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The Occurrence of Recent-Subrecent Seabed Acoustic Anomalies and Its Relationship with Structural Uplift around the Waipoga Trough, West Papua-Indonesia

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Abstract - Marine Geological Institute acquired high-resolution seismic and acoustic data during a survey in the Waipoga Trough-West Papua in 2018. The profiles show acoustically blanking, turbid, and cloudy occur along the trough floor over 3,000 km^2. Many accoustic chimneys are breaking through the seabed of recent and subrecent sediment layers. It is suggested due to the local expulsion of methane gas. The pockmarks occur as transparent and turbid acoustic characteristics. They locally have relief down to 2-10 m below the seafloor with horizontal dimensions up to 25 -100 m in width. Methane formation due to the rapid deposition of organic-rich sediment down the uplifted area around the trough, associated with thrust fold tectonics is suggested as a triggering agent for the acoustic anomaly formation.

Keywords: Waipoga Trough, seabed, acoustic, pockmarks, differential uplift, sedimentation

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Introduction

Background

The increase in oil and natural gas consumption as the primary energy sources in Indonesia encourages the government to make efforts for optimal energy fulfillment scenarios to realize the resilience of domestic energy reserves and supplies. One of them is through the main policy programme of the National Energy Committee (KEN) since 2005, namely increasing oil and gas exploration activities in new areas, including frontier and marine areas, as well as an inventory of potential biogenic gas resources from the Mio-Pliocene to Plio-Pleistocene age at a water depth of shallower than 1,000 m.

Marine Geological Institute is a research institution that has been required to provide introductory marine geology and geophysic data supporting the exploration programme. In addition, the RV Geomarin III, with qualified geophysical and geological equipments, was counted on to support study in a frontier area, particularly for biogenic gas potential targets. In 2015, the National Energy Committee recommended research on biogenic gases in ten Tertiary Basins in Indonesia, including Sibolga Basin, Central Sumatra, South Sumatra, Northwest Java, Northeast Java, Barito, Kutai, Tarakan, Sengkang, and Waipoga. Seven basins are proven to contain biogenic gases, and three of those basins are in the frontier area, including the Waipoga Trough.

Based on KEN recommendations and proposed research locations, the Marine Geological Institute has conducted a biogenic gas study in Waipoga Trough, in which the first and third authors of the present paper were involved as team members. This study aims to determine the relationship between the occurrences of recent-subrecent seabed acoustic anomalies (some called pockmarks) with the differential tectonic uplift of the surrounding areas resulting in a high organic-rich sedimentation down to the Waipoga Trough.

Regional Setting

The northern coastline of West Papua-Indonesia, where Cendrawasih Bay is situated, is one of the most tectonically active areas in the world due to the complex interaction of the Eurasian Plate in the west, the Philippine Sea Plate in the northwest, the Banda Sea Plate in the southwest, the Australian Continental Plate, and the Pacific-Caroline Plate in the northeast (Hamilton, 1979; Benz *et al*., 2011; and Hall, 2012). It is also considered as a hybrid forearc basin subduction-related accretionary prisms that are also part of the North Irian Basin, which lies between the Central New Guinea Mountain Ranges and the New Guinea Trench (McAdoo and Haebig, 1999). According to Charlton (2010), Cendrawasih Bay or Cendrawasih Basin is one of the physiographical characteristics of northern Papua. Cendrawasih Basin is the depocentre in a strange triangle on the north coast of Papua, separating the Bird Head and Bird Body, filled by Plio-Pleistocene sediments with a thickness of more than 4 km (Nobel *et al*., 2009) or even >8km sequence of undated deposits (Babault *et al*., 2018).

The studied area (Figure 1) is situated in the eastern corner of Cendrawasih Bay, commonly called the Waipoga Trough (Firdaus *et al*., 2021). Three main geological structures border Cen-

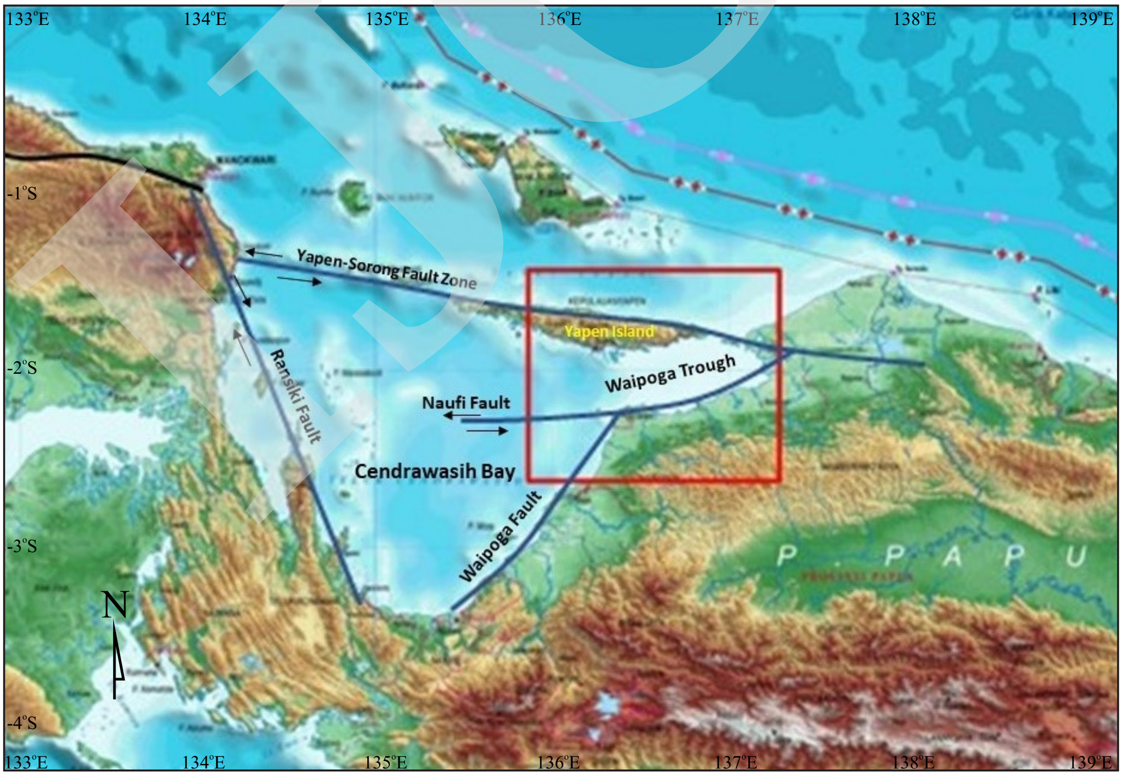

Figure 1. Major tectonic elements in Cendrawasih Bay. A red box indicates the location of the study in the Waipoga Trough. (Modified from Badan Informasi Geospasial, tanahair.indonesia.go.id, 2017).

drawasih Bay, those are the Yapen-Sorong Fault Zone to the north, the Ransiki Fault to the west, and the Waipoga Fault to the southeast. The Naufi Fault intercepts the Waipoga Fault and merges with the Yapen-Sorong Fault Zone flanking the eastern corner of Cendrawasih Bay. The trough is elongated in an east-west direction with a water depth of tens to 50s of meters and deeper to the centre of the Cendrawasih Bay, which is more than 1,250 m.

Methods

The subsurface survey of the seabed used the SyQwest Bathy 2010 Chirp Subbottom Profiler (SBP). A total of fifty-seven SBP trajectories with a total length of approximately 1,920 km have been obtained from September 23rd 2018 to October 7th 2018. Since SyQwest Bathy 2010 works using approximately 3.5 kHz, surficial sediment up to 30-40 m thick can be described in detail with high-resolution SBP data output in ODC. The format is then converted into a seg-y format for interpretation.

In addition, 2D multichannel seismic reflection data collection in the studied area was conducted using a 1,500 meters long Sercel Seal Streamer consisting of 120 active channels. Eight airguns of G-Gun II with a total array capacity of 1220 Cu inch were used. Compressed air was supplied by two units of the compressor of 800 SCFM capacity each at 2000 Psi working pressure. NaviPack triggered the system. A navigation system received position signals from a C-NAV Differential Global Positioning System (DGPS).

Results

Sub-Bottom Profiling (SBP) records from the offshore Waipoga Basin are presented. The occurrence of gas in the sediment layer significantly affects the SBP records because of its acoustic energy dissipation, resulting in various disturbance appearances in seismic reflection (Weering *et al*., 1989). SBP records are high resolution that can display images of sediment layers below the seabed up to several tens of meters, so that many acoustic features that characterize sediment-bearing gas can be distinguished. These features include pockmarks, acoustic blanking and turbidity, bright spots, and columnar disturbances (Missiaen *et al*., 2002; Tiehu *et al*., 2009; Chen *et al*., 2010; Hosseinyar *et al*., 2014). Acoustic and geochemical evidence in the Waipoga Trough indicate an extensive shallow gases accumulation in recent to subrecent sediments, some are trapped within these deposits, and some are escaping from the seafloor into the water column, creating a high-density pockmarked distribution (Figure 2).

Acoustic Turbidity and Acoustic Blanking

The acoustic blanking feature is an acoustic anomaly that occurs due to the disturbance of the sediment layer by gas migration or absorption of acoustic energy in the sediment-bearing gas above it (Schroot and Schüttenhelm, 2003). This feature is the most common phenomenon in every SBP record in the Waipoga Trough (Figure 3). Acoustic blanking features lie 10 to more than 15 m beneath the seafloor. While acoustic turbidity masks reflectors into chaotic and shallower positions (Missiaen *et al.*, 2002), even in some locations, this anomaly was found reaching the seafloor and appears as a sediment cloud anomaly in the water column.

Pockmark and Sediment Cloud

The pockmark feature on the seabed surface is a depression formed by local gas escaping into the surface (Hovland and Judd, 1988). Pockmarks are formed in fine-grained sediment layers due to the release of fluids or gases into the water column (Hovland and Judd, 1988; Firdaus *et al*., 2021). In acoustic profiles, pockmarks are expressed as minor depressions on the seabed surface. The pockmark features identified in the Waipoga Trough are associated with acoustic chimney features generated in the Pleistocene (?) sedimentary layer. A high amplitude anomaly (acoustic turbidity) in the Holocene sediment layer deposited above it

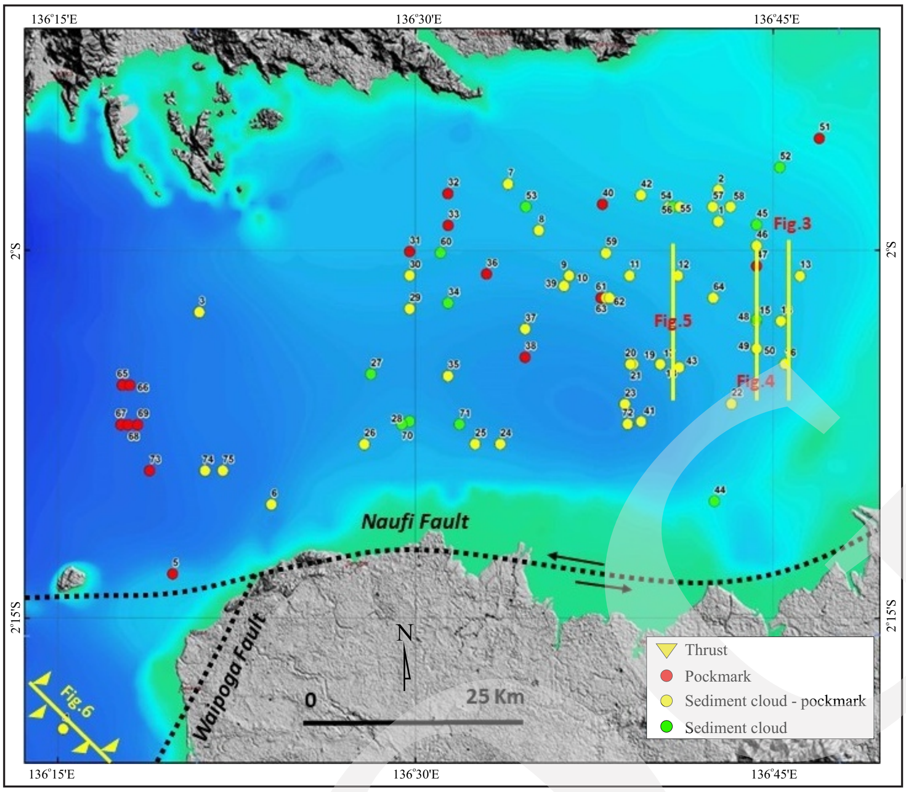

Figure 2. Map of acoustic anomaly distribution in the Waipoga Trough. The heavy lines illustrate the seismic and acoustic trajectories reproduced in Figure 3, Figure 4, Figure 5, and Figure 6. Note: Naufi-Waipoga Thrust Fold Zone indicated by yellow triangle symbols.

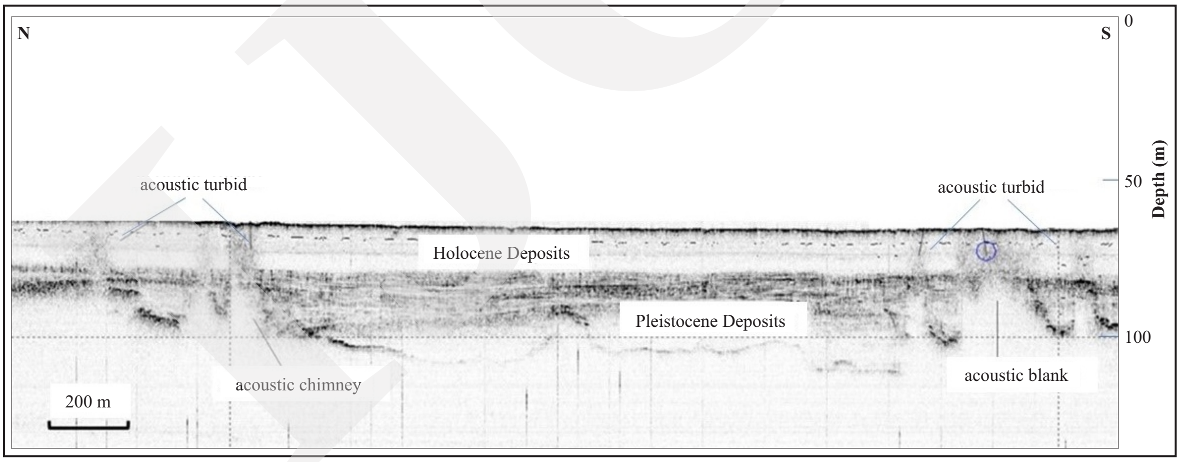

Figure 3. Accoustic turbidity and acoustic blanking indicated in SBP Line C-24. Note: the appearance of acoustic chimneys seem to break through the seabed (For the location, see Figure 2).

indicates a shallow gas accumulation at that location. In the centre area of the studied location, many pockmark features (Figure 4) are also associated with sediment clouds (Figure 5) within the sediment-water column interface, which indicates an active pockmark as a location for gas seepage.

Seismic Structures of Naufi-Waipoga Thrust Fold Zone

Following the morphological expression terms of the thrust-fold zone of Hesse *et al*. (2010), the Naufi-Waipoga Thrust Fold Zone (Figure 6) shows various compressional, syn-depositional

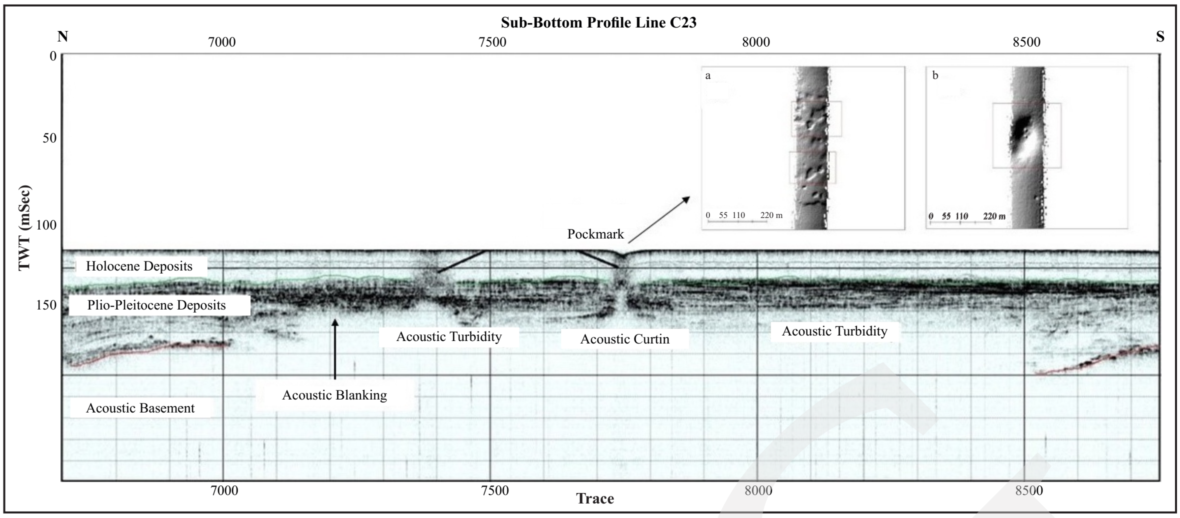

Figure 4. SBP profile from Waipoga Trough shows various acoustic anomalies such as turbid and curtain. Insets a and b show the variation of pockmark types; some are grouped, and some are as a single crater (For the location, see Figure 2).

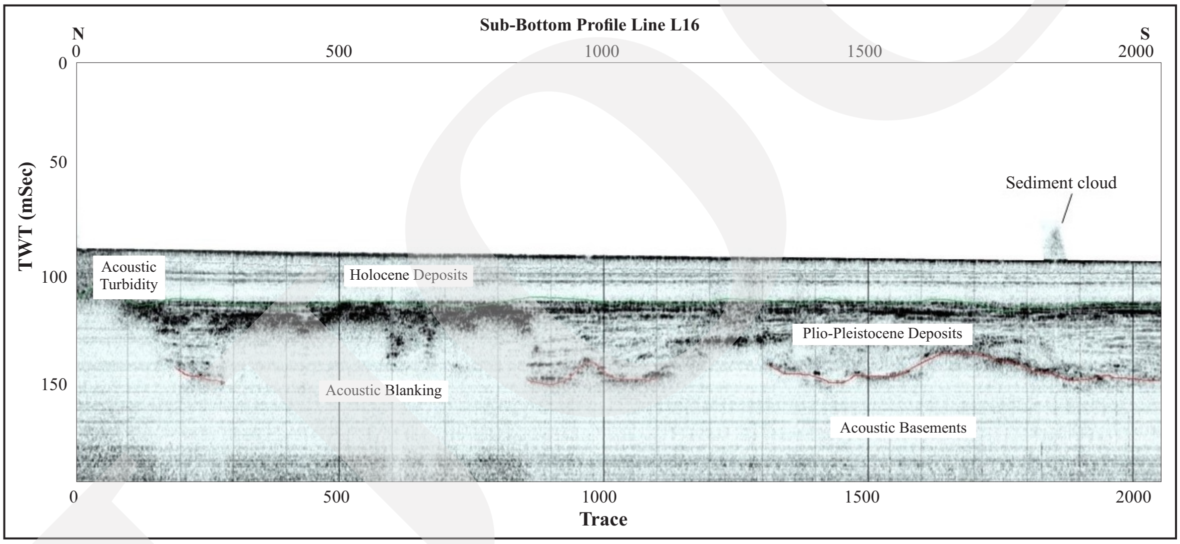

Figure 5. SBP profile from Waipoga Trough shows various acoustic anomalies, such as turbid, blanking, and sediment clouds (For the location, see Figure 2).

deformation features, and large-scale thrust faults. The anticlines are primarily asymmetric, with varying interlimb spans from 3-8 km. This morphological expression of the folds can be traced landward to form a). anticlines with large interlimb angles that represent no seafloor expression; b). anticlines with medium interlimb angles, seafloor relief, and a faulted anticline crest; c). anticlines with small to medium interlimb angles with a seafloor expression and flanks associated with slides and slumps down lap onto the back and forelimb; and d). thick and growth acoustically divergent strata commonly buried anticlines with small interlimb angles of sediment mass movement (slump?) or sediment-bearing gas.

Discussion

A high-resolution acoustic survey in Waipoga Trough revealed an extensive area marked by poor seismic penetration due to gas content in the subrecent sediment. The gas primary origin is in the shallow, organic-rich deposits of the

Late Pleistocene/Early Holocene age. The gas-related characteristics recorded on the acoustic profiles are mostly acoustic turbidity and blanking. Nobel *et al*. (2016) have conducted geological, geophysical, and deep-sea geochemical studies and explorations in the Cendrawasih Bay, where they demonstrated significant oil and gas seepages from biogenic sources on the seabed. Likewise, Nurwani *et al.* (2017), from their research in Cendrawasih Bay and Waipoga Trough, explained that hydrocarbons had a high potential, both thermogenic and biogenic.

Geochemical data from Waipoga Trough reveals 0.5% to 1.3% of organic carbon concentration, which shows that the sediments have a fair to a good abundance of organic matter (Firdaus *et al*., 2021). Since the hydrocarbon composition identified on the sediment samples is only methane, it suggests that the origin of the shallow gas was biogenic methane origin. However, some acoustic profiles indicate a local seepage of large bubbles or dissolved gas into the sediment-water interface, creating sediment clouds. Locally, the seepage of gas bubbles from many chimneys in the trough causes the depression, forming a big pockmark. As in the study of shallow gas distribution and acoustic characteristics in the Korea Strait Shelf (Kim *et al*., 2004), in the Waipoga Trough, their acoustic anomalies are increasing in the shallow waters. It indicates a relationship between a decrease in gas solubility and a decrease in water depth which consequently means a reduction in water pressure allowing gas release.

To obtain the relationship between the occurrence of the acoustic anomalies and the differential structural uplift around the Waipoga Trough, a high-resolution 2D seismic profile was used (Figure 6), which was considered the representative of the studied area, especially the southern flank of Waipoga Trough. Therefore, it is used as a model for discussion using the morphological terminology of the thrust fold zone introduced by Hesse *et al.* (2010).

Physiographically, the Waipoga Trough lies in the eastern corner of Cenderawasih Bay, where two stages of Cenozoic deformation have occurred since ~12 Ma in this tectonically active area. The first stage resulted in northwest-trending *en-echelon* folds and reversed faults. The second stage is a significant left-lateral horizontal fault subparallel to the regional strike of the inverted base (Ikhwanudin and Abdullah, 2014; Sapiie, 2016). In addition, the northeast-southwest trending belt system found in Cendrawasih Bay is the youngest deformation. It seems to associate with the current activity of the Yapen-Sorong Fault Zone that merges with the Sorong-Kofiau Fault segment west of Cendrawasih Bay (Permana and Gaol, 2018). These tectonic stages created an uplifted area around the Waipoga Trough and are thought to have served as a supplier of high-level terrestrial sediments since the Lower Pliocene. Rapid vertical uplifted and folded Upper Miocene to Lower Pliocene shallow marine muddy dominated the succession that unconformably underlain Pleistocene coral reef deposits also found in the northeastern Bird Head Peninsula (Gold *et al*., 2017; Saputra *et al*., 2022).

Seismic interpretations (Figure 6) show rapid geological structure and sedimentation growth. The shape of anticlines in the Naufi-Waipoga Thrust Fold Zone shows a narrower angle and anticline span toward the mainland. In addition, it shows that the compression intensity is stronger landward. Furthermore, the thinning of the divergent acoustic strata between the anticline limbs towards the mainland indicates that the differential uplift intensity is getting faster. Thus, it is suggested a high sedimentation rate down to Waipoga Trough due to the rapid vertical uplift of the surrounding areas as represented by the uplift of the Naufi-Waipoga Thrust Fold Zone Ridge, and is responsible for the formation of biogenic gas expressed by various acoustic anomalies in Waipoga Trough.

It is suspected that sediments began to accumulate in the Cendrawasih Bay and on land in the Late Miocene since the growth of the Central Mountains twelve million years ago. Since the last three million years, the accumulation of Plio-Pleistocene sediments can reach 6.7-10 km thick. Thrusting and uplifting localized transten-

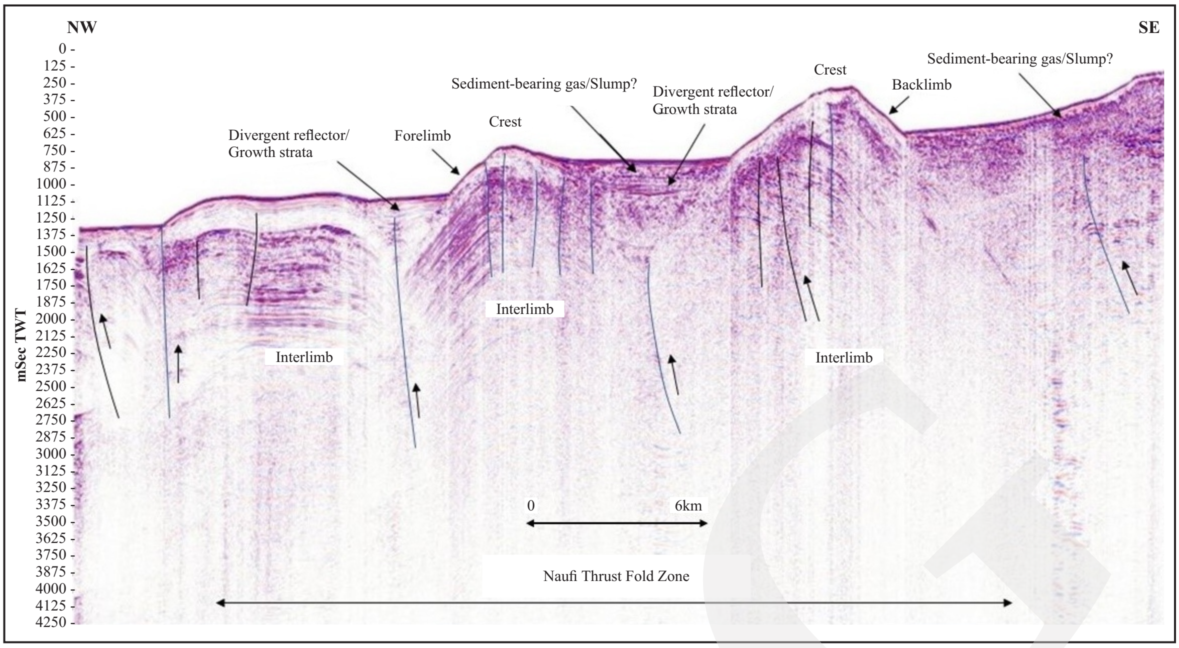

Figure 6. The seismic profile indicates Nauifi-Waipoga Thrust Fold Zone. Note that divergent reflection patterns within growth strata characterize uplifting lap onto the forelimb and backlimb of folds (For the location, see Figure 2).

sion and thrust tectonics may explain these high sedimentation rates in the overall sinistral sloping convergence setting (Babault *et al*., 2018). A spectacular east-west trending thin-skinned fold-thrust-belt system known as Naufi-Waipoga Fold Thrust Belt is primarily responsible for forming uplifted areas since the Late Pliocene (for details, the reader is referred to the deformation pattern and fault style map of Bird Head Region of Papua, Cendrawasih Bay Fold Thrust Belt – CBFTB of Sapiie *et al*. (2012).

Conclusion

Acoustic anomalies recorded by the subbottom profiler in the Waipoga Trough show the presence of biogenic gas in the sediment layer in the form of acoustic blanks, acoustic turbidity, and acoustic chimney features, as well as gas seepage. In addition, abnormal characteristics of sediment clouds and pockmarks on the seabed surface also characterize the anomaly. The rapid deposition of organic-rich sediments down to the trough associated with local transtension tectonics may explain this extraordinarily high sedimentation rate in overall sinistral slope convergence, and is suggested as a triggering agent for sediment accumulation leading to biogenic gas generation by a vertical differential uplift of a ridge along the Naufi-Waipoga Thrust Fold Zone high-angle fault

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