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Geomechanics of Deep Sea Mining

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ABSTRACT

The Solwara 1 deposit is a high grade copper-gold deposit located at approximately 1,550m water depth in the Bismarck Sea, 50 nautical miles north of Rabaul, Papa New Guinea. A geotechnical investigation program was conducted as part of the larger resource investigation between October 2010 and April 2011, including a seafloor drilling programme and on-board laboratory testing programme, from the REM Maritime support vessel the MT 6016 REM Etive. Geotechnical logging of core recovered from the sea bed included defect characteristics, rock mass strength and alteration; on-board geotechnical testing included point load (PLT), Brazillian indirect tensile testing (BTS), density and unconfined compressive strength (UCS) (with strain measurement). This paper will outline the testing regime, discuss the challenges in obtaining high quality data and discuss some of the geotechnical issues being investigated for deep sea mining.

Keywords: deep sea mining, remote operated drilling, sea floor massive sulphide mound

1 INTRODUCTION

The latest frontier to attract attention from miners in the search for new minerals is the deep sea environment (Hoagland et al. 2010).

Nautilus Minerals (Nautilus) has located a sea floor massive sulphide (SMS) deposit (Solwara) in the Bismark Sea, New Ireland province of PNG within a volcanic mound at a depth of 1,550m below sea level (Figure 1). The ellipsoid-shaped volcanic mound is 1.5km long, rises 200m above the sea floor, and hosts copper and gold mineralisation formed through precipitation of hydro-thermal fluids at and near the sea floor. Nautilus intends to extract the resource by open pit mining methods.

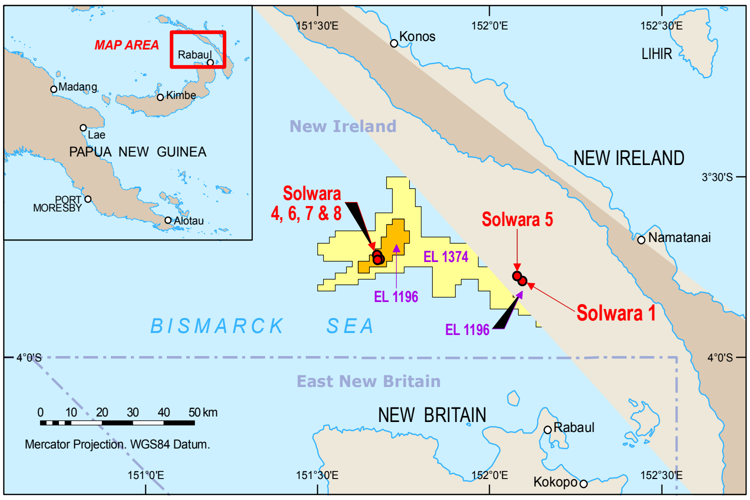

Figure 1. Location of Solwara 1 deposit (Source: Nautilus Minerals Inc)

This paper addresses the significant geotechnical challenges associated with development of a sea floor open pit mine at a depth of 1,550m below sea level including:

- drilling from the Rem Etive vessel by remotely operated vehicle (ROVdrill3 drilling system) to extract core samples for geotechnical logging and laboratory testing, and downhole *in situ* testing.

- establishment of on-board laboratory testing of samples.
- depressurisation effects on samples recovered from the sea floor leading to possible loss of intact strength.
- interpretation of the geological model in very complex volcanic terrain
- assessment of sea floor open pit slope stability under conditions of low strength (altered volcanics) footwall materials, ground shaking effects in an active plate environment and stability of localised “black smoker” pinnacles
- local stability of sea floor mining tool excavations
- trafficability and bearing capacity of sea floor materials in relation to mining tools
- stability of sea floor spoil dumps.

An overview of the proposed deep sea floor mining system is shown in Figure 2.

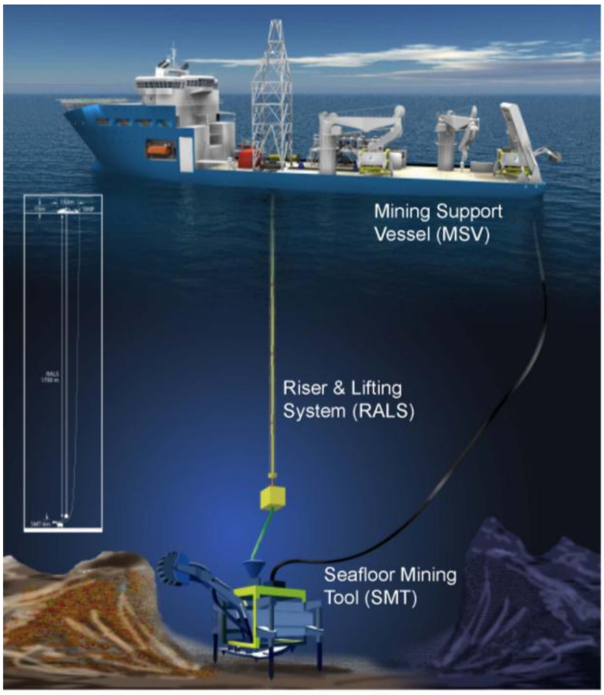

Figure 2. An overview of sea floor mining system (Source: Nautilus Minerals Inc)

2 GEOLOGY

Solwara 1 deposit lies on northwest flank of North Su volcano at depth of 1,500m to 1,660m below the sea surface. The Solwara 1 deposit is a massive sulphide mound formed of a series of andesitic lava flows erupting from the main summit of the mound around 5,000 years ago. A system of vertical chimneys has formed probably above sub-vertical feeder structures in the mound, referred to as “black smokers” which have been dated as ranging in age from 28 years to 4,000 years old. Volcaniclastic sedimentation has occurred contemporaneously with mound and chimney development. Mineralisation of the mound has formed through hydrothermic fluids producing precipitate mineralisation on the sea bed as well as with “black smoker” development. Additional mineralisation has occurred within the volcaniclastic sedimentation.

3 INVESTIGATIONS

3.1 Drilling investigations

Drilling investigations comprised triple tube core drilling using a remotely operated drilling rig capable of drilling 70mm core up to 80m deep. Core is collected in a carousel before being winched to the Rem Etive vessel on the sea surface. The purpose of the drilling investigation was to update resource estimates and collect geotechnical data. A total of 66 resource and geotechnical bore holes with a total length of 1,065m were drilled for the Solwara 1 deposit.

3.2 Geotechnical logging

Geotechnical logging was conducted on board the Rem Etive vessel soon after the drill core was retrieved to the deck. The geotechnical logging procedure involved the following main steps:

- Identification of drill runs and drill recovery
- Measurement of Rock Quality Designation (RQD)
- Identification of potential samples for laboratory testing
- Logging of rock mass characteristics (lithology, strength, alteration)
- Logging of geotechnical defects (depth, orientation, shape, roughness, infill, infill thickness)

A major concern of the geotechnical logging was the large core loss which averaged about 50%. High core loss was attributable to the practicalities of drilling remotely at depth as well as the presence of natural voids and anhydrous dissolution of sulphide dominant rocks. The allocation of core loss had a major impact on geotechnical logging and interpretation of data. To avoid inconsistency in the interpretation of geotechnical data, RQD and defect data were measured on the basis of the recovered core intervals, i.e. ignoring the segments with significant core loss.

3.3 Laboratory Testing

A geotechnical laboratory was established in an air-conditioned shipping container on board the Rem Etive vessel to facilitate rapid testing of core samples. Rock cutting and polishing equipment was used in the normal way for high quality sample preparation. The results of the on board geotechnical testing programme include:

- 158 dry valid dry bulk density measurements using the Archimedes method and 331 valid dry bulk density measurements using the calliper method.
- 48 valid uniaxial compressive strength test results
- 131 valid axial and 74 valid diametral point load test results.
- 70 Brazilian indirect tensile strength test results.

3.3.1 Dry bulk density

The dry bulk density of the rock units was measured by both the calliper method and the Archimedes methods as provided in the Australian standard (AS4133.2.1-2005) . Where done correctly, the techniques yielded similar results. Figure 3 shows a plot of the density measured through each method. Note that erroneous data has been removed from the data set.

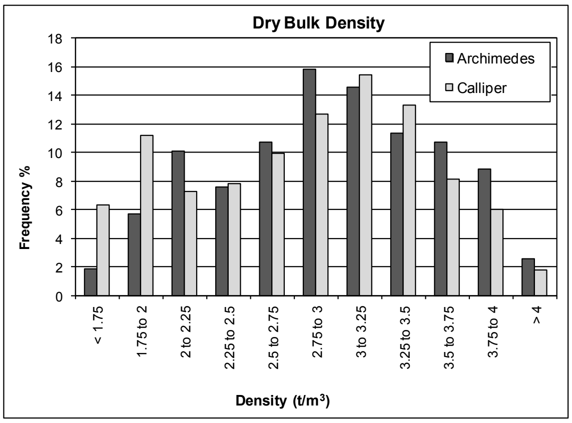

Figure 3. Bulk dry density

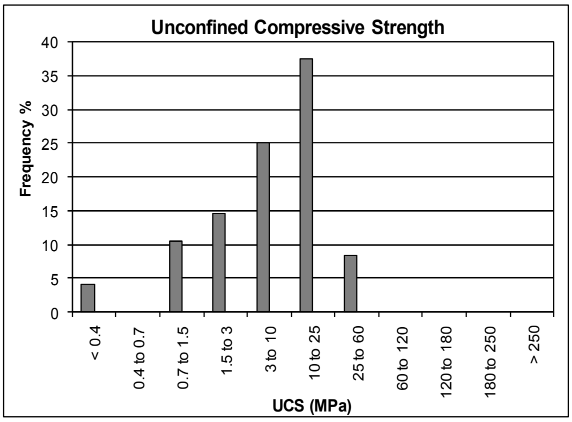

Figure 4: UCS test results

3.3.2 Strength Testing

UCS was tested with a strain controlled loading frame. Strain was measured during all testing using re-useable extensometers and/or glued on strain gauges as appropriate. Where valid data was obtained these measurements allow the estimation of both Young's modulus and Poisson ratio of the intact rock sample. Figure 4 shows a plot of the UCS results. These results show the UCS of about 60% of the samples is in the range 3 to 25 MPa, indicating very weak to weak strength rocks.

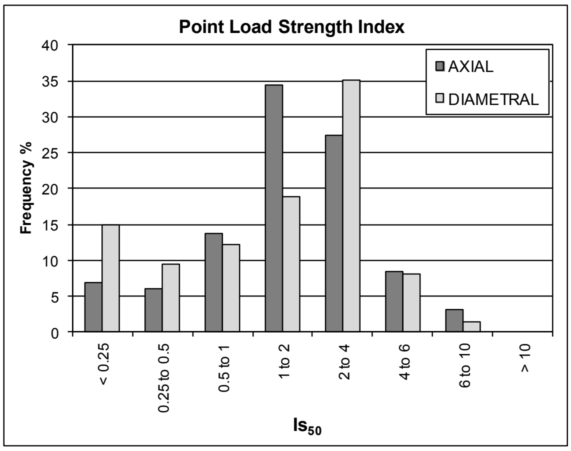

Figure 5. Point Load

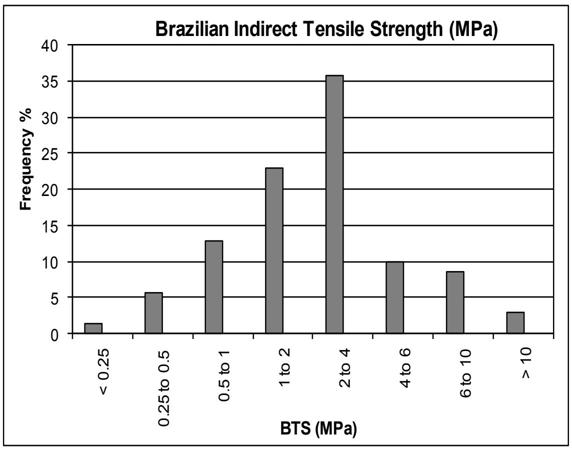

Figure 6: Brazilian Tensile strength test results

Axial and diametral point load testing (PLT) was routinely performed on the core samples using a GSA test apparatus (Figure 5), as was the Brazilian Indirect tensile strength (BTS) test (Figure 6). Thes results in Figure 5 show the point load strength index (Is_{50}) for more than 60% of the samples is in the range 1 to 4 for both the axial and diametral tests while Figure 6 shows the Brazilian tensile strength is mostly in the range 1 to 4 MPa.

4 EFFECTS OF PRESSURE

The seabed pressure of approximately 15MPa is in many cases larger than the UCS of the rock. The actual effects on the mechanics of this pressure needs to be carefully considered and understood to allow correct conclusions to be made. There are a number of cases where familiarity with working near the surface can lead to erroneous conclusions.

As an example the strength of materials are not necessarily improved (through "confinement") or diminished (through "pore pressure"). The water pressure acting on the outside of a slope, rock sample or rock block is in equilibrium with internal pore pressures since they formed there. There may in fact be no effect on effective stress and therefore strength.

One way in which it can be argued that the mechanics of the rock are affected is when considering individual grains or particles which do not have internal pore pressure. Due to the high modulus (low compressibility) of the intact particles compared with either soil or weak rock masses, this effect is likely to be negligible.

4.1 Effects of high water pressure on core samples retrieved from the sea-bed

It is currently postulated (by Nautilus) that the results of historic strength testing of seabed core samples may under-estimate *in situ* strengths and therefore the difficulty of cutting by seafloor mining tools (SMT) may also be under-estimated. The postulated cause for a core sample withdrawn from the sea bed to have reduced strength when tested is through the action of high pore pressures within the sample. Where a sample with sufficiently low permeability is retrieved up through the water column at a speed greater than that which allows those pore pressures to dissipate, tensile stresses may develop in the rock. These stresses may cause propagation of existing very small "micro-fractures" in the intact rock which can reduce the rock strength when measured in the form of UCS and BTS and could also reduce the assessed difficulty of cutting as indicated by testing such as the Cerchar test. In this way the rock is "damaged" during its retrieval.

The rate of dissipation of pore-water pressure within the core sample has been modelled by applying a continuously decreasing hydrostatic pressure on the external boundary of the sample and examining the resulting pore-water pressure distribution within the sample interior. The process has been simulated by transient flow analysis using the commercial software SEEP/W developed by Geo-Slope International. The pre-condition for development of tensile stresses is a sufficiently low permeability causing reduced rate of pore-pressure dissipation and leading to pore-water pressure within the sample interior in excess of the hydrostatic pressure along the external boundary. The tensile stress is proportional to $1- K/K_g$, where K is the of bulk modulus of the rock mass and K_g is the modulus of the grains.

Two simulations were conducted for core retrieval times of 1 hour and 1 minute. The numerical results for both cases showed that there is a very low pore-water pressure differential within the sample during sample retrieval from the seabed to the surface. The results indicate the prospect of developing tensile stresses within the core sample is unlikely for all the practically admissible rates of core retrieval and permeability.

Additional sensitivity analyses were conducted to assess the permeability coefficient which would result in a significant tensile stress within the sample. Numerical modelling of a 70mm wide sample using a very low permeability coefficient of 5.0×10^{-14} m/s and a fast sample retrieval time of 1 minute resulted in a difference in pore pressure of 590kPa. This is approximately half of a conservative estimate of BTS strength of 1MPa. This result indicates that only extremely low permeabilities coupled with unrealistically fast core extraction could lead to significant tensile stresses within the core during extraction.

Petrographic analysis of thin sections haven been taken from the core samples which have been pressure treated with dye which showed apparent micro-scale cracks. These cracks might be the effect of depressurisation on the micro scale rock structure. Further investigation is required to assess the effect of these micro cracks on the strength of the intact rock at macro scale. This aspect is beyond the scope of the current work and is left for future research work.

4.2 Effects of pressure on stability

An important aspect of the effect of the water pressure is that it exists at all places. For example this includes both on the surface of a rock and inside the pores in the rock. Since the water pressure is ubiquitously present, the pressures do not impose loads on rock surfaces, machines or spoil. Therefore, in the stability analyses, the water depth is not considered important in regard to the physics and forces imposed.

Although the ubiquitous pore pressures are not included in analyses, in some cases, pore pressures in excess of the static pore pressures can be induced by, for example during shearing or consolidation in soft clays. Due to the effective stress concept, these pore pressures would be included in analyses if appropriate. Importantly, these pore pressures, if present, are in excess of the ubiquitous water pressure.

5 SEA FLOOR MINING TOOL STABILITY

Excavation during mining operations is planned to involve the following three step process (Nautilus Minerals Inc, 2008):

1) The Auxiliary Cutter is a preparatory machine that deals with rough terrain and creates benches.
2) The Bulk Cutter is a tracked vehicle which excavates and breaks up the benched material. By excavating at the rear of the direction of movement, it leaves a trench containing excavated and bulked material.
3) A Collecting machine is a tracked machine which collects the excavated material for lifting to the sea surface for transport to the processing plant.

One of the critical issues in the above mining process is the stability of the Bulk Cutter particularly when operating beside a trench which has previously been excavated. The proposed trench depth is between 0.5 m and 1.0 m. Stability assessment of the bulk cutting machine has been conducted for the bulk cutter loading close to the previously mined ledge. These analyses were conducted using the finite element method and a static wedge analyses method. The results of both analyses were comparable and indicated:

- Acceptable stability for rock materials with R1 (very weak) strength or better.
- Significant sensitivity in the results to the Geological Strength Index (GSI) of the rock mass (which is an indication of the rock mass "blockiness").
- Marginal stability on hard (S6) clay strength soils
- Unsatisfactory performance (likely failure) on very stiff (S5) or weaker cohesive materials.
- Marginal stability for low bench heights (<0.5m) in gravelly, granular materials.

In addition to analyses which consider soil mass and rock mass strength, instability of the bulk cutter could result from discrete discontinuities or defects within rock. The impact of discrete defects on the bulk cutter operations is difficult to predict as the presence of discrete defects as well as their exact position, orientation and nature of defects is difficult to quantify ahead of excavation. Stability assessments for failures along defects indicated:

- Very low angle defects (dipping <15° into the excavation) are not expected to cause instability even for the lowest strength defects.
- Low angle defect (15° to 30°) may produce instability under the Bulk Cutter tracks depending upon the nature of the defect.
- Low to moderate dipping defects (30° to 40°) may be unstable unless they have upper bound characteristics exhibited by clean, rough, and undulating or stepped surfaces in better strength rocks.
- A defect dipping out of the bench at angles >40° may be unstable, even for the highest strength defects (i.e. exhibiting rough, undulating or stepped defects in better strength rock)

6 CONCLUSIONS

Sea floor mining of metalliferous deposits (copper, gold) at depths of 1.5km below the sea surface has never been previously attempted. There are significant geotechnical challenges associated with the development of an open pit in such a frontier environment which range from issues associated with site investigation and geotechnical characterisation of the rock mass, analysis of stable slope components (berm and bench configurations) for the various rock types that will be encountered during mining, breakage characteristics of the rock types to be excavated by the subsea mining tools which will be employed, and the bearing capacity of the footwall materials to safely support the load of the sea floor mining tool. The consequence of a geotechnical failure may also be substantial, with proposed mining tools being custom built and one of a kind.

This Paper discusses a few of the above geotechnical factors, while the investigation of many of the above factors is still ongoing.

7 ACKNOWLEDGEMENTS

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