

**In Situ Assessment of Initial Seafloor Massive Sulfide Mining Operation in Papua New Guinea
Using a Cabled Autonomous Underwater Vehicle System: A Proposition**

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Abstract

This project is a critical analysis of the impacts of the first effort to mine seafloor massive sulfide deposits (SMS). It will be linked to a proposal for assessment, and mitigation, of the negative impacts. Mining of SMS deposits is clearly being planned and because it is virtually unstudied it is important to evaluate this new frontier. Within the Exclusive Economic Zone (EEZ) of Papua New Guinea (PNG) is a hydrothermal ridge system with massive sulfide deposits being evaluated for mineral extraction subsea. Of these particular sulfide deposits, Solwara 1, which is the soonest to being mined, has been explored as a potential source of copper and other metals. PNG has allocated the rights of the area to a Canadian mining company, Nautilus Minerals. The objective of this scientific project is twofold: to investigate impacts of mining on the ecology surrounding Solwara 1, and to explore the economic ramifications for PNG and Nautilus Minerals when mining for SMS commences. This scientific study aims to identify ways to optimize the intended benefits, and to minimize the potentially negative impacts. The outcome of this study is to recommend placing an autonomous underwater vehicle (AUV) near Solwara 1 so PNG can monitor impacts during and after mining operations are complete.

Introduction

Copper is one of the most widely used metals in everyday life, and current terrestrial copper sources are increasingly limited and environmentally dangerous to mine (Figure 1) (Ferris, R., 2015). The estimated global population is expected to reach 9.6 billion by 2050, so unless demand for copper per capita diminishes, new sources will need to be found (United Nations, 2013).

The seafloor contains multiple sources that could potentially be mined for metals, including manganese nodules, Seafloor Massive Sulfide (SMS) deposits, and hydrothermal vents. Manganese nodules are found in the middle of the oceans on the seafloor and are roughly the size of potatoes. These nodules contain rare earth metals. Though good sources of these rare earth metals, attaining the rights to these nodules presents a challenge because it requires potential companies to go through the International Seabed Authority. However, recent discovery of hydrothermal vent systems and their accompanying sulfide mounds has created a new potential source for essential metals. Currently there are 327 known hydrothermal vent systems in the world's oceans although, less than a third have SMS deposits that would be worth mining (Collins, P.C. et al, 2012) (Figure 2). Fewer than 100 hydrothermal vents have actually been studied (Baker, M.C. et al, 2010).

Ocean law, established in 1982 by the United Nations, dictates that every country has a 12 mile sea limit that extends out from its shoreline (United Nations, 1982). This allows each country exclusive access to the seafloor below their designated coastline. However, the Exclusive Economic Zone limit (EEZ) allows each country to extend to 200 miles off their coasts (United Nations, 1982). Within the EEZ the 'parent' country has access to the water and seafloor with the ability to allocate those rights to another country. If the EEZ is allocated to another country, the 'parent' country has total control over what occurs in the area and retains the right to terminate activities with which they do not agree.

Beyond the EEZ is the international seabed, an area controlled by the International Seabed Authority (ISA) and established in 1982 under the same UN Convention as the Law of the Sea Treaty (ISA, 1982). The ISA has full control over all the activities beyond the area of

national jurisdiction, including the organization, regulation, and control of mining and other mineral related activities.

One of the most important early sulfide mining locations is a site called Solwara 1, located in Manus Basin, not far off the coast of Papua New Guinea (PNG) (Figure 3). The mining area of Solwara 1 is about 0.112 km², which is comparatively small when compared to terrestrial mines like the Bingham Canyon Open Pit Copper Mine, located in Utah, which is a little more than 5.34 km² and one of the largest open pit mines in the world (Rio Tinto Kennecott, 2014). Being of such a small size and within the EEZ of PNG makes Solwara 1 a good location for the first underwater sulfide mining location. Solwara 1 is located within the EEZ, which gives PNG jurisdiction over the natural resources that are found there (Smith, S. et al, 2008). Therefore, they can either mine the sulfide mounds themselves, or allocate the task to another country. PNG has chosen to allow Nautilus Minerals, the aforementioned Canadian company, to explore this area and eventually begin mining (Figure 4). Nautilus has found that Solwara 1 contains copper and gold in grades that are high enough to allow commercial development (Smith, S. et al, 2008). Because mining of this type has not been attempted before, once mining commences there will be a tailings plume that is created and until the mining operations and monitoring begin there will be no way to know for sure how large this mining plume will be or how far downstream it will travel.

The plume that is created could also have a large impact on local fishing and organisms. Fishing in PNG is a way for families to be fed and an economical source. If contaminants from mining get leached into the water column the concentrations of contaminants will increase moving up each trophic level. Once contaminants reach organisms that are consumed by Papua

New Guineans the concentration will be much higher than when it was first leaked into the water and could potentially cause sickness in the consumers. Also, the majority of organisms in the ocean are found near the sea surface, within the photic zone (upper 1,000m of water). In the photic zone they have access to the highest amounts of nutrients, dissolved oxygen, warm water, and sunlight. Near the surface phytoplankton are capable of photosynthesis; others are able to extract oxygen out of the water through various processes. Organisms that do not photosynthesize are able to get energy by consuming others. However, because the hydrothermal vents are below the photic zone, the heterotrophs that live there have to rely on the deep ocean water that is often rich in upwelling nutrients. These organisms have unique processes that allow them to extract their needed energy from electron exchange involving hydrogen, hydrogen sulfide, and methane that are venting from these systems (Baker, M.C. et al, 2010). However, the plume could bury organisms that are sessile or slow moving living on or near the seafloor.

Although mining of the seafloor holds promise as a source for natural resources, altering these hydrothermal vent environments creates many potential environmental impacts, including contaminations in fish, physical damage to the seafloor, destruction of isolated populations, sediment plumes, change in fluid flow, noise pollution, wastewater disposal, and leakage of equipment (Baker, M.C. et al, 2010). Mining of SMS is highly likely; it is essential that we determine the ecological impacts, determine how vulnerable the PNG population/economy is to a diminished fishing industry, and seek mitigation measures.

The Constitution of PNG states that “Papua New Guinea’s natural resources and environment [are] to be conserved and used for the collective benefit of us all, and be

replenished for the benefit of future generations” (Article 4, PNG Constitution, 1975). To uphold this objective, documentation of the large abundance and diversity of known, and unknown, species surrounding Solwara 1 must take place. Researching the ecological impacts of seafloor mining for massive sulfides is important in order to avoid an extinction/poisoning/degradation of organisms that contribute to the circle of life within the ocean.

As suggested by Nautilus Minerals, one possible solution for measuring negative impacts mining might have on the surrounding environment of Solwara 1 is to establish a reference location on the sulfide mound South Su, which is just south of Solwara 1 (Figure 3). There has been a modest amount of scientific research conducted on larval ecology and how populations are reseeded and evolve to inhabit previously uncolonized areas (Baker, M.C. et al, 2010). Research has found that most of the species living on and around hydrothermal vents have adapted to the harsh chemical disturbances. These species tend to be endemic to vents they currently occupy and may be sensitive to being moved to different habitats (Collins, P.C. et al, 2012). Hydrothermal vents experience irregular but natural catastrophic destruction capable of wiping out populations dependent on chemoautotrophic primary production (Van Dover, C.L., 2011). This process would suggest that the species living in these locations are also adapted to withstand brief periods of habitat loss (Van Dover, C.L., 2011). However, adding mining to the frequent eruptions might increase the impact on the numerous organisms living there and the ecological impacts could be cumulative (Van Dover, C.L., 2011). Typically a small number of species are present in a given habitat because of rapid changes in temperature, chemistry, and fluid flow from the hydrothermal vents (Baker, M.C. et al, 2010). The natural recovery time of

many hydrothermal vent species is 2-4 years, whereas recovery of species diversity can be more than 5 years (Van Dover, C.L., 2011). So, a major research question will involve the rates of ecological recovery surrounding Solwara 1 once mining the SMS gets underway. These issues must be studied, documented, and monitored throughout the process.

Although South Su has been suggested as a location for the establishment of a research reference spot, it is often found that the geological and geochemical structures are different from one vent to another (Collins, P.C. et al, 2012). These potential mismatches lead to ecological and evolutionary complications. Such processes are the drivers for the need to better understand the dynamics of different ecosystems that thrive in these seafloor systems. This knowledge could help create policies that may make seafloor mining more acceptable to many.

Despite possible environmental impacts, the economy of PNG, which is similar to those in developing countries, could greatly benefit from the financial infusions of seafloor mining. The overall economy of the country relies heavily on commercial fishing, the trading of goods with other countries, and the mining of terrestrial minerals. Implementation of seafloor mining, if properly handled, could provide certain opportunities to the citizens of PNG like training and employment, local businesses providing goods and services, monetary benefits, and an improvement in balance of trade, infrastructure, employment, and education (Smith, S. et al, 2008). According to the Constitution of PNG the fifth goal is “to achieve development primarily through the use of Papua New Guinean forms of social, political, and economic organization” (Article 5, PNG Constitution, 1975). PNG seeks to be economically self-sufficient, and seafloor mining would go a long way towards achieving that goal. As mentioned in their fourth constitutional goal, the citizens want to do their part in conserving their own natural resources

for the future. A current challenge to achieving that goal however, lies in a lack of funding and/or expertise for such ventures from within PNG.

The major opportunity in the near future involves Nautilus Minerals. Nautilus currently holds exploration and prospecting rights for Solwara 1. In 2010 copper was selling for \$2.5/lb and the cost of mining was \$1.5/lb (Figure 5). New and more efficient technologies account for this ratio. Knowing that the price and cost are both on a decline, along with ever changing technology, one might predict that Nautilus Minerals is making a sound investment in being the first company to mine the seafloor for sulfides. Nautilus must turn a profit to justify their efforts, as they seek to fill the gap in the inevitable increase in demand for minerals with population increase.

I propose that one mitigation solution, with the potential to alleviate some disagreements between PNG, Nautilus Minerals, and environmentalists, is to have the PNG government oversee the mining process at all times. If PNG observes practices they do not support, they can directly and quickly intervene to either end or modify activities. Through direct involvement, PNG will gain information about seafloor mining that could later be applied without an outside company. PNG will also acquire the capability to guide future negotiations between other countries and companies. Nautilus Minerals would serve as a leader to future mining efforts of other countries.

Any activity below the surface of the ocean is difficult to monitor because satellites and other cameras cannot penetrate water depths from the surface to get a clear image of underwater activities. However, having a permanent autonomous underwater vehicle (AUV) monitoring Nautilus Minerals' mining would allow videos and images to be sent directly to PNG.

Swedish aerospace and defense company, SAAB, has developed the Seaeye Sabertooth, which is an AUV that is tether free with a camera and other mapping systems that could monitor the area (SAAB Seaeye, 2014). The AUV has an underwater docking station that allows it to recharge its batteries and exchange data with the surface (SAAB Seaeye, 2014). With this type of technology PNG would monitor Nautilus' activities, and ensure they are in accordance with the previously established agreement. In addition, fitting a CTD onto the AUV would allow for water measurements to be taken. As well as having other sensors that could measure for increases in minerals, like arsenic, that are released from the mining and could have a negative impact on surrounding fishing industries if levels get too high.

Method of mining operation as proposed by Nautilus Minerals

Geology

Solwara 1 is home to about "40,000 hydrothermal vent chimneys over 0.25 m high" and the area targeted for mining on Solwara 1 is 0.112 km² (Smith, S. et al, 2008). Nautilus Minerals has gone through this proposed mining area and taken multiple core samples to get a better understanding of the area's underlying geology (Figure 6). From these core samples they found that the upper layer is about 2 m of unconsolidated sediments. Below this layer is the layer of SMS deposits that contain copper, gold, and other metals that they are hoping to mine at a profit. This section ranges in thickness from 7 m to 26 m. Underneath the SMS deposits is a layer of unknown potential. In one core sample this layer was drilled into approximately 2 m, giving some indication that there might be more SMS deposits deeper in the system.

Mining Tools

Nautilus will be prestripping the different areas of unconsolidated sediment and then grinding up the sulfide mounds, with special seafloor tools, to be vacuumed up to the surface where the water and fine particles will be separated out and pumped back to the seafloor (Smith, S. et al, 2008). There will be three levels of mining tools throughout the water-column (Figure 4). At the surface will be the Production Support Vessel, below that is the Riser and Lifting System and the Subsea Slurry Lift Pump that both run the entire water-column, and on the seafloor are the Seafloor Production Tools. The Seafloor Production Tools will consist of an Auxiliary Cutter, Bulk Cutter, and Collection Machine (Figure 7). The Auxiliary Cutter breaks apart the bulk of the potential ore within the mining site, prepping the worksite for the other two machines by forming benches. Once the benches are created the Bulk Cutter is able to continue crushing the covering rock that the Auxiliary Cutter was unable to reduce. Finally, the Collection Machine moves into the prepared area and gathers the broken material prepared by the previous two machines. This material is transported through a vertical pipe to the Subsea Slurry Lift Pump. This pump then powers the Riser and Lifting System which lifts the slurry to the Production Support Vessel where it is dewatered and the ores are separated from the coarse slurry mixture. Following this activity the slurry is pumped back to “between 25 m and 50 m above the seafloor” and is deposited, at an upward angle to the seafloor to help minimize the production of a tailings plume, in approximately the same area where it was collected (Smith, S. et al, 2008). The whole circuit from Riser and Lifting System, through dewatering, and back to the seafloor takes about 20 minutes.

Composition of Returned Slurry

The slurry returning to the seafloor will be comprised of the water from the dewatering process, along with sediments that range in size from fine grained clays to larger coarse grained sand and pebbles. Even though this slurry of material will not be shot straight down onto the seafloor, it is still predicted to form a plume in the water column. The waste slurry mixture will allow for the larger sized sediment to settle out closer to the point of origin, whereas, finer grained clays and silts will travel further downstream with the plume. In turn, this will have an effect closer to the mining site as well as downstream from it.

AUV Surveillance System

Cost

Installing a permanent AUV, with its docking station, and an accompanying cable to provide a source of power will cost \$27+ million (Figure 8) (Table 1). However, in the long run, this approach should be less expensive than continually bringing in a Remotely Operated Vehicle to make surveys. Installation of the cable will cost about \$13 million and requires multiple steps. First, a desktop study (DTS) is required to look at preliminary seafloor bathymetry, locating any potential hazards like volcanic activity, and identifying all other cables in the area that might interfere with the cable that is to be deployed. Also, it identifies any permitting that might be required. Second, a route for the cable will be laid out based on the DTS. For this to occur a route mapping survey vessel is required to run an ROV over the area to find the best route possible. From there, the cable ship lays out the cable and its accompanying equipment. For 30km of cable to be laid it is estimated to take 2 weeks to complete, this

includes the transit time for the ship as well as the actual time working. Once the cable is in place the fully loaded AUV and its docking station, costing about \$15 million, can be lowered to the seafloor. Deployment of the AUV and docking station could be accomplished by the cable-laying ship, so there would be no need for an additional ship to visit the site. Finally, three navigation beacons should be deployed to help triangulate the location of the AUV so it can be controlled and navigated within the area of interest.

Monitoring Concept

Calculating the settling time and distance of sediment from the plume will be the first step in analyzing the plume. These calculations are only dealing with net transport of sediment and do not take into consideration the possibility of elliptical cross tidal currents. Using the Ferguson & Church line from figure 9, when calculating settling times, gives an estimated time of 8 minutes for pebbles, 1.5 hours for fine sand, and 6 days for fine silt. From these settling times a settling distance can then be calculated using an estimated current velocity of 2cm/s and 5cm/s. A current velocity of 2cm/s results in about 10m from the output for pebbles, 100m for fine sand, and 1km for fine silt. On the other hand, calculating settling distances with a current velocity of 5cm/s resulted in about 25m from the output for pebbles, 250m for fine sand, and 25km for fine silt. Knowing estimated settling distances will enable the creation of survey paths for the AUV.

On a full battery charge and in optimal water conditions the AUV can travel about 100km. Since the planned mining site of Solwara 1 is so small, the AUV could do a full plume survey and a survey over the mining site everyday (Figure 10). Plume surveys will consist of

three different paths (P1, P2, and P3) which are each at different depths in the plume. Each path will then have at least five lines of survey (L1, L2, L3, L4, and L5). The lines will run the length and width of the plume at each of the three depths to construct a relative 3-Dimensional image of the plume. Three navigation beacons, which were placed around the mining site, will be used by the AUV to navigate its location while in the plume. In addition, the AUV would still have time to download data and recharge before taking potential water samples to Rabaul for analysis. Once or twice a week, the AUV could make a run down to South Su and do a survey of the evolution of biological activity on species that are transplanted there from Solwara 1.

Sensors

There will be many aspects to the mining operation that will require monitoring and this can be done by attaching various sensors to the AUV. Potential issues that people are most concerned about are the plumes that will be created, effects on biological activity at Solwara 1 and the transplanted species at South Su, impacts on the fishing industry, chimney recovery after they have been knocked down and mined, noise pollution from machinery, and making sure Nautilus Minerals is adhering to their agreement and not doing anything that PNG disagrees with.

Analysis of the plume can then be done by using a new cutting edge technology transmissometer, the LISST-Deep, which uses light transmittance to differentiate sediment particle densities in the water (Sequoia, 2016). Closer to the plume source light will be absorbed more quickly by particles because the density is greater with sediment particles barely having started to settle out. However, further from the source, light will be able to travel

a greater distance before being absorbed by the particles. Lower light absorbance would indicate the particle density is lower because the larger sediment particles have settled, leaving only finer clay sized sediment that have a small density but high abundance. Analyzing the surrounding, undisturbed, water before the plume is created and using estimated sediment settling distances will give a good basis for identifying the plume once it is created. This base will help indicate when the AUV is in the plume and when it has left the boundaries of the plume.

Seafloor mining tools used by Nautilus Minerals and support vessels at the surface will create some level of noise pollution in the water. Input of excess noise may have a negative impact on surrounding wildlife and, in turn, the fishing industry of PNG. To monitor this noise a hydrophone can be attached to the AUV. By taking recordings before mining commences a baseline will be set for how much noise is actually put into the water along with knowing when changes might need to be applied to the amount of noise being made.

Another sensor to put on the AUV will be a multibeam. While the AUV is making its survey paths over the various mining sites of Solwara 1, the multibeam will use sonar technology to map the seafloor. In turn, these maps can be used to monitor the level of destruction as well as potential recovery of the hydrothermal vent chimneys in both time and space.

One major tool that will be used on many aspects of the AUV monitoring will be the camera. The camera will be a major help in studying the biological activity at Solwara 1 and South Su and also in observing Nautilus Minerals and their underwater mining activities. The camera may potentially be used to analyze chimney recovery as well.

Having a sampling bottle rosette with Niskin bottles on it would allow for the AUV to take water samples throughout the plume, to later be analyzed for pollutants, from mining, like cadmium, mercury, and arsenic. Contaminant concentrations will increase when consumed by each new trophic level. If contamination levels raise to a point where eating locally caught fish is no longer an option then this will have a large negative impact on the people of PNG who rely on the fishing industry both to feed their families and economically for the whole country. Since Solwara 1 is such a small mining site, the AUV will most likely have time to survey the planned area, go back to its docking station to recharge and download data, and then make a trip inland, towards Rabaul, PNG, where it can deliver water samples it has taken throughout the plume, all in one day. Regular analyses would allow assessment of harmful chemical impacts on the local fish stocks.

My Proposition

I propose that this program be funded by Nautilus Minerals, but controlled and overseen by PNG. It is important for Nautilus Minerals to pay because they stand to make a big profit and should demonstrate accountability which the PNG oversight can enforce.

Laying down a cable from Rabaul to the Solwara 1 area would also allow for other companies/researchers to tap in and use the cable as well. If and when others want to use the cable, Nautilus Minerals can charge them a fee that they believe to be reasonable. Once Nautilus Minerals completes mining operations in Manus Basin they could hand over the cable to a company that may want to do long term environmental studies in the area, 25+ years down the road.

Placing PNG in charge of actual AUV monitoring would allow for unbiased data to be collected and perhaps shared with the public or other interested parties such as fishermen. PNG shares the interests of their economy, its people, and the environmentalists that it will need to look after at some level. If Nautilus were allowed to collect and report the data, the outcome might be biased or have limited results.

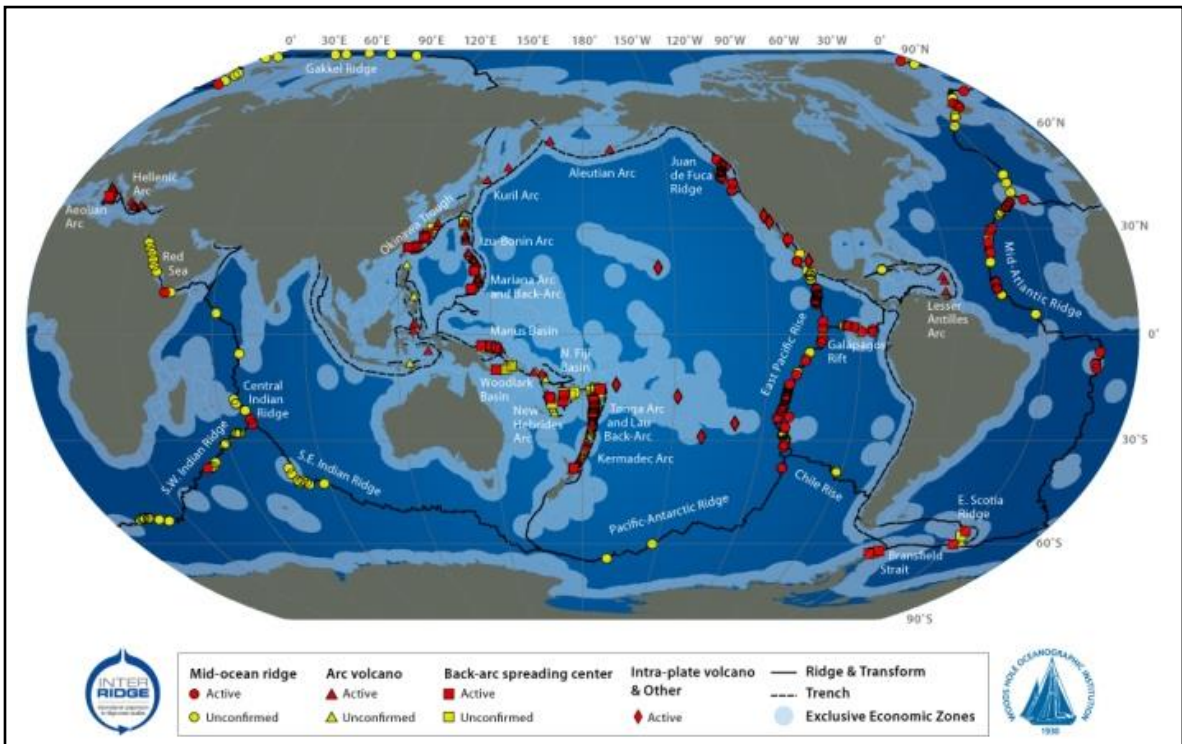
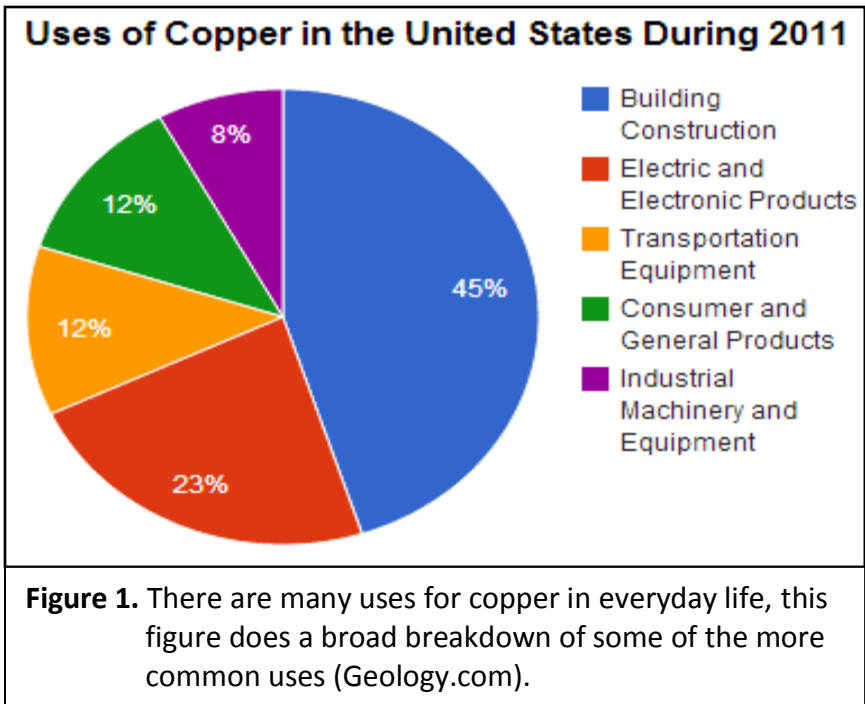
Once PNG has the data, it could be made widely available publicly online for all interested stake holders to access. By doing so this allows for future parties, that want to do similar SMS mining, to know what they are getting themselves into and to get a better understanding of the situation. This is a tremendous opportunity to closely monitor and study the positive and negative impacts of SMS mining, providing valuable data for future endeavors' impacts on local economies as well as the environment. Allowing the data to be widely available adds a level of accountability and transparency for PNG and Nautilus Minerals, showing that neither have anything to hide and that they are both trying to learn from this first operation.

On top of having immediate access to collected data, there should be a plan in place for the AUV to monitor the impact of the mining during and after operations are complete. With an estimate of two years to complete mining operations of Solwara 1, an additional five years of surveying the mining site and surrounding area should give insight into potential recovery times of hydrothermal vents and their biological ecosystems.

Adopting the surveillance plan is important to take full advantage of the first SMS mining operation. Once this information is gathered it can be applied to future SMS mining operations. Doing a complete hydrothermal vent study in this area may also give insight into

the workings of hydrothermal vents and how long it can take them to recover, both in size and biological activity. Studies done on the plume will allow us to see the impacts, in time and space, on surrounding biological life. Finally, monitoring of mining activities will allow PNG to keep an eye on Nautilus Minerals and to make sure their agreement is not being broken. The ocean is a vast unknown area that once further explored could unleash a world of information. The approach outlined herein would become a small addition to the major goal of understanding our ocean's resilience.

Figures



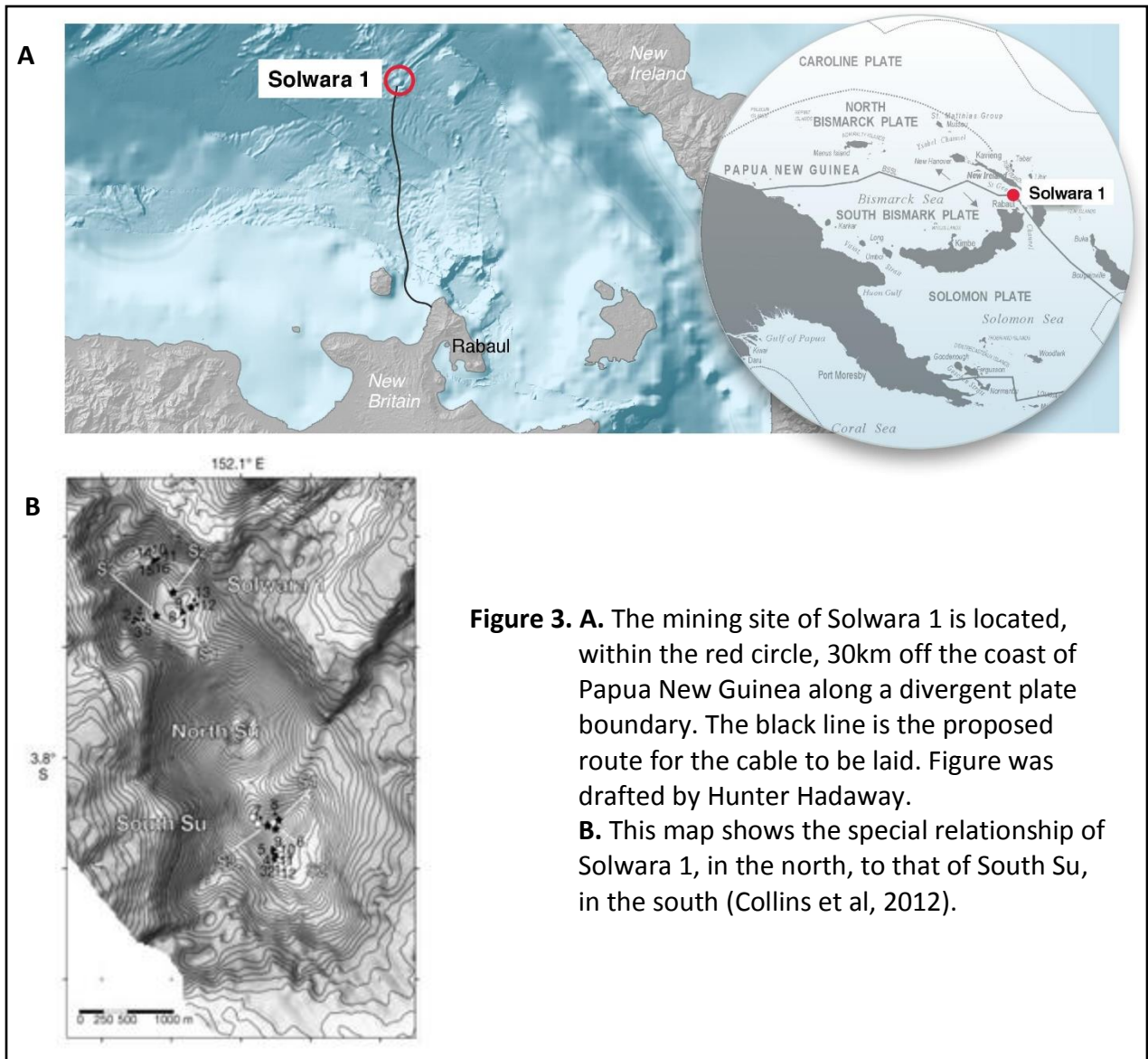


Figure 3. A. The mining site of Solwara 1 is located, within the red circle, 30km off the coast of Papua New Guinea along a divergent plate boundary. The black line is the proposed route for the cable to be laid. Figure was drafted by Hunter Hadaway.

B. This map shows the special relationship of Solwara 1, in the north, to that of South Su, in the south (Collins et al, 2012).

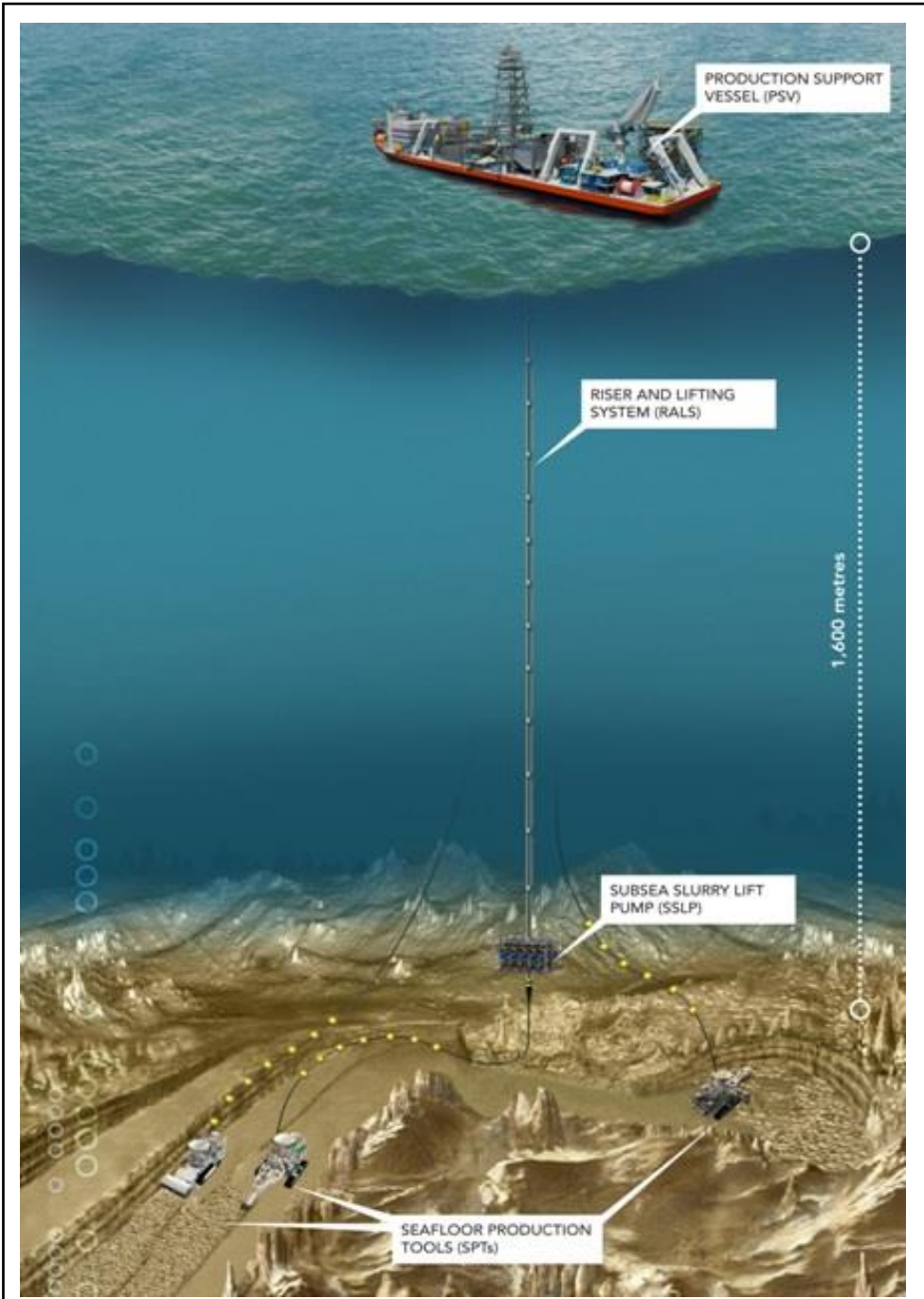


Figure 4. Nautilus Minerals Technology Overview, 2016 mining production tools layout.

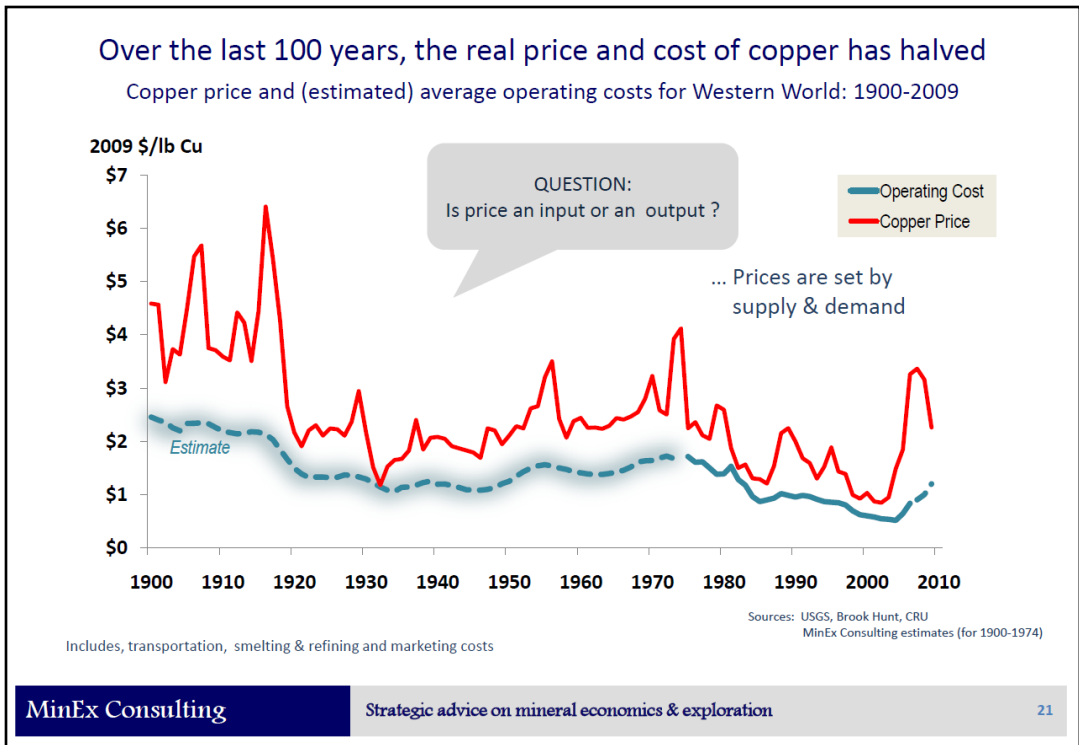


Figure 5. Copper price and mining operating costs for the last 100 years.

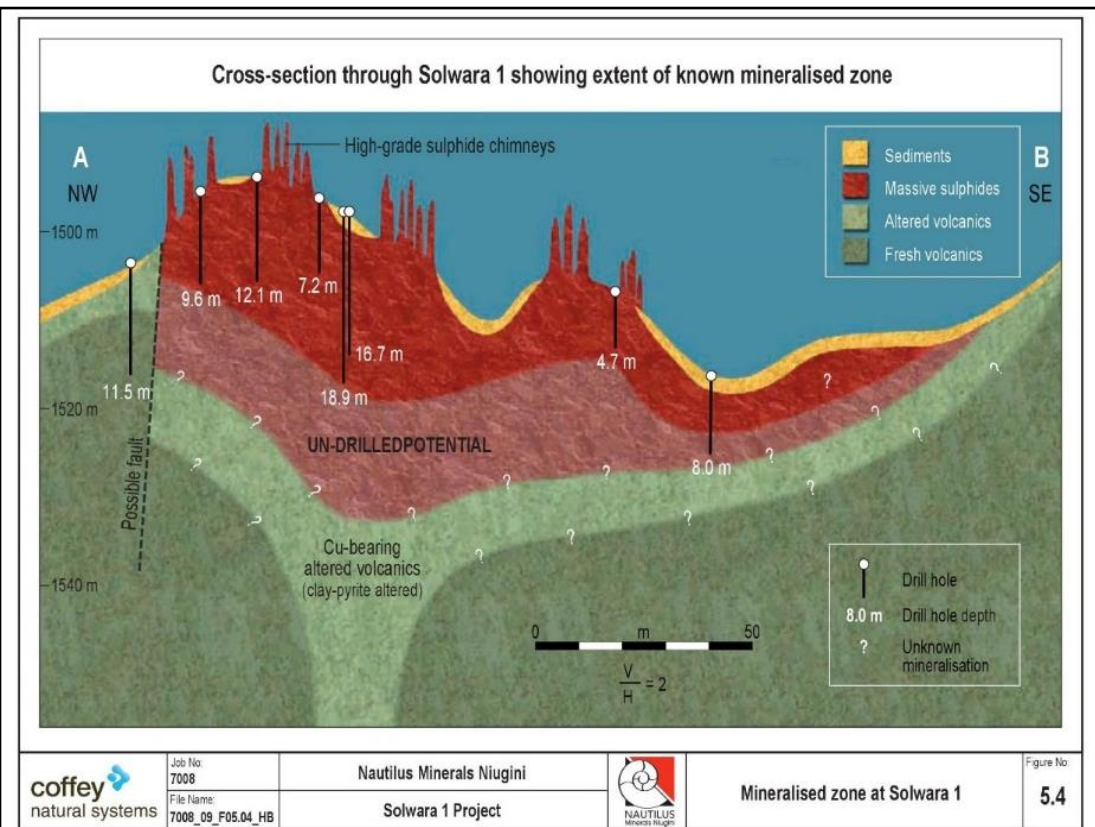


Figure 6. Cross section of Solwara 1 created from multiple core samples. This cross section depicts the layout of Solwara 1 and its accompanying sediments and minerals.

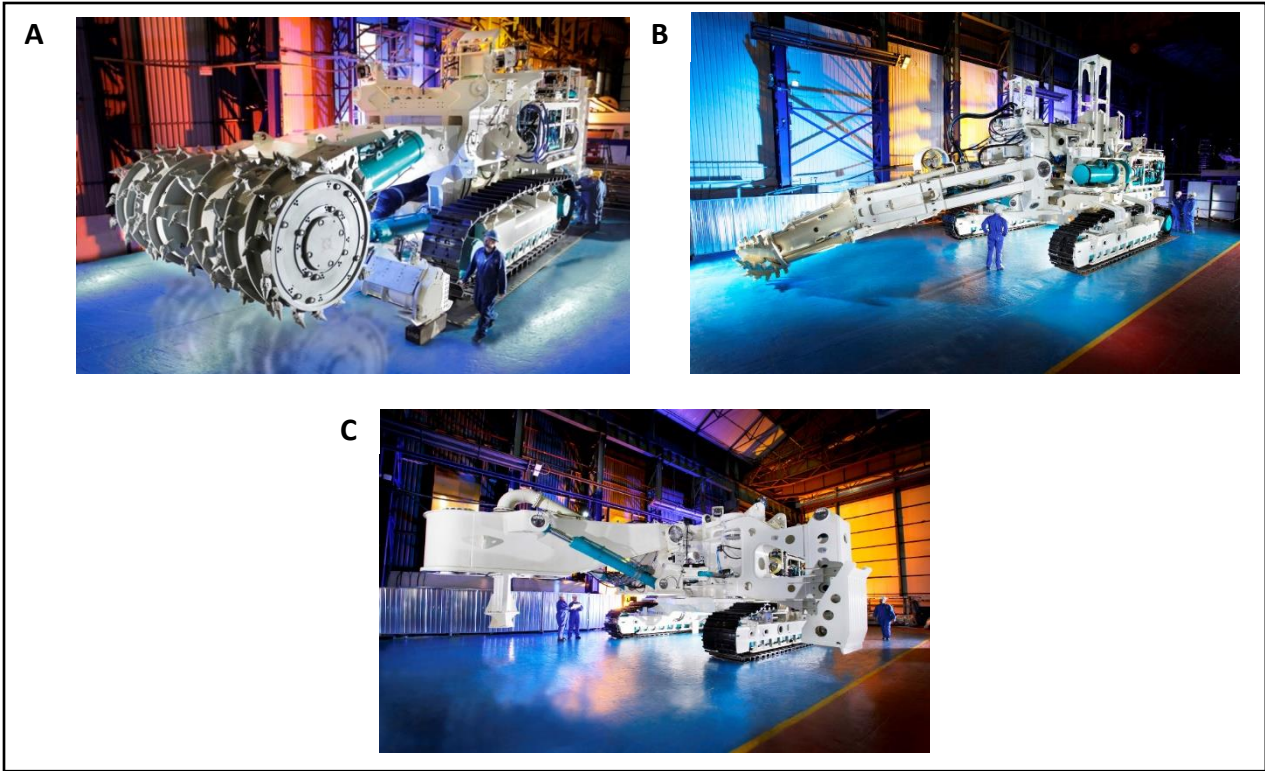


Figure 7. A. Auxiliary Cutter, breaks apart the initial seafloor material, prepping benches for the other machines to work on. **B.** Bulk Cutter, also cuts apart material, but must work on benches. Like the Auxiliary Cutter it leaves the cut material on the seafloor. **C.** Collection Machine, collects the cut up material that was placed on the seafloor by the Auxiliary and Bulk cutters. Material moved to Riser and Lifting System.



Figure 8. I propose the use of a SAAB Seaeye Sabertooth AUV to monitor the mining operations. The approach outlined herein will allow assessment of the balance between economic and ecological impacts of such activities before, during, and after the mining operation, providing essential information for future mining activities in comparable situations.

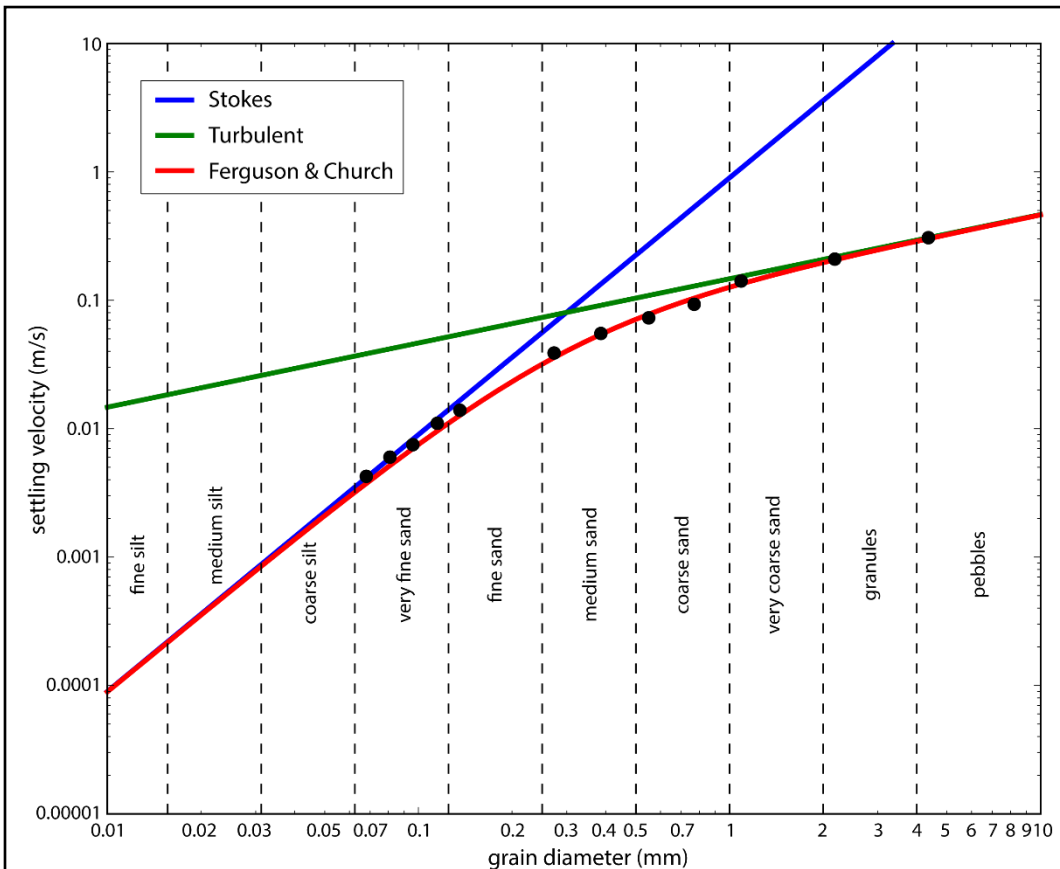


Figure 9. Chart showing the Settling Velocity vs. Grain Diameter for various

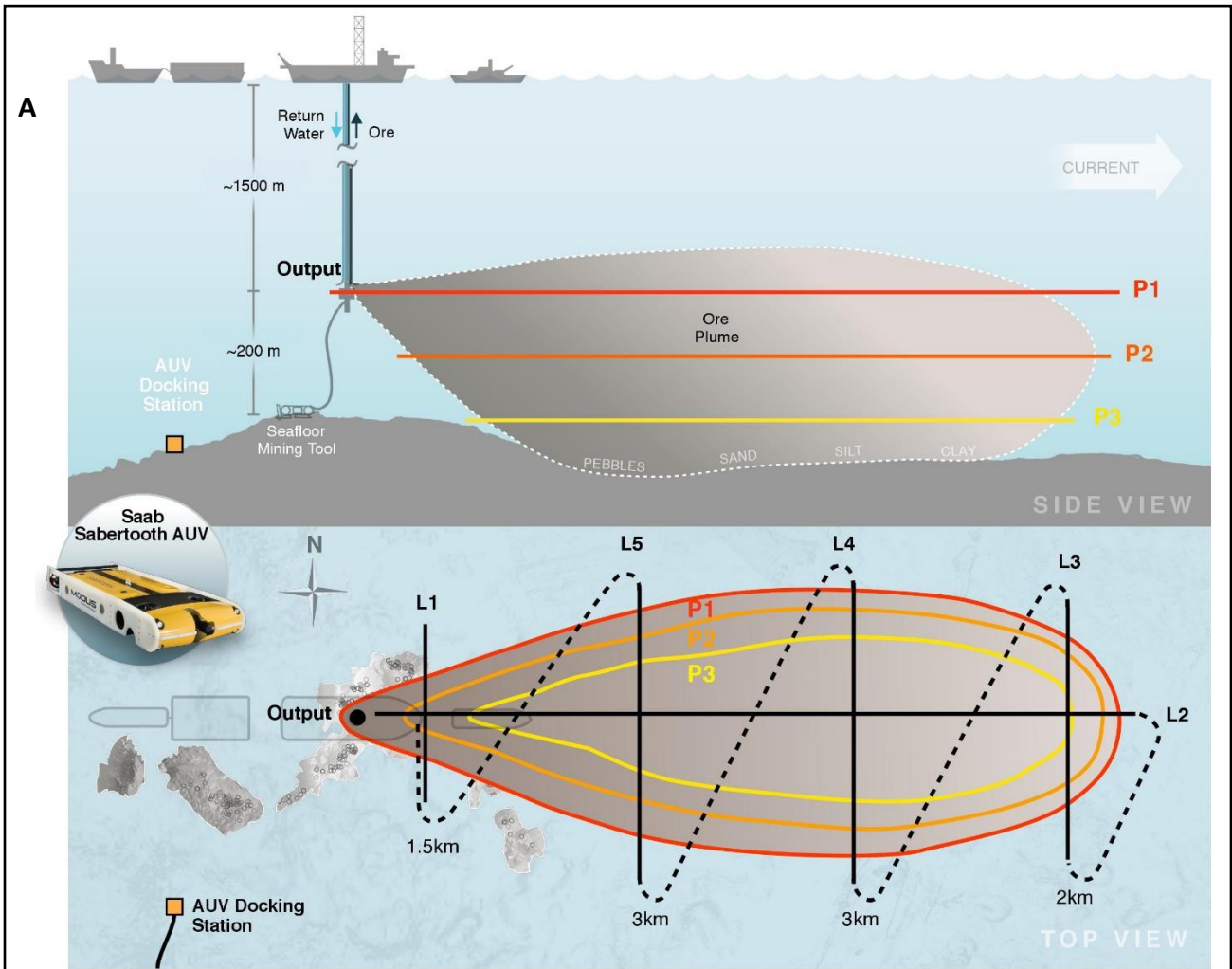
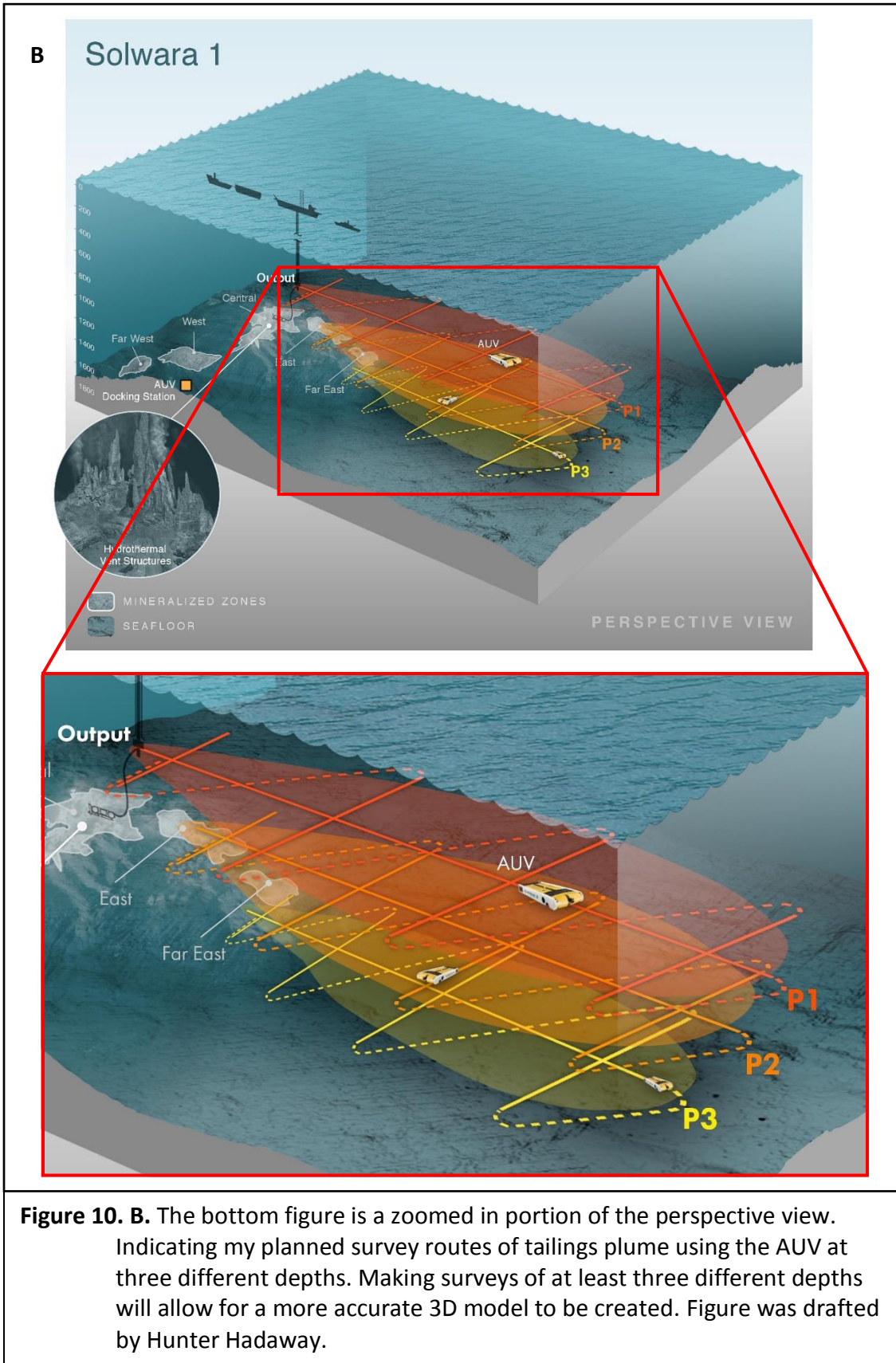


Figure 10. A. My planned survey routes of tailings plume using the AUV. The dark grey to light grey gradated color within the plume indicates that the majority of sediment settling will occur quickly near the area of output. Figure was drafted by Hunter Hadaway.



Tables

Table 1. Cost breakdown of AUV and its accompanying Cable.	
Price Breakdown of AUV	
SAAB AUV Vehicle	\$4,000,000
Docking Station	\$5,000,000
Junction Box	\$250,000
Total of Equipment at both ends of cable	\$5,500,000
Navigation Beacons	\$90,000
Total	\$14,840,000
Price Breakdown of Cable	
Desktop Study	\$25,000
Environmental Compliance Firm	\$200,000
Multibeam Survey	\$50,000
Cable Ship (2 weeks)	\$1,750,000
Assist Vessel	\$60,000
Cable (40km)	\$800,000
Termination Equipment	\$1,000,000
Transmission Equipment	\$1,000,000
Permits	\$10,000
Bore Hole Under Beach (13km)	\$8,000,000
Total	\$12,895,000
Project Total	\$27,735,000

References

- Article 4, Constitution of the Independent State of Papua New Guinea (1975).
http://www.wipo.int/wipolex/en/text.jsp?file_id=199188
- Article 5, Constitution of the Independent State of Papua New Guinea (1975).
http://www.wipo.int/wipolex/en/text.jsp?file_id=199188
- Baker, M.C., Ramirez-Llodra, E.Z., Tyler, P.A., German, C.R., Boetius, A., Cordes, E., E., Dubilier, N., Fisher, C., R., Levin, L., A., Metaxas, A., Rowden, A. A., Santos, R. S., Shank, T. M., Van Dover, C. L., Young, C. M., Warren, A. (2010). Biogeography, Ecology and Vulnerability of Chemosynthetic Ecosystems in the Deep Sea, Life in the World's Oceans: Diversity, Distribution, and Abundance, McIntyre, A, D. (Ed) Chapter 9, pp. 161-182, Blackwell Publishing Limited.
- Beaulieu, S. Global Distribution of Hydrothermal Vents, *Woods Hole Oceanographic Institution*.
<http://www.whoi.edu/main/topic/hydrothermal-vents>
- Collins, P.C., Kennedy R., Van Dover C.L. (2012). A biological survey method applied to seafloor massive sulphides (SMS) with contagiously distributed hydrothermal-vent fauna, *Marine Ecology Progress Series*, vol. 452, pp. 89-107.
- Copper Uses, Resource, Supply, Demand and Production Information, *Geology.com*.
<http://geology.com/usgs/uses-of-copper/>
- Ferris, R. (2015). Future of mining may be on the ocean floor, *CNBC*.
<http://www.cnbc.com/2015/06/15/future-of-mining-may-be-on-the-ocean-floor.html>
- International Seabed Authority (1982). United Nations Convention on the Law of the Sea and the 1994 Agreement, <https://www.isa.org.jm/authority>
- Nautilus Minerals Technology Overview (2016).
<http://www.nautilusminerals.com/irm/content/technology-overview.aspx?RID=329&RedirectCount=1>
- Rio Tinto Kennecott (2014). Operation, <http://www.kennecott.com/operation>
- SAAB Seaeye (2014). Seaeye Sabertooth Rev 2,
http://www.seaeye.com/pdfs/Seaeye_Sabertooth.pdf
- Sequoia (2016). LISST-Deep, <http://www.sequoiasci.com/product/lisst-deep/>

Smith, S. et al (2008). Environmental Impact Statement Solwara 1 Project, *Nautilus Minerals Niugini*, <http://www.nautilusminerals.com/irm/content/pdf/environment-reports/Environmental%20Impact%20Statement%20-%20Main%20Report.pdf>

United Nations Department of Economic and Social Affairs (2013). World population projected to reach 9.6 billion by 2050.
<https://www.un.org/development/desa/en/news/population/un-report-world-population-projected-to-reach-9-6-billion-by-2050.html>

United Nations Law of the Sea Treaty (1982). The United Nations Law of the Sea Treaty Information Center, <http://www.unlawoftheseatreaty.org/>

Van Dover, C. L. (2011). Mining seafloor massive sulphides and biodiversity: what is at risk? *ICES Journal of Marine Science*, vol. 68, pp. 341-348.