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Acoustic and geochemical evidences of shallow gas distribution offshore Waropen Basin, Papua, Indonesia

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Abstract: Sub-Bottom Profiling (SBP) records and results of geochemical analysis of 12 surficial sediment cores from various water depths collected from the offshore Waropen Basin-Papua are presented. Presence of gas is clearly observed on sub-bottom profiler records. Shallow gas was identified through acoustic response due to gas accumulation and gas escape on sub-bottom profiles. Acoustic evidences of gas accumulations within near surface geology consist of high amplitude reflections and associated acoustic blanking, gas plumes and morphological features like pockmarks. Total organic carbon analysis of 12 surface sediment cores varies between 0.5% to 1.3% which indicate that the sediments have an abundance of organic matters. Gas chromatographic analysis of hydrocarbon composition detected only methane, a biogenic origin of shallow gas. Acoustic and geochemical evidence in the Waropen Basin indicates extensive shallow gas accumulations in the Late Quaternary sediments, some trapped within these deposits and some escape from seabed into the water column which then created a high distribution of pockmarks.

Keywords: Sub-bottom profile, acoustic evidences, pockmark, geochemical analysis, shallow gas, Waropen Basin

INTRODUCTION

Gas accumulations are commonly identified on acoustic surveys in coastal to deep-water environments. Origin of gas could be derived from two types of gas sources, namely biogenic methane (over 96% of methane content) due to decomposition of organic matter in shallow formations and the thermally derived natural gas that migrated from deep formations through faults (Missiaen *et al*., 2002; Ren *et al*., 2019). Many scientists studied the origin and distribution of shallow gases. The shallow gases in marine sediments cause acoustic anomalies due to the contrast in acoustic impedance between gas-free and gas-bearing sediments (Carlson *et al*., 1985; van Weering *et al*., 1989; Fader, 1991; Judd & Hovland, 1992; Yuan *et al*., 1992).

Acoustic anomalies were first reported by Schuller (1952) in Garcia-Gil *et al*. (2002). Masking effects appear on echosounder records were due to free gas escape from shallow marine sediments. He named it as “basin effect” (beckeneffekt). Since the earliest report of gas accumulation in marine sediments many authors have similarly reported accumulation of gas methane and other gases in near-surface sediments indicated by acoustic anomalies. Each author has conducted different background studies researching gas concentration in near-surface sediments. Broadly, there are four kinds of background study, as follows:

- Geological and geophysical analysis about how the gas is formed, how the acoustic anomalies emerge, and how its morphological features such as free gas-pockmark (Webb *et al*., 2009; Canet *et al*., 2010; Zsuzsanna, 2013; Vardar & Alpar, 2016). Gas bearing sediments form transparent zones and mask deeper reflections on chirp seismic sections. The interfaces between the gas bearing and neighboring sediments are rather sharp and vertical. Other clues supporting the evidence of free gas in sediment are the pockmarks. The appearance of shallow sediments characteristic depend on tectonic setting and depositional systems (Vardar & Alpar, 2016).
- Hydrocarbon exploration (Hakan *et al*., 2018; Canales, 2001).
- Geological hazardous (Carlson *et al*., 1985; Judd & Hovland, 1992; Bastia *et al*., 2011; Shaoran *et al*., 2019). The shallow gas with thermal origin is normally featured of higher pressure than that of the biogenic methane. In general, there is no essential difference among different types of shallow gas in terms of geo-hazards for drilling operations, it all depends on its dimension and pressure coefficient (Shaoran *et al*., 2019).
- Biological productivity (Hovland & Thomsen, 1989; Dando *et al*., 1991; Hovland *et al*., 2012).

Acoustic evidence indicative of shallow gas accumulations on sub-bottom profiler records consist of strong amplitude anomalies, acoustic blanking, gas columns and gas plumes. Individual pockmarks are probably formed from defluidisation (water/gas) process of soft superficial sediments due to natural sediments compaction and the pressure introduced from the massive water column. Its distribution is usually associated with underlying geological structure and zone of weakness in the sediment (Hovland *et al*., 1996; Bøe *et al*., 1998; Hasiotis *et al*., 2002). These features are easily investigated with a variety of acoustic surveys such as, multibeam bathymetric, sub-bottom profiling and side scan sonar. However, these are considered as indirect indicators of shallow gas presence within the near surface sediments.

Direct evidence of gas-bearing sediment is commonly provided by geochemical analysis. Measurement of shallow gas concentration may be undertaken on three types of sample: **1)** drilling core, **2)** seabed sediment core, and **3)** near-bottom seawater. Geochemical analysis of seabed sediment core commonly uses total organic carbon analysis and gas chromatography.

OBJECTIVE OF STUDY

The objectives of this study are to investigate the presence of biogenic gas based on acoustic evidence supported by geochemical analysis of marine sediment cores, particularly the total organic carbon and gas chromatography. This information would be the initial key to biogenic gas exploration, safe drilling and a better understanding of geological knowledges.

SETTING OF THE STUDY AREA

The study area (Figure 1) lies among four prominent physiographic features i.e. Yapen Island, Mainland of Papua, Cendrawasih Bay and the Caroline Sea. In general, Papua Island formed at the convergent margin between the Indo-Australian continental plate and oceanic plate - either the Pacific Plate or the Caroline Plate (Hamilton, 1979; Dow & Hartono, 1982; Hutchinson, 1989; Longley, 1997; Hall, 2002). Convergence of the Indo-Australian Plate and the Caroline-Pacific Plate is continuing. Orientation of the convergence is about 35° NE based on recent measurement (McAdoo & Haebig, 1999). This orientation is parallel to the coast line of New Guinea, roughly the east-west trace of the New Guinea Trench and Yapen Fault Zone.

A magmatic arc complex and forearc basin formed along the convergent margin between the Caroline-Pacific Plate and Indo-Australian Plate, likely during Palaeocene. Late Cretaceous to Early Tertiary collision occurred between the magmatic arc complex and Indo-Australian Continent, followed by suture of the arc in the Late Miocene (McAdoo & Haebig, 1999; Noble *et al*., 2016). The east-west trending mountain ranges of North Papua, New Guinea and Yapen Island reflect this collision.

Focus of the study area is Waropen Bay, a sub-basin of the North Papua Basin in which a forearc basin developed between the New Guinea Trench and the magmatic arc occurred at Paleocene time. During collision of the arc and Indo-Australian Plate, the North Papua Basin had experienced in basin subsidence with rapid sediment deposition. The North Papua Basin is elongated with its long axis trending generally east-west, approximately 600 to 700 km in length, 200 to 250 width and 3 to 8 km of sediment fill thickness.

The stratigraphy of the North Papua Basin is illustrated in Figure 2. The study is focused to the uppermost strata, Pliocene to Holocene, which consists of Mamberamo and Koekoendoeri formations. The Mamberamo Formation deposited in the fluvial, deltaic and bathyal environments.

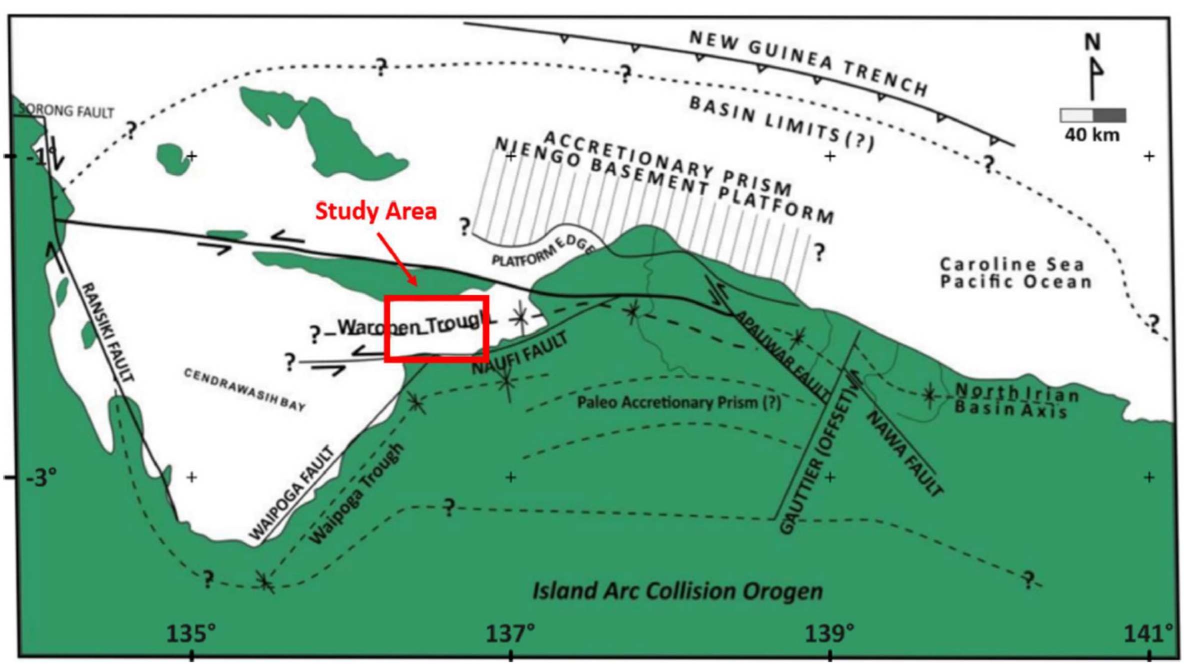

Figure 1: Study area located at Waropen Bay, a sub basin part of North Papua Basin (McAdoo & Haebig, 1999; Noble *et al*., 2016).

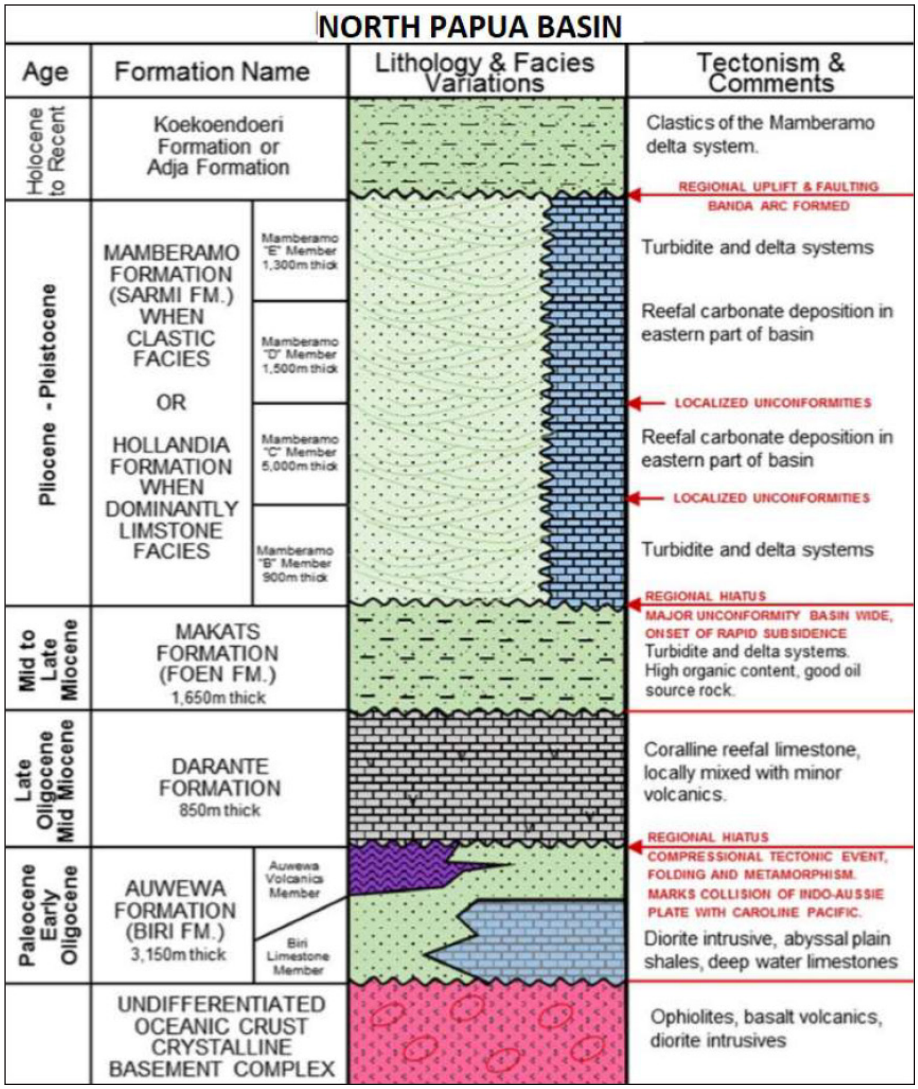

Figure 2: Stratigraphy of North Papua Basin (McAdoo & Haebig, 1999).

The Mamberamo Formation is overlaid unconformably by Koekoendoeri Formation which is alluvial deposits (McAdoo & Haebig, 1999).

MATERIALS AND METHODS

The acoustic survey was using Sub-Bottom Profiling (SBP) and Multibeam Echosounder. The line spacings is 2.5 km in E-W direction and 5 km in N-S direction. SBP data were acquired using chirp system-Syqwest Bathy 2010-3.5 kHz, and multibeam data were acquired using Simrad EM3000. The total SBP line surveys is approximately 730 km, covering an area of about 900 km^2. Multibeam was only recorded on line survey with north-south direction. SBP data were processed using SonarWiz5 and Kogeo, while Multibeam Bathymetric Data were processed using Eiva.

Sediment cores were obtained from 12 locations using gravity corer which has a core liner up to 4 m in length (Figure 3). The maximum length of the cores recovered is approximately 2.7 m. Core samples for sedimentological analysis were preserved and then subjected to grain size and geochemical analysis, such as total organic carbon (TOC) and Gas Chromatography (GC). TOC analysis was carried out by the Geochemical Group of the Center for Research and Development of Oil and Gas Technology (*Lemigas*) using the LECO carbon analyzer instrument. GC analysis is directed to determine the composition of the hydrocarbon gas contained in the sediment samples.

RESULTS

Acoustic evidence of shallow gas accumulations

Shallow gas plumes rise towards the surface under the influence of buoyancy, but the ability to rise is controlled by the nature of the overlying sediments and the availability of migration pathways; fault and weak zone.

Fault is migration pathways of the gas to escape to the upper deposits, but this geological structure was not identified along all SBP profile. Low permeability of the overlying sediments could become seal facies and prevent

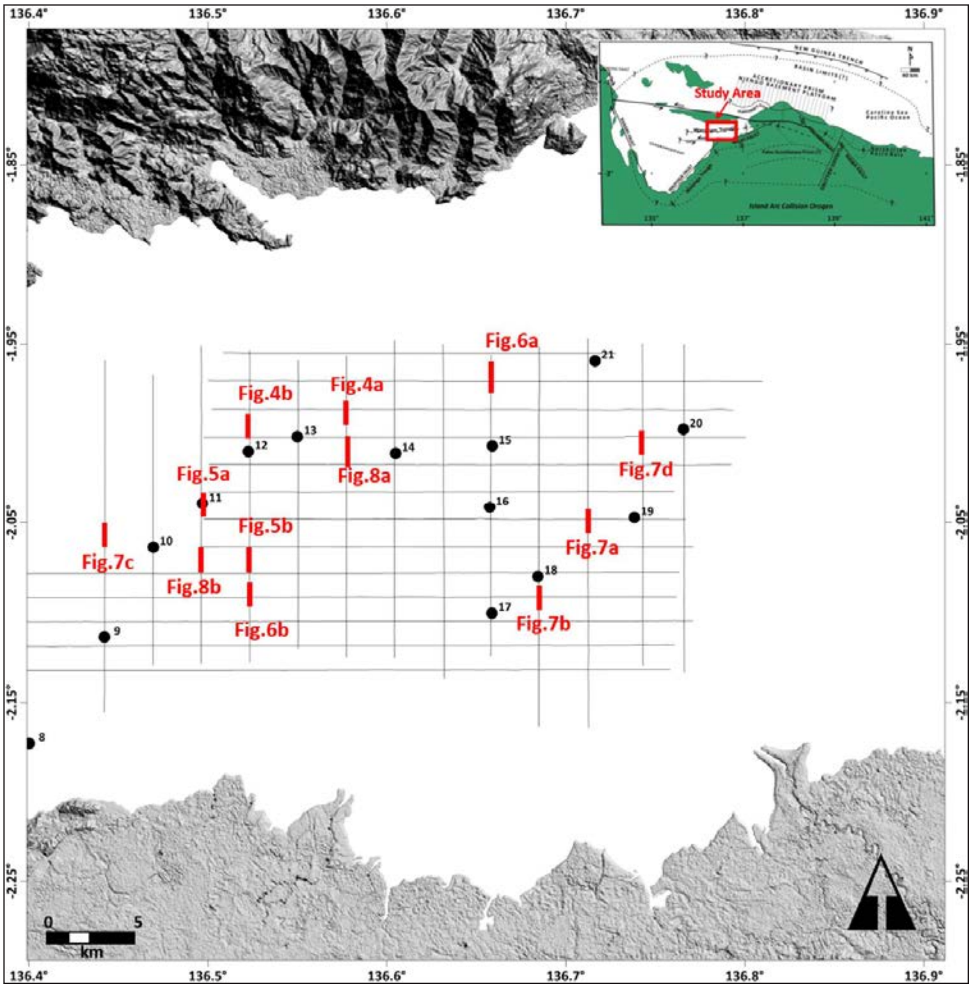

Figure 3: The study area, showing survey lines and locations of sediments cores (black dot).

gas escape to the upper deposits, while high permeable or unconsolidated overlying sediments let the gas escape.

Zone with permeable seal facies is namely weak zone. These conditions state that gas accumulation and gas venting in the study area are controlled by nature of the overlying sediments.

Gas accumulation in the sediment - gas bearing sediment are widely observed almost all over the study area. These sediments are characterized by different acoustic reflectors on SBP data, such as acoustic blanking and columnar disturbances. Gas escape is also identified at certain region as morphological feature – pockmark and acoustic plume, which then is verified with multibeam bathymetric data. Details of acoustic and morphological evidence of gas accumulation and gas escape are as follows:

High amplitude reflections and columnar disturbances

Presence of gas features characterized by high amplitude reflections, which appears as a strong reflector at top boundary where the gas accumulated. They usually mask the deeper event due to the presence of gas on sediments absorbs the energy of acoustic waves (Hovland & Judd, 1988; Garcia-Gil *et al*., 2002; Vardar & Alpar, 2016), while columnar disturbances or gas chimneys identified on sub-bottom profiler data as vertical feature across the shallow geological layers indicative of upward migration of shallow gas.

These types of gas often reaches the seafloor and follows seabed morphology. It was appearing as masking amplitude above columnar disturbances (Vardar & Alpar, 2016). Acoustic evidence represents gas accumulation could be seen in Figure 4. Columnar disturbances was found in Late Quaternary deposits and observed at 126 locations.

Acoustic blanking

Acoustic blanking appears as acoustic masking or reflection free zone (Hovland & Judd, 1988), a result of energy absorption that imply gas content. Acoustic blanking could become an indicator of gas accumulation when accompanied by enhance reflection at top boundary where the gas accumulated.

These types of gas accumulations (Figure 5) are observed on SBP profile observed at 56 locations. These zones contain gas (Judd & Hovland, 1992; Garcia-Gil *et al*., 2002; Vardar & Alpar, 2016). Methane gas accumulated in the study area is thought to be trapped in the upper sediment deposits of the Late Quaternary age.

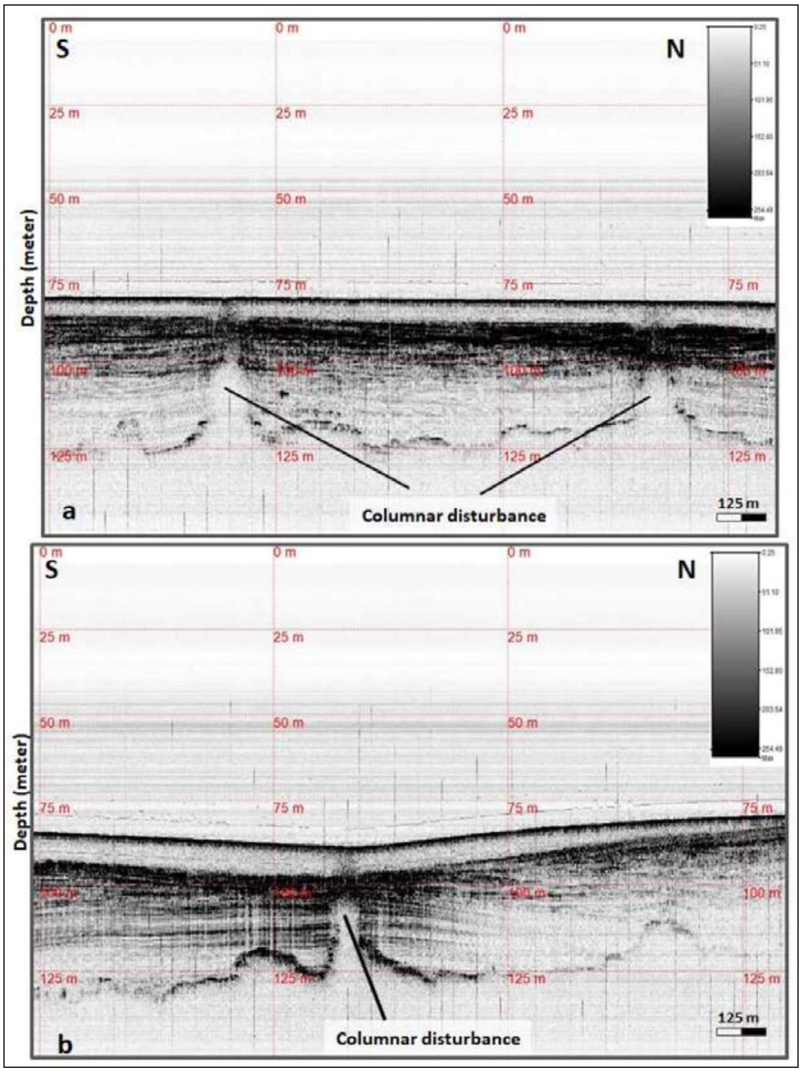

Figure 4: Data example of columnar disturbances in SBP profile C-17(a) and C-15(b).

Acoustic plume / gas

Acoustic plumes associated with gas escape through seabed are identified on SBP profiles. They appear as water column anomalies sticking above the seabed as a cloud. This acoustic character appears on SBP profile sometimes concurrent with pockmarks (Figure 6). Acoustic plume is observed at 19 locations.

Pockmark

Pockmarks (Figure 6) appear on the seabed as morphological evidence of fluid escape i.e. gas through the soft seabed sediments. This morphological feature show v-shaped profile. Pockmark are evenly distributed throughout study area, in total there are approximately 1001 pockmarks. Pockmarks in this region have been classified into four types; 1) unit pockmark; pockmark cluster which consists of small diameter pockmarks clustered together, 2) normal rounded pockmark, 3) elongated pockmarks. The rounded pockmarks are usually more recent and show clear shape. The elongated pockmarks are older and their appearance is indicative of water bottom current effects that are flowing in the elongated direction of the pockmarks, and 4) eyed pockmark (Figure 7); are actually seabed depressions with much larger dimensions and development of corals at the bottom. The corals appear due to changes in bottom water temperature and chemistry promoting development of marine growth. Normal and elongated types are the most common. Pockmarks are ubiquitous throughout the Waropen Basin, of varying dimension. The diameter of pockmarks in this area range from 5 to 90 m while depth can vary from 0.72 to 15 m (Lestari, 2019). Spatial distribution of pockmarks indicates shallow gas accumulations throughout the study area.

Geochemical evidence

Surface sediment cores have been acquired at 12 locations using gravity corer. The length of sediment cores varies between 40 – 267 cm. Grain size analysis has classified the sediment textures into: sandy clay, silt and sandy silt. Composition of sandy sediments consists of

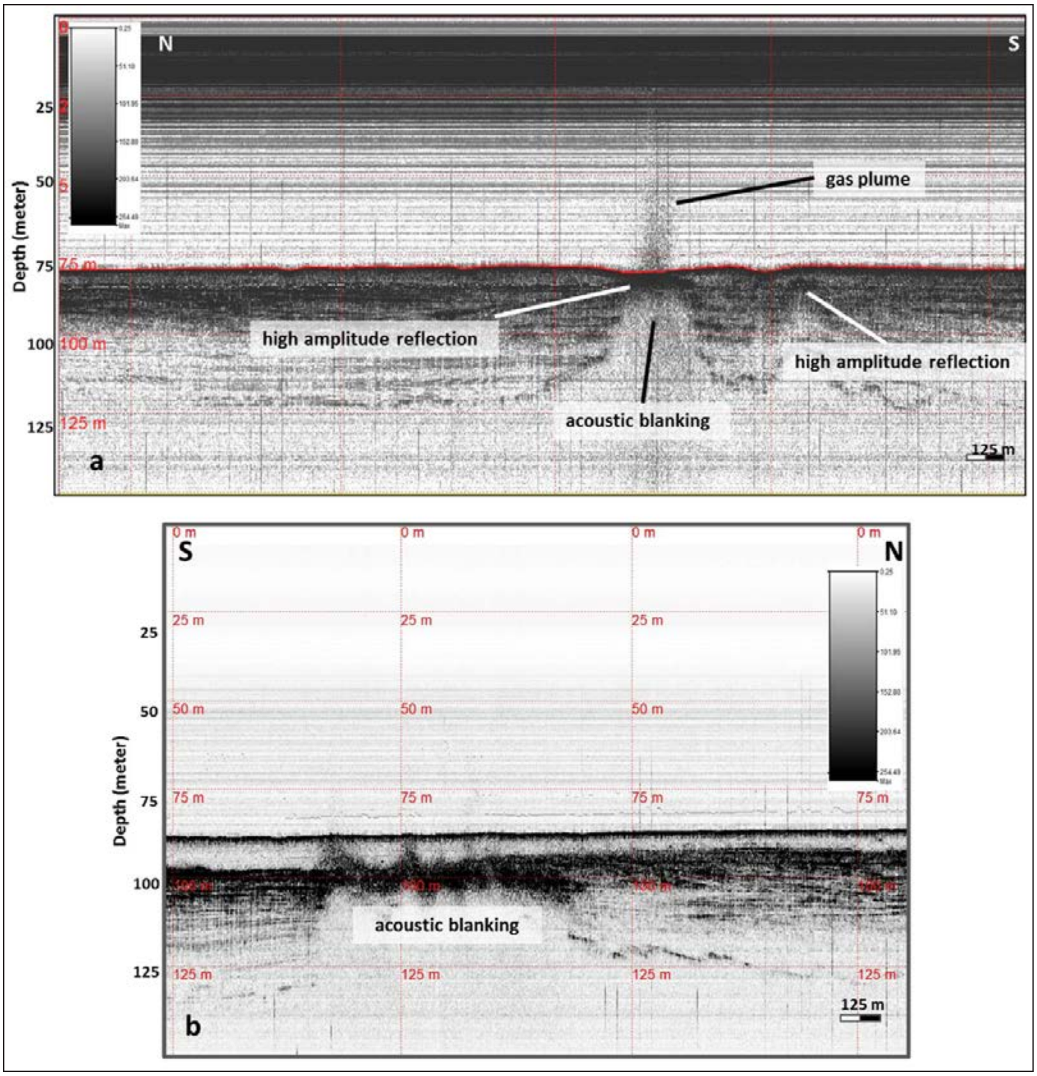

Figure 5: Data example of acoustic blanking in SBP profile C-14 and C-15. (a) Enhanced reflection also appears on the top of acoustic blanking in profile C-14, and likely released to water-column as an acoustic plume feature.

silt or clay mineral with shells fragments of foraminifera and gastropod.

Geochemical analysis has been carried out using Total Organic Carbon (TOC) and Gas Chromatography (GC). Total Organic Carbon content of 12 sediment cores varies from 0.5% to 1.3% (Table 1). The values indicate that the sediments have fair to good abundance of organic matter. Hydrocarbon composition identified by gas chromatography of sediments core indicates only methane. It indicates that the origin of the shallow gas is biogenic (Table 2).

Interpretation of sub-bottom profile

The sedimentary sequences are divided into three intervals, these are; sequence A of Pre- Late Pleistocene representing the deepest interval penetrated by acoustic waves. It is characterized by discontinuous low amplitude at the upper boundary. This sequence is overlaid by the second interval - sequence B suggested of Late Pleistocene unconformably, where its acoustic pattern is semi-parallel, continuous to a semi-continuous and strong reflector. In some parts. it seem to be folded and eroded (Figure 8). This sequence seems to have undergone an erosional process that was possibly during the lowstand of sea level or by differential uplift as this area is tectonically active. The uppermost interval - sequence C of Holocene is characterized by transparent reflector overlaying the second interval unconformably. This uppermost interval suggests it is undergoing the highstand of sea level till the present day.

DISCUSSION

Gas accumulation is controlled by sedimentary facies, permeability, porosity and quantity of gas (Saint-Ange *et al*., 2014). The sedimentary facies will control the gas to be accumulated or escaped because sediments can become a seal facies. In the study area, the sedimentary facies are sediment deposited during Pre-Late Pleistocene and Holocene.

The important factor controlling the accumulation of shallow gas is the porosity of gas bearing sediments and permeability of seal facies. Areas with gas accumulations are associated with intervals with high porosity sediments

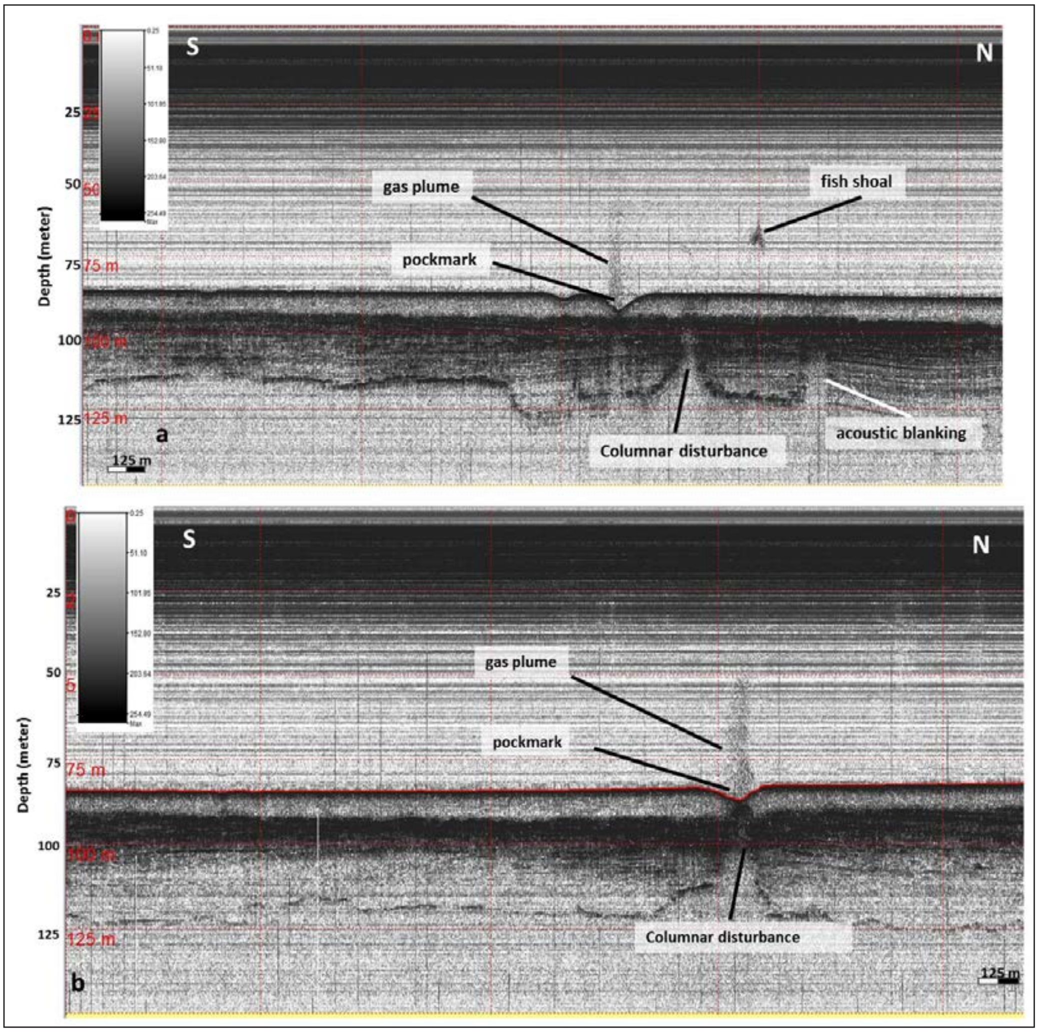

Figure 6: Data example of acoustic plume in SBP profile C-15 and C-20. Acoustic plume on this survey area always correlated with pockmark and columnar disturbance. Another acoustic anomaly in water-column such as fish shoal also appear and can be distinguished with acoustic plume (Figure 6a).

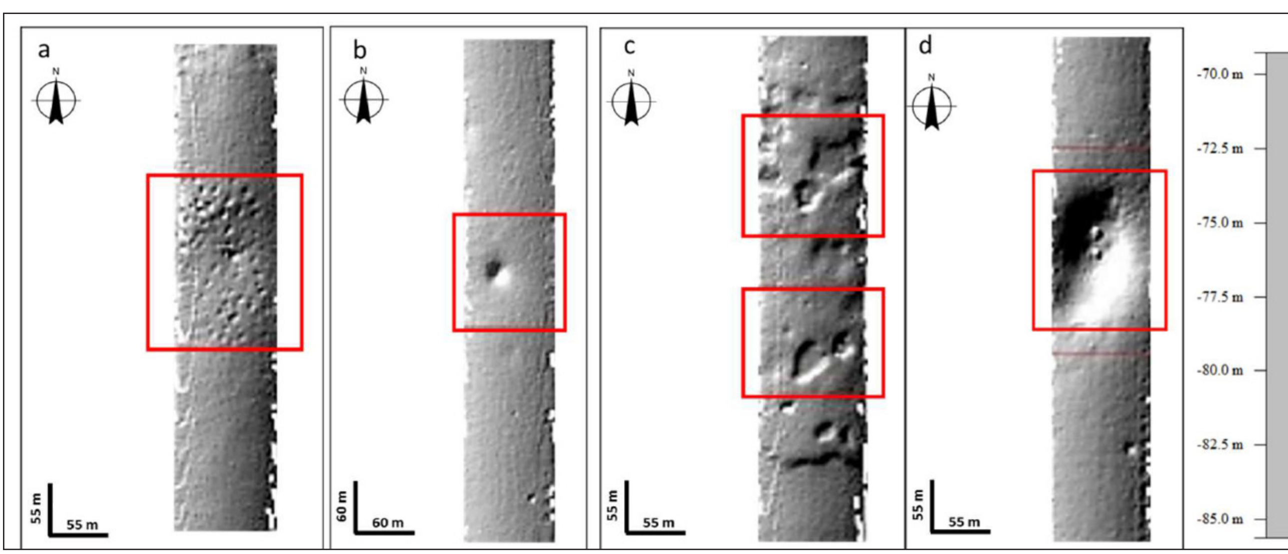

Figure 7: Multibeam bathymetric showing four type of pockmarks, a) unit pockmark, b) normal pockmark, c) elongated pockmark and d) eyed pockmark. Shaded bathymetric grayscale generated with light direction of 45^o azimuth and 65^o altitude.

Table 1: Results of TOC analysis of 12 surface sediment cores.

No.	Sample Code	Depth of Core (cm)	TOC (%)	No.	Sample Code	Depth of Core (cm)	TOC (%)
1	WPG-09	90.00	0.98	13	WPG-09	181.00	0.65
2	WPG-10	80.00	0.85	14	WPG-10	167.00	0.74
3	WPG-11	92.00	0.57	15	WPG-11	187.00	0.59
4	WPG-12	132.00	0.84	16	WPG-12	252.00	0.85
5	WPG-13	92.00	0.81	17	WPG-13	157.00	0.79
6	WPG-14	177.00	1.14	18	WPG-14	205.00	0.90
7	WPG-16	82.00	1.11	19	WPG-16	169.00	0.82
8	WPG-17	82.00	0.91	20	WPG-17	169.00	0.88
9	WPG-18	87.00	1.09	21	WPG-18	181.00	0.87
10	WPG-19	96.00	0.92	22	WPG-19	195.00	0.92
11	WPG-20	90.00	0.94	23	WPG-20	180.00	0.95
12	WPG-21	117.00	0.89	24	WPG-21	180.00	0.80

Table 2: Results of gas chromatography analysis of 12 surface sediment cores.

No.	Sample Code	CO_2	O_2	N_2	C1	C_2	C_3	iC4	nC4
1	WPG-09	0.15	15.68	83.85	0.31	0.00	0.00	0.00	0.00
2	WPG-10	0.13	13.26	86.27	0.34	0.00	0.00	0.00	0.00
3	WPG-11	0.71	18.83	80.25	0.20	0.00	0.00	0.00	0.00
4	WPG-12	0.19	16.64	82.81	0.35	0.00	0.00	0.00	0.00
5	WPG-13	0.19	15.26	84.27	0.28	0.00	0.00	0.00	0.00
6	WPG-14	0.11	17.61	81.98	0.30	0.00	0.00	0.00	0.00
7	WPG-16	0.10	17.06	82.57	0.28	0.00	0.00	0.00	0.00
8	WPG-17	0.08	16.95	82.79	0.18	0.00	0.00	0.00	0.00
9	WPG-18	0.36	16.34	84.97	0.33	0.00	0.00	0.00	0.00
10	WPG-19	0.00	14.48	83.21	0.55	0.00	0.00	0.00	0.00
11	WPG-20	0.26	16.20	70.09	0.32	0.00	0.00	0.00	0.00
12	WPG-21	0.41	29.37	70.09	0.14	0.00	0.00	0.00	0.00

overlaid by low permeability sediments. They are characterised by enhanced amplitude reflections and associated acoustic blanking. While, gas chimneys occur in areas dominated by high porosity sediments overlaid by high permeability or unconsolidated seal facies.

Sub-bottom profile records provide evidence of gas accumulation throughout the Waropen Basin. Gas accumulation characterized acoustically in columnar disturbances or gas chimney are mostly present in marine deposits of Quaternary age. Columnar disturbances features are distributed in the western and northern parts of the study area. Other gas accumulation showing acoustic blanking features are mostly distributed in the eastern part, and some identified in the southern part of the study area. Gas bearing sediment in the study area is mostly identified as Late Quaternary deposits.

Gas venting identified in the SBP as acoustic plume is typically characterized by the masking amplitude in the water column. The acoustic column identification must consider masking amplitude in the water column and acoustic anomalies that appear in the subsurface to avoid misinterpretation due to similar features between gas venting and fish shoals or other marine life. Both masking amplitude and other anomalies such as columnar disturbance or acoustic blanking appear simultaneously in the SBP profile. In the study area, masking amplitude that is associated with acoustic plume is usually seen starting from the seabed along tens of meters.

Presence of gas is evident at the river mouth and is supported by seismic attributes such as enhanced acoustic amplitude reflections, acoustic blanking and more common gas chimneys.

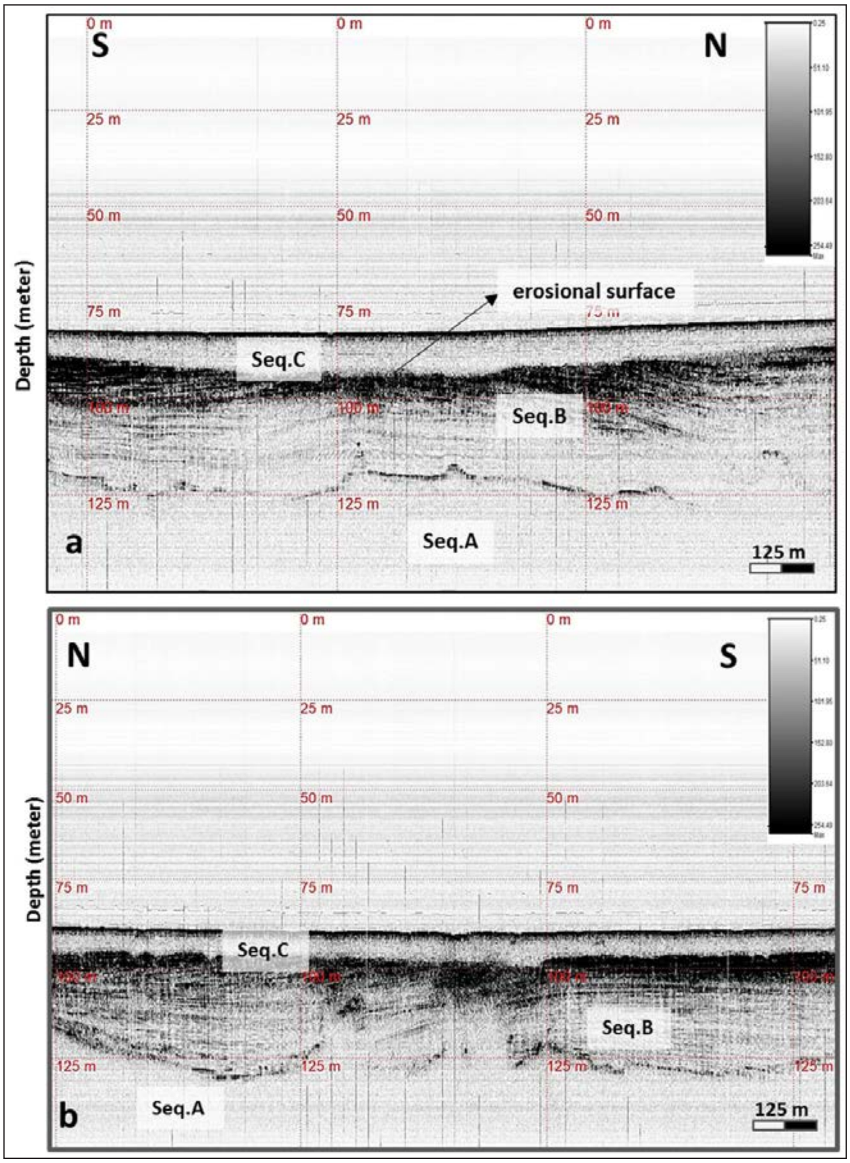

Figure 8: Data example of interpretative sedimentary sequences. Sequence B interpreted as a Late Pleistocene sediment which has semi parallel, continuous to semi-continuous reflector, and eroded (a), also folded (b) in some part.

Pockmarks are morphological features indicative of fluid escape most probably gas from underlaying sediments. Gas plumes occasionally associated with the pockmarks are another good evidence of gas escape through migration pathways across near surface geology. These pathways could not be depicted on the sub-bottom profiler records due to acoustic blanking.

Grain size analysis of 12 cores indicate the surface sediment in the study area to consist mainly of unconsolidated sandy clay, silt and sandy silt. Composition of the sandy sediments cores consists of silt or clay mineral with shells fragments of foraminifera and gastropod. The composition of hydrocarbons extracted from the surficial sediments/ drop cores resulting from gas chromatography analyses is dominated by methane gas produced by bacterial degradation of organic matter at low temperatures. Based on these results, it is assumed that the shallow gas within the basin is biogenic methane (Missiaen *et al*., 2002). Distribution of gas accumulation and gas venting shown (Figure 9) implied that there was abundant organic matter deposited during the sedimentary process in Late Quaternary periods that led to biogenic gas evolution.

CONCLUSIONS

This indirect evidence of shallow gas distribution throughout the Waropen Basin is completely proven. Acoustically, the occurrence of gas accumulations observed on SBP profiles is indicated by columnar disturbances and acoustic blanking features.

Gas escape was identified by the presence of acoustic plume and morphological depression-pockmarks.

Origin of the gas accumulated in the study area is biogenic methane. Gas accumulations mostly are trapped within the Late Quaternary deposits.

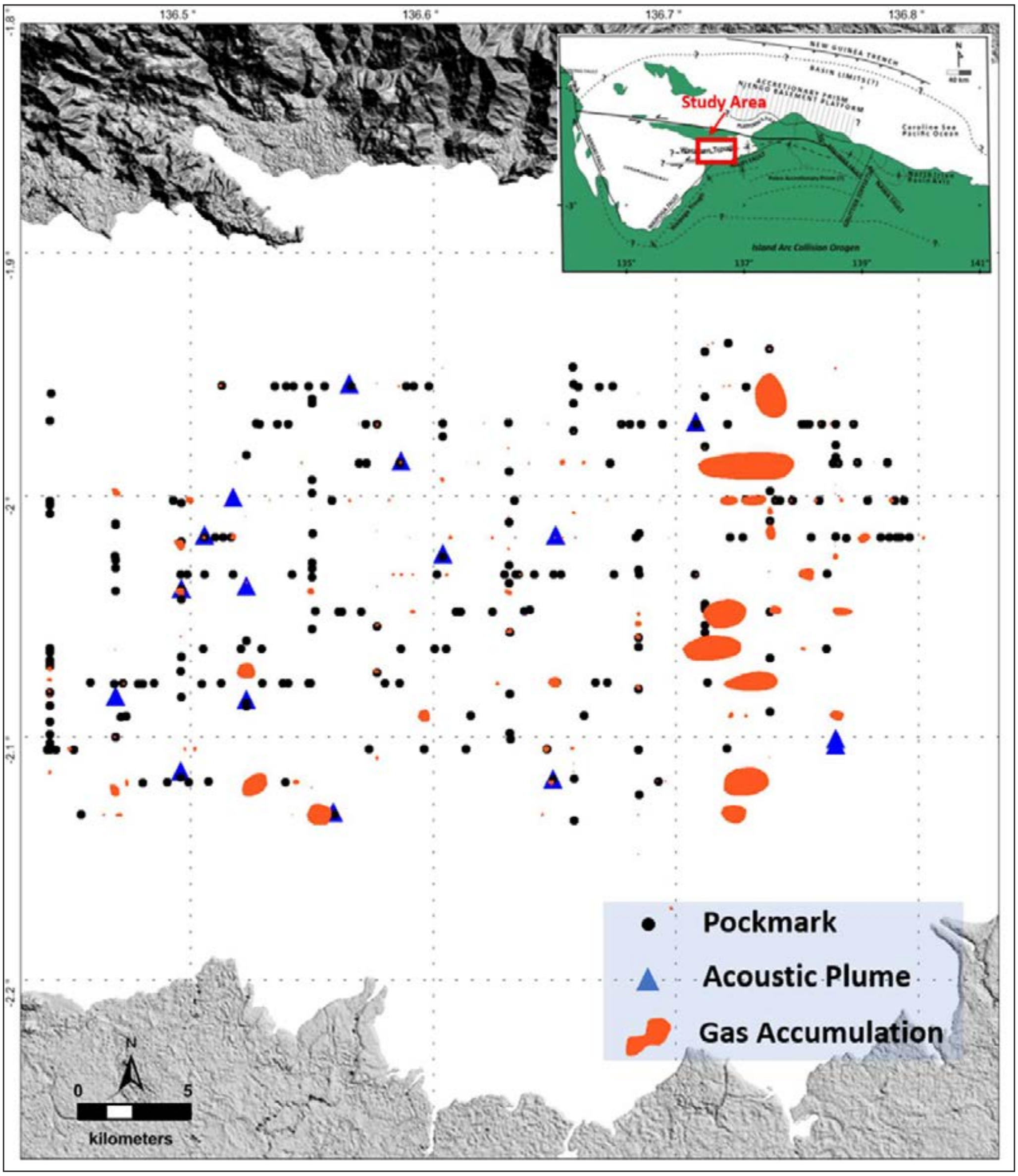

Figure 9: Distribution of gas accumulation and gas venting in the Waropen Basin.

High permeability of seal facies permits gas escape to the seafloor and form numerous morphological depression such as pockmarks, while low permeability of seal facies prevent gas from escaping and it was accumulated in the Late Quaternary deposits.

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