromagnetic energy are transmitted into the subsurface where the energy is reflected back from the electrical boundaries, and the amplitude and the two-way travel time in nanoseconds are recorded. The electrical boundaries are created at the interfaces of the geological materials with different dielectrical properties (Pasannen, 2008). The velocity of the electromagnetic wave is dependant on the relative dielectric value, and the abrupt changes in this value cause the radar reflections (Pasannen, 2008). In sediments, the abrupt changes in dielectrical preperties are mainly caused by changes in water content and lithology (van Dam & Schlager, 2000).

Radar reflections from the interface are governed by the differential in the dielectric constant and conductivity of the materials.

Features a cable connects the antenna with receiving and recording instruments. The radar pulses are diplayed in real time on a screen and are recorded on the computer digitally. By recording a signal return every three inches a continues profile is developed.

The subsurface strata are shown the lithology in detail profile, Quarternary sediments and the pra Quartenary sediments.

The physical basis for the GPR method is given by Annan and Davis (1976) and Daniels et al.(1988) among others.The propagation and reflection of the electromagnetic wave is analogous to an acoustic wave, therefore, an approach similar to seismic stratigraphy (Roksandic, 1978; Sangree & Widmier, 1979) can be used for GPR interpretation and its called as GPR stratigraphy. Radar stratigraphy is based on the recognition and interpretation of radar surfaces (bounding surfaces), radar facies (bed assemblages) and radar packages (geometry of the deposits) (Neal et al., 2002). The principles of radar stratigraphy are given by Gawthorpe et al. (1993) and later reviewed by Neal (2004). The GPR method has been widely used in sedimentological studies (cf. Neal, 2004) and has been successfully applied to glaciofluvial sediments, e.g. by Beres et al. (1995, 1999) and Mäkinen and Räsänen (2003), and to deltaic and glaciodeltaic sediments, e.g. by Jol and Smith (1991), Smith and Jol (1992, 1997), Roberts et al. (2003) and Pelpola & Hickin (2004).

Figure 4. GPR survey operation by using GSSI SIR 20 and 40 MHz Sub Echo antennas.

The GPR equipment used in this study comprised of the GSSI SIR 20 and 40 MHz Sub-Echo antena (Figure 4). Raw data were postprocessed using RADAN 5.5. software.

The correlation and calibration have been made by using the log bor data and surficial geological map around the GPR survey area.

RESULT

Analysis radar facies

The procedure of sedimentological facies analysis have been used to analize the radar facies .The radar facies is resulted from analize of the GPR data set is consisted in the identification of individual radar facies, were grouped into radar unit.The depositional environments will be resulted from radar unit interpretation (Budiono, 2013)

Based on distinctive reflection configuration, they are five radar unit which are characterized by differences radar facies mainly unit A, B, C, D and E respectively.

Sub parallel – parallel facies

Sub parallel facies and parallel facies is characterized by continuous medium to strong reflector and moderately to high amplitude. From the GPR image data (Figure 5) show that sub parallel facies is characterized by more thin layer, more transparent and laminated between parallel facies. Parallel facies can be divided into series of horizontal layer and wavi layer. The parallel and sub parallel horizontal form can be seen in the upper part and gradually became more wavi in to the bottom part.

Sub parallel and divergen facies

This radar facies is characterized by closely-spaced, continous, medium reflector and moderatly amplitude (Figure 5). They are two type of sub parallel reflection which can be identified in the study area: even-parallel and wavy parallel. Even sub parallel is shown by GPR image which consists of series horizontal layered, interfingering wih t divergen facies (Figure 5). The wavy sub parallel facies is dominated by small undulating reflector, medium reflector and moderately amplitude.

Mound and divergen facies

Mound and divergen facies is the lowest most layer, its characterized by continuous medium to strong reflector and moderately to high amplitude.

Corelation and calibaration

Radar discontinuities were recognized by the analysis of different styles of reflection terminations. These discontinuities show good correlation with the surface geological condition and core drilling data of Anyer coastal plane. Five radar unit 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.

The calibration and correlation between GPR facies and core drilling data can be explained as follow (Figure 6) :

Unit A, B and is characterized by sub parallel – parallel facies continuous, horizontal and wavi form, medium to strong reflector and moderately to high amplitude. Based core drilling data, these unit is dominated by intercalation between clay and sand. Unit C is characterized by medium reflector and moderately amplitude and can be correlated with sand or sandstone.

Unit D below the unit C, its characterized by sub parallel and divergen vacies, medium reflector and moderately amplitude and interpreted as intercalation between sand and clay (Figure 6).

The lower most layer is unit E, its dominated by mound undulating and divergen facies, strong reflector and high

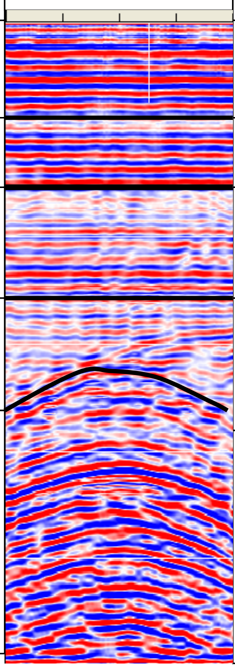
GPR Unit	GPR Image	GPR Facies
Unit A		**Subparallel – Parallel, continous,medium – strong reflector, moderatly to high amplitude**
Unit B		**Subparallel – Parallel,wavi, continous,low – strong reflector, medium to high amplitude**
Unit C		**Subparallel, parallel wavi, continous, low – medium reflector, moderately - high amplitude**
Unit D		**Subparallel, divergen, continous, medium reflector, moderately amplitude**
Unit E		**Mound, divergen, continous, medium to strong reflector, medium – high amplitude**

Figure 5. The radar unit and radar facies of GPR image of study area

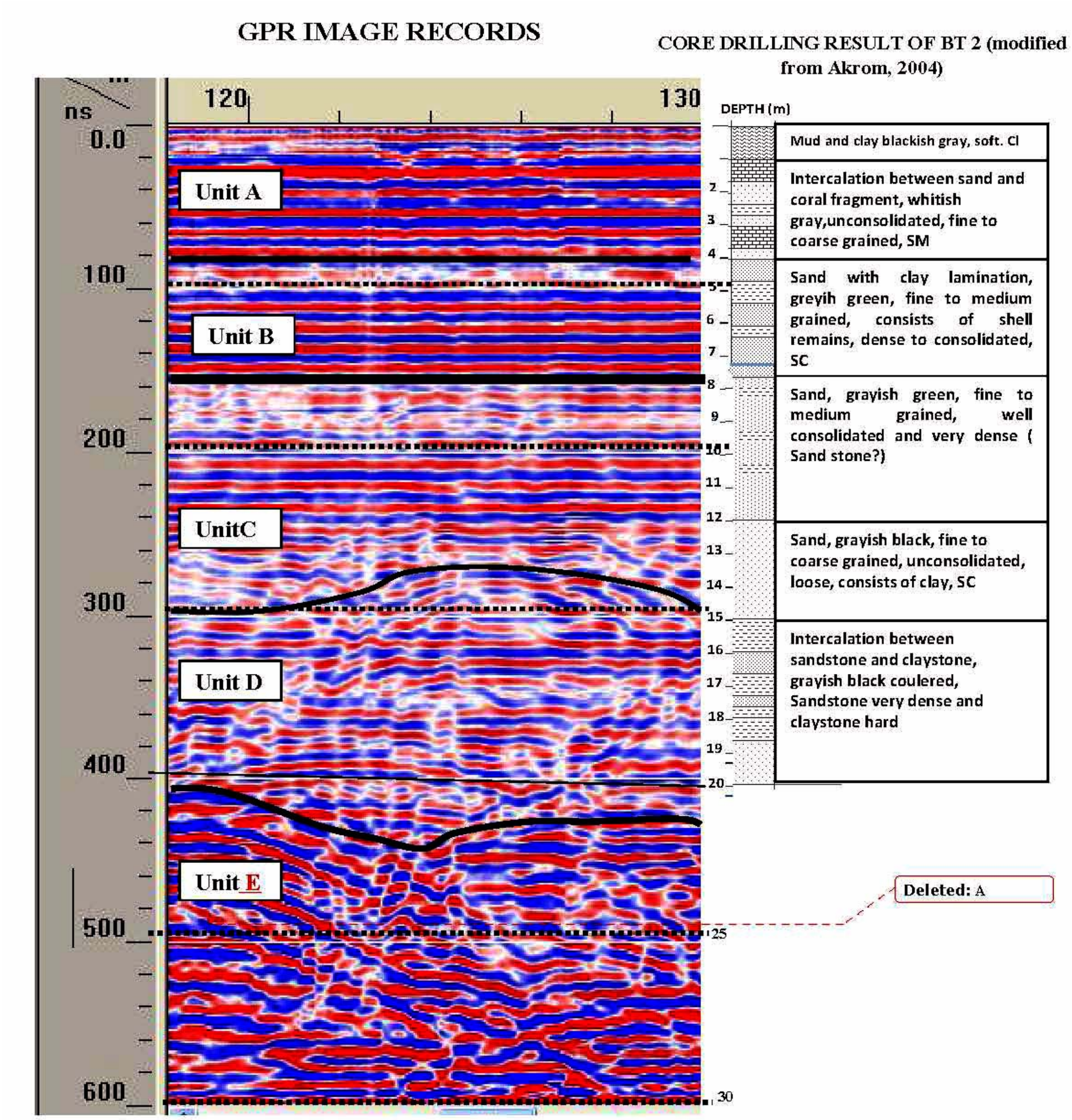


Figure 6. Correlation between GPR facies and core drilling data

amplitude. Based on the stratigraphy of Anyer region, this facies can be assumed as Volcanic rock.

Radar unit interpretation

Line 1 and Line 2

Line 1 was imaged by using 40 MHz antenna and the radar unit can be divided into 5 unit mainly unit A, B, C and D, and E with maximum penetration about 30 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 4 m depth and was interpreted as alluvium deposit. (Figure 7).

Based on the GPR facies analyses and correlation with the core drilling data the upper most layer is characterized by sub parallel facies, medium reflector and moderately amplitude and interpreted as mud layer, very soft with depth about 1 m. Below the mud layer until 4 m depth its intercalation between sand, clay and remain of coral reef.

Based on the surface lithology observation, all of these lithology is interpreted as coastal deposits.

Below the unit A is unit B. On line 1 and 2, it shows that this unit is characterized by continuous parallel, strong reflector and high amplitude. On the bottom of unit B facies is dominated by discontinuous sub parallel low to medium reflector and moderately amplitude.

Based the core drilling data unit B is dominated by sand with laminated clay, fine to medium grained, consists of shell remain. The standard penetration test (SPT) show that this layer is characterized by 1/30 – 60/15 blow/Cm. From this data its interpreted that this layer as still coastal deposit or near shore deposit.

Unit C is underlain unit B. On line 1 and 2, in upper part is characterized by sub parallel, chaotic and wavi, medium reflector and moderately amplitude, in the middle part is dominataed by parallel, continuous, strong reflector and high amplitude, and in the bottom part is is found again the same facies as in the upper part. Core drilling data from 8.00 – 12 m depth is characterized by sand, fine to medium grained and well consolidated with SPT about 20/30 and 60/15 blows/Cm. From 12.00 to 15 m depth is dominated by loose sand, fine to medium grained. The SPT result is about 17/30 blows/Cm.

Below unit C is unit D, located between 15.00 m and 20.00 m depth, characterized by sub parallel and divergen facies, wavi, un continuous , medium reflector and moderately amplitude. Based on the core drilling data, this facies is characterized by alternating between clay stone and sand stone, very dence and hard with no blows of SPT about 27/30 and 60/15 blows/Cm.

Unit E is the lowest most layer, dominated by mound undulating and divergen facies, strong reflector, high amplitude and continuous. Based on the stratigraphy of Anyer Quadrangle, probably this facies can be correlated with upper Banten tuff.

DISCUSSION

The data presented here show how GPR imaging can be used to extend sedimentologic information from outcrops and core drilling result thus allowing large-scale stratigraphic analysis of sedimentary fades and environments. Although this methodology has been applied as a tool to help analyzing the sedimentological record, most of the studies documented in the literature

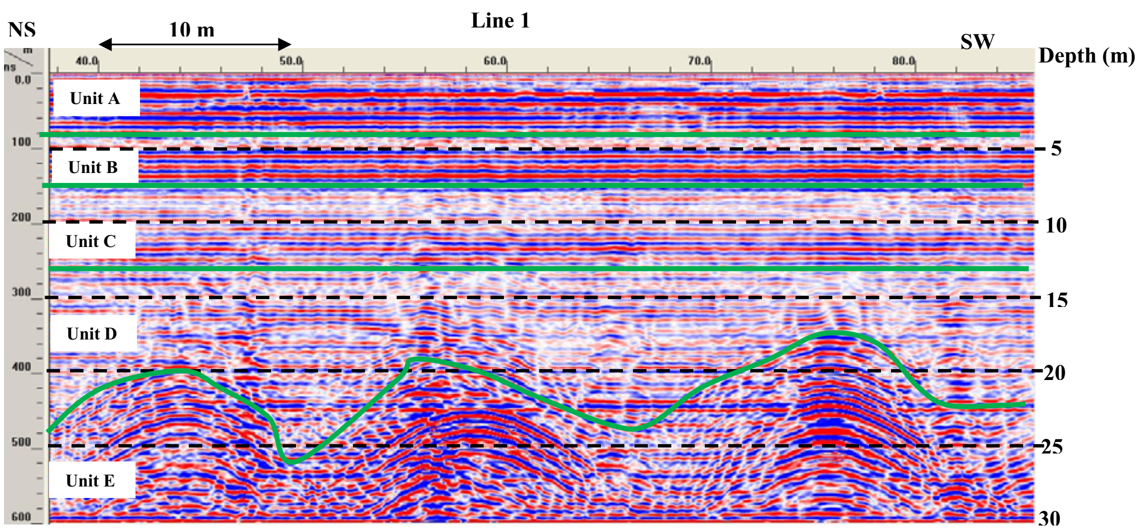


Figure 7. The GPR image of line 1

were concerned with holocene sedimentary environments, with particular emphasis on lacustrine, eolian and fluvial deposits (Jol and Smith 1991, Huggenberger 1993, Beres *et al.* 1995, Van Dam and Schlager 2000). Only a few publications have shown the application of GPR surveys in coastal depositional environments (Baker 2004, Van Heteren *et al.* 1998). The sedimentary record of this type of setting is complex due to the highly variable facies distribution both laterally and vertically.

The radar image which was resulted by GPR survey have shown the radar facies which can be correlated with sediments facies. In many contamination problem, the sub bottom stratigraphy information below the coast of study area is spare and surface geological mapping description only give a limited picture of geometry of inhomogeneties. The result of GPR survey aloowed the studied of subsurface stratigraphy to be subdivided into several unit which have good correlation with the stratigraphy unit along the Anyer coastal plane. Comparasons of radar unit which is established by radar facies and sediments which is exposed along the coastline and core drilling record ,will give more information about the horizontal and vertical geometry of the Quatenary stratigraphy of the study area.

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.

The result of correlation between radar facies and the Quatenarry sediment deposits around the study area show that unit A is a uppermost layer which is interpreted as coastal 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 8m depth.The characteristic of radar facies of unit B correspond to package of consolidated sand. Unit C corresponds to unconsolidated to consolidated sand deposits of alluvium Holocene with thickness about 7 m. Unit D which is characterized by continuous sub parallel, wavi and divergen facies. Based on correlation with the core drilling data it is interpreted as intercalation between sand stone and clay stone. Santosa (1982) interpreted that this sediments is part of Banten tuff rock with Early Plistocene age.

Unit E is located bellow the unit D between 20.00 m to 30.00 m depth. The characteristic mound undulating and divergen facies with strong reflector indicate that this facies can be correlated with the breccias of Banten tuff.

Based on the standard penetration test, show that from 0.00 – 5 m depth the sediment is classified as a soft sediment. From 5.00 m – 12.00 m depth the sediment is classified as a loose to unconsolidated sediment and back again became loose sediment until 14.00 depth. From 14.00 m to 30.00 m depth the sediment is characterized by very dence to consolidated sedimen with SPT more than 50 blows / 15Cm.

CONCLUSSION

The GPR profiles provided a better overview of the distribution of facies and stratigraphic surfaces within the study area (Fig. 8 and 9). Hence, correlate with core drilling record, unit A and B consists mostly of continuous even, sub parallel and wavy parallel radar facies attributed to intercalation of sand and clay.

Generally the GPR facies can be used to extend the sedimentologic information from the outcroup and log bor data. 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.

Bellow unit B is unit C which corecponds to unconsolidated and consolidated sediment of Holocene age. Unit D is below unit C which represent the sandstone and claystone of Plistocene Banten Tuff

The GPR subsurface investigations provided more information to beteer reconstruct the depositional 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.

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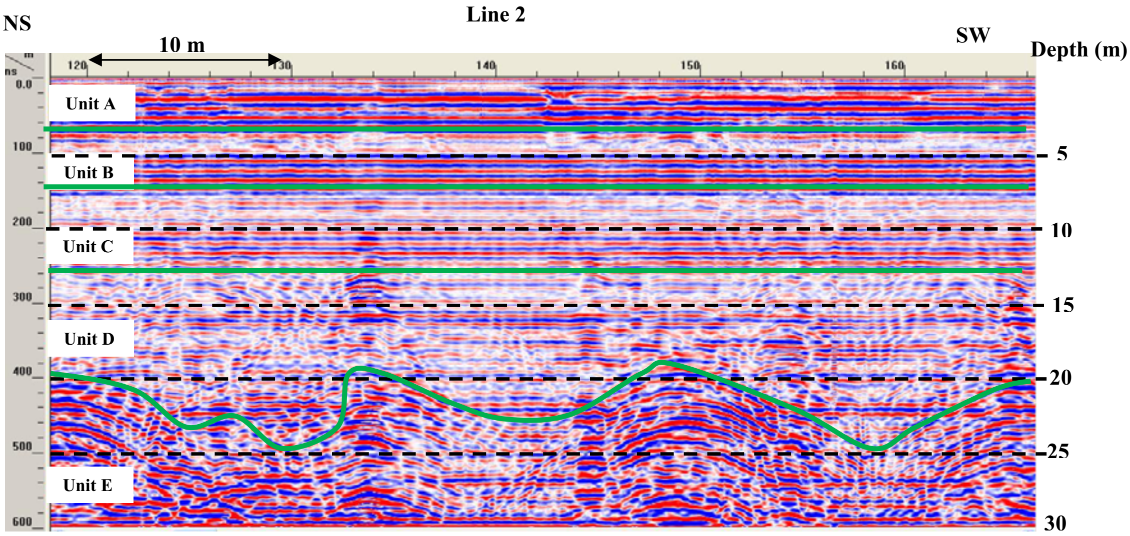

Figure 8. The GPR image of line 1

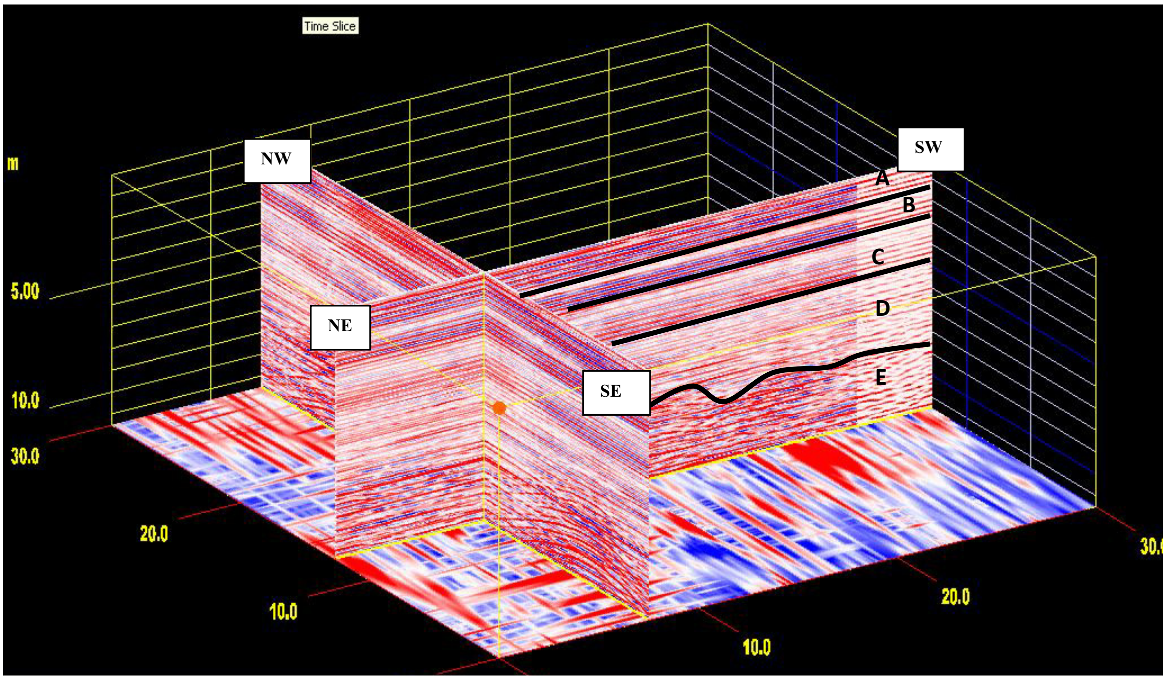

Figure 9. 3D slace of GPR image of Study area

REFERENCE

[1] Annan, A.P. & Davis, J.L., 1976. Impulse radar sounding in permafrost. *Radio Science* 11, 383–394.

[2] Alzwar M., and Akbar N. 1975. The geothermal exploration on Banten area, West Java. Archives on Library of *Diretorate of Volcanology*, Bandung

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

[4] Beres, M., Green, A., Huggenberger, P. & Horstmeyer, H.,1995. Mapping the Architecture of Glaciofluvial Sediments with 3-Dimensional Georadar. Geology 23, 1087– 1090.

[5] Beres, M., Huggenberger, P., Green, A.G. & Horstmeyer, H., 1999. Using two- and three-dimensional georadar methods to characterize glaciofluvial architecture. 129, 1–24.

[6] Budiono, K., Noviadi, Y., Latuputty, G., Hernawan, U., 2012, Investigation of Ground Penetrating Radar for Detection of Road Subsidence, Norh Coast of Jakarta, Indonesia, *Bulletin of the Marine Geology, Vol. 27 Number 2, December 2012*

[7] Daniels, D.J., Gunton, D.J. & Scott, H.F., 1988. Introduction to subsurface radar. *IEE Proceedings* 135, 128–320.

[8] Gawthorpe, R.L., Collier, R.E.L., Alexander, J., Bridge, J.S.& Leeder, M.R., 1993. Ground penetrating radar: application to sandbody geometry and heterogeneity studies.*Geological Society, London, Special publications* 73, 421–432.

[9] Huggenberger P. 1993. Radar Facies: Recognition of Facies Patterns and Heterogeneities within Pleistocene Rhine Gravels, NE Switzerland. *In J.L. Best & C.S. Bristow (eds.) Braided Rivers.* Geol. Soc. Spec.Publ., 75:63-176.

[10] Jol, H.M. & Smith, D.G., 1991. Ground Penetrating Radar of Northern Lacustrine Deltas. Canadian Journal of Earth Sciences 28, 1939–1947.

[11] Mäkinen, J. & Räsänen, M., 2003. Early Holocene regressive spit-platform and nearshore sedimentation on a glaciofluvial complex during the Yoldia Sea and the Ancylus Lake phases of the Baltic Basin, SW Finland. *Sedimentary Geolog*y 158, 25–56.

[12] Mustafa K. 2004. Penyelidikan Geologi Geofisika Perairan Selat Sunda Dan Sekitarnya, Kabupaten Serang dan Sekitarnya. *Pusat Penelitian dan Pengembangan Geologi Kelautan*

[13] Neal, A., 2004. Ground-penetrating radar and its use in sedimentology: principles, problems and progress. *Earth- Science Reviews* 66, 261–330.

[14] Neal, A., Richards, J. & Pye, K., 2002. Sedimentology of coarse-clastic beach-ridge deposits, Essex, southeast England.Sedimentary Geology 162, 167–198

[15] Pasanen, A. and Lunkka, J.P., 2008. Glaciotectonic deformation of till-covered glaciofluvial deposits in Oulu region,Finland. *Bulletin of the Geological Society of Finland* 80, 89–103.

[16] Pelpola, C.P. & Hickin, E.J., 2004. Long-term bed load transport rate based on aerial-photo and ground penetrating radar surveys of fan-delta growth, Coast Mountains,British Columbia. *Geomorphology 57*, 169–181.

[17] Roksandic, M.M., 1978. Seismic facies analysis concepts. Geophysical Prospecting 26, 383–398.

[18] Sangree, J.B. & Widmier, J.M., 1979. Interpretation of depositional facies from seismic data. *Geophysics 44*

[19] Roberts, M.C., Niller, H.-P. & Helmstetter, N., 2003.Sedimentary architecture and radar facies of a fan delta, Cypress Creek, West Vancouver, *British Columbia.Geological Society, London, Special Publications 211*, 111–126.

[20] Smith, D.G. & Jol, H.M., 1992. Ground-Penetrating Radar Investigation of a Lake Bonneville Delta, Provo Level, Brigham-City, Utah. Geology 20, 1083–1086.

[21] Santosa S., Sutrisno T., Turkandi T., Ratman N., Sukanta U. 1982. Geologi of the Anyer Quadrangle, west Jawa. *Geological Research and Development Centre*

[22] Van Heteren S. & Van De Plassche O. 1997. Influence of relative sea-level change and tidalinlet development on barrier-spit stratigraphy, Sandy Neck, Massachusetts. *Journal of Sedimentary Research,* 67:350-363.

[23] Van Heteren S., Fitzgerald D.M., Mckinlay P.A., Buynevich I.V. 1998. Radar facies of paraglacial barrier systems: coastal New England, USA. *Sedimentology, 45:*181-200.

[24] Van Dam R.L. & Schlager W. 2000. Identifying causes of ground penetrating radar reflections using time-domain reflectometry and sedimentological analysis. *Sedimentology.* 47:435-449.