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Deep Sea Mining of Submarine Hydrothermal Deposits and Its Possible Environmental Impact in Manus Basin, Papua New Guinea

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Abstract

The Manus back-arc basin host three distinct well known submarine hydrothermal deposits of Vienna Wood, Pacmanus and Onsen sites. The Vienna Wood site is a typical Cu-Zn type of mineralization consisting predominantly of pyrite, marcasite, sphalerite, wurtzite and chalcopyrite. The Pacmanus site is a polymetallic type of mineral deposit consisting of sphalerite, chalcopyrite, bornite, wurtzite, pyrite, marcasite, enargite, tennantite, galena, Pb-As-Sulphosalt, gold, covellite, digenite and chalcocite. The Onsen site is the first deep sea acid sulfate type of mineralisationconsisting ofenargite, covellite, chalcopyrite, pyrite and marcasite.

The Papua New Guinea (PNG) Government has granted exploration license to Nautilus Mineral Cooperation to explore for submarine hydrothermal deposit in the Manus Basin. It has done extensive exploration around the existing hydrothermal deposits of Vienna Wood, Pacmanus and Onsen site. This has resulted in the discoveries of well over twenty hydrothermal deposits (Solwara 1 to Solwara 20). Nautilus Minerals has done resource drilling on Solwara 1 and Solwara 12 deposit due to its polymetallic type of mineralization and its geochemicalsimilarities to the Pacmanus site. From resources drilling, Nautilus Minerals reported an indicated and inferred mineral resource of 1030 kt and 1540 kt respectively for the Solwara 1 project at 2.6% Cu equivalent cut off grade. The PNG government has granted mining lease (ML154) to Nautilus Minerals to mine the Solwara 1 deposit in January 2012. If mining activity commences at the Solwara 1 site then Nautilus needs to address possible environmental impacts of water usage and discharge, water quality, sedimentation and dewatering and preservation of hydrothermal vent communities.

1. INTRODUCTION

Hydrothermal mineralization along the mid-oceanic ridge systems and back-arc basin spreading centers is one of the most actively researched subjects in the Earth Science. Most of these hydrothermal deposits are either end-products of simple basalt seawater interaction (e.g. Tag hydrothermal field, Hannington et al., 1988a) or felsic volcanic rocks seawater interaction with significant magmatic fluid involvement (e.g. Pacmanus site, Manus back-arc basin, Yang et al.1996; Binns et. al, 1995; and HinaHina site, Lau back-arc basin, Herzig et al., 1998). These hydrothermal deposits contain significant amount of metals which are of economical interest to mining companies.

The Manus Back-arc basin hosted three hydrothermal deposits. The Vienna Wood site in the Central Manus Basin (CMB) and Pacmanus and Onsen hydrothermal sites in the Eastern Manus Basin (EMB) spreading centres. These deposits have been documented by a lot of researchers (e.g. Both et al., 1986; Tufar, 1989; Scott and Binns, 1995; Binns et al., 1993; Gena et al., 1997). It was discovered that the Vienna Wood and Pacmanus hydrothermal deposits are present analogue of ancient Cu-Zn and Zn-Cu-Pb-Au type of deposit on land respectively while Onsite site is the first deep sea analogue of terrestrial high sulfidation type epithermal deposits. All these deposits have distinct mineral assemblages, chemistry and metal content compared to terrestrial analogues.

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The government of Papua New Guinea (PNG) has given exclusive exploration license to Nautilus Mineral Corporation to explore for these types of mineral deposits in the entire Manus Basin. Nautilus is currently doing aggressive exploration to quantify their resource in Solwara 1 and Solwara 12 projects which is located in the Eastern Manus Basin. Nautilus has reported grades better than terrestrial deposits of similar nature and has already acquired Mining license to develop these resources.

In this paper, I provide detailed mineralization processes, unique hydrothermal vent organisms and possible environment impacts if Nautilus Minerals decide to mine mineral resources within its leasesof in the Manus basin

2. GEOLOGICAL SETTING

The Manus back-arc basin is one of the immature back-arc basins of the southwest Pacific and is bounded by calc-alkaline volcanic islands of Manus, New Ireland and New Britain to the north, north-east and south respectively (Fig. 1A). The Manus back-arc basin consists of the Central Manus Basin (CMB) and Eastern Manus Basin (EMB) spreading centers. The CMB spreading centers are offset by the Dyaul and Willaumez transform faults to the east and west respectively (Fig. 1) while the Eastern Manus Basin (EMB) is bounded to the east by Weitin transform fault and to the west by Dyaul transform fault (Fig. 1).

The first discovery of hydrothermal activity in the Manus basin was the Vienna Wood hydrothermal system located in the CMB (Fig. 1, Auzende et al., 1996). It is well documented by a lot of researchers (e.g. Both et al. 1986; Tufar, 1989; Shadlun et al. 1993).

The Pacmanus hydrothermal system is located in the EMB, southwest of the calc-alkaline volcanic island of New Ireland (Fig. 1). The individual volcanic edifices in the EMB basin are generally perpendicular to the extensional zone and are dominated by felsic volcanic rocks of geochemically coherent fractionation series ranging from basalt to ryholite (Binns et al., 1995). The basement rocks are composed of rifted island-arc crust similar to Oligocene-Miocene exposure observed on the New Britain and New Ireland (Martinez and Taylor, 1996).

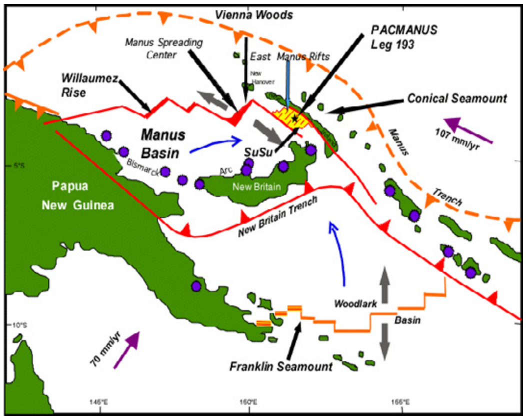

Figure 1. Regional tectonic setting of Manus back arc basin & locality of hydrothermal sites

The Desmos caldera is part of the Eastern Manus Basin (Fig. 1) and it was discovered by the AQUARIUM expedition in 1990 (Gamo et al. 1993). It is slightly elongated in the NNW direction with a dimension of 1.5 by 2.0 km and deep circular depression of about 150-250 meter. The vigorous venting milky-white smokers with low pH of 1.54 to 2.1 and temperatures of 88 to 120°C were discovered at the north-west terrace of the Desmos caldera during the 1995 ManusFlux cruise and called Onsen hydrothermal site (Fig. 1).

3. MINERALISATION

3.1. Vienna Wood Site

The Vienna Wood hydrothermal system is about 300 meters in diameter and consists of both active and dead sulfide chimney structures hosted on top of partly oxidized massive sulfide mound (50 cm high). The active chimneys in the center of Vienna Wood hydrothermal system has single trunk and multiple slender chimney branches discharging black and grey smokers with an end member temperatures of 285 to 310°C and pH of 4.5. By contrast, dead chimneys are restricted to the periphery of the hydrothermal field. Fragments of fallen death chimneys are common features on the sulfide mound. Selective samples of the active and dead chimneys were collected from the center and periphery of the Vienna Wood hydrothermal system, respectively.

The sulfide chimney ores collected from the Vienna Wood hydrothermal system are classified into active and dead chimneys. Petrographic study reveals a moresimpleparagenesis involving sequential deposition of anhydrite and frequent replacement of earlier-precipitated assemblages due to the evolution of the sulfide chimney ores. The mineral assemblage is dominated by sphalerite, wurtzite, chalcopyrite and gangue minerals of anhydrite, gypsum and silica (Shadlun et al., 1993). .

The tenor and character of the ore, mineral assemblage, and dimension strongly indicate that the Vienna Wood hydrothermal deposit is a present analogue of the ancient ophiolite hosted volcanogenic massive sulphide and basalt hosted hydrothermal deposits in the mid-oceanic ridge systems, and contrast strongly with felsic volcanic hosted polymetallic type of mineralization in back-arc basins.

3.2. Pacmanus Site

The Pacmanus hydrothermal system is hosted on the crest of the 35km long, 500m high Pual Ridge dominated by dacite to rhyolite (Binns and Scott, 1993; Gena K., 2001). The Pacmanus hydrothermal system consists of four major hydrothermal fields (Tsukushii, Snowcap, Satanic Mill, Romans Ruins) that cover a total distance of about 2.5km. The hydrothermal activities within the individual fields are manifested by dead and active chimneys, areas of diffuse venting, iron-oxides, faunal activity and fallen dead chimney fragments (Binns and Scott, 1993; Gena, 2001). The sulfide chimney ores collected from the Pacmanus hydrothermal system was classified into chalcopyrite-rich, sphalerite-rich, pyrite-rich and silica-rich ores (Gena, 2001). Microscopic observation of the four ore types reveal slight inconsistency in the paragenetic sequence and in the spatial distribution of the sulfides and gangue minerals which suggest that similar hydrothermal process does not exist across the four types of ores samples. The major ore minerals consist of sphalerite, chalcopyrite, bornite, wurtzite, pyrite, marcasite, enargite, tennantite, galena, Pb-As-Sulphosalt, gold, covellite, digenite, chalcocite and gangue minerals of barite, amorphous silica and minor amount of anhydrite + gypsum.

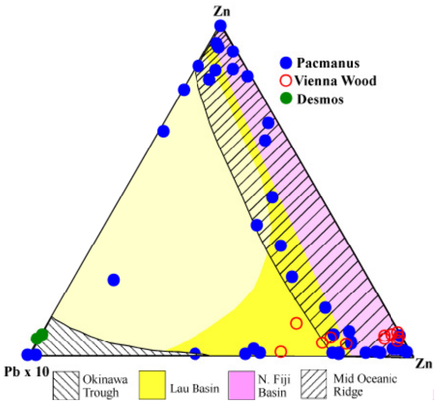

Figure 2. Bulk chemical composition of ores from the Vienna Wood, Pacmanus and Onsen site superimposed on submarine VMS deposits

The chemical composition of sphalerite, galena, gold and tennantite-tetrahedrite series are quite different compared to that from the Kuroko deposits. The sphalerite has high Pb (2.0 to 6.0wt%), As (0.1 to 5.5wt%) and Ag (0.1 to 0.5wt%) content, galena has high Ag (0.1 to 0.6wt%) and Sb (0.7 to 2.7wt%) content, gold has low Ag content (1.4-2.4wt%, Fig. 3) and tennantite－tetrahedrite series has slightly higher iron (5.0 to 7.0wt%), Ag (11 to 18wt%) and copper (44.6-45.9wt%) content. The other sulfide minerals such as bornite, pyrite and chalcopyrite has significant amount of lead. The bulk chemical composition of the ores indicates that the mineralisation in the Pacmanus site is of the Zn-Cu-Pb-Au type (Fig. 2). The presence of magmatophile elements (As, Sb, In, Te) and low sulfur isotope values (-0.6 to +5.9‰) indicated that the polymetallic type of mineralization observed in the Pacmanus site is probably caused by interaction of mixture of magmatic and seawater with the felsic volcanic rocks (Gena, 2001).

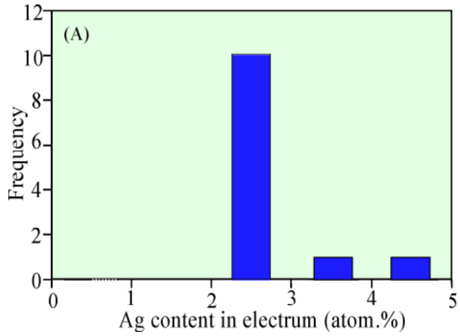

Figure 3. Histogram of Ag content in gold from Pacmanus site

3.3. Onsen Site, Desmos caldera

Unlike most hydrothermal massive sulphide deposits and alteration on mid-oceanic ridges systems and back arc basin spreading centres, the mineralisation at the Onsen site is a typical acid-sulphate type of mineralisation. Three stages of advanced argillic alteration are observed within the Onsen hydrothermal activities. Stage I advanced argillic alteration occur at temperatures of 260°-340° and pH of 1-3 to form pyrophyllite while stage II advanced argillic alteration occur at temperatures less than 250° and pH of 1-3 to form quartz, smectite(15Å-14Å mixed layer minerals), natroalunite and cristobalite. The present hydrothermal activity is in a waning stage with temperatures of 88-120°C and pH of 1.5-2.1 and acid stable phases of amorphous silica, native sulphur, marcasite, pyrite and covellite are formed in those conditions. All the major elements except SiO2 in the cores and rims of the altered samples are totally depleted. However, silica is enriched up to 78 wt% compared to the fresh basaltic andesite (SiO2 = 55 wt%, n = 8). This is a first reported case where major elements are depleted but silica is enriched in the altered rocks from the ocean floor (Gena et.al. 2001). The LREE in the rims of the altered basaltic andesite are strongly depleted with profound negative Eu anomaly indicating that the type 2 rocks have been subjected to alteration by high temperature hydrothermal solution responsible for stage I advanced argillic alteration. (Gena et.al. 2001)

4. GASTROPODA

Unlike most hydrothermal-vent communities in the eastern Pacific, where large vestimentiferan tubeworms and bivalve molluscs are the most conspicuous organisms, the hydrothermal-vent sites in the SW Pacific are dominated by gastropods (Desbruyeres et al. 1994). In the Manus, North Fiji and Lau back arc basins, Alviniconcha and Ifremeria gastropods of the Provannidae family are the dominant primary consumers (Desbruyeres et al. 1994). For their nutrition, the 2 provannid gastropods are known to depend on the intracellular chemoautotrophic bacteria found in specialized cells called bacteriocytes in their gill filaments (Suzuki et al. 2005a,b, Urakawa et al. 2005, Fig. 4). Previously, Ifremeria gastropods from the Manus and North Fiji Basins were grouped as a single species, Ifremerianautilei (Kojima et al. 2000). Urakawa et al. (2005) reported phylogenetic affiliations of endosymbionts in I. nautilei from the Manus Basin. Alviniconcha genus consists of 5 lineages (Kojima et al. 2001), each of which harbors phylogenetically distinct chemoautotrophic bacteria belonging to either the γ- or the ε-Proteobacteria (Suzuki et al. 2005a,b, 2006, Urakawa et al. 2005). Given that Alviniconcha and Ifremeria gastropods employ similar nutritional strategies and inhabit similar hydrothermal vent habitats, Ifremeria gastropods may have established endosymbiotic relationships with diverse groups of chemoautotrophic bacteria. In the study of gastropoda from the Manus Basin, it was recognised that two distinct type of Alvinconcha type 1 and type 2 host distinct types of bacterial endosymbionts (γ-Proteobacteria and ε-Proteobacteria) This discoveries will shed light on how bacterial endosymbionts plays a critical role in the morphology transformation of the host organisms.

Figure 4. Gill filament ofIfremeria gastropods from the Manus Basin

5. RESOURCES ESTIMATE OF SOLWARA 1 AND 12

The Solwara 1 and Solwara 12 seafloor massive sulphide deposit contain significant resources of massive base metal sulphides, Au and Ag. From a technical report compiled under NI143-101, Mineral Resource Estimate, Solwara Project, Bismark sea, commissioned by Nautilus Minerals Nuigini Limited, it was recognised that the maiden resource estimated as at December 22, 2007 for Solwara 1 of over 2 million tonnes at 4% Cu cut off grade (Table 1, Lipton, 2008). From 2010/2011 drilling program, they estimated a maiden indicated resource of 1020 kt and inferred resource of 1540 kt at 2.6% Cu equivalent cut off grade for the Solwara 1 and inferred resource of 230 kt at Solwara 12 (Ian Lipton, 2012).

Table 1. Mineral Resource for Solwara 1 (Lipton, 2008)

Classification	Domain	Tonnes	Cu%	Au (g/t)	Ag (g/t)	Zn %
Indicated	Massive sulphide	870,000	6.8	4.8	23	0.4
Inferred	Chimney	80,000	11	17	170	6
Inferred	Lithified sediments	2,000	4.5	5.2	36	0.6
Inferred	Massive sulphide	1,200,000	7.3	6.5	28	0.4
Indicated	Total	870,000	6.8	4.8	23	0.4
Inferred	Total	1,300,000	7.5	7.2	37	0.8

Nautilus Minerals spent a lot of money in trying to assemble a mining method that is never practiced anyway the world. They are eager to deliver first deep-sea mining in the world. However, on the 1st of June, 2012, Nautilus Minerals cautioned that its Solwara project would be delayed or even cancelled due to a dispute with the government of PNG over ownership of the undersea mine (National, Tuesday 12th June, 2012). The current mineral resource would be impossible to warrant a mine on the land. And secondly, the mining method that Nautilus Minerals is planning to use in Manus Basin was never practised anyway around the world even though it is trying to use existing technology. In addition, the mining cost of this type of mining method is still uncertain.

6. POTENTIAL ENVIRONMENTAL IMPACTS

Marine life varies with the depth of water. At the Solwara 1 site the ocean may be divided into three broad zones;
The '*Surface Mixed Layer'* which is the upper water column between ~0 – 200 mBSL and contains mostly pelagic fish species including tuna, squid and sharks. Other animals known to exist in the area include dolphins, turtles and migrating whales.
The '*Mesopelagic Zone'* which is the mid water column between ~200 – 1000 mBSL and where amongst others squid and occasional short visits by, for example, tuna in search of prey and migrating whales may occur.
The '*Bathypelagic Zone'* which is the bottom water column, deeper than ~1000 m where animals typical of active hydrothermal vent sites, such as gastropods, shrimp, crabs, barnacles, etc occur. Away from venting, animals present include bamboo coral, stalked barnacles, hydroids and others. Other animals observed include octopus, swimming sea cucumbers, Chimera, deep sea fish species. Although the impacts to the seafloor, its hydrothermal chimneys and associated vent fauna, have been identified as the main defining environmental issue for this project, there may be impacts throughout all three zones. The process of impact assessment was approached through internal risk assessment of issues at each step of the process (John B. et. al, 2010).

Several aspects that may give rise to environmental impacts are water use and discharge, water quality, noise and vibration, sedimentation and dewatering (John B. et. al, 2010).

6.1. Water Use and Discharge

Potable water on the production support vessel (PSV) will be obtained by two 35 kL/day reverse osmosis desalination plants resulting in brine production of up to 82 kL/day (. This brine will be discharged to the sea. The brine salinity will typically be double the salinity of the sea water, but is not expected to have any material impact. However pre-treatment requirements for the desalination plants such as chlorination, bromination, dechlorination, coagulation and filtration may lead to waste streams that may require treatment prior to discharge (John B. et. al, 2010).

6.2. Water Quality

Impacts on water quality may occur due to accidental hydraulic fluid leaks, fuel spills during transfers at the site of the PSV, ore spills during transfer to barges and bulk ore carriers and in extreme cases due to accidental collisions resulting in loss of vessels. Unexpected equipment malfunctions could result in the loss of material in the Riser and Lifting System ("RALS"). The maximum amount of mined ore in the riser pipe at any one time is approximately 11 m3, which could be lost to the seafloor. Any of these occurrences could cause localised impact to water quality near the seafloor or in surface waters, along with associated smothering of animals on the seafloor.

6.3. Noise and Vibration

Transmission of noise from operating machinery through the water is an important consideration due to thepresence of marine turtles and whales, both of which are protected by international conventions. It wasidentified that the most likely source of noise which may cause disturbance is from the vessel power generation, dynamic positioning system ("DPS") thrusters or Seafloor Mining Tool ("SMT"). Modelling indicated that noise levels will drop rapidly within the first 2 km, and more slowly thereafter. These sounds may be audible (e.g., to whales) at up to 600 km but at long ranges, the sounds will not be greatly above that of background ocean noise depending on sea surface conditions. This noise is similar to any DP vessel, of which a number have been operating in the Bismarck Sea. The maximum distances for specific received level thresholds being exceeded show that it would not be until an animal approached closer than 1.1 km from the source that the levels would be greater than 140 dB. Harmful effect to whales is unlikely as literature suggests behavioural avoidance at levels generally between 130 to 140 dB. Masking of marine animal calls may occur if the mining vessel noise interrupts or prevents the listener from detecting the communicative signal. The operational noise associated with the DP (propulsion) system of the mining vessel is continuous over a wide frequency bandwidth. Animals may suffer signal-masking effects at similar ranges up to approximately 15 km (John B. et. al, 2010).

6.4. Sedimentation and dewatering

Prior to mining, pre-stripping of unconsolidated surface sediment will be required. It is anticipated that approximately 130,000 t of unconsolidated sediment and 115,000 t of competent waste rock will be moved within the mining zones (John B. et. al, 2010). The unconsolidated sediment will be disposed of, and competent waste material side cast, at a number of locations adjacent to the mining area. While suspended sediment plumes may be created, no significant geochemical changes are expected to occur as the unconsolidated sediment and competent waste material will remain near the seafloor and will not be exposed to any increases in temperature or oxidation. Where practicable, relocation of low-grade material is to be conducted in such a way so as to minimise sediment re-suspension and plume generation. As such the intention is to discharge such material horizontally along the seafloor rather than into the water column to minimise plume formation and enhance the rate at which material settles to the seafloor. The waste water plumes from dewatering will be discharged such that it will not have an impact in the water column shallower than 1300 m. It is proposed to discharge the water from dewatering close to its point of origin at depths between 25 to 50 m above the seafloor, and not at shallow or mid-water depths (John B. et. al, 2010).

Discharge plumes of the slurry waste water is therefore not expected to impact fish and other animals in the mid (~200 to 1000 m) and upper (0 to 200 m) water column(John B. et. al, 2010). It is intended to keep exposure time of cold and un-oxygenated seawater recovered from the seafloor to surface to a minimum so as to not lead to an unacceptable change in oxygen or temperature levels when pumped back. Discharges from dewatering are not expected to have any adverse toxicity effects to seafloor ecosystems and will have negligible overall effects(John B et. al, 2010).. However, due to presence of toxic and heavy elements in the sulphides, it will have some environmental consequences

7. CONCLUSIONS

Unlike terrestrial mineral deposits, the following conclusions can be drawn for the hydrothermal deposits in the Manus back-arc basin.

(1) The Vienna Wood site has a simple mineral assemblage and the mineralization indicated that the mineral deposit formed through simple basalt seawater interaction at elevated temperature. The Vienna Wood site is a modern analogue of ancient ophiolite hosted massive sulphide deposits on land.

(2) The Pacmanus hydrothermal deposits has polymetallic type of minerals with strong evidence of magmatic fluid involvement where mixture of magmatic and seawater interact with the felsic volcanic rocks.

(3) The mineralization and alteration in the Desmos Caldera indicated that the Onsen hydrothermal deposit is a typical acid-sulphate type of epithermal deposits. There is evidence of magmatic fluid involvement in the mineralization.

(4) The hydrothermal vent communities associated with these hydrothermal deposits has distinct feeding mechanism. For their nutrition, the gastropods are known to depend on the intracellular chemoautotrophic bacteria found in specialized cells called bacteriocytes in their gill filaments. The gastropoda will definitely go into extinction if their habitat is destroyed through the proposed mining activity.

(5) If deep sea mining becomes a reality in Solwara 1 and Solwara 12 deposits, then the developer needs to critical come up with concrete mitigation measures toaddress environmental impacts of water use and discharge, water quality, noise and vibration, sedimentation and dewatering

(6) The current mining method proposed by Nautilus Minerals is never practiced in the mining world. Although Nautilus Minerals is planning to utilize existing technologies, the economics of this type of mining methods is still uncertain. The successful or failure of the proposed mining method will set the bench mark for deep sea mining.

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