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An Approach to Determine Suitable Mining Ground and Quantifying Mineability Risk for Diamond Mining Vessels in the Atlantic 1 Mining Licence, Offshore of Namibia

By

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A thesis submitted in partial fulfilment of the requirements for the degree of Masters in Exploration Geology.

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Abstract

Diamonds are recovered offshore of the southern coast of Namibia in the Atlantic 1 mining licence (Mining Licence 47). In the mining licence the diamondiferous gravel is mostly found in an unconsolidated form, with occasional semi consolidated gravel. Areas of competent outcrops also exist but are considered unmineable with current technology. This is due to the design of the current mining tools, that were created to remove the unconsolidated sediments from the seafloor. Two main technologies are currently deployed within the company, namely the crawler mining tools and the drill bit mining tools (big bits and small bits). Both technologies have their strengths and weaknesses when it comes to the mining terrain, whereby the drill bits can handle rougher terrains while the crawlers are better suited in smooth terrains. Multibeam bathymetric data is collected on all prospective areas within the mining licence, before any sampling or mining takes place. This data provides valuable input in aiding the visualisation of the seabed, as well as the nature of the terrain. Bathymetric data, together with sampling data, is used to determine the suitability of each mining tool to mine an area. For this study, new ways of determining vessel applicability to certain areas have been investigated, as well as determining the risk of mining those areas. A three pronged approach was applied. The first part utilised the benthic terrain mapping method to assess if the outputs can be used to categorise geological features and thereby develop zones of different vessel ground suitability. The second part was to create sedimentary facies maps over the area, to determine if this adequately classifies the different geological features in the study area. The third part was to use the existing sampling information to quantify the mineability and associated risk of an area for each vessel group (small bits, big bits and crawlers).

Acknowledgements

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My dear family: my husband Wilko, our son Kiran and our twin daughters Tara and Robin that we were blessed with at the beginning of this year, I thank you from the bottom of my heart for the support and for allowing me to take the time to complete this degree. Your love and patience for me were and still are unmatched.

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CHAPTER 1

INTRODUCTION

1.1. Locality

De Beers Marine Namibia (Pty) Limited (Debmarine Namibia) is a joint venture company based on a 50:50 shareholding between the government of the Republic of Namibia and the De Beers Group of Companies. The Company operates in Mining Licence 47, which is situated 8 km off the southwest coast of Namibia (Figure 1). Mining Licence 47 is commonly referred to as “Atlantic 1”. Namdeb Holdings (Pty) Ltd. holds the mining licence for both onshore and offshore mining operations. It fully owns the two operating companies, namely: Namdeb Diamond Corporation (Pty) Ltd. that operates on land, and De Beers Marine Namibia (Pty) Ltd. operating the offshore portion of the licence (Muvi-Tjikalepo et al., 2019).

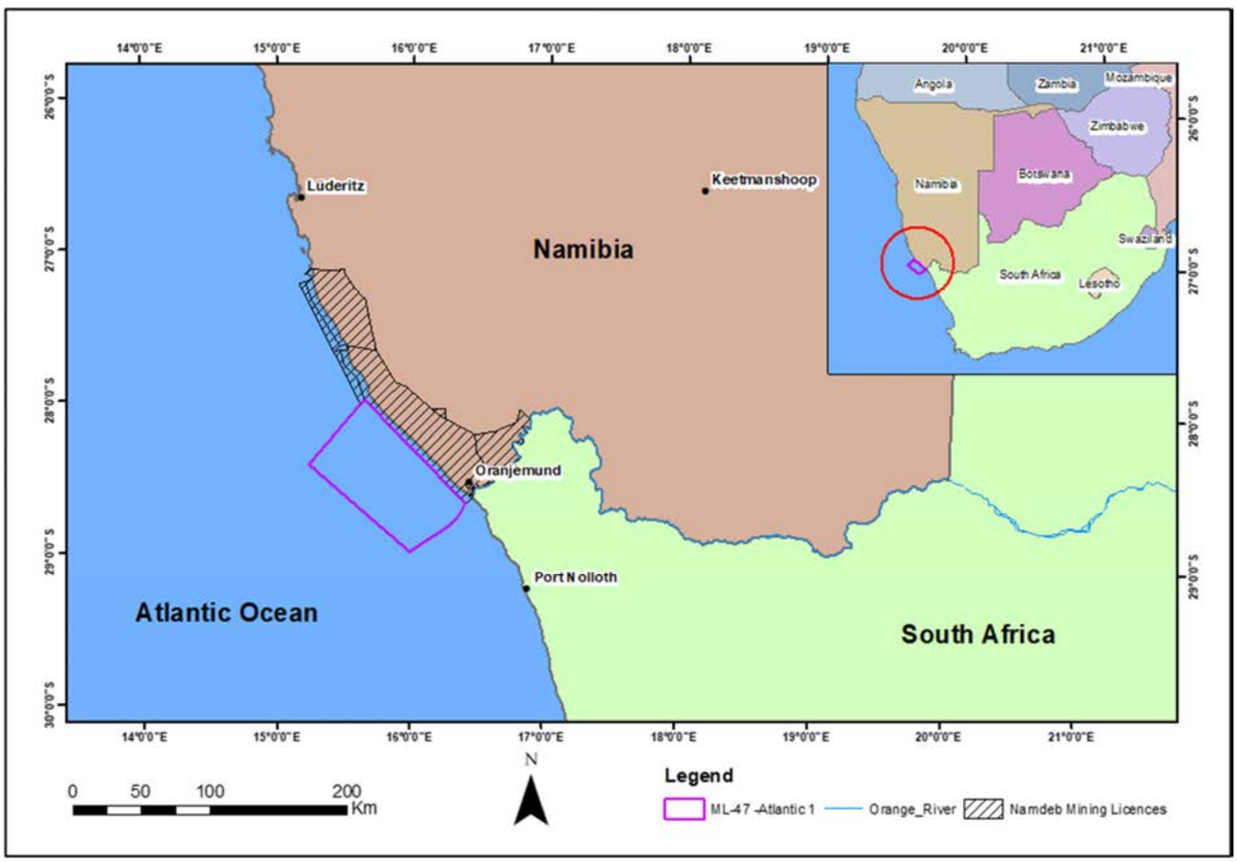

Figure 1: Location of the Atlantic 1 mining licence (ML-47).

1.2. History

Diamonds have long intrigued humankind. In more recent times and after excellent marketing, the diamond is the most common symbol for engagements, signifying resilience and longevity of a marriage.

While the first diamonds were discovered as early as the 4^{th} century BC in India, it was only in 1908 that the first diamond was discovered in Namibia: then South West Africa, a German colony. This discovery was followed by a turbulent time of diamond prospecting and mining along the country's coastline. Many started believing that the diamond riches along the coast extended into the shallow and deep ocean. It was a sheep farmer from Beaufort West, Johann Viviers, who proved the existence of diamonds beneath the deep ocean in the late 1950's to a water depth of 23.7 m (Schneider, 2009). These were the first diamonds to be mined from below sea level. Viviers however, had no desire to mine the offshore diamonds economically. In came Samuel Vernon Collins, a Texas oil and pipeline man, who together with a group of diamond enthusiasts, founded the Marine Diamond Corporation and bought the offshore licence from Viviers. This was the birth of commercial marine diamond mining. Collins assembled a mining fleet and mined successfully for 4 years, recovering more than 577 000 cts (Schneider, 2009). However, during these four years, bad weather had caused costly breakdowns, and even the loss of vessels, and so Collins sold De Beers a majority share of his company to De Beers in 1965.

With no prior sampling or geological knowledge of the ore body, Collins did not follow a systematic approach to mining the licence areas. When De Beers took control, substantial mapping and sampling was done to better understand these marine deposits. De Beers also applied a different strategy, sending out a sampling vessel to do exploration and only deploying a high cost mining vessel once a resource was established. During this time, production was low, with an increased focus to surveying and sampling. Up until 1971, mining and sampling had been done in water depths of <30m. During a period of poor weather in 1971, when the sampling vessel could not access the shallow waters, a few grab samples were taken in water depths of 100m. Concentrated heavy minerals were identified in the sediment, providing the first indication of paleo-beaches beyond the 30m water depth (Richardson, 2007). In the years to follow, a large amount of research, bathymetric survey and sampling was undertaken to better understand the resource and build a reserve. Sampling lines of 500m to 1000m, with sample intervals of 40m were drilled along the lines in an inshore->offshore direction (Muvi-Tjikalepo et al, 2019). For ease of reference, a 10km by 10km grid was placed over the prospective area within the licence and each block within the grid was labelled as a "region". To date, 60 regions exist within the Atlantic 1 mining licence.

In the early 1970's, Marine Diamond Corporation was fully owned by De Beers and was incorporated in to Consolidated Diamond Mines (CDM). A world class diamond deposit was delineated offshore by 1983 but CDM did not have the means to mine it. South Africa's interest in offshore mining had peaked during this time and De Beers Marine was formed as a contracting company to mine in both Namibian and South African waters. In 2001, De Beers formed the wholly Namibian company, De Beers Marine Namibia Ltd, to operate solely in Namibian waters (later renamed Debmarine Namibia).

CHAPTER 2

GEOLOGY OVERVIEW

2.1. Primary Diamond Sources and Emplacement

Diamonds are generally formed at depths of 150 to 200 km in the mantle, under high pressures and relatively low temperatures (Figure 2). They are commonly brought to earth's surface by three main types of magmas: kimberlite, lamproite and lamprophyre (Gurney et al., 2010). Kimberlite magmas are by far the most common transporters of diamond, with about a thousand diamondiferous kimberlites currently known (De Beers, 2014). According to Clifford (1966), diamondiferous kimberlite pipes are limited to those intruded through stable Archean cratons, where the relatively thicker mantle lithosphere allows for stable, long-term, high pressure and relatively low temperatures, providing the best conditions for diamonds to form. Therefore, regions with large areas of Archean-aged crust have the greater potential to be endowed with diamonds (Bluck et al., 2005).

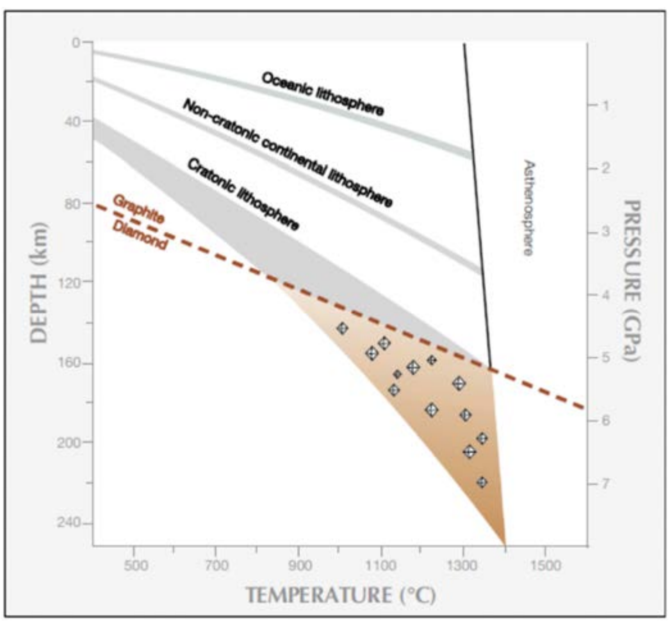

Figure 2: Ideal conditions for diamond creation and preservation (modified by Shirey and Shigley, 2013, from Tappert and Tappert, 2011).

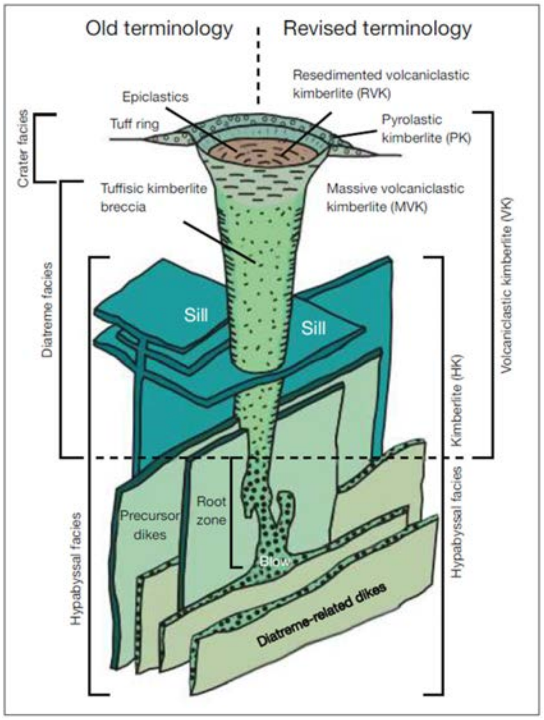

Figure 3: Schematic section showing the classic kimberlite pipe model, with dykes and sills of kimberlitic magmas (Kjarsgaard, 2007).

Kimberlitic magmas are generated at depths of >140 km, at which diamonds are stable, are generally high in volatiles, MgO rich and rise to surface rapidly. All these characteristics make it possible for diamonds to be brought upwards without a high level of resorption, that would otherwise destroy them (Shirey et al., 2013). Kimberlitic magmas vary in composition depending on proportions of disaggregated mantle and crustal xenoliths, the ratio of H_2O to CO_2 in the volatile phase, phenocryst phases, such as olivine, and interaction with metasomatic minerals in the subcontinental lithospheric mantle (Shirey et al., 2013). Eclogites and peridotites are the main mantle rocks hosting diamonds. Diamonds are released from these rocks by alteration and disaggregation during the sampling of these rocks by the kimberlitic magma (Kirkley et al., 1991). Eclogites, diamondiferous and barren, are able to survive the transport by kimberlite as xenoliths (Shirey et al., 2013). The diamond concentration in peridotites is generally quite low and hence most peridotites xenoliths do not contain many diamonds (Shirey et al., 2013). Diamonds, together with garnets, olivines, chrome diopside and ilmenite are released during disaggregation of peridotites on decompression during the upward movement of the kimberlitic magma. Therefore, these minerals are used extensively to explore for diamondiferous kimberlites at surface (Gurney et al., 2010).

Two major compositional types of kimberlites have been identified: namely the Group 1 and Group 2 kimberlites. Group 1 and Group 2 kimberlites are distinguished on the basis of mineralogy, geochemistry and isotopic composition.

The Group 1 kimberlites are generally volatile rich (CO_2), potassic ultrabasic rocks and generally contain olivine, ilmenite, garnet macro- and mega-crysts set in a fine-grained matrix of olivine, serpentine, carbonate and minor phlogopite. Group 2 kimberlites are generally ultrapotassic, volatile rich (H_2O) peralkaline rocks, which have macrocrysts of phlogopite and olivine in a fine-grained matrix of mainly phlogopite, as well as olivine and diopside and other minerals. The main difference, then, between Group 1 and Group 2 kimberlites is the much higher micaceous content in the Group 2 kimberlites.

Isotope geochemistry provides another notable difference between Group 1 and Group 2 kimberlites. Group 1 kimberlites generally have slightly depleted isotopic signatures, with Sr ratios lower than bulk earth and Nd ratios higher than bulk earth. The opposite is true for Group 2 kimberlites, which have a slightly enriched isotopic signature, with Sr ratios higher and Nd ratios lower than bulk earth (Smith, 1983a,b). Group 1 kimberlites have been emplaced over a wide range of ages, from the Proterozoic to the Cretaceous, whereas Group 2 kimberlites were emplaced mainly between 114 and 200 Ma (Smith et al., 1985). Table 1 shows some of the better known southern African diamond producing kimberlite pipes and their intrusion ages.

Table 1: Well-known diamond bearing kimberlite pipes and their intrusion ages.

Kimberlite Pipe/Mine	Kimberlite Type	Intrusion Age
Kimberley	Group 1	Cretaceous – 78 – 92 Ma (Davis, 1977 and 1978)
Orapa	Group 1	Cretaceous – 93.1 ± 6 Ma (Davis, 1977; Allsopp et al., 1989)
Jwaneng	Group 1	Permian - 235±2Ma (Kinny et al., 1986, 1989)
Venetia	Group 1	Cambrian - 530±4 Ma (Allsopp et al., 1995)
Premier – Cullinan	Group 1	Proterozoic - 1179 ± 36 Ma (Smith, 1983b)
Voorspoed Mine	Group 2	Cretaceous - 131.3±0.6 Ma (Phillips et al., 1998,1999)
Finsch Mine	Group 2	Cretaceous - 118±2.8 Ma (Smith et al., 1985)

2.2. Secondary Diamond Deposits – the Namibian Mega Placer

The kimberlites of the Kaapvaal craton are unanimously accepted to be the source of the alluvial diamonds deposited along the west coast of southern Africa, called a mega placer deposit. According to Bluck et al. (2005) a diamond mega-placer refers to a series of interconnected deposits that result from one continuous process of transport and deposition. Such a deposit must encompass at least 50 million carats with 95% or more being of gem quality. To produce this mega placer requires a craton hosting intrusions of diamondiferous kimberlites that have a range of ages, as well as a large drainage system with a limited final constrained outlet to the ocean and that had sufficient energy at the placer site to remove sufficient sediment accompanying the diamonds away from the placer site (Bluck et al., 2005). Figure 4 shows the different placer types.

The drainage system that transported diamonds to the coast has been well documented by de Wit (1991). Post the Gondwana breakup, the Karoo River in the south and the Kalahari River in the north were the two main rivers flowing westwards from the hinterland towards the coast (Figure 5). The Karoo River reached the ocean in southern Namaqualand through the current Olifants River mouth, whereas the Kalahari River exited into the ocean close to the current Orange River mouth. During this time, due to rapid erosion, diamonds were released from kimberlites and transported by the Kalahari and Karoo rivers to the coast. During the Late Cretaceous, there was a change in this drainage system, when the lower Kalahari River captured the upper portions of the Karoo River (shifting the Karoo River northwards), creating a much larger drainage system, close to what we see today as the Orange River system/network (De Wit, 1999). The change in river courses was mainly as a result of landscape denudation and continental uplift.

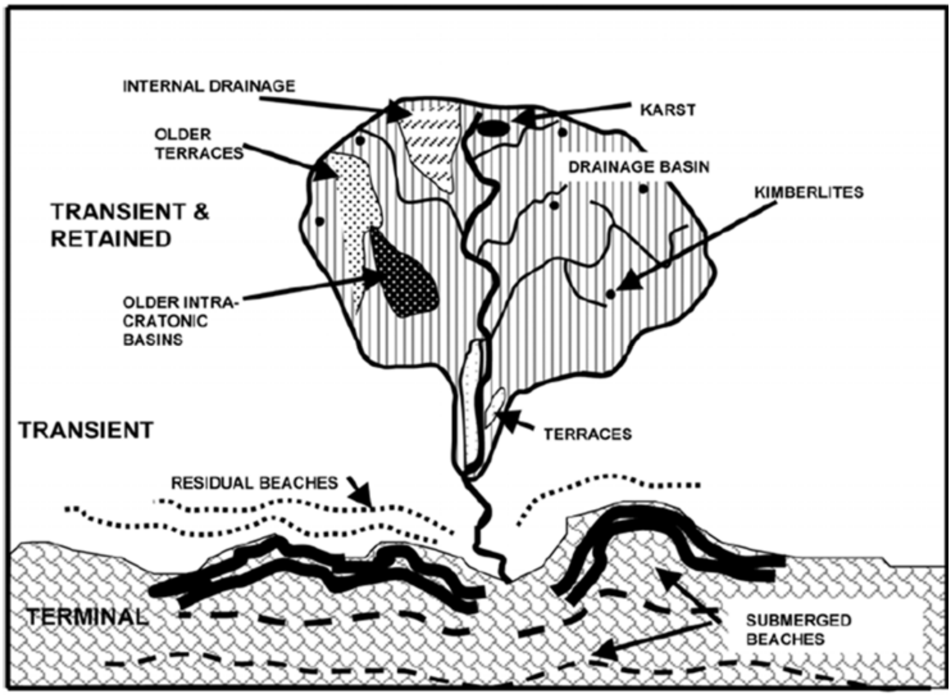

Figure 4: Placer Types (Bluck et al., 2005).

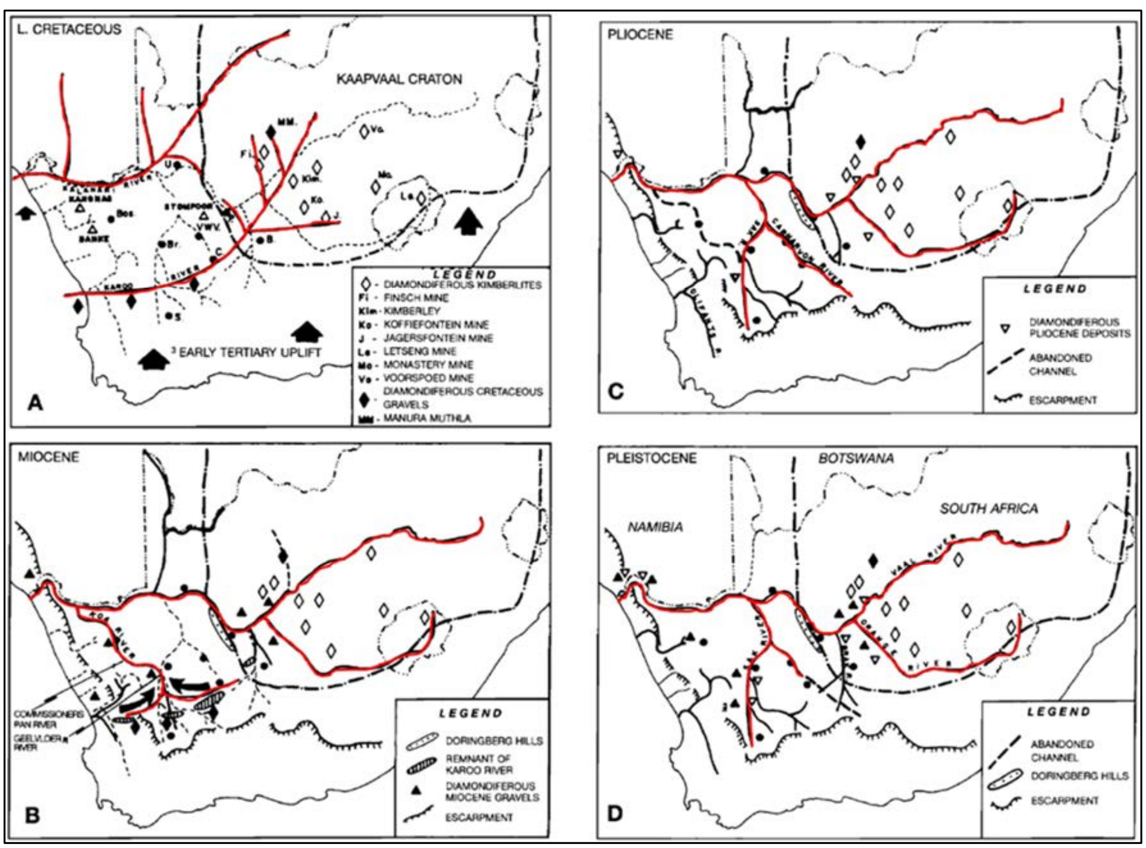

Figure 5: Schematic showing the change in the southern African drainage system over time (de Wit, 1991). The Kalahari and Karoo rivers are marked in red to show the change in drainage over time.

The post Gondwana uplift in southern Africa played an important role in the development of the placer: slope was increased, resulting in the rivers cutting deeper into the craton and reaching deeper lying diamonds as well as reworking existing fluvial deposits (Bluck et al., 2005, Jacob et al., 1999). This changed the river system from a suspended-load to bed-load dominated system, an increase in coarse material together with diamonds was transported by the rivers to the Atlantic (Bluck et al., 2005). In the lower Orange, very coarse material was derived from the coastal Neoproterozoic fold belts, mainly as large quartzite clasts (Nama Group) (Bluck et al., 2005) which are observed during mining today.

A large drainage area translates into large volumes of sediment being transported into the Atlantic Ocean. In order for the diamonds to further segregate from the sediment and to retain a gravel fraction as the diamond host, an energetic coastal regime is necessary. The Atlantic coastline is a very high energy system and has experienced windy and stormy conditions during the winter months, in which the high energy waves are formed in the South Atlantic (Gurney et al., 1991). They are enhanced by strong south-westerly winds, that attack the coastline from the southwest and create a strong northerly littoral drift of sediments (Gurney et al., 1991). This northward longshore drift carries gravels along with diamonds northwards from the Orange River mouth and is deposited as beaches and in the offshore environment. The morphology of the shelf also aided in the formation of the placer, whereby sediments were segregated, transported and diamonds were concentrated on a shallow, broad and low gradient shelf (Bluck et al., 2005), where changes in sea level have reworked the sediments. For gravels and sediment to be trapped, accommodation space is necessary, and this was created during the formation of the Orange Basin, that developed in a passive rifted margin.

It has been shown that diamond sizes decrease northwards from the Orange River mouth, as larger stones are deposited closer to the source, while smaller stones are more easily transported by the ocean currents (Gurney, 1991, Spaggiari et al., 2006). While initial mining in the Atlantic 1 mining licence confirmed this trend, more recent sampling and mining data in the northern sections of the licence area have demonstrated that larger stone sizes are also recovered at a distance from the mouth, based on unpublished in-house mining and sampling data. This could potentially be due to another source of diamonds to the north of the Orange River (unpublished theory). Fractured diamonds that do end up in the ocean are destroyed in the high energy environment of the Atlantic and as a consequence, recovered marine diamonds are predominantly (over 95%) of gem quality (Gurney, 1991).

2.3. Geology of the Atlantic 1 Mining Licence Area

Mining Licence 47 (referred to as Atlantic 1) lies offshore of southern Namibia on the mid-continental shelf, which is characterized as a gently sloping submerged land extending from the coastline to the steeper continental slope. The mid-continental shelf is characterised by very low relief and sea floor gradient (De Decker and Woodborne, 1996). Water depths generally range from 50m to 150m, with most mining taking place in water depths ranging from 90m to 150m. The continental basement consists of Precambrian rocks of the Damara Belt. The Precambrian basement rocks in the Atlantic 1 mining licence have only been intersected in the extreme inshore portions of the licence area during early sampling and are never intersected by mining in deeper waters. Thick sequences of younger clay, sandstone and claystone units cover the Precambrian basement in the Atlantic 1 mining licence area, and range in age from Upper Cretaceous to Holocene. Mining does not extend to older sequences as the mineralization potential is low and current technology is not designed to cut through thick sequences of clay or competent sandstone. Therefore, the younger sequences (Upper Cretaceous to Plio-Pleistocene) are termed ‘footwall’ in the context of the Atlantic 1 mining licence area and will be referred to as such in this dissertation.

Figure 6 shows the footwall ages as per the geological model of the licence area. Where Holocene sediments are shown in Figure 6, mud and silt layers are sufficiently thick that footwall has not been intersected. The geozones model shown in Figure 7 is a subset of the geological model based on the footwall ages. Geozones group areas of similar geological and physiographic characteristics. Each distinct geozone is chosen according to its period of formation or emplacement, together with its texture and morphology (Fernandes, 2015). These zones make up the smallest unit in the overall geological model of Atlantic 1.

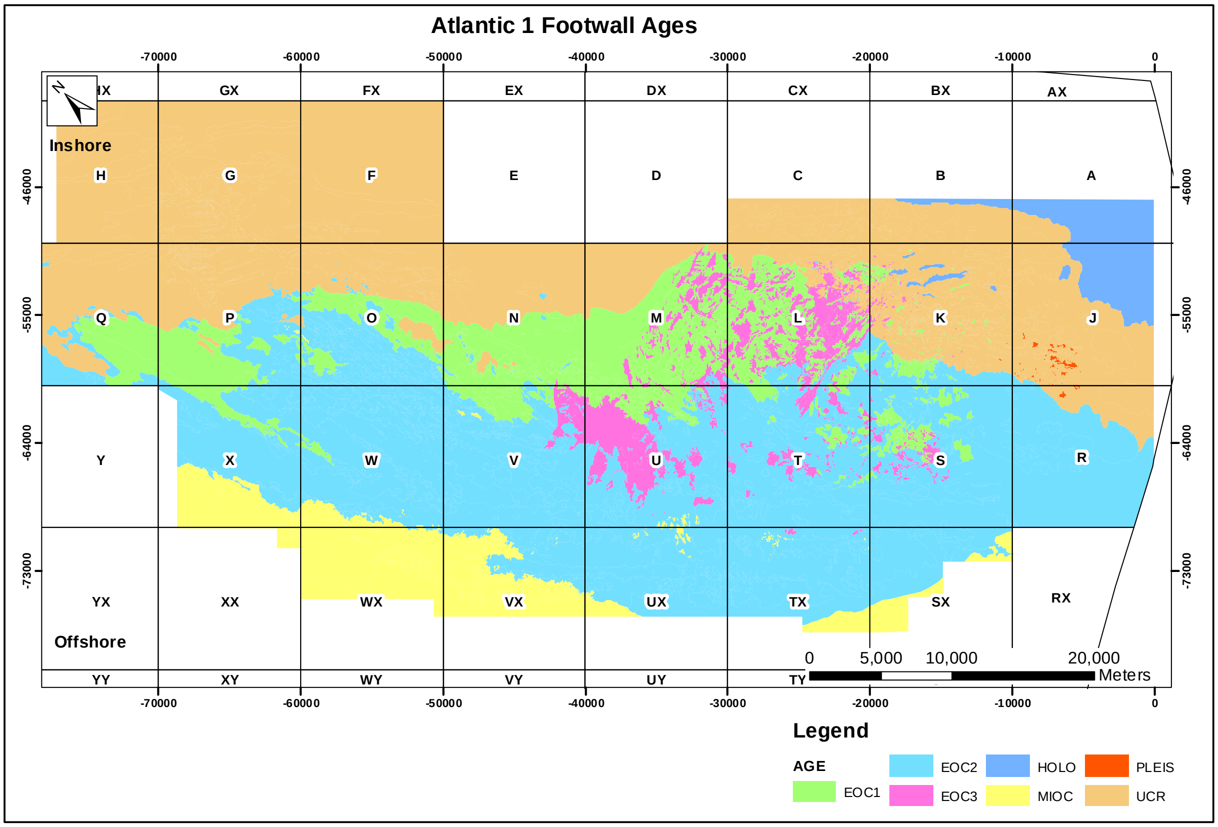

Figure 6: Base map of the Atlantic 1 licence area displaying the ages of footwall. Water depth increases from inshore to offshore (see Table 2 for legend explanation).

Table 2: Description and ages of the lithological units.

HOLO	Holocene	Acoustic blanketing layer in mud and clay, minor gravel bars
PLEIS	Plio-Pleistocene (~ 5 - 0.01 Ma)	Sandstone and conglomerate remnant outcrops
MIOC	Miocene/Aquitanian (~ 23 - 20 Ma)	Calcareous sandstone and conglomerate pavements, grades offshore into carbonates
EOC 3	Eocene 3 (? Sequence not dated)	Gritty sandstone/conglomerate isolated remnants
EOC 2	Eocene 2/Bartonian 1b (~ 41 - 38 Ma)	Clay dominated with secondary conglomerate and sandstone as well as minor sand
EOC 1	Eocene 1/Bartonian 1a (~ 41 - 38 Ma)	Firm to hard glauconitic green clays
UCR	Upper Cretaceous/Coniacian (~ 90 - 86 Ma)	Hard clays interbedded with sandstone layers that dip 5 degrees offshore and outcrops on the seafloor

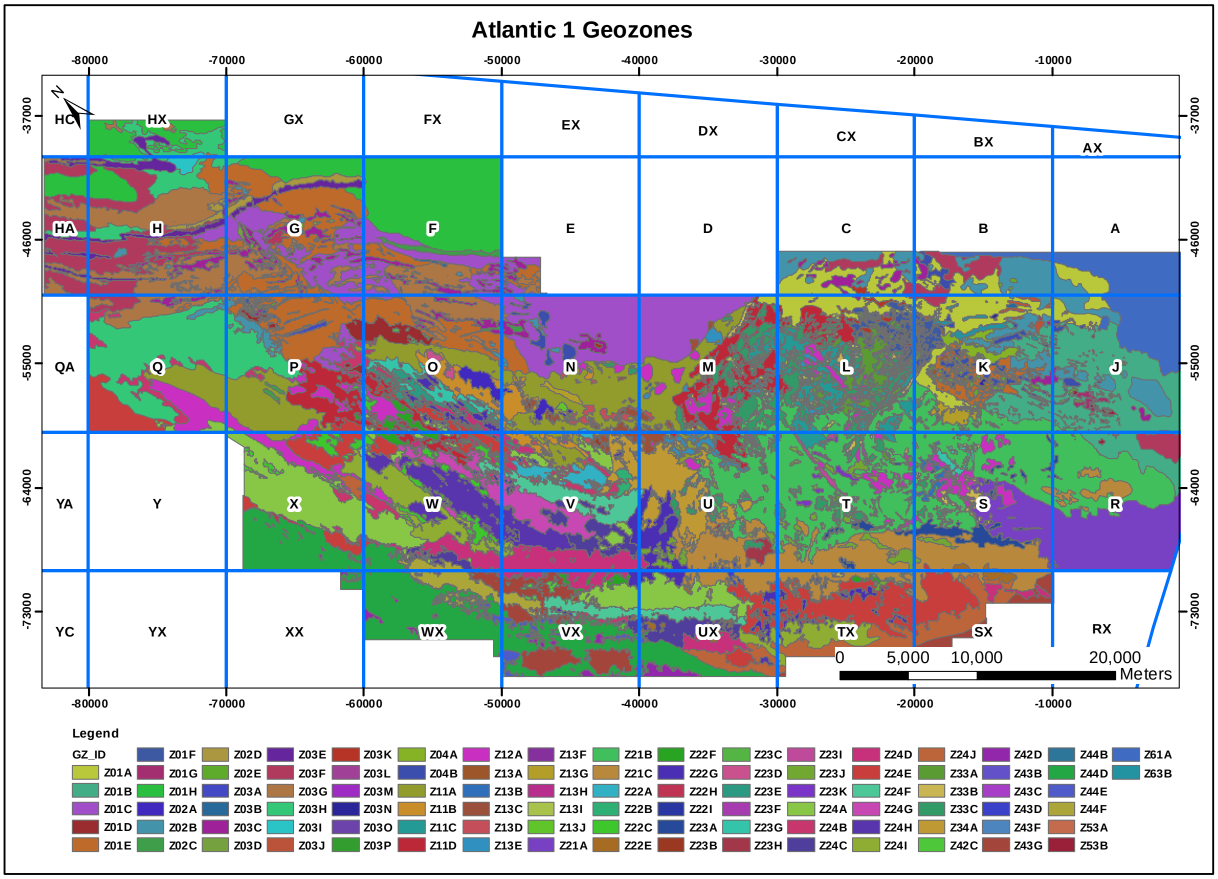

Figure 7: Atlantic 1 Geozones Model.

The footwall stratigraphy of Atlantic 1, on which the geozones are based, does not include the orebody horizon. The mineralization is mostly found in unconsolidated gravel lags, that were deposited in several phases of deposition and reworking. These gravel lags (Eocene to Meso) overlie the footwall sediments in the licence area. Recent silty and muddy sediments, in turn, overlie the unconsolidated gravels. There are, however, also areas of so-called paleo-placers, that are covered by a competent sandstone capping.

In-house clast assemblage studies have been conducted in the licence area to link the Atlantic 1 deposit with the Orange River deposits (Sitoka et al., 2020). Gravels are believed to have first reached the Atlantic Ocean by the late Eocene; these were composed of Vaal River type agates, BIFs and chert with very little Karoo sediments. The next flush of gravels, termed the Pre-Proto gravels, came during the Late Oligocene (30 Ma) and are identified by an abundance of clasts from the banded iron formations, Vaal River Type agates, yellow chalcedonies and darker, resinous-looking agates. Karoo "black and shiny" phosphate rich shale pebbles are also abundant (Shithigona and Burger, 2018). Pre-Proto gravel is known for its high diamond grades, but small stone sizes (Bluck et al., 2005). The Proto gravel influx arrived in the lower Orange River during the Miocene about 17 Ma ago, and is identified by an increase in Karoo sediments, epidosites and fewer BIFs and Vaal River

Type agate clasts (Shithigona and Burger, 2018). Diamond grades started to diminish, however, diamond stone sizes increased. The last influx, the Meso, came during the Pliocene (possibly 5 Ma ago). Karoo sediments diminished, while epidosites persisted. Riebeckite and ironstones increased and Orange River Type agates and jasper started to appear (Shithigona and Burger, 2018). Diamond grades decreased even more but the stone sizes increased even further (Bluck et al., 2005).

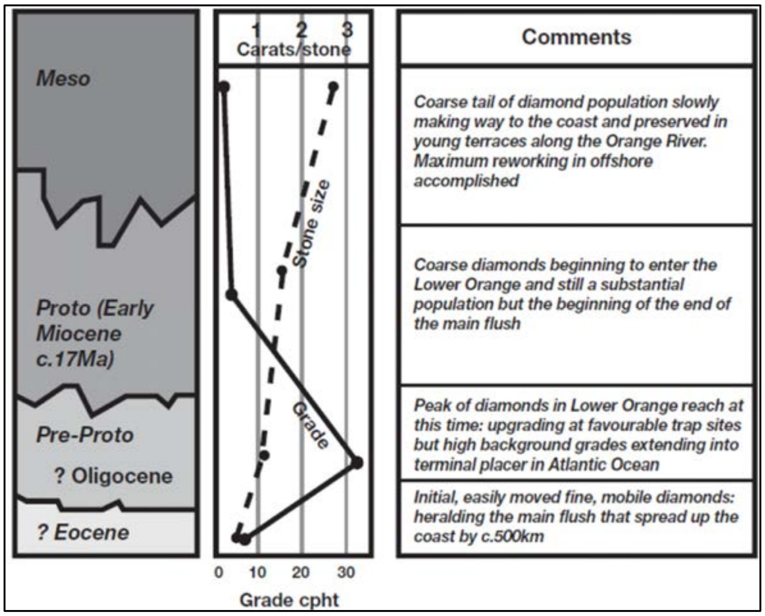

Figure 8: Section through the Lower Orange River Terraces showing grade and stone size variation (Bluck et al, 2005).

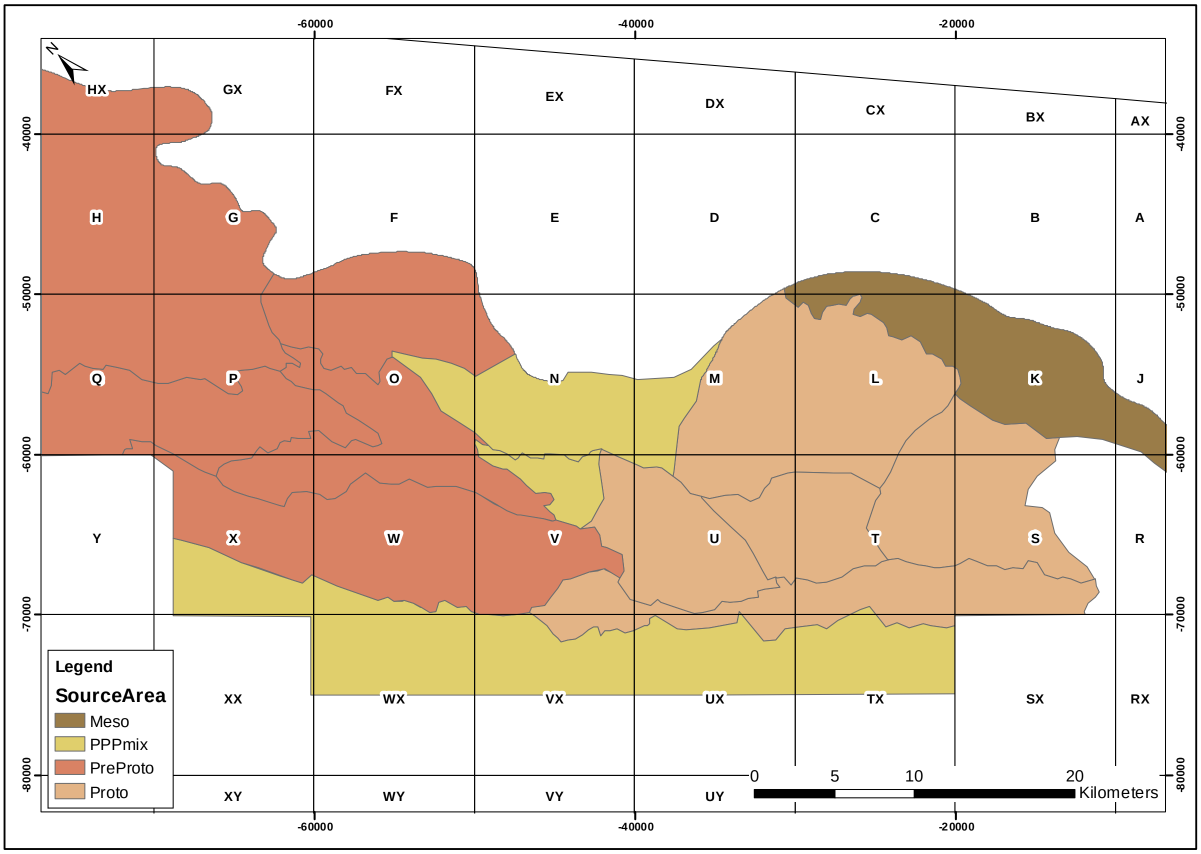

Figure 9: Atlantic 1 Mineralisation Model – gravel emplacement ages (Sitoka et al., 2020). PPP mix stands for Pre-Proto and Proto mix.

To concentrate diamondiferous gravels, trapsites need to be available. Trapsite potential is a function of the geomorphology of the footwall surface and is also dependent on the supply of mineralized gravel. When the footwall topography is rough, the potential to trap diamonds is greater than on a smooth footwall topography (Mubita, 2015). Large sandstone slabs also create efficient diamond trapsites. Diamondiferous gravel often accumulates in potholes, gullies, local depressions, scarp slopes, gravel beach berms or around ridges and outcrops. Reworking of the gravel through wave action and sea level changes, remove the finer sediments and concentrate gravel and diamonds.

2.4. Geology of Study Area

The focus for this study is an area located in Region H of the Atlantic 1 mining licence, which lies in the northern inshore area of the licence (Figure 10).

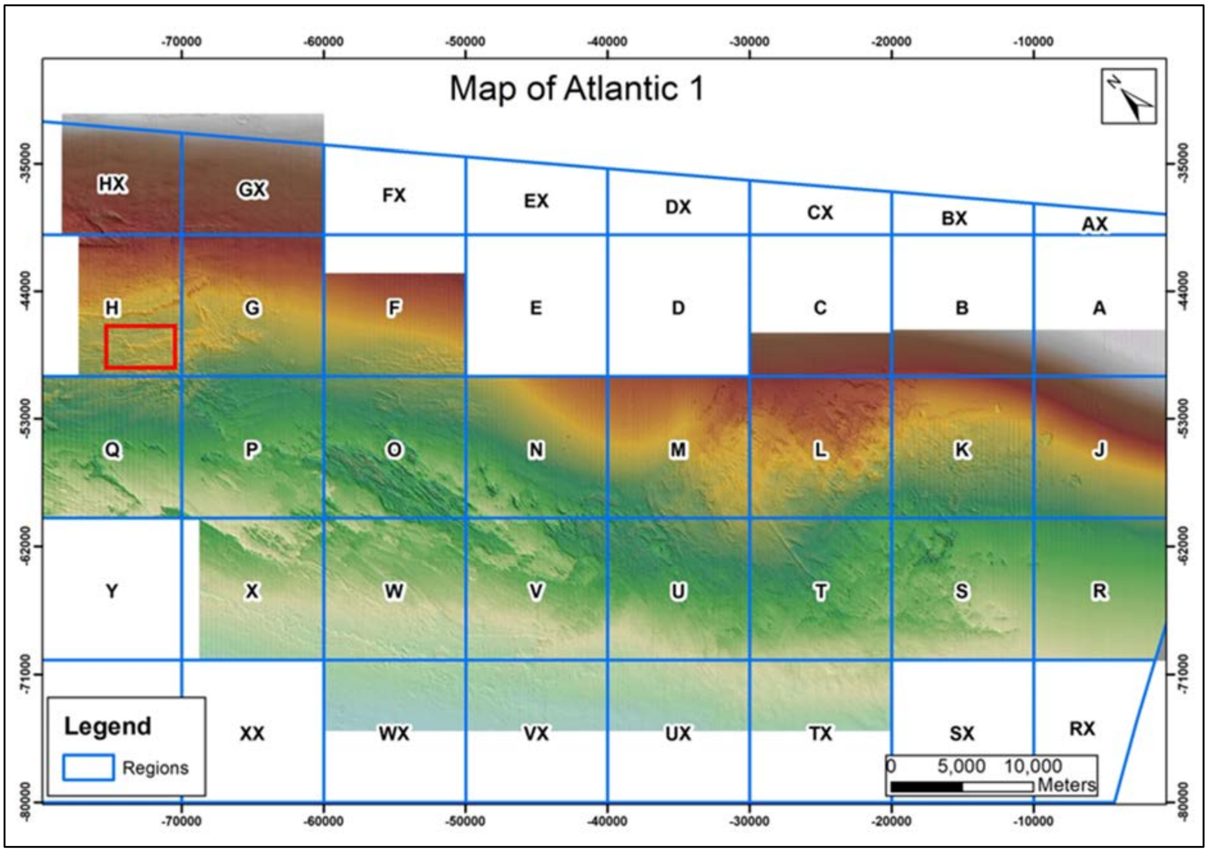

Figure 10: Map of the Atlantic 1 Mining Licence with the study area outlined in red in Region H. The brown colours on the map indicate shallower seabed, while the greens indicate deeper seabed.

The study area covers an area of 17.5 km^2 and the footwall units are Upper Cretaceous in age (90 – 86 Ma). The footwall is mainly hard clay, intercalated with sandstone layers. The intercalation of clay and sandstone formed during alternating wet and dry periods during the Cretaceous. During rifting, the offshore Cretaceous strata were tilted and a period of erosion commenced. Clays were easily eroded, and the more competent sandstone layers remained: these are known as sea dipping reflectors. Further breakdown of these sandstone reflectors created high sandstone slab frequencies.

Six different geozones have been identified in the company's current geological model, ranging from competent ridge zones to eroded flats and depressions, as well as channels and gulleys (Figure 11).

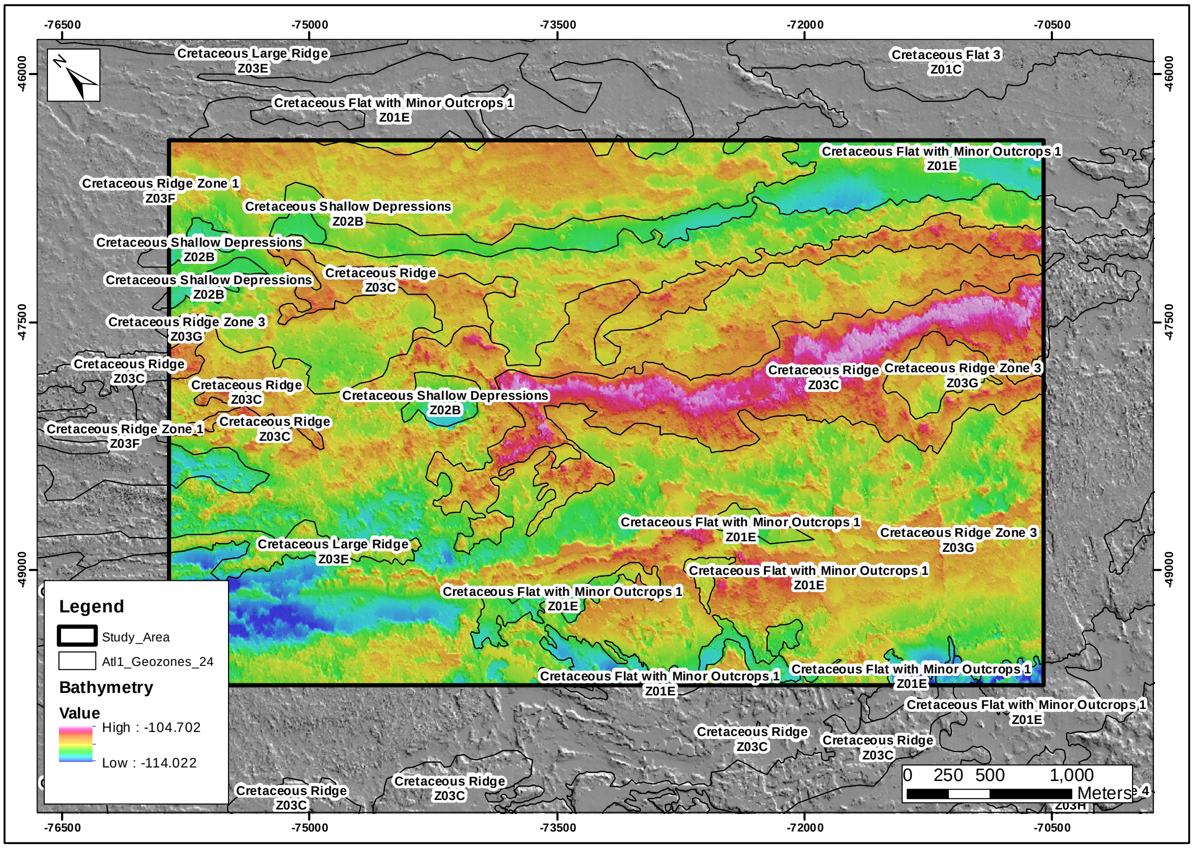

Figure 11: Study area bathymetry and geozones.

The nature of the geozones are detailed below.

Cretaceous Ridge Zone 3 (Z03G) geozone

The Cretaceous Ridge Zone 3 (Z03G) geozone is characterised by a rough terrain that is made up of closely spaced Cretaceous sandstone reflectors. Highly variable gravel accumulations are expected, with a high slab frequency, due to the weathering of the sandstone reflectors. The dominant footwall is usually Upper Cretaceous clay, however, this can depend on the degree of weathering. Sampling generally intersects a sand footwall, with lesser clay and sandstone footwall.

Cretaceous Ridge Zone 1 (Z03F) geozone

The Cretaceous Ridge Zone 1 (Z03F) geozone is characterised by a relatively flat to slightly undulating terrain. Soft clay footwall dominates this zone with minor occurrences of sand footwall.

Cretaceous Large Ridge (Z03E) geozone

The Cretaceous Large Ridge (Z03E) geozone is characterised by large north-south striking ridges, formed by closely spaced outcropping sandstone reflectors. Alternating ridges and small valleys create the rough topography in this geozone. High slab frequency of very large slabs are common in this geozone. From sampling, the dominant footwall type is sandstone with lesser clay and sand in more weathered areas.

Cretaceous Flat with Minor Outcrops 1 (Z01E) geozone

The Cretaceous Flat with Minor Outcrops 1 (Z01E) geozone is a flat area with Cretaceous reflectors, Eocene outcrops, Pleistocene conglomerate, and minor gravel accumulations. The footwall is dominated by the Upper Cretaceous clay footwall. Shallow depressions, scours, and raised platforms are common within the overall smooth areas of the geozone. The depressions are thought to be cut on the lee side of the reflectors and outcrops. As a result, the texture and gravel volumes are expected to be coarser and thicker towards the inshore area of the reflectors and outcrops. The general footwall intersected by sampling was clay.

Cretaceous Ridge (Z03C) geozone

The Cretaceous Ridge (Z03C) geozone is characterised by closely spaced thick outcropping north-south striking sandstone reflectors. The terrain is rough with minor valleys between the sandstone ridges. The gravel is generally thick but variable. Very high slab frequency can be expected. The footwall types vary from soft clay to hard sandstone, where the reflectors or outcrops are encountered. Sampling intersected sandstone and conglomerate as the dominant footwall types, minor clay and sand footwall types were also intersected.

Cretaceous Shallow Depression (Z02B) geozone

The Cretaceous Shallow Depression geozone consists of shallow depressions that are cut into the Cretaceous clays. Due to the shallow nature of the depressions, gravels are generally washed towards the offshore ends of the depressions, where gravel can accumulate. However, the shallow depressions are generally sparse in terms of gravel. The dominant footwall is clay.

Gravel input to the study area occurred during the Late Oligocene (Pre-Proto gravels) and gravels are largely unconsolidated that accumulated in trapsites. Clasts of Banded Iron formation, Vaal type agates and yellow chalcedonies are present within the gravel. During the Late Oligocene, there was an increase in Karoo-type clasts, with a large proportion of the gravel dominated by “black and shiny” phosphates, which is observed in the plantfeed fraction during mining in the area. Higher diamond grades are associated with gravels in smaller weathered potholes that occur within partially weathered ridges. Zones with alternating crests and valleys also create good diamond trapsites, whereby gravel can be trapped in the narrow valleys.

CHAPTER 3

CURRENT SAMPLING AND MINING PRACTICES

3.1. Atlantic 1 Resource

Historically, several sampling vessels have sampled in Atlantic 1, covering most of the licence. Figure 12 shows the spatial distribution of the footwall strata recovered during sampling. Today, the merchant vessel (mv) Sam Shafiishuna Nujoma (SSN) is the only sampling vessel operating in the licence area. The vessel was commissioned and started sampling in May 2017. The SSN is fitted with an enhanced frame-based sampling tool that covers an area of 10 m^2 (Figure 13). Her predecessor was the mv Coral Sea (CS). The CS was subsequently converted to a mining vessel and joined the company's current mining fleet within the licence area.

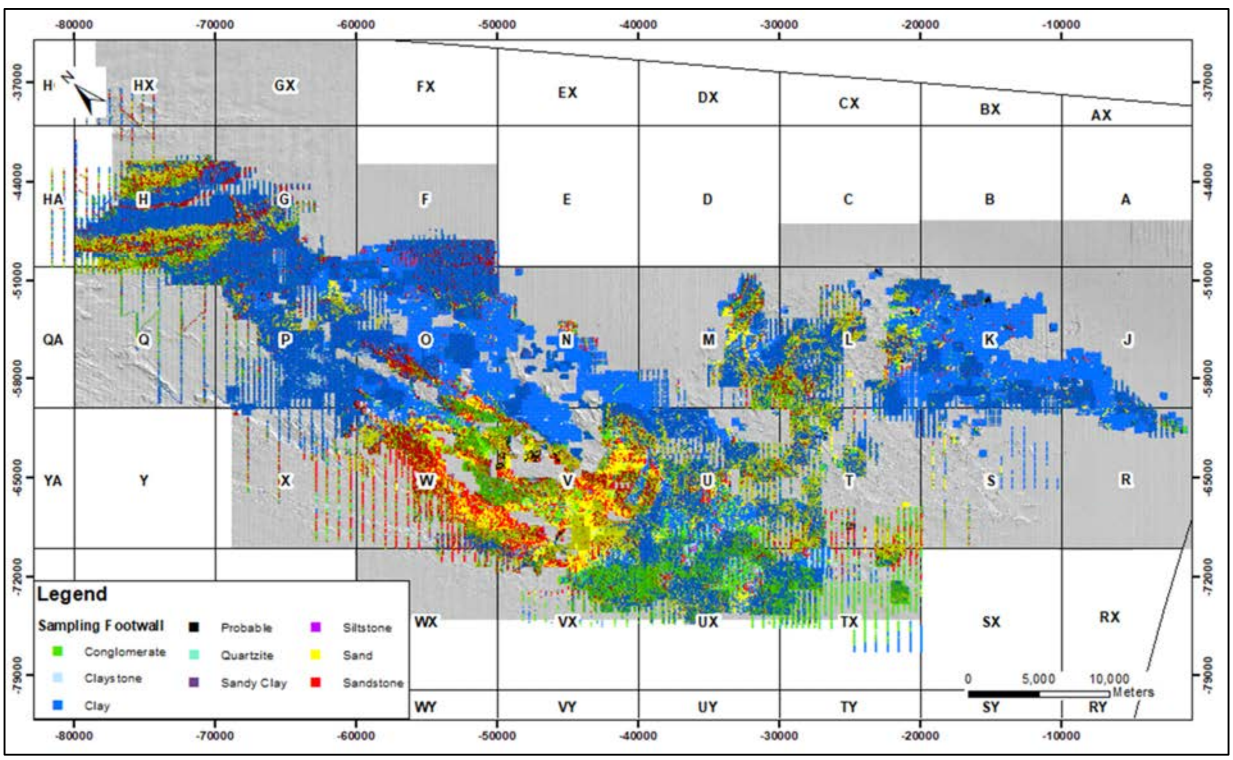

Figure 12: Sample coverage in Atlantic 1. The colours reflect the different types of footwall that were intersected during sampling.

Figure 13: The sampling vessel SSN on the left and the sampling tool in its frame on the right.

In newly identified areas with mineralization potential, identified from the geological model, greenfield sampling is done at a very wide sample spacing (800m x 400m). Brownfields sampling (200m x 200m) is then done in areas that showed economic potential during greenfield sampling. Areas with higher grade potential from the brownfields sampling are then followed up by a much tighter interval of generally 100m x 50m, called Pre-Production Development (PPD) sampling. From PPD sampling, the resource in Atlantic 1 is outlined on 100m x 100m blocks on a regular grid throughout the licence area and is referred to as the Local Block Estimate (LBE). At a sampling density of 100m x 50m, each 100m x 100m block is covered by two samples. In highly variable terrain or geology, the sampling density of 50m x 50m is applied.

The grade for the deposit is expressed in two dimensions: carats per square meter (cts/m^2) as outlined in the SAMREC Code for marine alluvial deposits. This is different to the grade for other primary and alluvial deposits, which are reported as carats per one hundred tonnes (cpht) or cts/100m^3. The reason for using a grade per square meter in Atlantic 1 is due to the fact that gravel thickness is generally very thin. Figure 14 shows the grade distribution across the licence area, with light blue depicting the lowest grades and the red showing the highest-grade distribution. Higher grades are found in areas that have good trapsite potential (depressions, gulleys, lee side of slopes and outcrops) compared to lower grades that are found in flatter terrains with less trapsite potential.

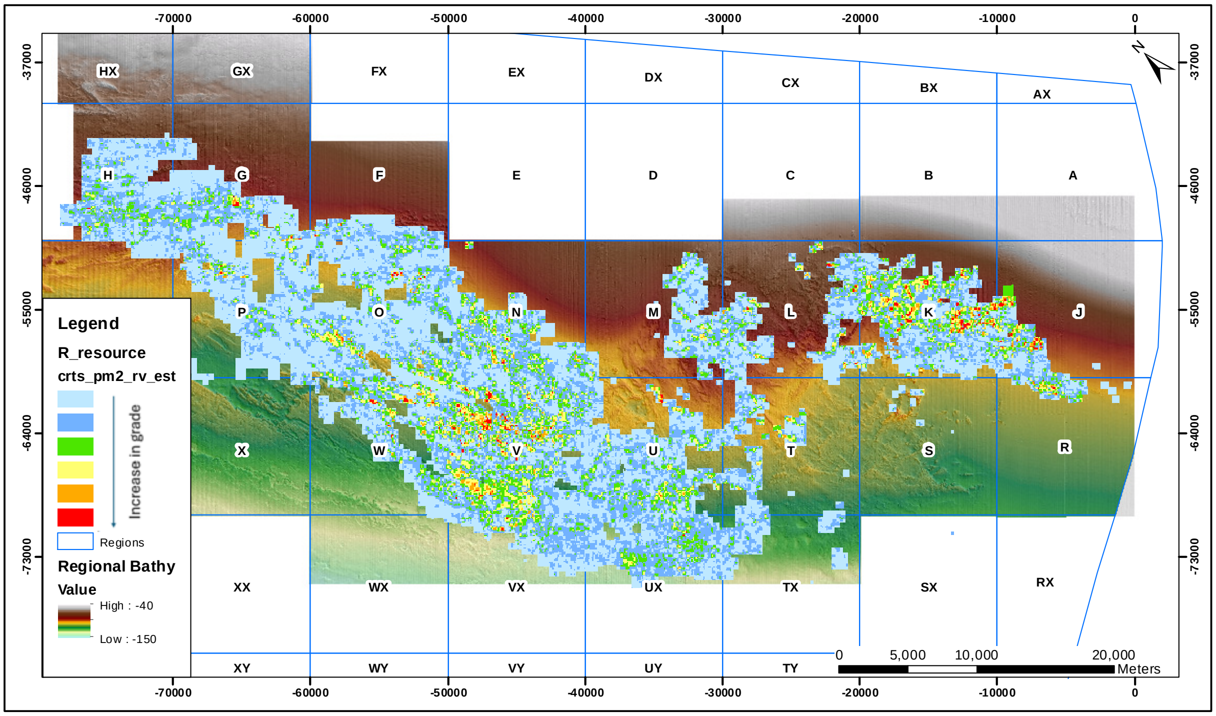

Figure 14: Current resource in Atlantic 1, with low grades displayed in cooler colours, while higher grades are displayed by warmer colours. Grades are expressed as cts/m^2.

3.2. Mining Fleet and Current Mining Practices

Mining is completed on the 100m x 100m estimated blocks. Mining is executed by the seven mining vessels, namely the merchant vessels Debmar Atlantic (DA), Debmar Pacific (DP), !Gariep (GP), Grand Banks (GB), Coral Sea (CS), the Mafuta (MFT) and the Benguela Gem (BG) (Figure 15). The vessels are divided into drill bit and crawler carrying vessels. Debmar Atlantic, Debmar Pacific, !Gariep , Grand Banks and the Coral Sea are all drill equipped vessels; Mafuta and Benguela Gem mining vessels are equipped with crawlers.

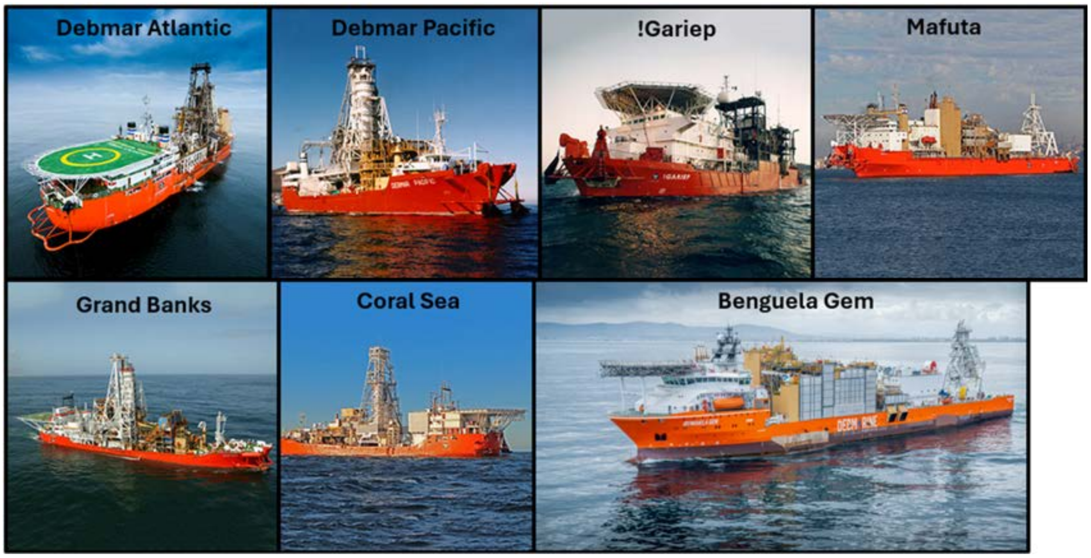

Figure 15: The Debmarine Namibia Mining Fleet.

3.2.1 Drill bit Vessels

Drill bit vessels make use of a vertical mining system, whereby a drill bit is connected to the vessel by a rigid steel pipe through an opening in the centre of the vessel (Figure 16). Mining is done by sucking up unconsolidated to semi-consolidated gravel through the rotating drill bit into the drill string until footwall has been reached. This is done by lowering the drill bit onto the seabed in a specific location and once all gravel is removed (footwall reached), the drill bit is lifted and moved to an adjacent overlapping hole position. The drill bits are not true drill bits in the conventional sense in that they do not cut through the rock but rather suck up the gravel.

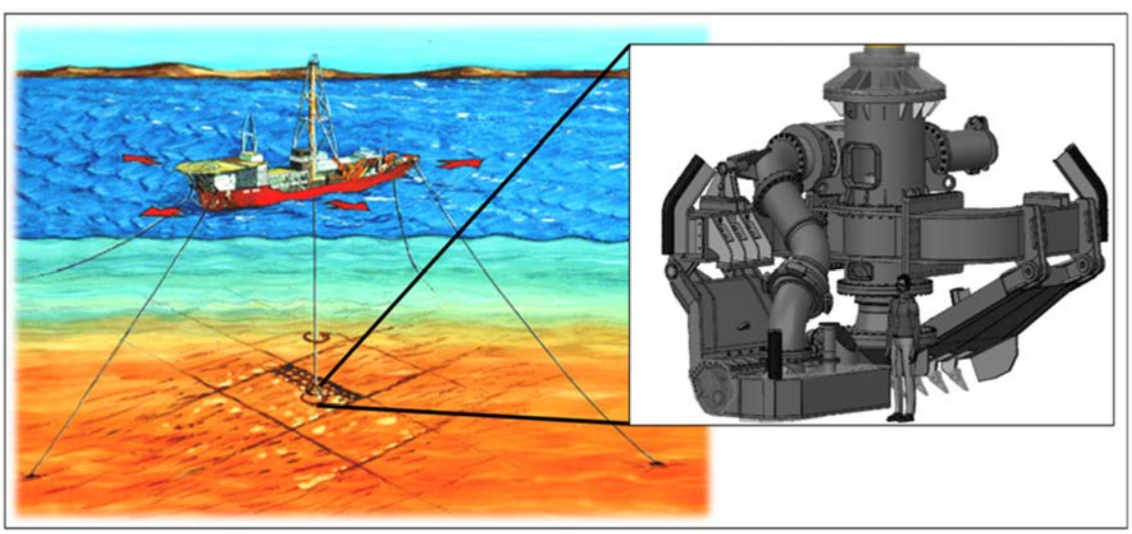

Figure 16: A drill bit mining vessel on an anchored spread with the drill mining tool zoomed in.

Each vessel mines a number of mining panels a year, depending on their mining rates. Mining panels are generally between 40 000m^2 to 160 000m^2 in size. Therefore, between four to sixteen economic 100m x 100m Probable Diamond Resource blocks are combined to form a mining panel. Figure 17 shows a mining panel consisting of eight 100m x 100m mining blocks. The circles within most of the blocks represent the already mined holes (these are not to scale, therefore are not showing the hole overlap).

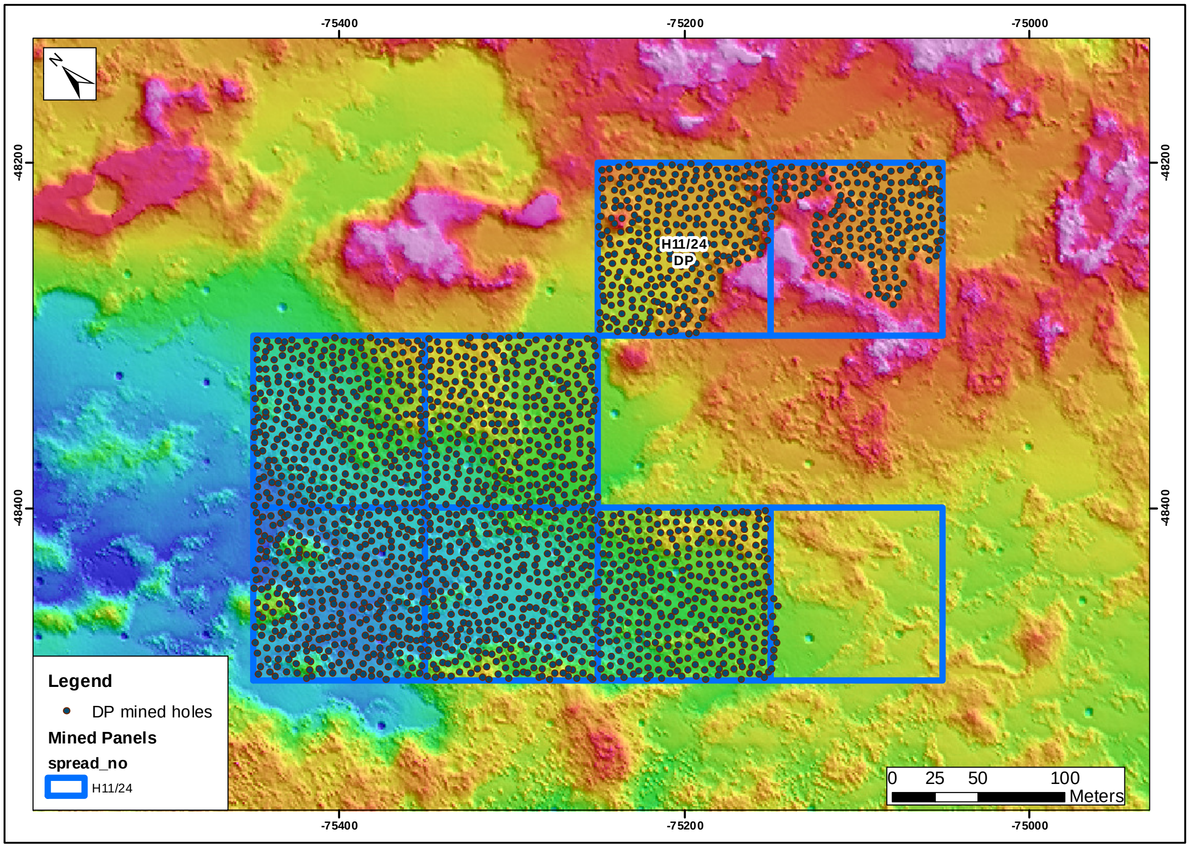

Figure 17: A map showing a mining panel consisting of eight 100m x 100m blocks. Within seven of the blocks, mined holes are shown. Individual holes are mined in an overlapping hole pattern to cover the ground sufficiently. Note that the already mined holes on this map are not to scale.

3.2.2 Crawler Vessels

The crawler vessels are fitted with a crawler tool that is connected to the vessel by a flexible riser pipe at the back of the mining vessel (Figure 18). In order to optimise on the mining rate, the crawler mining tool essentially drives across the sea floor on tracks and mines in lanes (Figure 19), rather than individual holes. Lanes are 20m wide and have a 2m overlap, in order to cover the area effectively, bringing up marine gravel, shell and clay with the nozzle and transferring the material through the flexible riser pipe onto the vessel. The crawler vessels generally mine larger mining panels of up to 200 000m^2. Currently, the MFT and the BG are equipped with crawler mining tools.

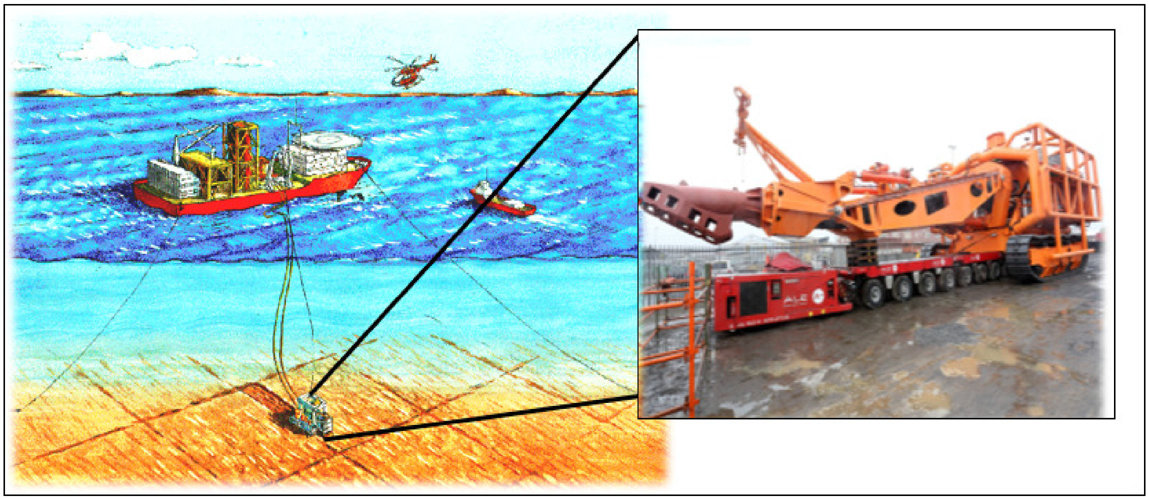

Figure 18: A crawler mining vessel on an anchored spread with detail of the crawler mining tool shown in the zoomed in inset.

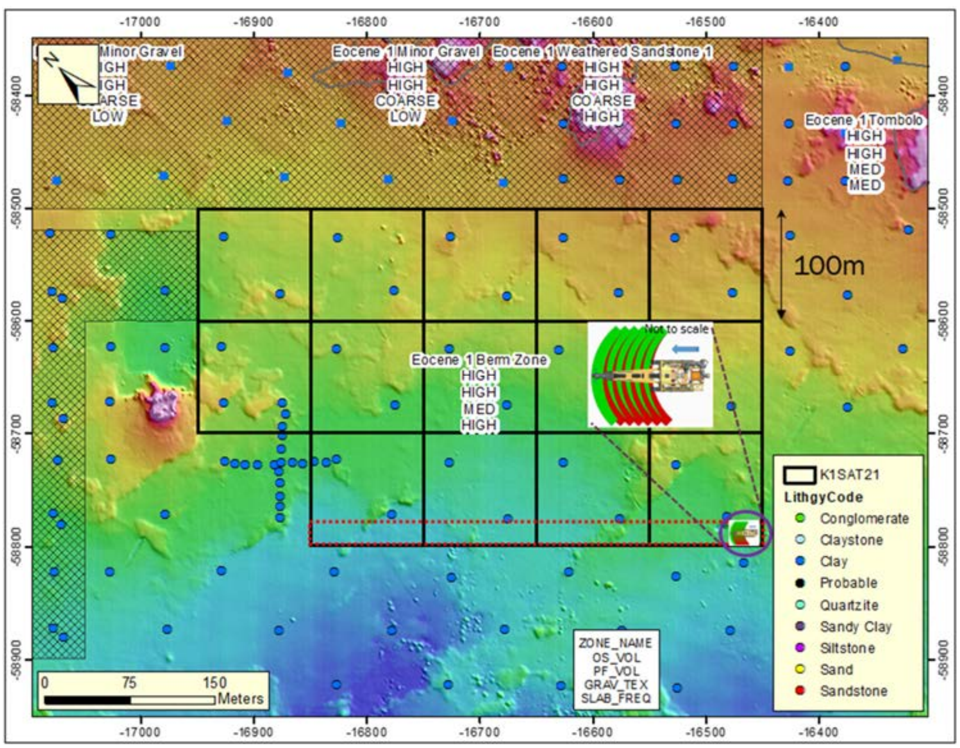

Figure 19: Current crawler mining practice, with crawler mining lanes from offshore to inshore of a panel.

Both the crawler and the drill bit vessels are equipped with their own processing plants with the size of the mining system dictating the plant capacity. After the comminution section, the screened material passes through a dense media separation (DMS) plant. From there the DMS concentrate is fed to the X-ray diamond recovery machines. The final concentrate is flown to shore, while the waste material is returned to the seabed. The majority of the vessels are kept in place by four anchors while mining. The sampling vessel (SSN) and the Benguela Gem on the other hand are on a dynamic positioning system (the vessels position and heading is maintained by its thrusters and propellers through a computer-controlled system).

3.3 Vessel Tool Capabilities, Ground Interaction and Plant Capacities

3.3.1 Drill bits

As discussed above, the drill vessels DA, DP, GP, GB and the CS are equipped with a drill bit and pipe of variable size diameters (Table 3). Based on the diameters of the drill bits, the vessels are further divided into two categories, namely small bits (CS and GB) and big bits (DA, DP and GP). The mining tool on all drill vessels is referred to as the ADS, which stands for Alternate Drill-string System (Figure 20). The tool consists of four main components, namely the structure, the central spud, the suction element and the rake. During mining when the tool is on the seabed, the spud anchors the tool. As the tool rotates, the rake prepares the ground by loosening any slabs or gravel accumulation, while the suction element follows, through which the gravel passes via the grizzlies into the drill string. The structure of the tool keeps all components in place.

Table 3: Vessel Configurations (Muvi-Tjikalepo et al., 2019)

Vessel	Tool type	Tool Size
Coral Sea (CS)	Drill and rigid riser pipe	6.1m drill and 500mm pipe
Grand Banks (GB)	Drill and rigid riser pipe	6.1m drill and 500mm pipe
Debmar Atlantic (DA)	Drill and rigid riser pipe	7.5m drill and 700mm pipe
Debmar Pacific (DP)	Drill and rigid riser pipe	7.5m drill and 600mm pipe
!Gariep (GP)	Drill and rigid riser pipe	7.5m drill and 600mm pipe

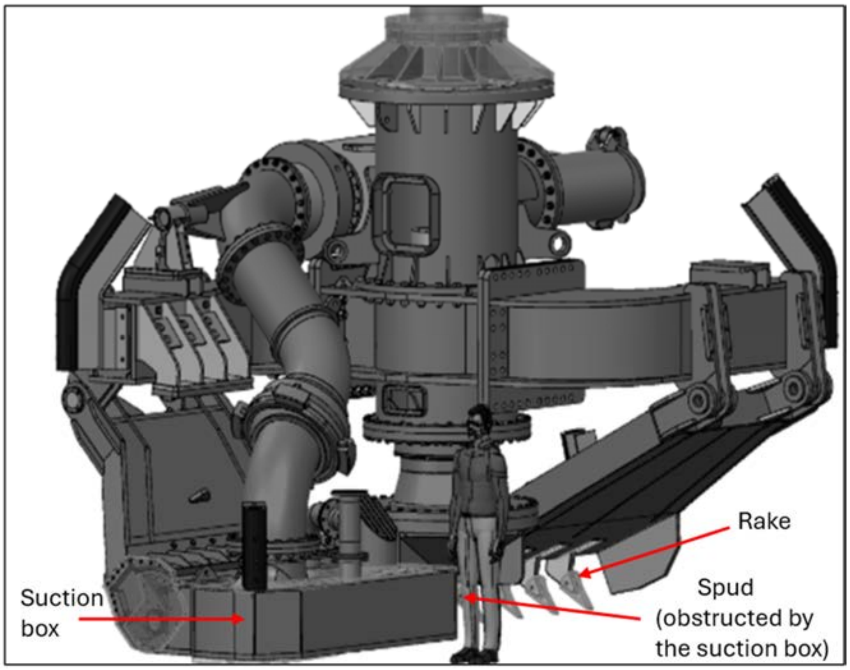

Figure 20: ADS mining tool. Major elements are the stationary spud in the centre of the tool and the suction box and rakes on either side of the tool.

Plant capacities differ for the different drill vessels, with the DA and the DP having the largest plant capacities. The GP, while having a similar pipe size to the DP, has a slightly smaller plant and can therefore not handle areas with very high volumes of course textured gravel as efficiently as the DA and the DP. The small bit vessels CS and GB have smaller mining systems and therefore are less capable of handling high volumes of coarse textured gravels (will cause processing delays). Shell handling capabilities also vary across the vessels: the DA and DP are able to handle shell volumes of up to 80% (percentage shell in plantfeed); the GP up to 70% shell; while the small bit vessels up to 60% shell volumes.

The easiest ground to mine for all drill vessels are geological terrains characterised by a smooth seabed, with minor cementation and little undulation, along with a low sediment package. However, the drill tools can handle various degrees of terrain roughness. Roughness refers to the nature of the bathymetry of an area. Very rough areas are characterised by highly undulating terrains, for example cemented/partially weathered sandstone that forms closely spaced pinnacles, tight valleys alternating with outcrops. The smaller diameter small bit mining vessels (CS, GB) are more effective in cleaning up the gravel in areas with rougher, more undulating and cemented terrains, where smaller potholes are common. The small drill bits can access smaller depressions and potholes, due to the smaller tool size (diameter).

Terrain that is too rough can cause tool stalling, whereby the tool stops turning due to an obstruction. Often redrilling is not successful, compromising the clean-up of gravel. Figure 21 shows panel H66/24. The green circles represent holes where no stalling has occurred, and the orange and red circles shows holes where stalling has occurred. The current mining tools are not designed to break or drill through hard rock in the conventional way but rather designed to suck up the unconsolidated sediment. Therefore, tool penetration challenges occur in cemented areas. However, depending on the degree of weathering, the weight on the drill bits can be increased, which can break a partially cemented layer (depending on degree of weathering) and grant access to the gravel layer below.

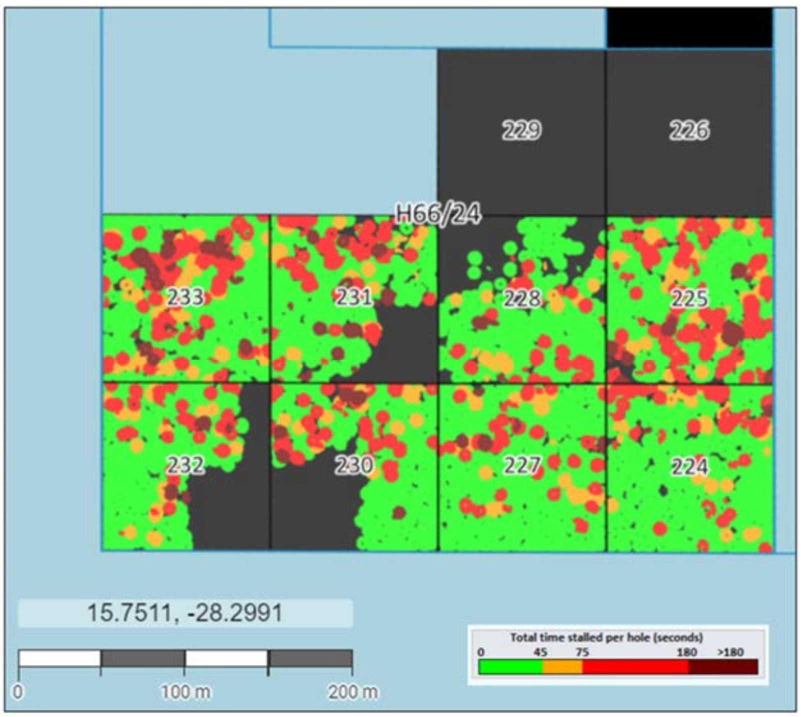

Figure 21: Stall duration for individually mined holes by a drill ship.

In rougher terrains, the drill ships have the flexibility to change the location of a mining hole slightly (a few centimetres to a meter), to avoid a steep slope or eliminate a geological feature (Figure 22). Steep slopes can lead to poorer cleanup, as the tool might not be fully engaged with the seabed. Slopes that are too steep can also cause tool slippage or breakage.

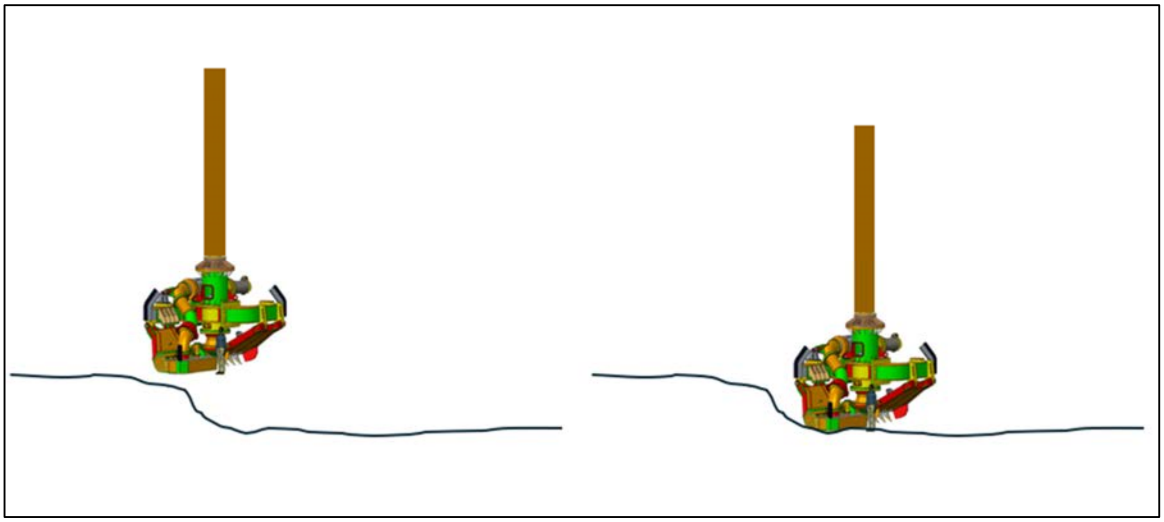

Figure 22: Left illustration showing the tool being lowered onto a predetermined mining hole, which is located on an area with a steep slope. To avoid the tool landing on a sloping area and potentially not cleaning up the ground, the hole can be offset as shown in the illustration on the right.

3.3.2 Crawlers

The MFT and the BG vessels are both fitted with a crawler mining tool (Table 4). The crawler consists of a framed structure on tracks with a nozzle attached to the end of the boom (Figure 23). During mining, the crawler drives across the seafloor on tracks, while the boom moves from side to side – sweeping the ground with the nozzle and sucking up gravel through the apertures of the nozzle. The number of sweeps required is determined by the gravel thickness. In thicker gravel packages the number of sweeps are increased to reach the footwall before the crawler moves forward. Different nozzles can be used on the crawler vessels, as the designs are constantly streamlined or improved.

Table 4: Vessel Configurations (Muvi-Tjikalepo et al., 2019)

Vessel	Tool type	Tool Size
Mafuta (MFT)	Crawler and flexible riser pipe	Various nozzles and 700 mm pipe
Benguela Gem (BG)	Crawler and flexible riser pipe	Various nozzles and 700 mm pipe

Figure 23: Crawler mining tool.

Plant capacity for both crawlers is much larger than the drill ships and can therefore handle areas with high gravel volumes. Shell handling capabilities of the crawler plants is better than the drill ships and can handle up to 90% shell volumes in the plantfeed. The capacity of the plants dictates the rate of mining. The MFT and the BG have large plant capacities and can therefore mine at higher mining rates.

Crawlers are most efficient in areas that are very smooth, with a thin sediment package, no cementation and very little undulation. Because the crawlers mine in straight lanes across an area, it is more difficult to navigate undulating terrain or areas with any outcropping features. Crawler mining tools were originally designed to mine flat terrain, and tracking up high slopes may limit the nozzles reach, meaning that it might not be able to lower the boom enough to reach the bottom of gravel for the area (Figure 24). The current fleet crawlers are limited to slopes of 10-degrees or less.

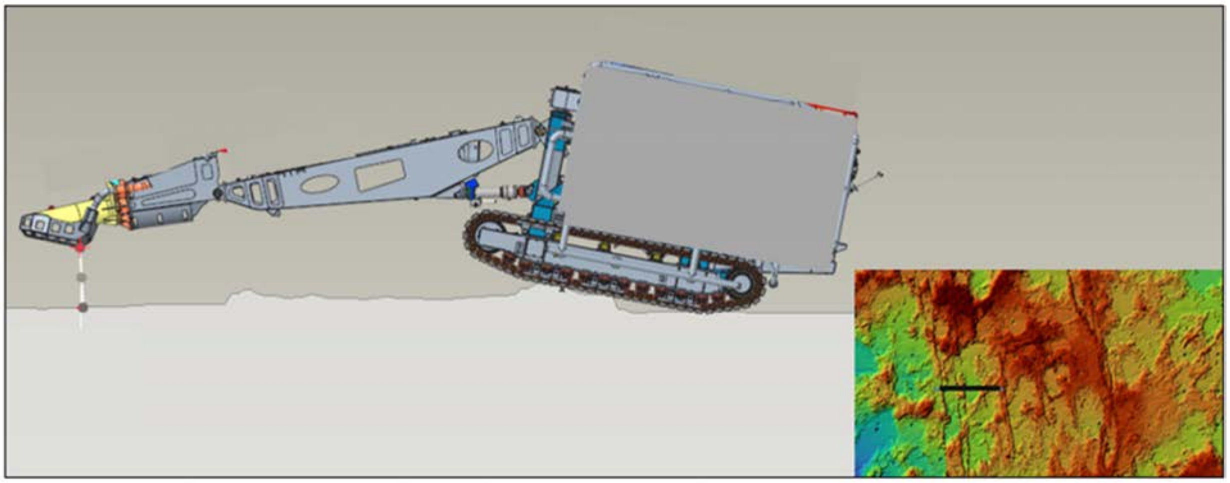

Figure 24: Steep slopes that need to be tracked up by the crawler may limit the nozzle of the crawler to reach down far enough for sufficient clean-up. The map insert on the bottom right shows the location (black line) of the crawler on the underlying bathymetry.

Table 5 shows the vessel tool combinations in the mining fleet and the associated capabilities and limits in terms of the terrain roughness, footwall types, gravel texture, sediment thickness and shell content.

Table 5: Applicability criteria (Muvi-Tjikalepo and Kubirske, 2021).

	Mineability Parameter		Applicable	Not Applicable
Small bits (CS & GB)	Terrain roughness		smooth to rough	Very rough and pose risk of breaking tool
	Footwall types		Soft to hard	Hard compounded with very rough terrain
	Gravel texture		Fine to coarse with low to medium slab frequency	High to very high slab frequency
	Sediment thickness	Overburden thickness	thickness up to 6m	thickness beyond 6m, risk of collapsing on the tool
		Gravel thickness/volume	thickness up to 6m	thickness beyond 6m, risk of environmental delays, high wear & tear on the treatment plant and adverse impact on mining rate
		Total package	thickness up to 12m	thickness beyond 12m, risk of collapsing on the tool and environmental delays
	Shell content		Up to 60%	beyond 60%, risk of full wet bin delays and not sufficient crushing in the ball mills
Big bits (DP & DA)	Terrain roughness		smooth to moderate	rough to very rough and pose risk of breaking tool
	Footwall types		Soft to hard	Hard compounded with rough to very rough terrain
	Gravel texture		Fine to coarse with low to medium slab frequency	High to very high slab frequency
	Sediment thickness	Overburden thickness	thickness up to 6m	thickness beyond 6m, risk of collapsing on the tool
		Gravel thickness/volume	thickness up to 6m	thickness beyond 6m, risk of environmental delays, high wear & tear on the treatment plant and adverse impact on mining rate
		Total package	thickness up to 12m	thickness beyond 12m, risk of collapsing on the tool and environmental delays
	Shell content		Up to 80%	beyond 80%, risk of full wet bin delays and not sufficient crushing in the ball mills
Big bits (GP)	Terrain roughness		smooth to moderate	rough to very rough and pose risk of breaking tool
	Footwall types		Soft to hard	Hard compounded with rough to very rough terrain
	Gravel texture		Fine to coarse with low to medium slab frequency	High to very high slab frequency
	Sediment thickness	Overburden thickness	thickness up to 6m	thickness beyond 6m, risk of collapsing on the tool
		Gravel thickness/volume	thickness up to 4.8 m	thickness beyond 4.8m, risk of environmental delays, high wear & tear on the treatment plant and adverse impact on mining rate
		Total package	thickness up to 10.8m	thickness beyond 10.8m, risk of collapsing on the tool and environmental delays
	Shell content		Up to 70%	beyond 70%, risk of full wet bin delays and not sufficient crushing in the ball mills
Cra	Terrain roughness		smooth to moderate	rough to very rough with outcrops, pose risk of breaking tool and pitch & roll of the crawler

	Footwall types		Soft to hard	Hard compounded with rough to very rough terrain
	Gravel texture		Fine to coarse with low to high slab frequency	Very high slab frequency
	Sediment thickness	Overburden thickness	thickness up to 12m	thickness beyond 12m, risk of collapsing on the tool
		Gravel thickness/volume	thickness up to 6m	thickness beyond 6m, risk of environmental delays, high wear & tear on the treatment plant and adverse impact on mining rate
		Total package	thickness up to 15m	thickness beyond 15m, risk of collapsing on the tool and environmental delays
	Shell content		Up to 90%	beyond 90%, risk of full wet bin delays and not sufficient crushing in the ball mills

3.4. Mine Parameter Model

The Mine Parameter Model (MPM) is a dynamic spatial model that encompasses the current knowledge of the performance and mineability of the resource area as derived from sampling and mining activities (Hiveluah, 2007).

The MPM contains five major components:

- Mineability: the ability to mine an area efficiently;
- Applicability: whether or not a specific vessel tool combination (VTC) is suited to mining a specific area;
- Mining rate: The rate defined in square meters per hour (m^2/hr) that a VTC can mine an area;
- Extraction coefficient: denotes the estimated proportion of diamonds that the mining tool is able to extract from the seabed and deliver to the treatment plant; and
- Recovery coefficient: denotes the estimated proportion of diamonds that the treatment plant can recover from the ore delivered to the treatment plant by the mining tool. It represents the recovery efficiency of the treatment plant

The MPM is based on the same 100m x 100m blocked grid used in estimation. Therefore, the MPM's data is spatially linked to each 100m x 100m block. Ultimately, the MPM is used in developing the short and long term mine plans for the company.

3.4.1 Current Applicability Determination

Applicability is the suitability of a specific vessel tool combination (VTC) to mining in a specific area. The current applicability determination is based on the geological and resource interpretations of an area (Figure 25), inputs to the interpretation are gathered from geophysical, sampling and historical mining data, and the existing geological model.

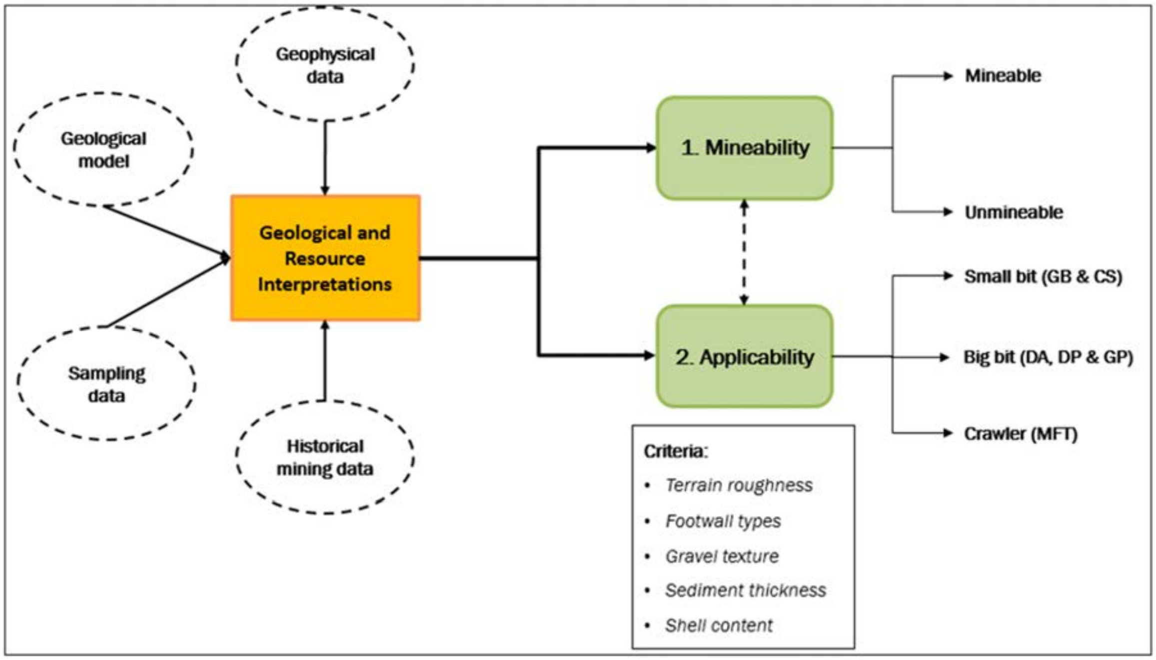

Figure 25: Current applicability determination method (Muvi-Tjikalepo, 2017).

Geophysical data reveal the physical nature of the ocean floor. The sampling data enhances the knowledge by recording the type of footwall, whether the terrain is soft with clay footwall or cemented with a conglomerate or sandstone footwall. Terrain roughness (visual inspection of the bathymetry), footwall types, gravel texture, sediment thickness and shell content are the main criteria used to assign a certain vessel to an area. The plant type and plant capacity on the vessel also controls the applicability or suitability of the different vessel types.

The geologist responsible for the MPM update assesses and analyses each 100m x 100m block according to the above-mentioned criteria and assigns the vessel applicability. The purpose of the current study was to move the mineability allocation from a qualitative approach to a quantitative approach, as well as using additional available datasets, which are currently not used.

3.4.2 Research Aim

The aim of the current study was to develop a quantitative approach for the mineability determination, to replace the current approach, which is a qualitative determination.

The current qualitative approach is one in which, once a resource block is loaded, the responsible geologist is tasked to allocate the suitability of the vessels to the 100m x 100m blocks. This is done by considering the geozones in the resource block as a starting point. Each geozone is visually analysed in terms of homogeneity using the bathymetry, together with the sampling data (footwall, maximum penetration, drill duration, shell content). Suitability allocation is then done mainly on a geozone basis and the blocks within a geozone are assigned the same applicability. Local variations within a geozone can therefore become masked as the allocation is done on a much larger scale than the actual mining panels (resource block size can be $1km^2$, while a mining panel is generally 160 $000m^2$). Mineability risks on a mining panel scale could therefore only become evident once the mine plans have been developed and are not identified at the MPM stage. Qualitative analysis can potentially also introduce subjectivity through the interpretation/view of the person responsible for the project.

The frequency of slopes is not considered in the allocation of the vessels, although the roughness of the terrain plays a major role in the successful mining of an area. The efficiency by which an area is mined will be reflected by the recoveries of the panel, as diamondiferous gravel could have been left behind.

The aim of the study was therefore to move from a qualitative applicability determination to a more data-based (quantitative) process. This was done by exploring different ways of extracting data from the bathymetry as well as creating a risk profile for each 100m x 100m block using the sampling data. Each 100m x 100m resource block was therefore assigned an overall mining risk, depending on the terrain and the vessels capability to mine the area. An acceptable risk was then identified per vessel, showing the level of risk that each vessel would encounter when mining a specific block. Slope maps were also created to aid the vessel applicability to an area.

This method reduces subjectivity and also introduces a risk profile for each block. Risk ranking in terms of mineability on a local scale is currently only done once a mine plan has been developed. The method from this study implements a mineability risk per 100m x 100m block and therefore the risk is immediately available once a mine plan is developed. This can help to potentially swap panels to vessels that are more capable of handling certain terrains, in order to reduce risk.

CHAPTER 4

METHODOLOGY

4.1 Methodology Used for this Research

To determine mineability and applicability, the terrain needs to be defined. While the geozones model groups together areas with similar geology, geozones are seldom homogenous throughout. This means different areas in a specific geozone can be of higher risk to mine than others (mainly dependent on degree of weathering). Therefore, a three-pronged approach has been applied in the current project. Part one was to identify a process or method to quantify information from the available bathymetry data to define the suitability of each vessel; currently the bathymetry maps are viewed, and assessments are made which vessel is most suitable to mine a specific area. The second part was to create facies maps over the area, to determine if this adequately classifies the different geological features in the study area. The third part was to use the existing sampling information to quantify the mineability and risk of an area for each vessel type (small bits, big bits and crawlers).

By determining the risk of each geological terrain on an MPM level, mine plans with higher confidence can be developed. Current practice is to sample – estimate – update the MPM – run a mine plan – complete a risk ranking for each mining panel. A major part of risk ranking each individual panel is the mineability – how easily can the terrain be mined by the vessel it was allocated to. As discussed earlier, rougher terrains can compromise gravel clean up. Therefore, a risk profile for each panel will be immediately available after developing a mine plan. Determining the risk at MPM level will also make vessel allocation easier in areas that have not been mined before, instead of allocating a vessel and then realising it cannot mine the area.

4.1.1 Extraction of Data from Bathymetry

As the mining area is in a marine environment, the multibeam bathymetry collected over the area before sampling and mining is key to identifying the geomorphology of the seafloor. For the current mineability and applicability determination, the inspection of the bathymetry is mostly visual when updating the MPM and is mainly based on the geozone model. Each geozone gets treated as having homogenous geological features, whereas, in reality, there are commonly variations in the roughness within each geozone. Therefore, for this study, different ways of extracting information from the bathymetry were explored, in order to map different geophysical zones.

Wilson et al. (2007) described a method called *benthic habitat mapping*, in which bathymetry data is manipulated to map out different geological units to distinguish different habitats for different fauna. This approach has been applied to the study area's bathymetry to assess its usefulness to determine mineability and vessel applicability.

According to Wilson et al. (2007) there are four major classes of information that can be extracted from bathymetric data: slope, orientation, curvature and relative position, and terrain variability (Figure 26). The three most useful classes are slope, curvature and relative position, and terrain variability.

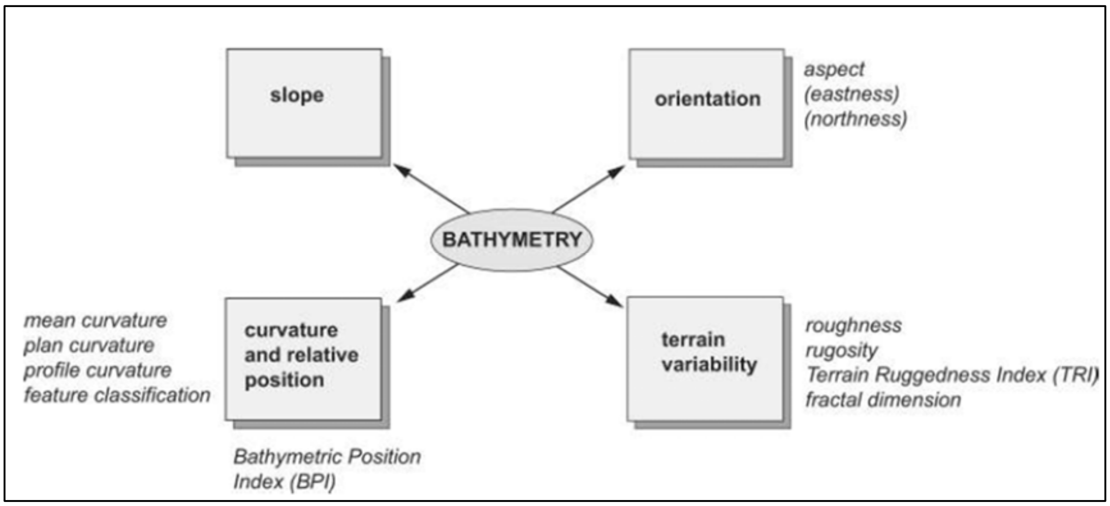

Figure 26: Bathymetric data extraction classes (after Wilson et al., 2007).

Slope is important from a mining perspective, as the mining tools are sensitive to slope. The crawler vessels perform best in slopes under 10 degrees. While crawlers can still manoeuvre on slopes of more than 10 degrees they are less likely to properly track and clean up efficiently. The drill ships struggle with stalling of the drill bits in terrains with high frequency of steep slopes, for example in areas with small sandstone outcrops of more or less a meter apart. Slope maps are generally produced shortly before mining on a local panel scale. Therefore, the risk of slopes is not adequately addressed early on, leading to changes of the original risk on a panel (high frequency of high slopes cause tracking challenges for the crawlers, therefore, increasing the mining time to manoeuvre the crawler negatively affects the planned mining rate). Clean-up due to the reach of the nozzle can also be compromised (as seen in Figure 24) leading to lower recoveries than expected in a panel.

The open source add-on tool “Benthic Terrain Modeler” (which can be downloaded from Esri) has different functionalities for benthic habitat mapping. Grids of bathymetric position index (BPI), slope and terrain ruggedness can be generated using this toolbox.

The bathymetric position index (BPI) distinguishes the high-lying from the low-lying features in the bathymetry by calculating the variation of cells within a specified radius (Wilson et al., 2007). The BPI defines high lying and low-lying areas relative to the overall landscape. Both broad scale and fine scale iterations of the BPI can be run, depending on the area of interest. The output of the broad scale and fine scale BPI is then run together with the slope map to define different geological features. Different radii were tested in this study for broad scale and fine scale bathymetry. A radius of 25 – 250 m gave the best results for the broad scale bathymetry position index and a radius of 5 – 25 m for the fine scale bathymetry position index. The software supplies a standard classification table but users of the software can create their own classification tables to optimise the outputs from the tool. The classification table used for this study is shown in Table 6, which was adapted for the different zones that were required. The output of the BTM tool is a map that distinguishes between different geomorphological features. This tool has not been used by the company before in terms of allocating vessels to specific areas.

Table 6: Classification table developed for the study area to run the Benthic Terrain Modeler function in ArcMap.

Class	Zone	BroadBPI_Lower	BroadBPI_Upper	FineBPI_Lower	FineBPI_Upper	Slope_Lower	Slope_Upper	Depth_Lower	Depth_Upper
1	Slopes larger than 10 degrees					10			
2	Platforms	300	557		1803				
3	Ridges	150	300						
4	Depressions	-250	-150						
5	Transition zones	-150	150						

4.1.2 Facies model

Facies mapping is of importance, as it is a way to group rocks of similar physical properties, formation and composition, or other attributes. In the marine environment it is easiest to distinguish between facies based on their physical attributes, depths, and sometimes, composition.

The current practice is to do detailed facies mapping on a mining panel immediately before mining of the panel to guide the mining. In this study, broad scale facies mapping has been investigated to ascertain its value when done upfront, in order to adjust the MPM.

The facies model was run using the reclassify function in ArcMap, a function available in the 3D Analyst extension. The input for the facies model is the bathymetry of the study area. The tool continuously reclassifies data, in this case elevation, into categorical classes. The output is a raster file that delineates the different geological zones or facies. Once the raster file is created, it can be converted to a shapefile which can then be edited as and when needed. A few iterations, with different number of classes, were run in order to choose the best outcome.

4.1.3 Mineability Model derived from Sampling Data

Several parameters are collected during sampling and generally include footwall type, maximum penetration (indicating sediment thickness), rate of penetration (ROP), shell volumes and texture of the gravel. The aim was to use the recorded sampling data to develop a risk matrix across each 100m x 100m mining block. To develop the risk matrix, a scale was developed for each parameter per sampling hole ranging from 1 to 6, 1 being the easiest, and 6 the most difficult to mine.

1. <u>Footwall</u>

Terrains with soft footwall like clay and sand are easiest to mine, especially if the terrain is smooth and flat. Gravel clean-up on clay footwall is generally good, as clay is clearly visible on the scalping screens and signifies true footwall. Sandstone footwall is more difficult to mine on as these areas are often competent where vessel tools cannot break through the capping, or where the seabed surface is too rough and irregular. The footwall scores are listed in Table 7 where N/A indicates that no footwall was reached.

Table 7: Footwall Type Score

Score	Footwall Type
1	Clay
2	Sand
3	Claystone
4	Conglomerate, Sandy Conglomerate
5	Sandstone
6	N/A

2. Maximum Penetration

Maximum penetration is measured by the sampling tool and gives an indication of the total sediment thickness at each sample point. Thinner sediment packages are easier to mine. Generally thicknesses of <2.4m are easiest to mine for the fleet and therefore this option was assigned a score of 1. Most difficult to mine areas are those with a sediment package of more than 12m, as gravel is either very coarse or overburden is present with high shell volumes. Anything above 12m therefore scores a 6 (Table 8).

Table 8: Maximum Penetration Score

Score	Max_pen (m)
1	0 - 2.4
2	2.41 - 3.6
3	3.61 - 4.8
4	4.81 - 6
5	6.1 - 12
6	12.1 - 24

3. Rate of Penetration (ROP)

The rate of penetration of a sampled section is also useful in assessing the ease of mining. Faster rates of penetration therefore indicate easy mining and anything with a rate of penetration of more than 0.1 m/min scored a 1. Sample points that struggle to penetrate with less than 0.02 m/min were assigned a score of 6 (Table 9).

Table 9: Rate of penetration Score

Score	Rate of penetration (m/min)
1	>0.1
2	0.081 - 0.100
3	0.061 - 0.080
4	0.041 - 0.060
5	0.021 -0.040
6	<0.02

4. Shell

The recovery plants on the various fleet vessels differ in their capability to handle shells. Dependant on the crushing ability and the type of shell, the small bit equipped vessels can mine in areas of up to 60 % shell, big bits up to 80 % shell and the crawler vessels up to 90% shell. Higher shell percentages can however lead to full bin delays and potential processing challenges, which add to the mining time and reduces the overall mining rate. Therefore, areas with 0 – 15% shell content are easiest to mine and were assigned a score of 1 and any areas between 70% to 90 % scored a 6 (Table 10).

Table 10: Shell Score

Score	Shell %
1	0 - 15
2	15.1 - 30
3	30.1 - 45
4	45.1 - 60
5	60.1 - 75
6	75.1 - 90

5. Gravel Texture

Gravel texture also influences mineability. A fine- textured gravel is easier to entrain than coarse gravel (Table 11). In Atlantic 1, coarser gravel is often also associated with thicker gravel beds. Although the texture parameter is derived from the geological model and is not 100% accurate, it generally provides a good indication of the expected texture.

Table 11: Gravel Texture Score

Score	Gravel Texture
1	Very Fine
2	Fine
3	Medium
4	Coarse
5	Very Coarse

6. Overall Score

After all scores have been applied to the individual sampling parameters, these are weighted to produce a score for each sampling point. Sampling points within a 100m x 100m resource block are then averaged to get an overall score per block.

Weightings of the parameters differ depending on their overall influence on the mineability (Table 12). Footwall and rate of penetration (ROP) carry the highest weighting. Harder footwall types like sandstone can be competent and due to the bigger footprint of the mining tools compared to the sampling tool, the tools are not able to penetrate or break the capping to get to the underlying gravel. A rough seabed with sandstone footwall also causes challenges with stalling, whereby gravel clean up can be compromised. Rate of penetration is also given a high weighting as it acts as a proxy for the "difficulty" in drilling. Longer rate of penetration can be due to hard substrate or due to very coarse gravel. Shorter rate of penetration gives an indication of the ease of mining, which can be a thin gravel package with fine or medium textured gravel.

Maximum penetration (Max_pen) is also an important factor, identifying sediment depths that can be mined. Shell and texture of the gravel play smaller roles when it comes to mining challenges and are therefore weighted at 15% each. Because this study is a trial to establish a risk matrix using the sampling data, comparison with actual mining may result in changes to these weightings.

Table 12: Score Split

Sampling Parameter	Split
Footwall	25%
Max_pen	20%
RoP	25%
Shell	15%
Texture	15%
Total	**100%**

CHAPTER 5

RESEARCH RESULTS

5.1 Extraction of Bathymetry Data

The multibeam bathymetry data forms the basis of this analysis as it provides a visual perspective of the seabed depth, distinguishing between outcrops, valleys, smooth terrains and undulations. Figure 27 shows the bathymetry of the study area overlain by the current geological model (geozones model). It is apparent that there is still a large variation in terms of roughness or features such as outcrops in the terrain in each geozone. Therefore, no geozone terrain is homogenous meaning that within a single geozone, there can be rougher seabed conditions interspersed with smoother seabed conditions. As discussed in Chapter 3, in the current MPM update the mineability and applicability is visually analysed per geozone. While this practice is sufficient, especially in areas that have adjacent mining data for comparison, it can be insufficient in new resource areas, that do not have adjacent mining data for comparison. Texture of the seabed is well displayed by the bathymetry data.

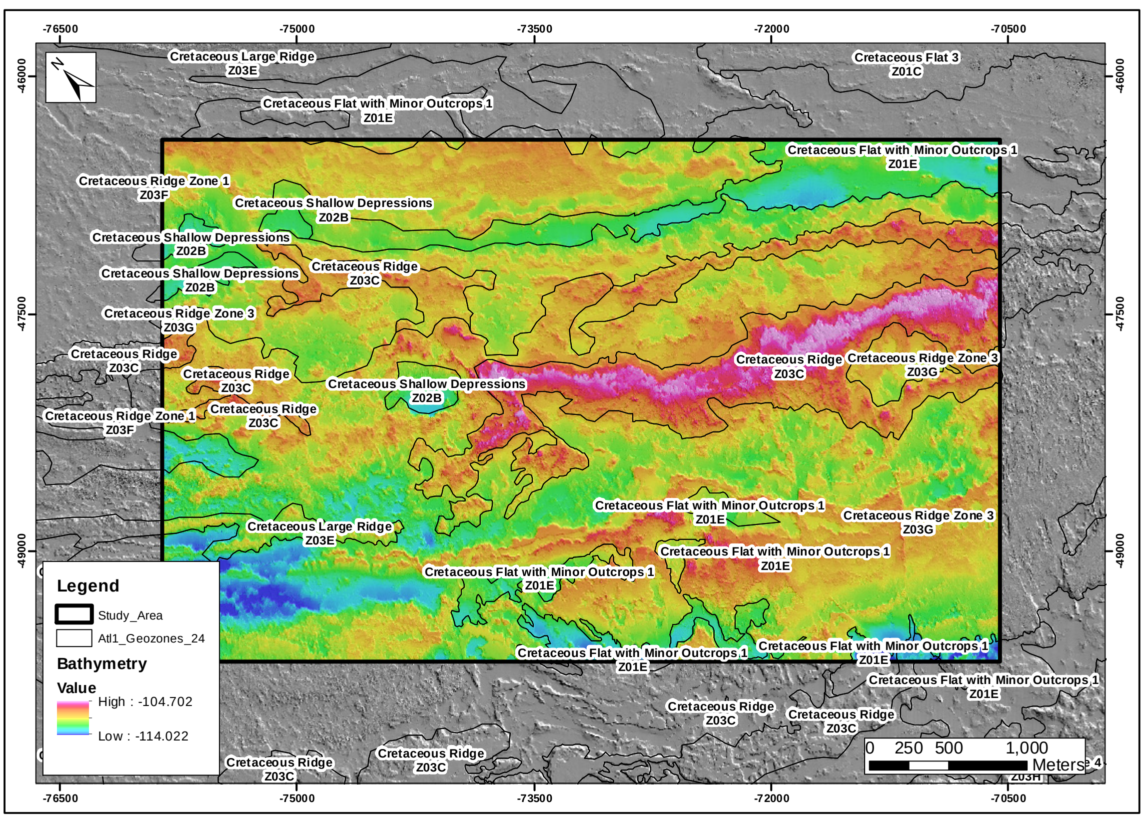

Figure 27: Bathymetric map of the study area, overlain by the geozones model.

In Figure 27, the Cretaceous Ridge Zone 3 shows small depressions (green) within higher lying features (orange). The depressions have a smooth seabed texture, while the higher lying features show a grainier texture and more undulations. Higher lying features could therefore seem more difficult to mine than the depressions. However, the sampling footwall (Figure 28) in this particular geozone, is predominantly soft clay and therefore easily mineable by all vessel types. The Cretaceous Ridge geozone in the central part of the study area shows a smooth texture on top of the higher lying features (pink), with a more rugged appearance moving from the shallower (pink) to deeper areas (darker orange) (Figure 29). The footwall types in both areas are sandstone and conglomerate, both hard footwall types, indicating that the area will be more difficult to mine for all vessel types.

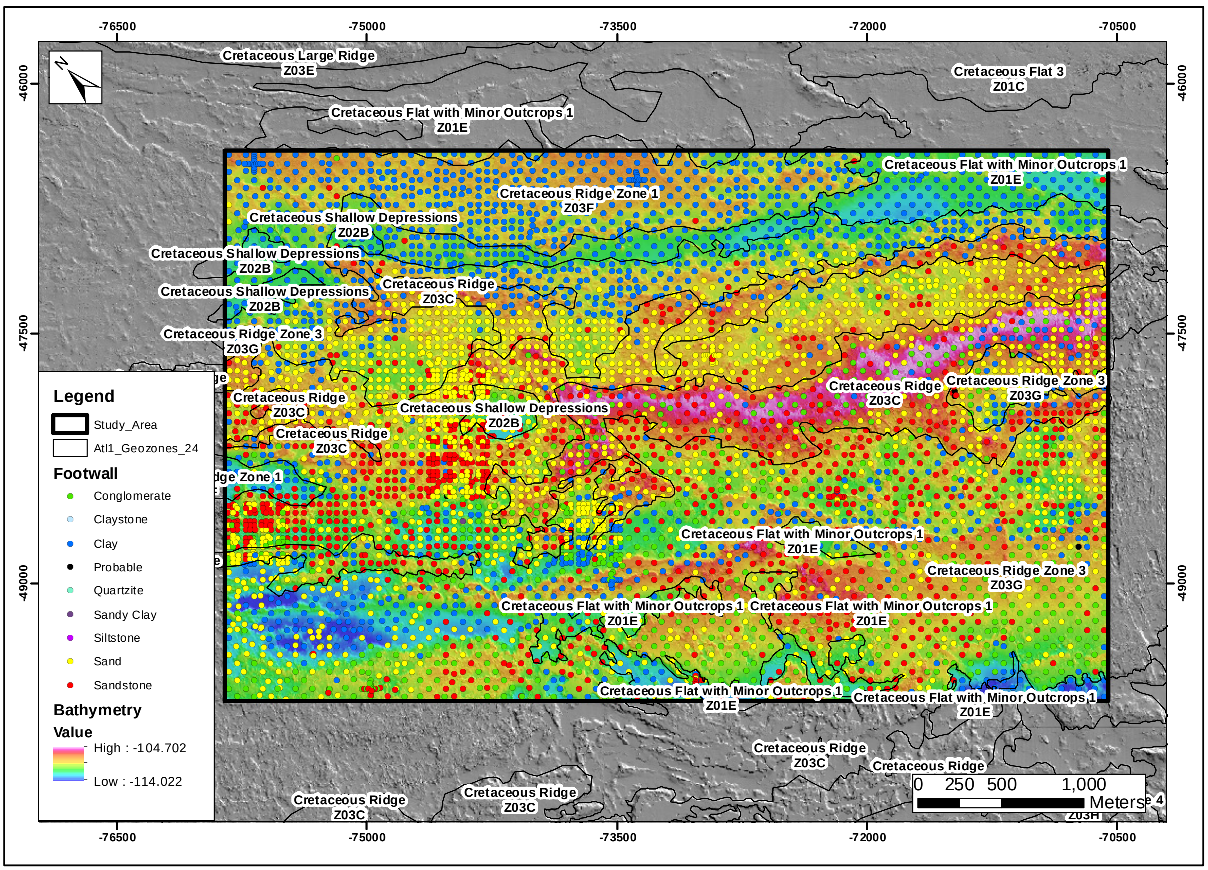

Figure 28: Bathymetric map of the study area, overlain by the geozones model with SSN footwall displayed.

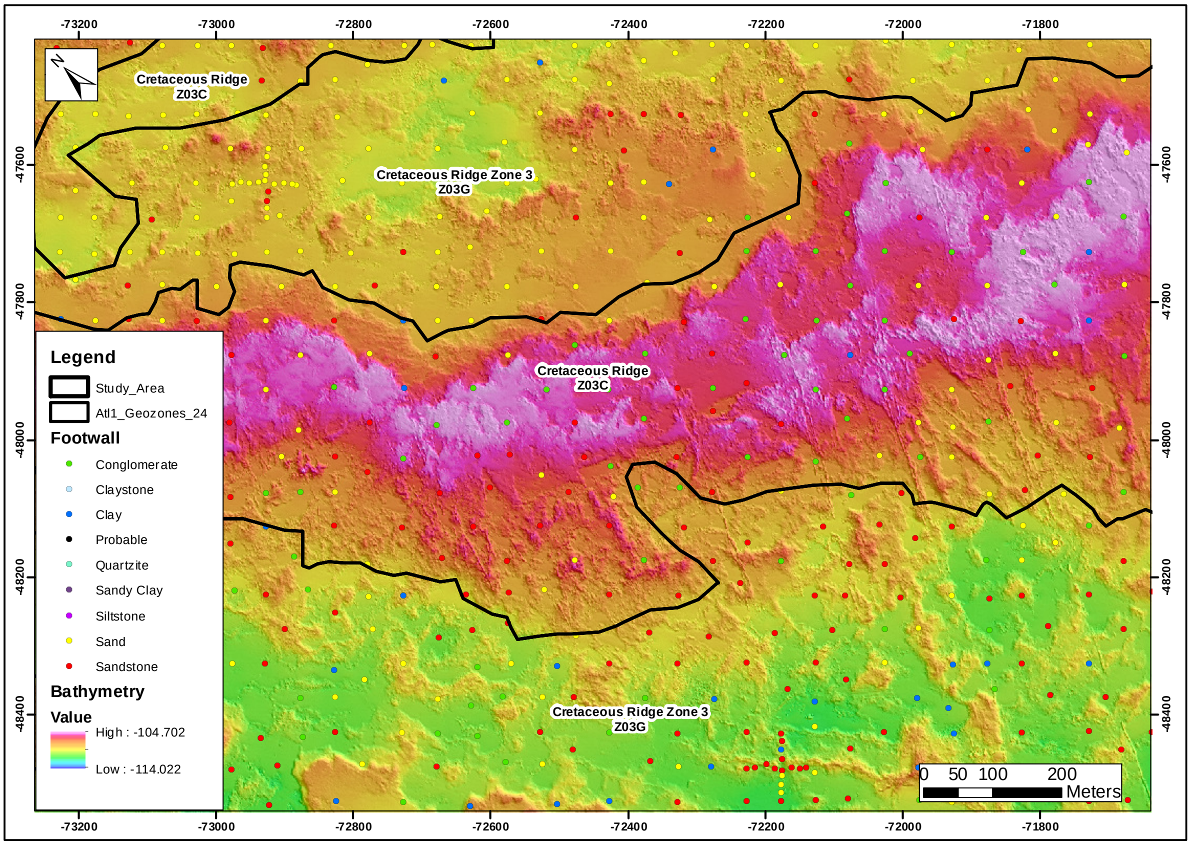

Figure 29: Zoomed in area showing the Cretaceous Ridge geozone, flanked inshore and offshore by the Cretaceous Ridge Zone 3.

In an attempt to move away from the purely visual analysis of the bathymetry data, the ArcGIS Benthic Terrain Modeler (BTM) tool has been applied to the study area's bathymetry to assess its usefulness to determine its mineability and applicability. Both broad scale and fine scale bathymetric position indices were extracted (see Chapter 4). The bathymetry raster (30cm resolution) of the study area was used as the input in conjunction with the classification table (as shown in Chapter 4). Different radii (broader and finer) were tested for the terrain in the study area to derive the optimum range for the terrain. The broad scale BPI was run on a radius of 25 m to 250 m (to identify larger features) and the fine scale BPI was run on 5 m to 25 m (to identify smaller local features). The output is shown in Figure 30.

The BTM output map in Figure 30 shows the 5 zones delineated in the study area, namely platforms, ridges, depressions, transition zone and slopes higher than 10 degrees. The geozones were not considered separately in this process and the bathymetry data of the study area was used as a whole. The output significantly reduces the noise of the bathymetry and groups together similar features. Major value is added by the slopes that are directly incorporated into the output, as steep slopes are not considered at all when the applicability of the resource ground is determined. As seen in Chapter 3, slopes give an indication of the roughness of the terrain, which plays a major role in terms of tool – ground interaction. The BTM output therefore not only defines the different features but combines this with slopes. The slope limit can be set and in this case all slopes larger than 10 degrees are shown. Slopes higher than 10 degrees cause tracking and ground interaction challenges for the crawler (nozzle not reaching all of the orebody) and these are generally associated with platforms (red) and ridges (orange) in the study area (Figure 30).

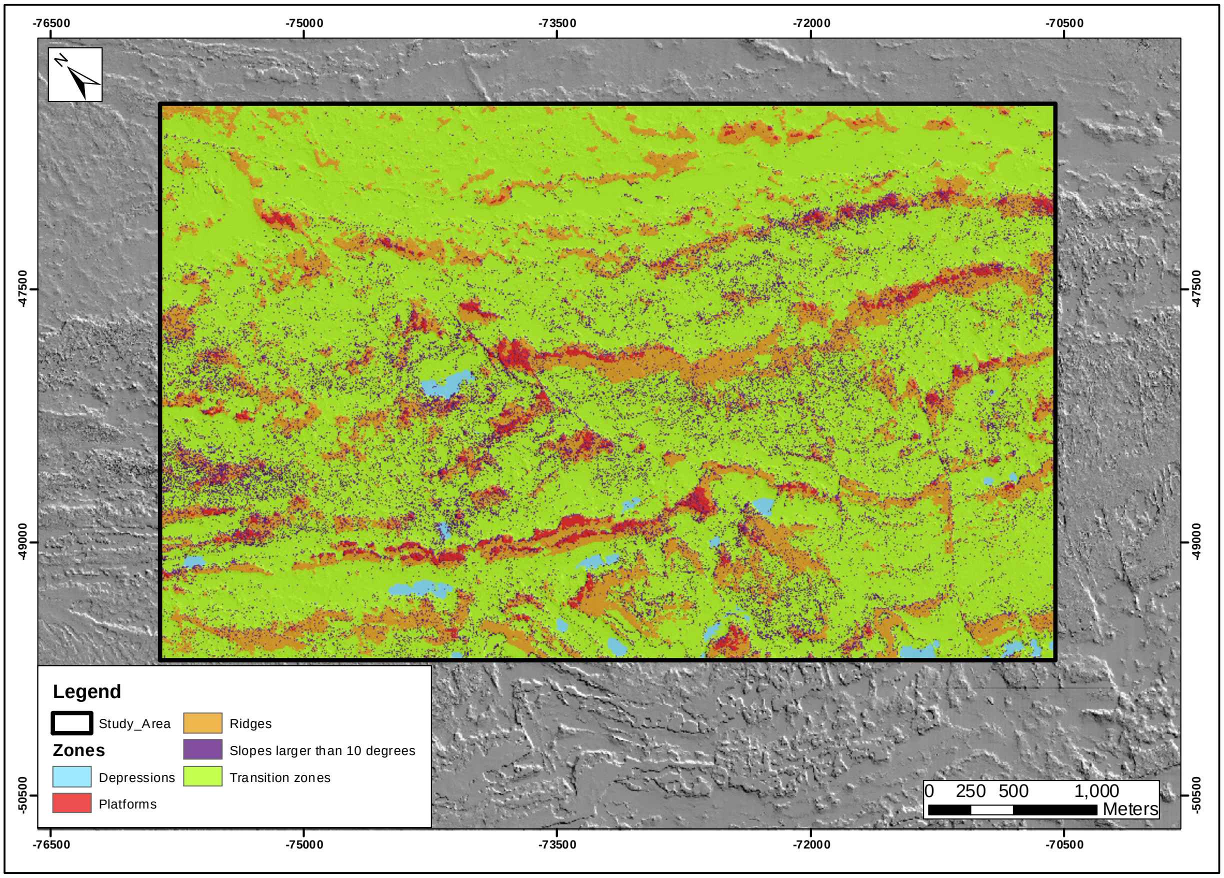

Figure 30: Output of the benthic terrain modeler in ArcGIS.

There is a good correlation when comparing the bathymetry to the output zones from the BTM: high-lying features (pink and dark pink) have been delineated as the ridges and platforms on the BTM output (orange and red). The lower lying, smoother areas are delineated as the transition zone, where ground is more weathered and easier to mine. Depressions (light blue) are also visible on the output of the BPI, however these are less pronounced than the depressions on the bathymetry (light blue and blue). This effect arises from the radius applied, since the northern offshore depressions are shallower and widespread. As a result, when the radius encompasses surrounding areas, the difference between one point and another are minimal.

A potential downside of the BTM output is that the transition zone (green zone) may be too broad as there are visible areas within the zone that have a high frequency of steep slopes, while other areas are relatively flat, i.e., have a low frequency of steep slopes. The inshore area on the transition zone barely shows any slopes higher than 10 degrees, while the central areas on the transition zone suggest a higher distribution of slopes larger than 10 degrees.

The map in Figure 31 shows a slope raster, also an output of the BTM tool. The slopes in the study area range from 0 to above 20 degrees. The dark green represents areas of smooth terrain with very low slopes but as the colours become warmer, the slopes increase. Higher slopes are found around the ridge features in the central areas of the panel where softer less competent areas have been eroded out, leaving behind more competent features that form small crests and ridges. The inshore parts of the study area show gentle slopes, giving an indication of the smoothness of the seabed. The slopes are integrated in the output of the BTM (Figure 30), shown by the purple lines (slopes above 10 degrees).

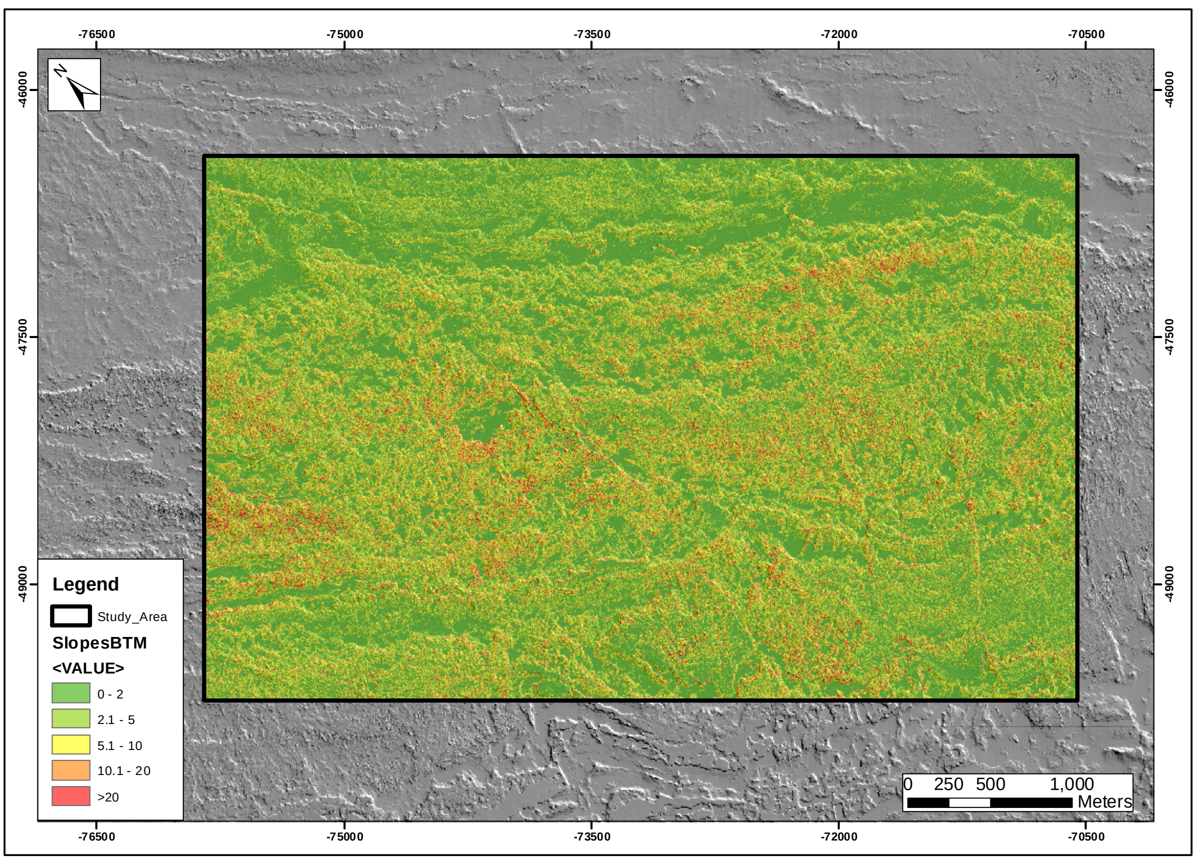

Figure 31: Slope map of study area.

5.2 Facies model

Figure 32 shows the facies model output for the study area, which groups together points with similar depths to distinguish geological features. The bathymetry was classified into nine (9) different facies. While the facies define the geomorphology much better than the geozones model, some of the more subtle local differences are potentially hidden. In the offshore, the competent ridge zone covers a large area, however, when zoomed in it shows much more variation. Therefore, it seems that developing a facies model for an area needs to be done at varying localized scales to capture the variability better on a mining panel scale (up to 16 mining blocks added together). On the map in Figure 32, the high lying outcrops are shown in light pink and are identified as the most competent ridges. Footwall types in the competent ridge facies are sandstone and conglomerate, indicating a hard substrate. Just off the competent ridges are the partially weathered ridges, where the terrain tends to be partially eroded. Moving from the warmer colours to the cooler colours, the terrain changes from competent and rough, to a more rugged terrain and finally into a smooth and even seabed.

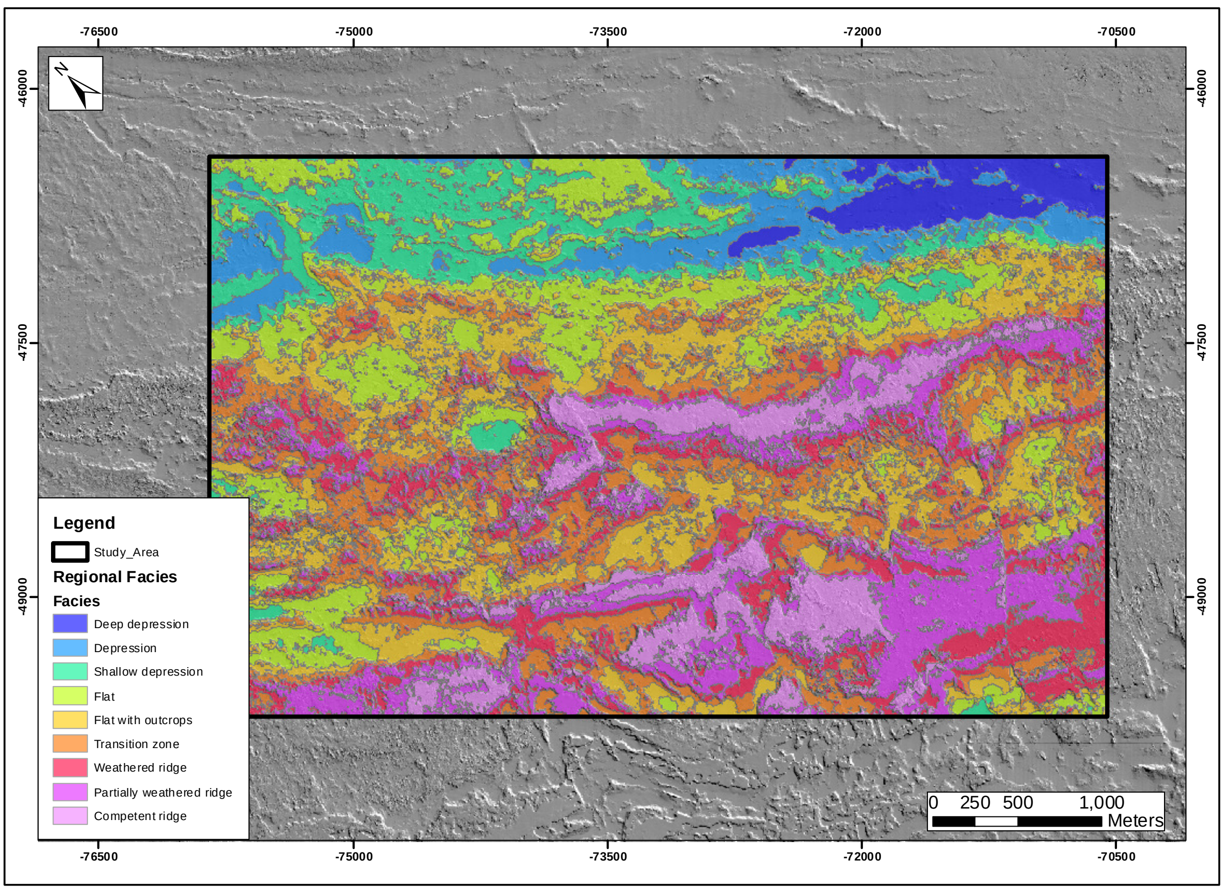

Figure 32: Regional facies map, indicating the individual identified facies.

5.3 Mineability Model using Sampling Data

The mineability model results for the area are shown below as maps of the individual parameters (Figs. 33 to 37). The overall weighted risk for the combined parameters is highlighted in Figure 38.

The distribution of the sampling footwall compared to the overall risk of the mining block is shown in Figure 33. The risk scale is from 1 to 6, where 1 is the easiest ground to mine while 6 is the most difficult to mine. In terms of the footwall nature in the inshore of the study area a low mining risk was identified on predominantly clay footwall. Clay footwall is the easiest footwall for all vessels to mine on, as the nature of the surface is generally smooth and it is easy for both the geologist and the driller onboard to terminate a hole, when sufficient clay coming over the screens. Moving offshore of the clay area, sand footwall dominates, which indicates a high degree of erosion of the former ridge zones. The central portions of the study area start showing hard footwall types, such as sandstone and conglomerate, which are associated with the more competent and weathered ridge zones. Interspersed clay footwall is seen again towards the offshore, before more competent hard footwall dominates most of the extreme offshore.

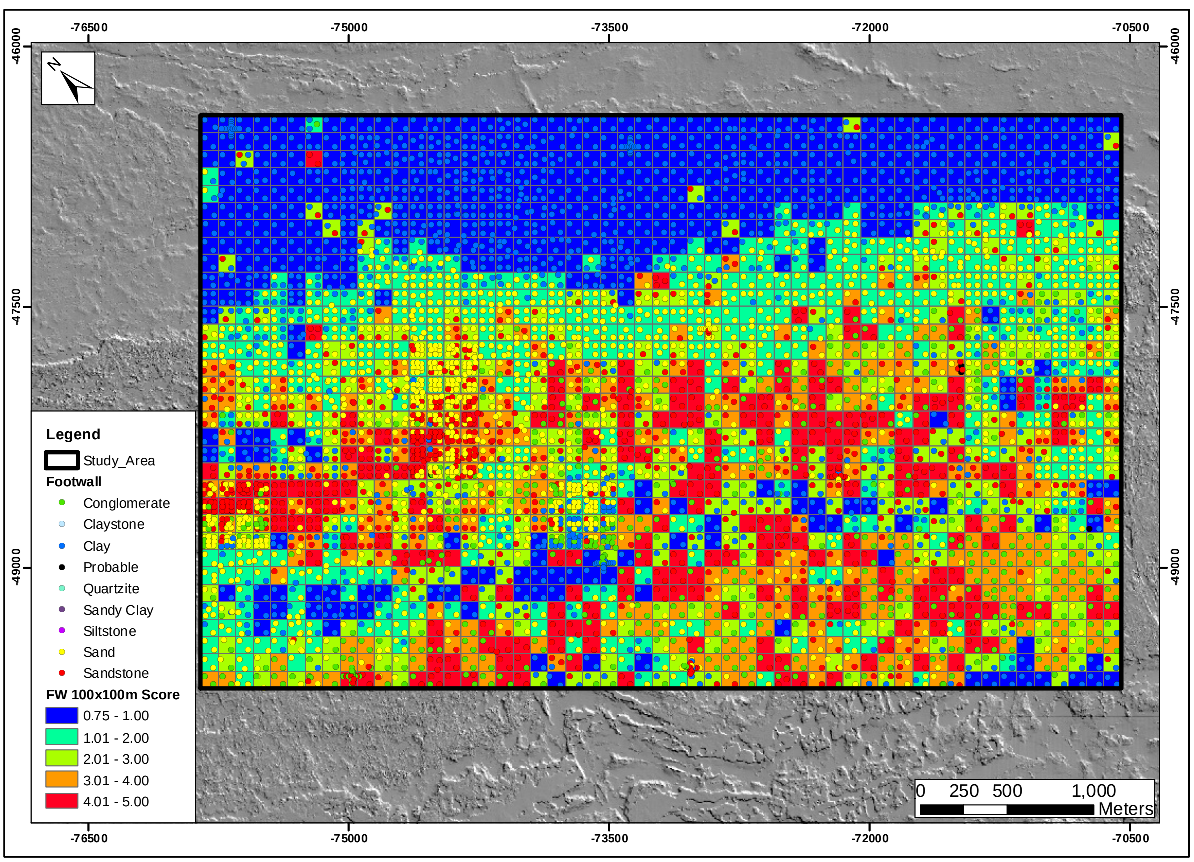

Figure 33: Sampling footwall underlain by footwall score averaged for 100 m x 100 m mining blocks.

The maximum penetration from sampling is a proxy for the sediment thickness. As discussed in section 4.1.3, the thicker the sediment package, the more difficult it becomes to mine. Figure 34 shows the maximum penetration distribution. The inshore areas recorded the lowest maximum penetration, and the central areas show the deepest penetrations, mainly around the outcropping ridge features.

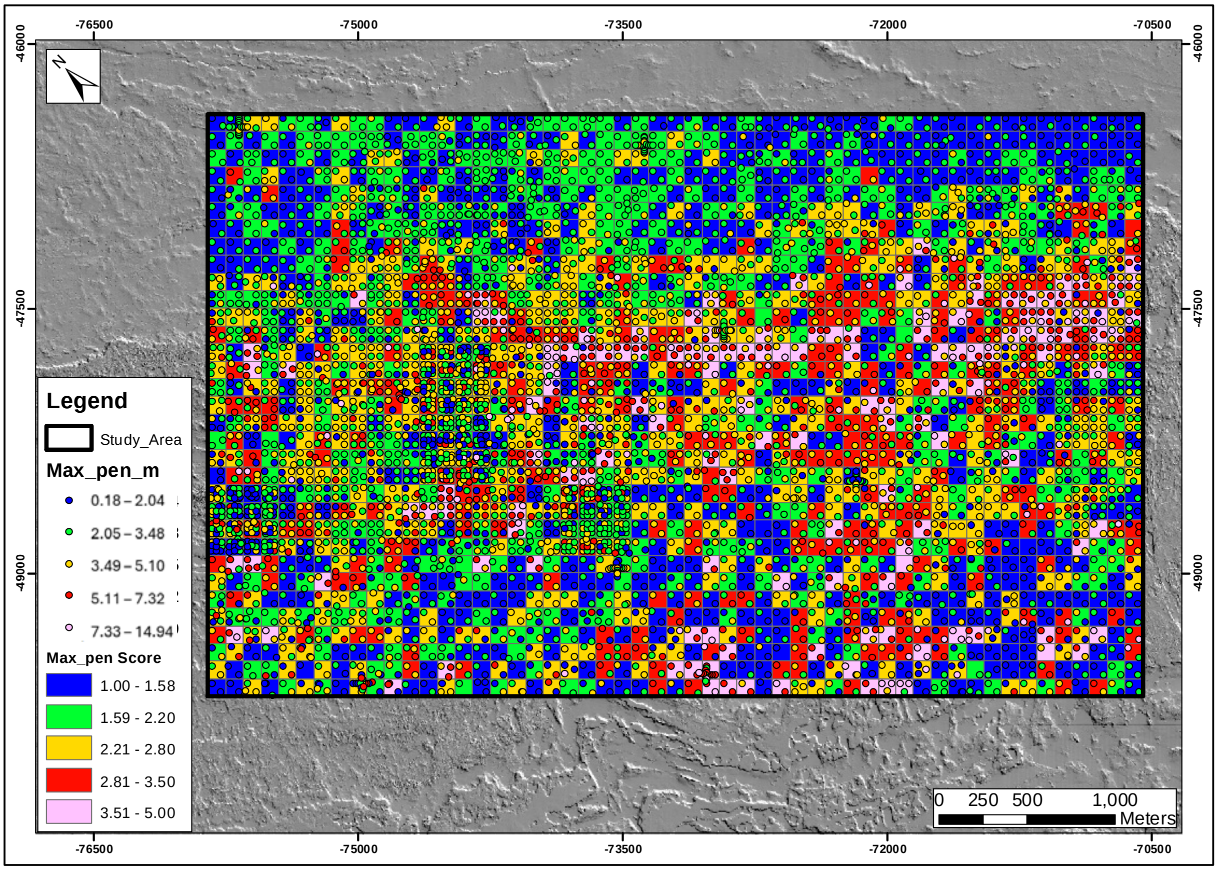

Figure 34: Maximum penetration by sampling (meters) with the maximum penetration score averaged for 100 m x 100 m mining blocks.

Figure 35 shows the rate of penetration per sampling hole as well as the combined risk score per 100m x 100m block. Higher penetration rates are seen in the inshore of the study area, which indicate a low mining risk. The inshore area was characterised as a smooth seabed with soft clay footwall, allowing good assurance for cleanup. Low rates of penetration are seen mostly in the offshore of the study area, with a high risk of mining.

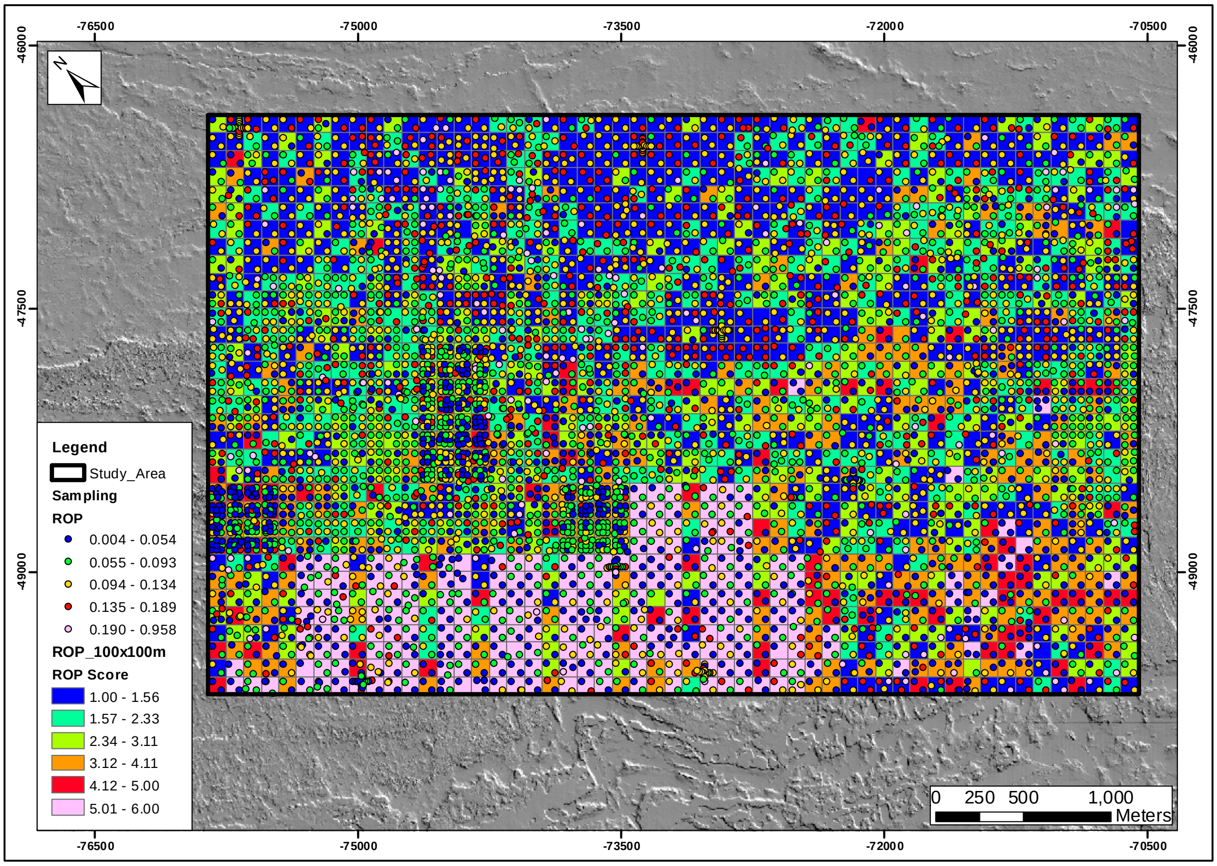

Figure 35: Sampling rate of penetration underlain by ROP score averaged for 100 m x 100 m mining blocks.

The study area is generally low in shell concentrations (Figure 36), with average shell risk scores only going up to a score of 4 (45% to 60% shell). Higher shell concentrations are found in scattered patches within the study area.

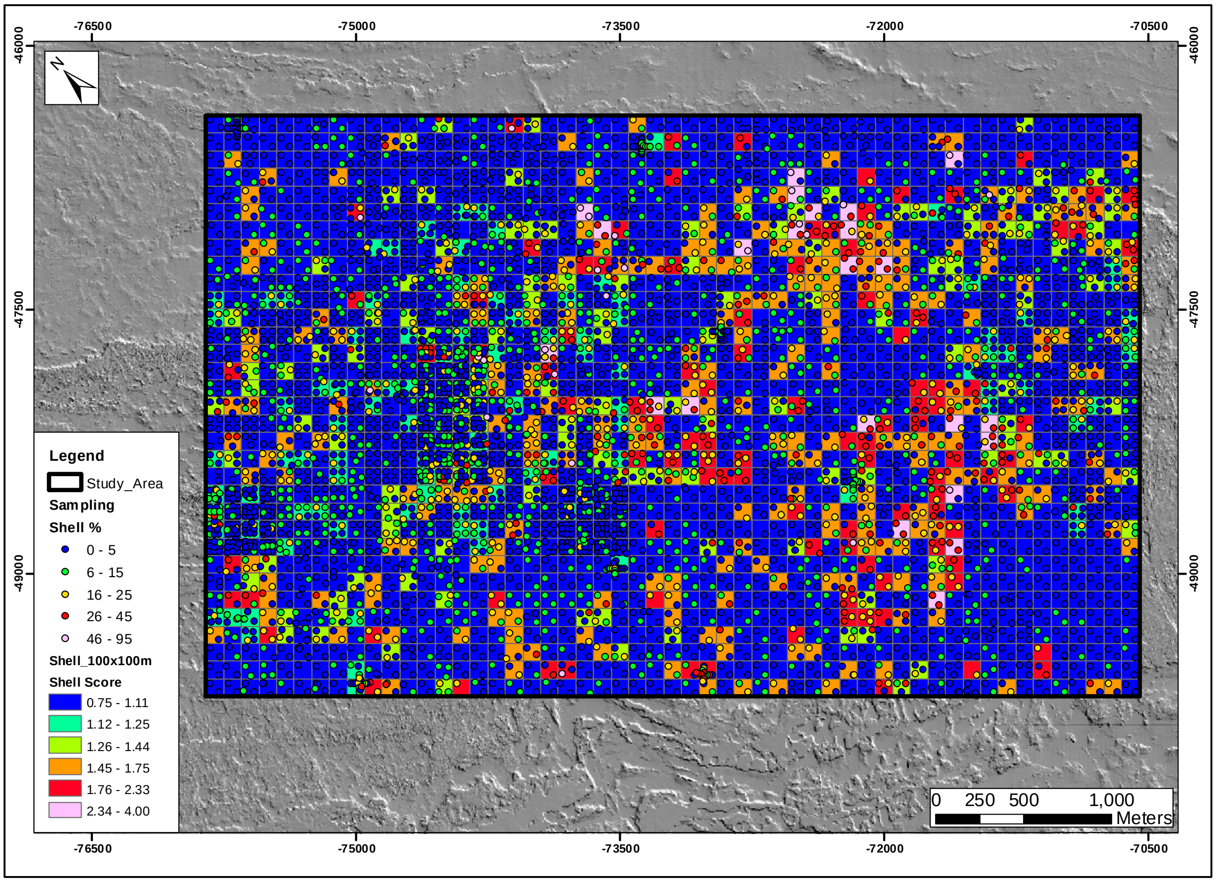

Figure 36: Sampling shell underlain by shell risk score averaged for 100 m x 100 m mining blocks.

The texture of the gravel was extracted from the geozones model. Only medium and coarse gravel textures are expected in the study area (Figure 37). Coarse gravel texture is mainly found in the inshore of the study area within the depressions, whereas fine gravel texture is expected in the central and offshore areas.

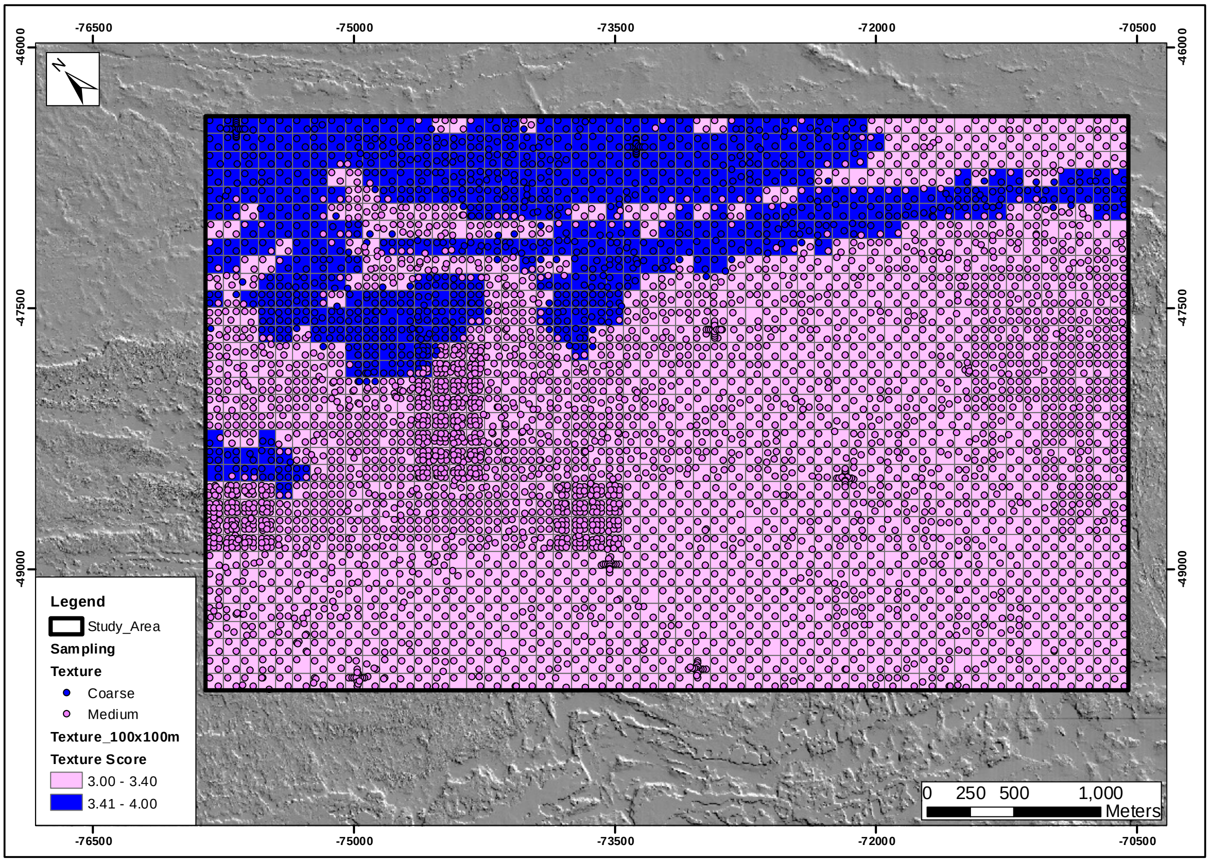

Figure 37: Sampling gravel texture underlain by texture score averaged for 100 m x 100 m mining blocks.

The overall risk per block is shown in Figure 38. The overall risks per block match the geology well, as the larger more open depressions in the inshore of the study area with soft footwall and relatively smooth terrain show the lowest mineability risk. Moving offshore, the competent and more weathered ridge zone carry a higher risk, as they are more difficult to mine, due to harder footwall, more undulating terrain and low rates of penetration.

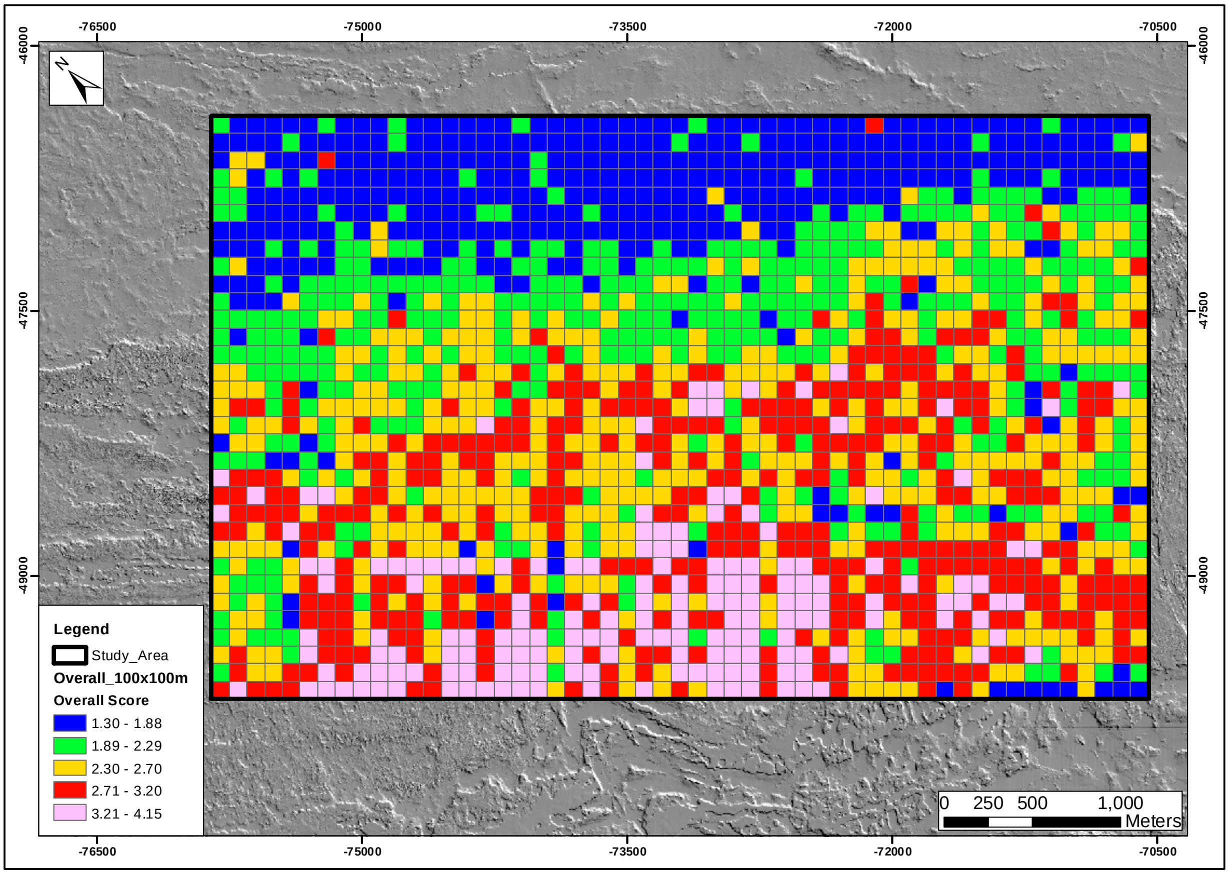

Figure 38: Overall score per 100 m x 100 m block, where blue indicates low risk and pink indicates high risk.

CHAPTER 6

DISCUSSION

Diamonds are mainly located at the base of the sediment package, close to the boundary of the footwall. Therefore, it is crucial for the mining tools to reach the footwall during mining. This can only be achieved if the vessels mine the right areas with the right tools and mine them efficiently.

In this study, three different approaches were explored to determine the risk of an area, namely the use of the benthic mapping tool, facies on a regional scale and the use of sampling data. The first approach was to explore if the “Benthic Terrain Modeler” tool used for benthic mapping could possibly be useful to determine the applicability of the mining vessels. This tool identifies different geological features, to differentiate the habitats of different fauna (for example, some species prefer silt filled depressions, while other species prefer rocky outcrops). It also incorporates slope maps, which are important when determining mineability, especially for the crawlers.

The importance of categorising geological features lies in the ability of the vessels to mine these features. Hard competent ridges, platforms or outcrops are a challenge to mine for all vessels, because the mining tools are designed to lift unconsolidated to semi consolidated gravels to the vessel. Larger depressions are generally smooth and are therefore easy to mine by all mining tools. The transition zone is widespread in the study area.

A number of shortcomings of the BTM model (Figure 39) are shown when comparing to the bathymetry map in Figure 40. The depressions in the BTM output are concentrated only in the offshore of the study area and only small depressions are highlighted. When comparing this to the bathymetry map, the larger depressions (blue to green areas on the bathymetry) are not defined in the BTM output. This effect arises from the radius applied, since the northern offshore depressions are shallower and widespread. As a result, when the radius encompasses surrounding areas, the difference between one point and another are minimal. Depressions are generally the easiest geological features to mine (unless they contain a sediment package of more than 12m) by all mining tools and should therefore be well defined.

The transition zone is dominant across the study area. The underlying bathymetry shows a highly variable terrain, with different degrees of weathering and erosion. Areas with more competent rougher terrain within the transition zone will pose mineability risks to potentially all mining tools, while smoother areas could be allocated to all mining tools. Therefore, the transition zone is too widescale to use for vessel applicability. The ridges and platforms seem to align well when comparing the BTM output to the bathymetry. However, the BTM does not consider the type of footwall recorded. Some areas, especially to the inshore of the study area, have been identified by the BTM as ridges, however, sampling recovered clay footwall. Clay footwall generally characterises a smooth seabed and therefore the identified ridges are in fact only footwall highs/undulating terrain and not competent ridges. The BTM output maps also do not show any texture of the seabed, which could give an indication of the mining difficulty.

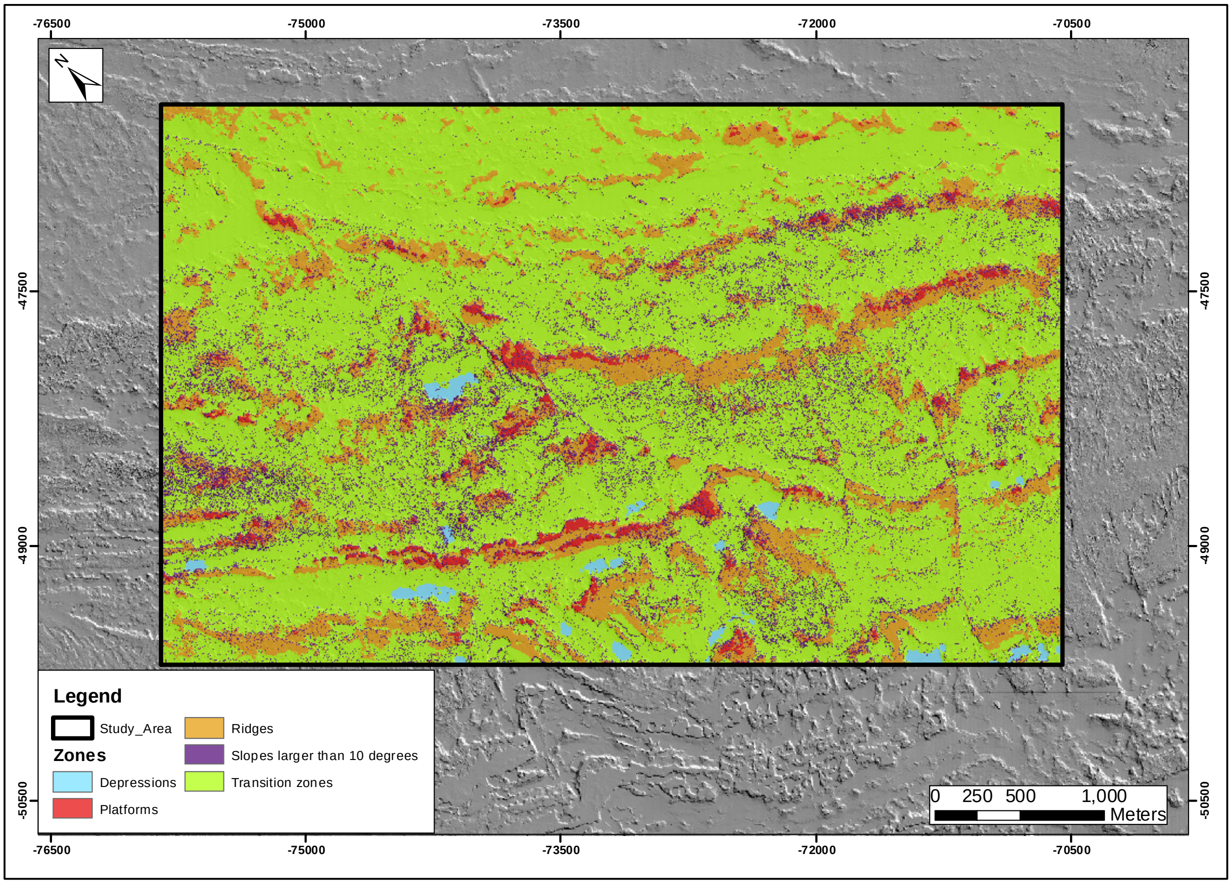

Figure 39: Output of the benthic terrain modeler in ArcGIS.

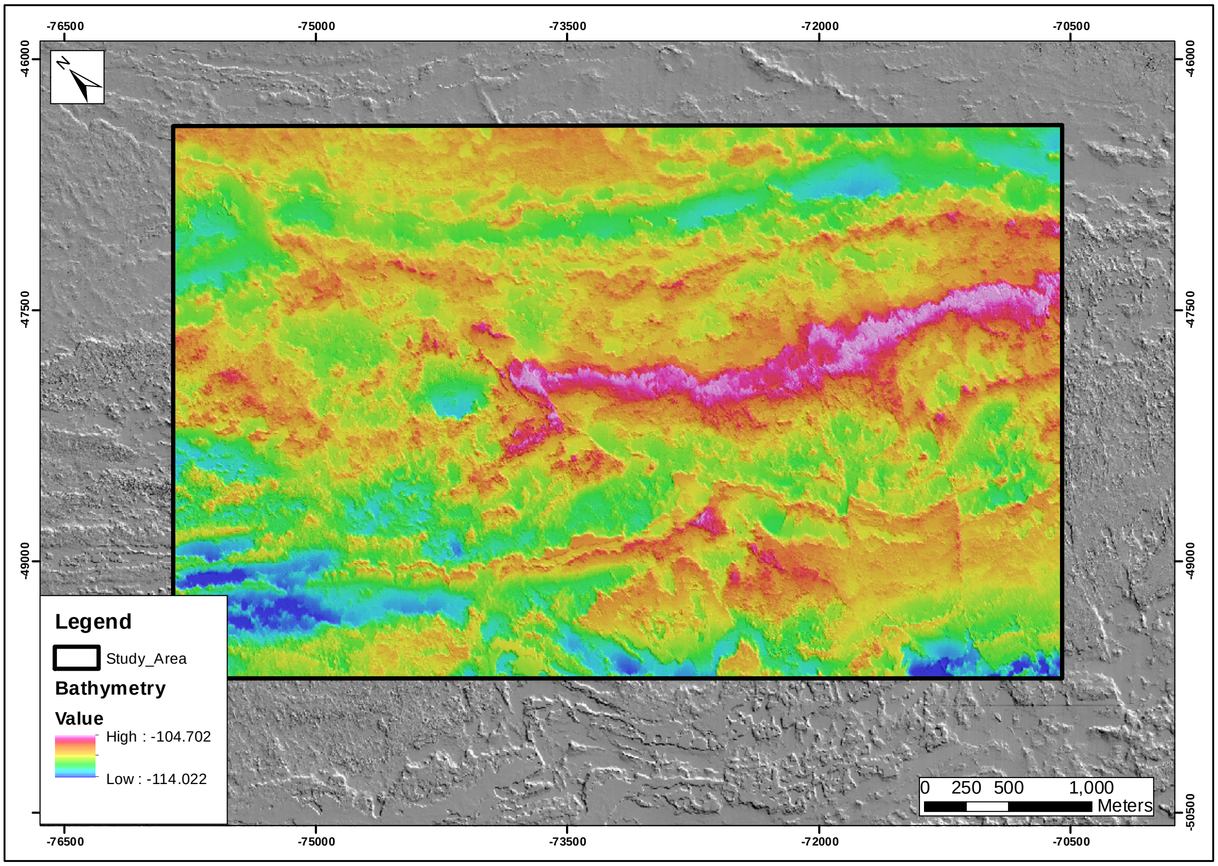

Figure 40: Bathymetry map of the study area.

The transition zone in the central and offshore southern areas (circled in blue) shows a high density of slopes that are greater than 10 degrees (Figure 41). This makes the areas circled in blue more difficult to mine with the current tools, when compared to the areas circled in red, also in the transition zone and which have slopes lower than 10 degrees. Zooming into an area in the northern central part of the study area, the transition zone on the inshore and offshore of the ridge (orange) shows the variability of the terrain (Figure 42). Inshore of the ridge, the transition zone is characterised by a lower frequency of slopes larger than 10 degrees, whereas the transition zone offshore side of the ridge shows a high frequency of slopes larger than 10 degrees. Sampling footwall is also different, whereas clay footwall is dominant in the inshore, the offshore shows conglomerate, sandstone and sand. This gives an indication that there is a higher degree of weathering and erosion in the inshore side of the ridge compared to the offshore. Figure 43 shows a profile (A to B) across the ridge. Due to weathering of the sandstone, the surface to the offshore of the ridge is irregular and undulating, making proper clean-up of the gravel ore body challenging. Both drill bits and crawler nozzles would therefore engage with the ground at an angle, potentially hindering the clean up on one side of the tool.

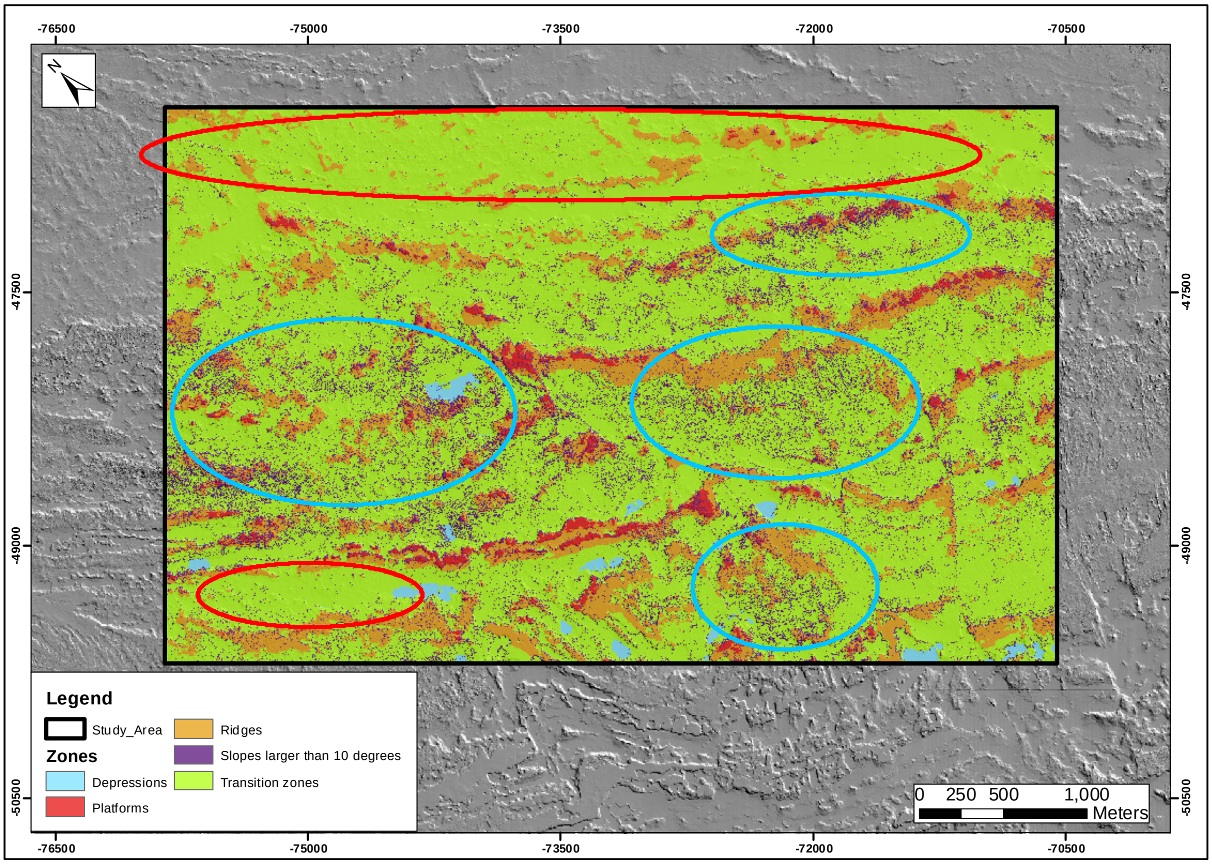

Figure 41: BTM output with red circled areas indicating the smoother areas on the transition zone and blue circles showing the rougher areas with high frequency of high slopes.

As the tools were not designed to break any capping, penetration on competent ridges is hindered. The offshore part is therefore best mineable by the small bit tools. The big bit mining tools will most likely struggle due to the rough terrain, causing stalling. Stalled holes often do not reach the desired footwall and are redrilled, which in very rough terrain, are often not successful. The crawler tools would experience challenges in this area, as the frequency of the steep slopes is high, making tracking (movement of the crawler on its tracks) difficult, as the tool slides or would get stuck. Continuous pitching and lifting of the crawler across short distances across the ground over these steep slopes will cause the nozzle of the crawler to not consistently engage with the gravel, hindering proper extraction of the gravel. Therefore, the crawler tools should not mine in this type of terrain.

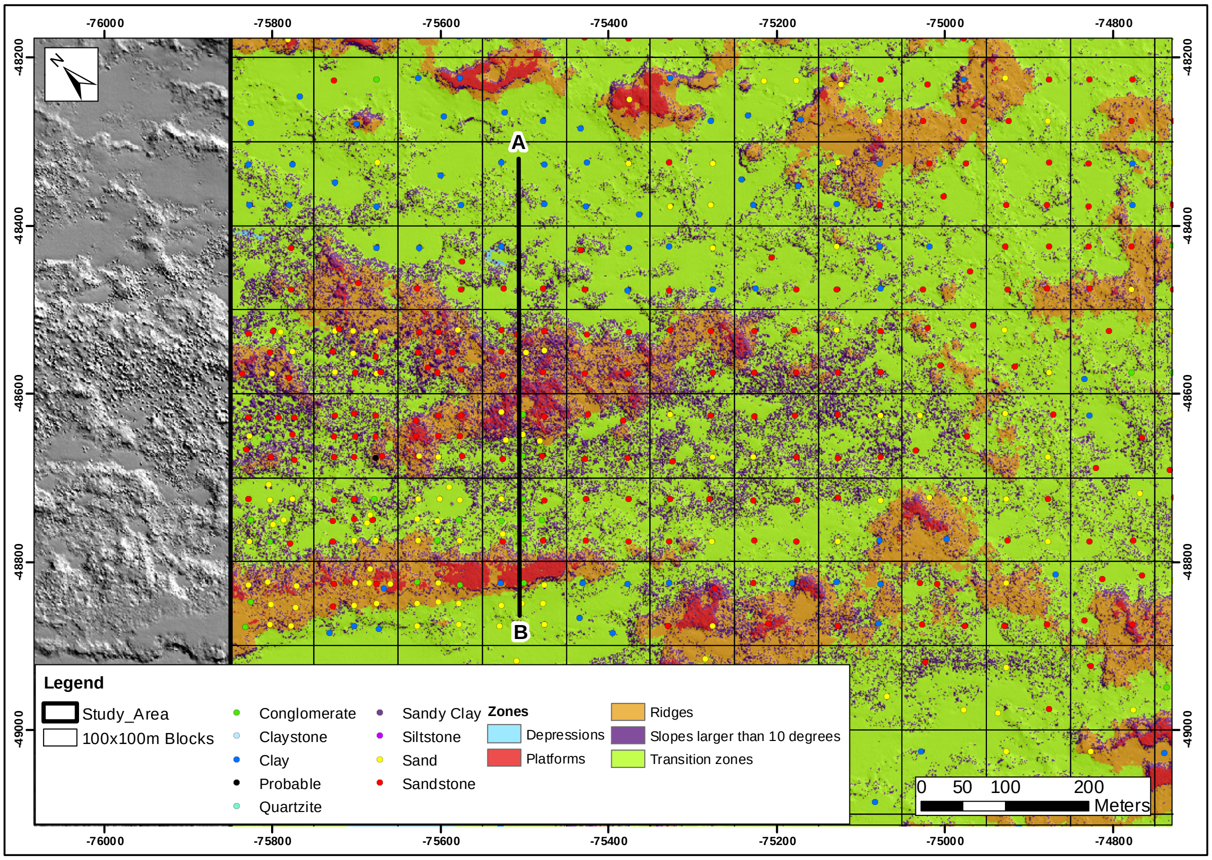

Figure 42: BTM output zoomed in on the northern offshore area. The ridge close to the edge of the study area, as well as the surrounding transition zone, show mostly competent footwall and high slope frequency.

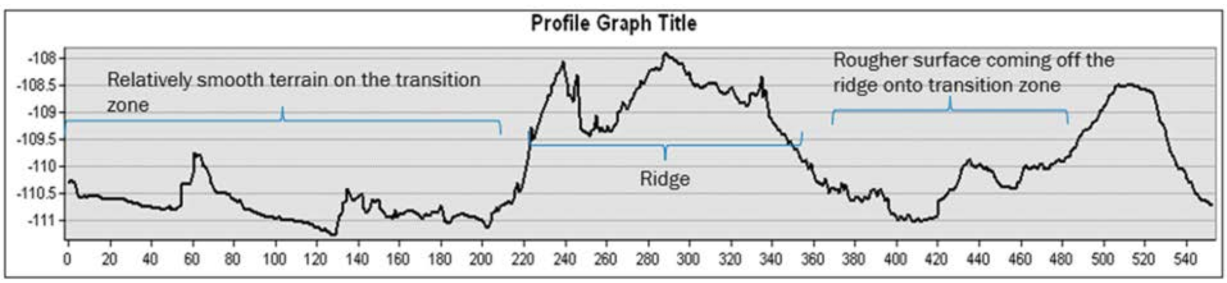

Figure 43: Line A to B showing a bathymetry profile across the transition and ridge zone.

Mining in the northern offshore part of the study area was only done by the big bit mining vessels, DA, DP and GP. All three vessels experienced significant tool stalling, linked to the rough terrain, where the sandstone remnants formed small pinnacles indicated by high frequencies of slopes on the map. Figure 44 shows the slope contours across the mined panels, and areas that had high stall durations are circled in black.

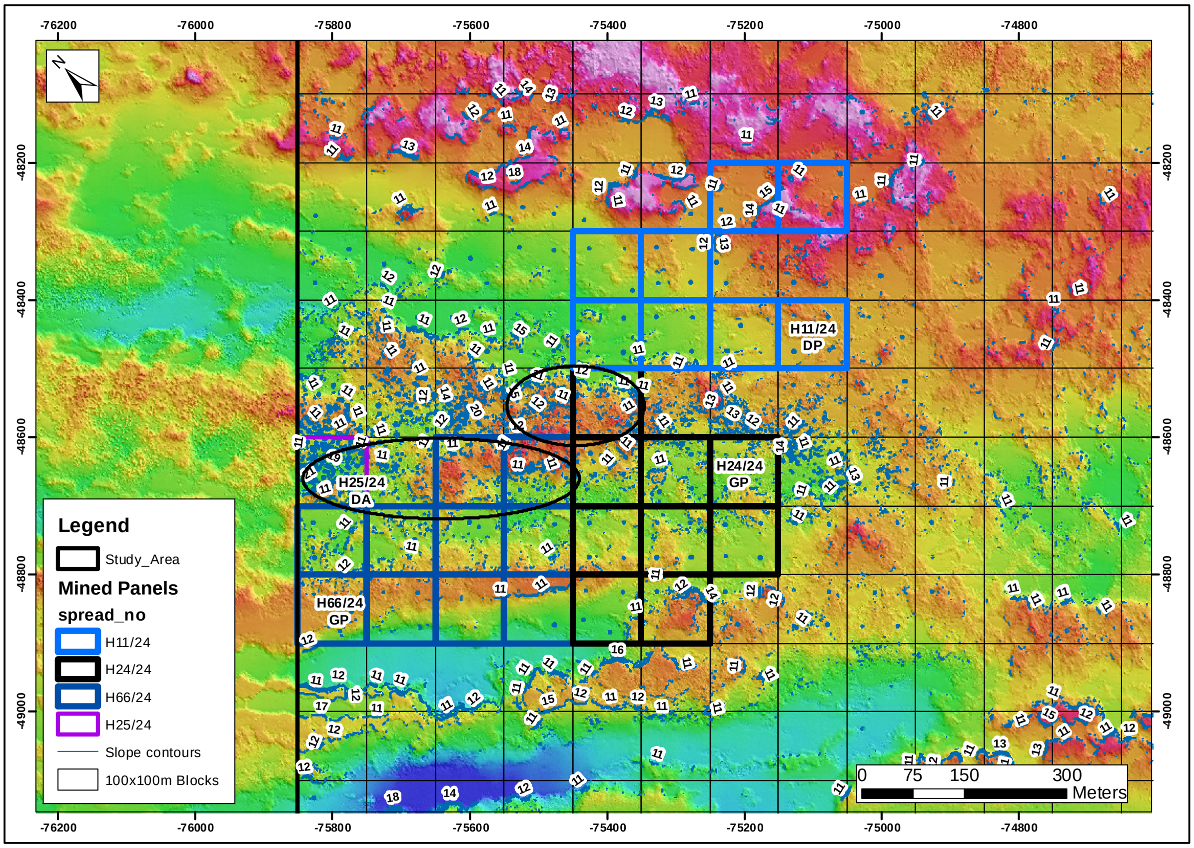

Figure 44: Northern offshore area showing the mined panels overlain by the slope contours (labelled).

Figure 45 shows a zoomed in area in the southern central part of the study area. Both drill bit tools and crawlers have mined here. The crawler vessels generally performed poorly in this area due to the rough nature of the terrain, while the big bit vessels had mixed recoveries. The footwall recovered by the sampling is mixed, implying different degrees of weathering. The crawler panels (MFT and BG) did not perform well and encountered high pitch and roll due to the undulating terrain. As these panels are just offshore of the ridge, the slopes above 10 degrees are also quite frequent in the mined panels. The footwall in the crawler panels was also mainly hard sandstone, while the big bit panels (GP and DP) were mainly on softer clay footwall with fewer slopes above 10 degrees. An advantage of the drill ships is that they can slightly alter the mining hole pattern to avoid steeper slopes. However, in areas where there are high frequencies of steep slopes, there is not much opportunity for shifting the hole pattern.

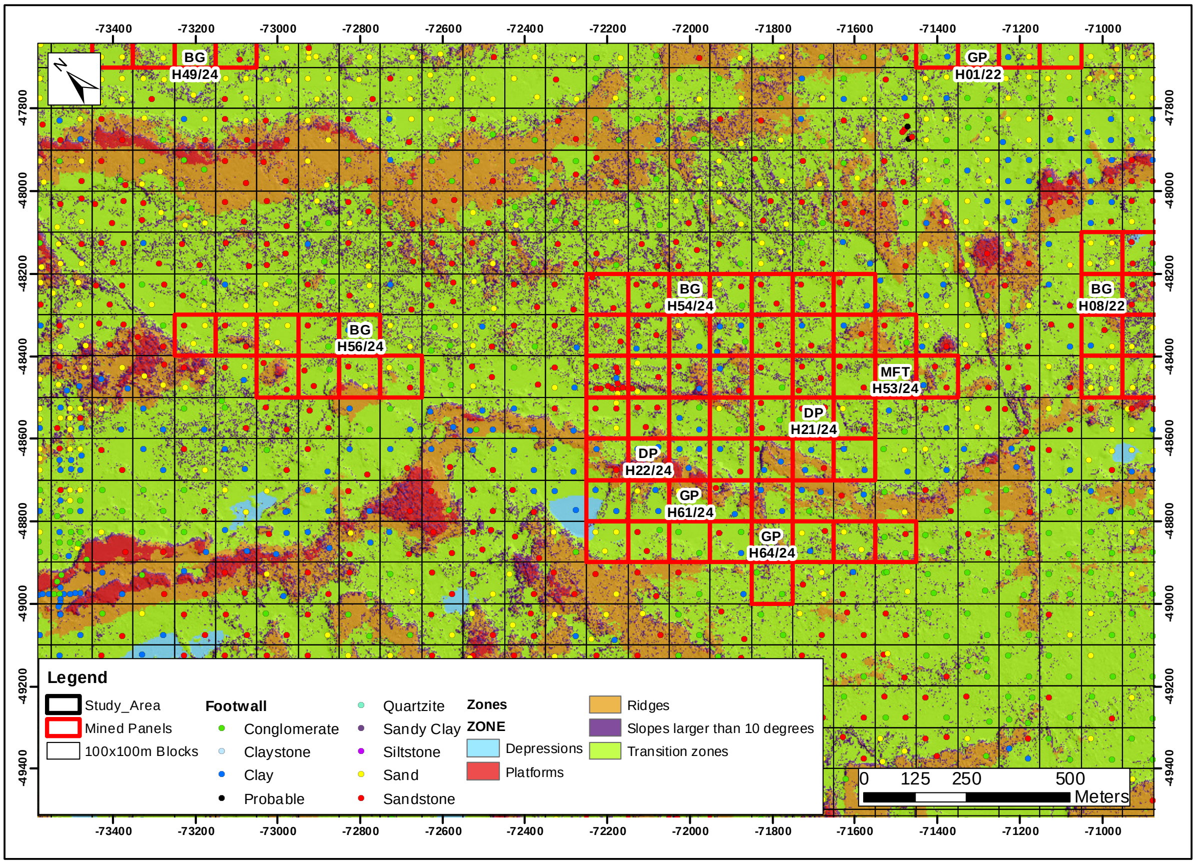

Figure 45: Southern central area with mined panels and BTM zones. The labels on the map indicate the vessel as well as the panel name.

The platforms and ridges are generally well defined by the BTM output, but these cannot be analysed in isolation. The footwall recorded by sampling plays a major role in the ease of mining of an area. In Figure 46, the ridges and platforms in the inshore of the study area are dominated by a clay footwall, indicating a high degree of weathering (black circled ridges). Slope angles are also low and therefore the ridges in the inshore part of the study area identified by the BTM output, are easily mineable by the crawler vessels as well as the drill bits. The ridges marked with yellow circles recorded mainly sandstone and conglomerate footwall, giving the indication of more cemented and competent ridges. Slope angels around these ridges are high and slopes are frequent, therefore those ridges and platforms are not mineable by the crawlers. The big bit mining tools will also face challenges on very competent ridges and drill bit stalling will be common in these areas. The small bit vessels would be most suitable in mining the ridges, however, penetration challenges due to competent units are likely.

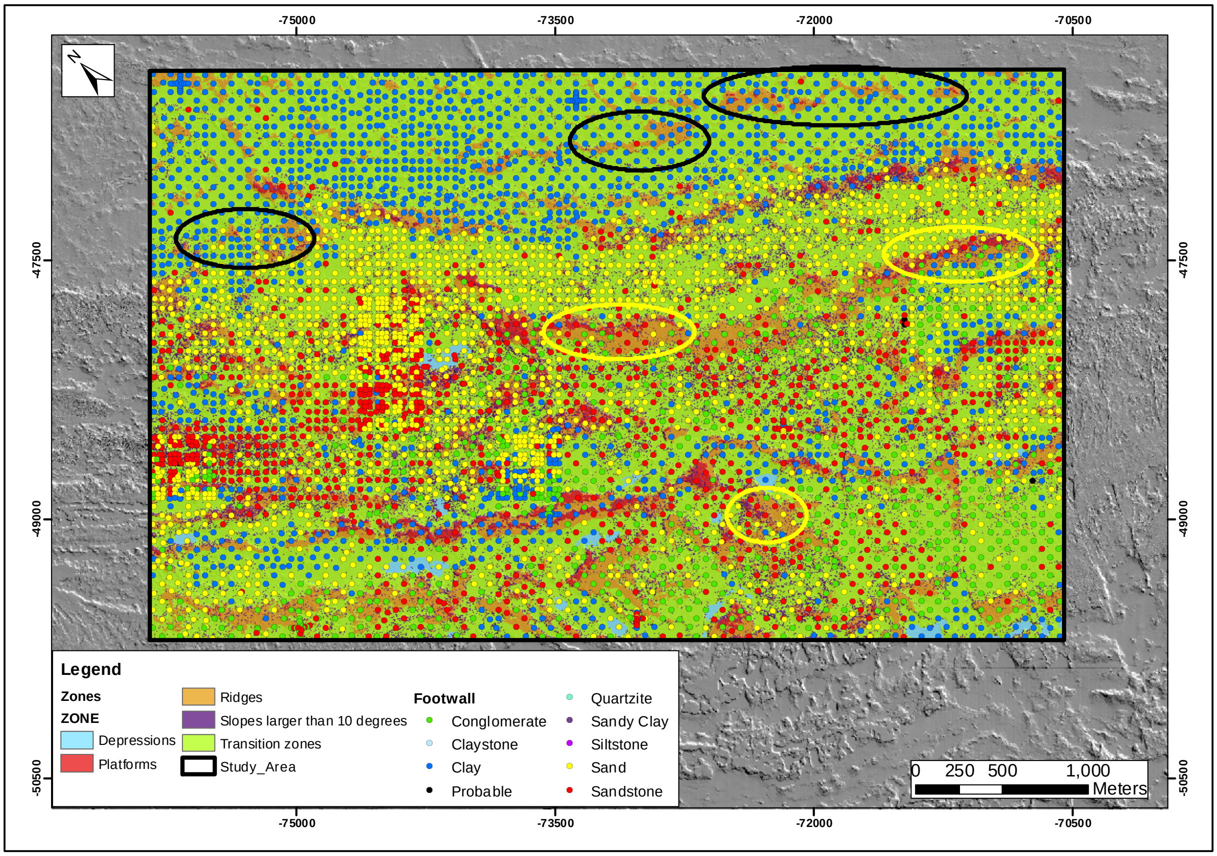

Figure 46: BTM output with sampling footwall. Black circled areas showing soft clay footwall on the identified ridges while yellow circled areas indicate more competent hard footwall types on the ridges.

The facies model produced by the reclassify tool in ArcMap provides a more detailed output when compared to the BTM output, with nine (9) different geological zones mapped compared to four (4) in the BTM output (Figure 47). While the facies are mainly mapped on elevation, they give good indication of different types of geology. Therefore, tweaking of the facies output is required to align the facies model to the geological model, requiring manual intervention. The terrain in each facies is generally homogenous. The inshore part of the study area is mainly identified as depressions and shallow depressions, which are also the smoother areas identified with clay footwall, in which mining of the crawlers encountered no mineability challenges. The ridges are also well defined, split into competent ridges, partially weathered ridges and weathered ridges. Between the ridges and the depressions are zones of variable degree of weathering.

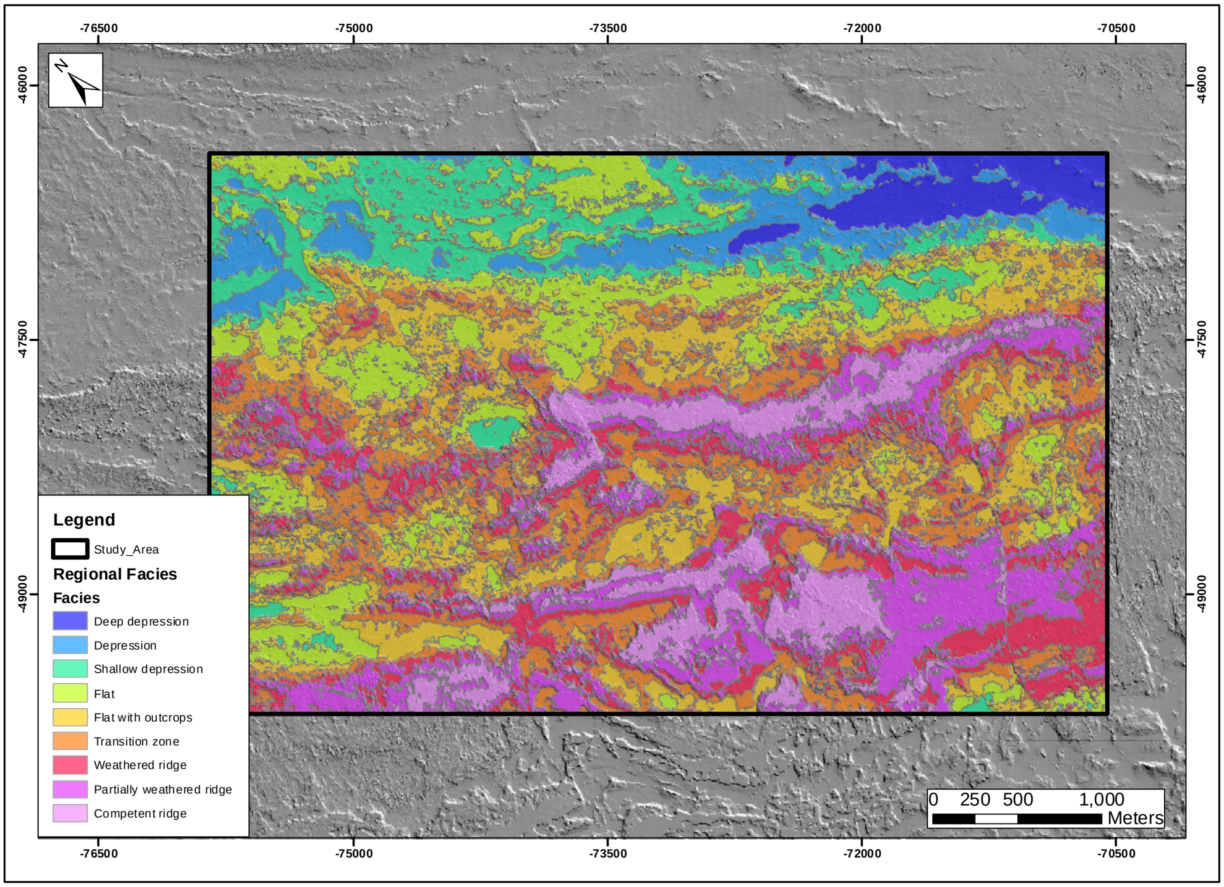

Figure 47: Regional facies map, indicating the individual identified facies.

Figure 48 shows a zoomed in area in the southern offshore of the study area. The bathymetric hillshade underlies the facies model, showing the texture of the terrain, while the colour stretch shows the different facies. Ridges and outcrops are clearly defined in pinks and reds, while the lower lying areas in the shades of orange show the more weathered areas. Figure 49 shows the facies map with the recovered footwall types from sampling. In terms of mineability, the logical approach would be to make the competent ridges and partially weathered ridges not applicable to the crawlers and perhaps the big bit mining tools. However, once the footwall is plotted, it shows that some areas that are defined as competent ridges have recorded clay footwall from sampling (circled in yellow). These areas would therefore be applicable to all mining tools. Other areas on the competent ridge and partially weathered ridge are dominated by sandstone and show a rugged texture and these would therefore be inapplicable to the crawler mining tools (circled in black). Similarly, the transition zone and the Flat with outcrops facies show mixed footwall types, indicating different degrees of terrain hardness in the same zone. For this reason, facies are a good indication of the geology, however, there are major variations within each zone, which could therefore not be blindly used for vessel applicability and these need to be refined by the geologist.

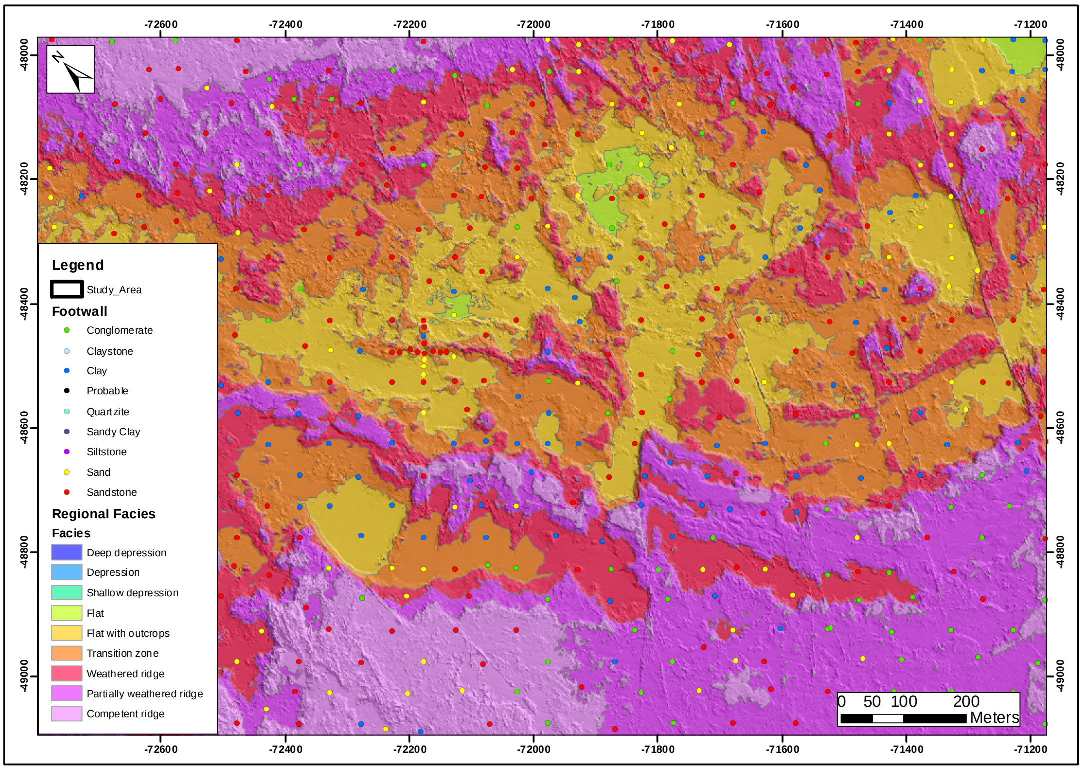

Figure 48: Facies map in the southern offshore of the study area.

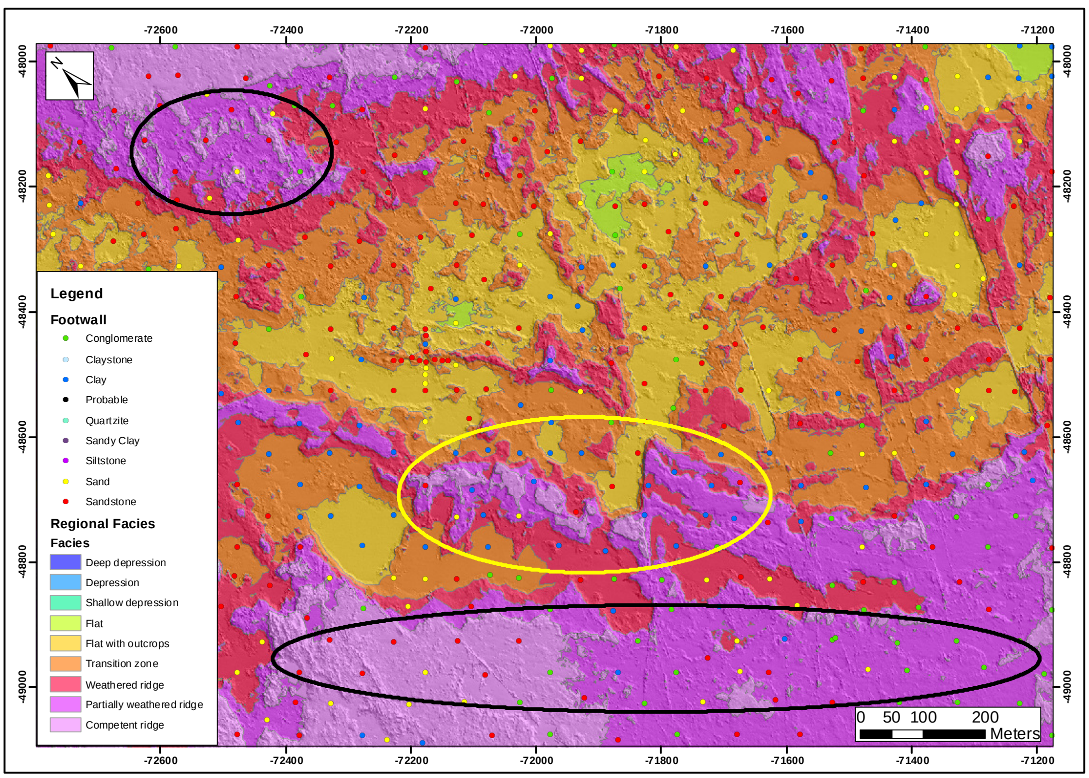

Figure 49: Facies map in the southern offshore of the study area, with sampling footwall. The area circled in black shows competent ridges with hard sandstone and conglomerate footwall. Within the yellow circle, the competent ridges are more weathered as sampling intersected soft clay footwall.

Mining in the area was done by the two crawler vessels in the inshore (blue and red outlined blocks) while the offshore was mined by the big bit vessels (Figure 50). The crawlers performed poorly in terms of diamond recoveries, which is linked to the mineability challenges encountered in these panels. On numerous occasions, the crawler tools were pitching and rolling and not reaching and cleaning up all areas. Despite the fact that these were located on lower lying facies, believed to be easier to mine. The offshore two panels, which were mined by the GP and DP, and although located on higher lying facies, performed better in terms of diamond recoveries. Footwall types also differed from the inshore to the offshore panels. The soft clay footwall was dominant in the offshore panels, while hard sandstone footwall dominated the inshore panels. Texturally from the underlying bathymetry, the inshore panels display a more rugged terrain, especially visible in the Flat with outcrops facies as well as the Transition zone facies. The crawlers were pitching and rolling while mining the two inshore panels, due to the rough terrain.

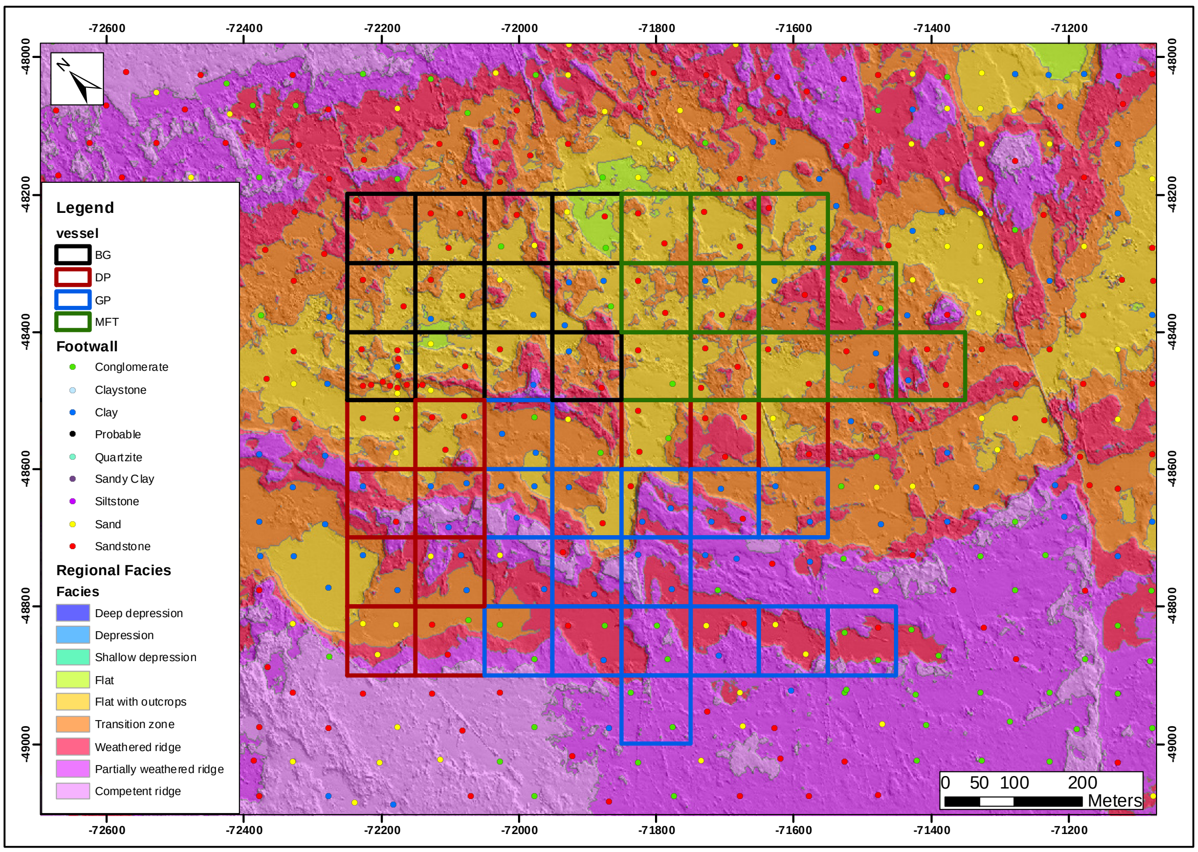

Figure 50: Facies map in the southern offshore of the study area, showing the mined panels per vessel.

The mineability risk model based on sampling data was created on a 100m x 100m grid, that is currently used for mining. Mineability and applicability of mining tools to an area are a major part of the MPM. Currently the MPM is set up in a way that the applicability of a vessel to a 100m x 100 m block is only indicated by a yes or no. However, in reality as the geology changes, there are different levels of difficulty in a mining tool being able to mine an area. The mineability risk model based on sampling data was therefore created to provide these levels of difficulty. Different sampling data was used to create a risk matrix for each 100m x 100m block. The risk matrix would inform the MPM of each blocks risk and therefore, once a mine plan is developed, the risk on a panel could be averaged to have an upfront mineability risk.

One of the key elements in mining in Atlantic 1 is the type of footwall in an area. Once the bathymetry is overlain by the sampling footwall, the geological features can be identified, for example, a high lying feature visible on the bathymetry might look like an outcrop that could possibly be difficult to mine. Once the footwall type is determined, the feature can either be identified as a competent outcrop if the footwall type is sandstone or conglomerate, or the feature could be a footwall high (an elevated area with soft footwall that is easy to mine). The risk scale for the footwall types were applied from the easiest ground to mine (score of 1) to the most difficult ground to mine (score of 6). Clay footwall received the lowest score while sandstone or probable scored the highest. The output is shown in Figure 51, indicating the sampling footwall and the underlying risk score per 100m x 100m block. Clay footwall is dominant in the inshore of the study area, which corresponds very well to good recoveries achieved by the mining in this area. Figure 52 shows the panels that were already mined within the study area. The area on clay footwall, circled in yellow, did not pose any mineability challenges to the crawler vessels and big bit and small bit mining tools would also not encounter any challenges in this area. Moving further offshore, the area is partially weathered, with soft sand footwall being dominant. The terrain here already becoming more rugged and rough, introducing tracking challenges on the crawler mining tools. The recoveries in this area, however, were on target. The area marked in purple with mainly competent sandstone footwall, caused mineability challenges and tool stalling, and hence mainly poor recoveries. In the area circled in green, which is a mix of hard and soft footwall on variable terrain, the crawlers performed poorly, and the recoveries from the drill vessels were mixed. The crawler generally struggled with proper clean-up due to the high slopes. A good correlation of footwall and mineability, and the ability to recover the estimated grades is therefore present.

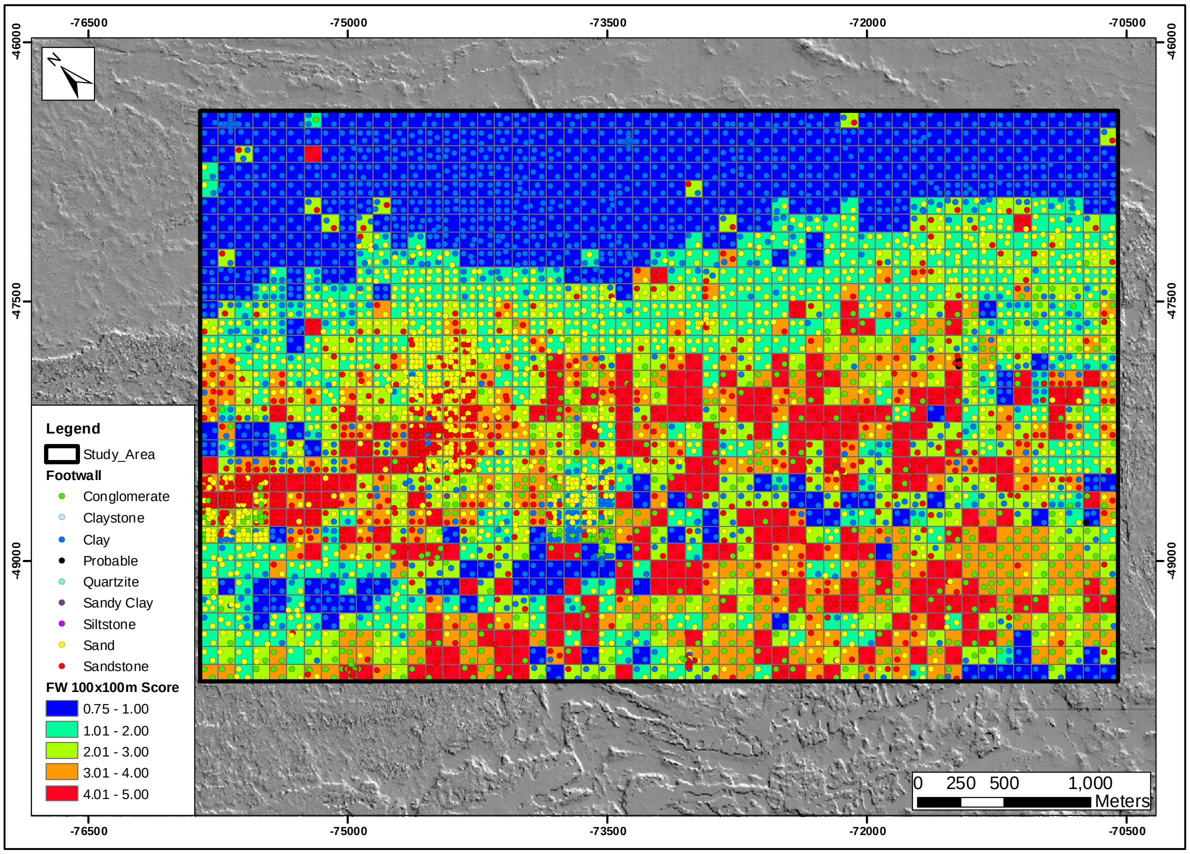

Figure 51: Sampling footwall underlain by footwall score averaged for 100 m x 100 m mining blocks.

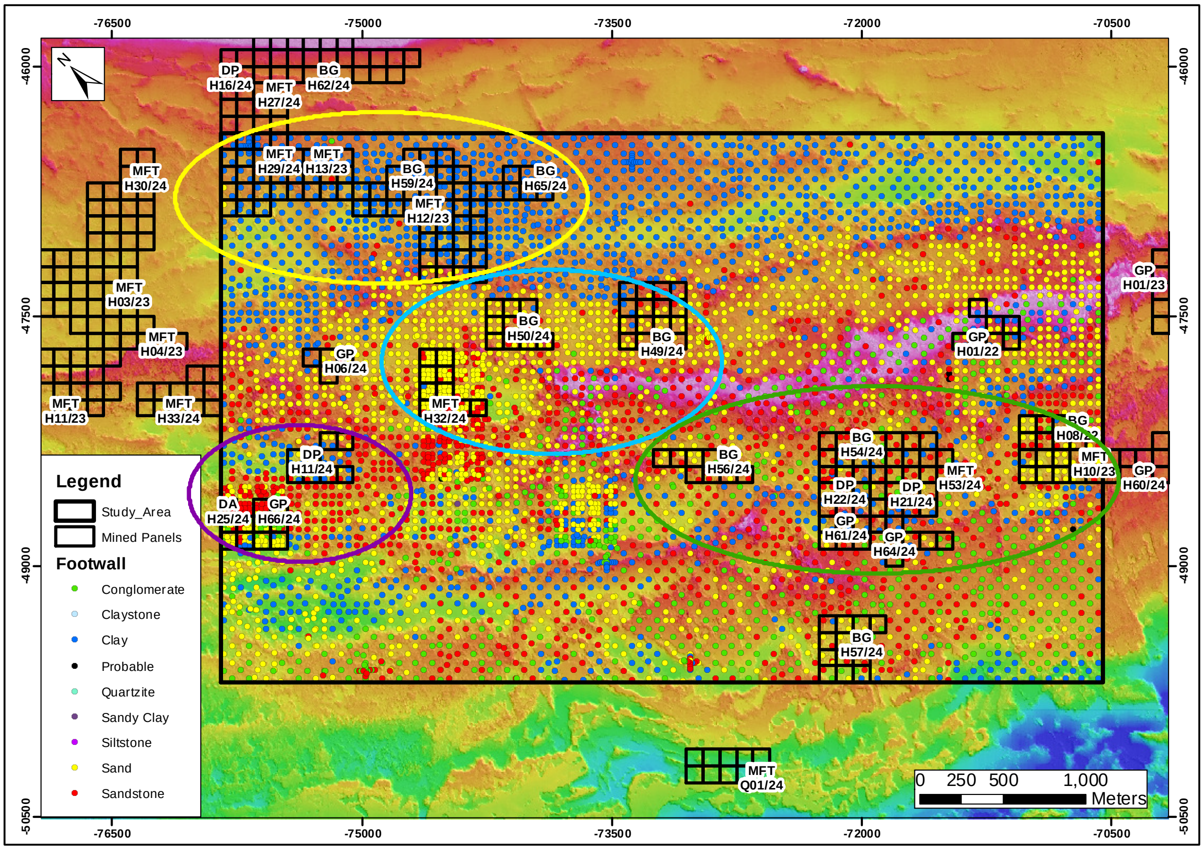

Figure 52: Map showing the mined panels in the study area, underlain by the sampling footwall and the bathymetry. The yellow circle shows the mining by the crawlers on clay footwall, an area easily mineable for the tools. The blue circle shows crawler mining in slightly more competent terrain, with mostly sand footwall. The purple circle shows drill ship mining in more variable terrain and footwall types and the green circle shows crawler and drillship mining on very rugged terrain.

The maximum sediment thickness that can currently be mined without major challenges is 12m. The study area is dominated by lower maximum penetrations of between 0 and 3.48m, while higher maximum penetration from sampling exists around the ridge features, where thicker gravel packages accumulate in depressions and gulleys (Figure 53). Maximum penetrations of up to 14.94 m exist in the study area, however, these are isolated cases and are most likely localised depressions or potholes. From all historical mining in the study area, no major challenges regarding the thickness of the ore body were observed. The maximum average risk per block in the study area therefore is a 5. There are however areas in the Atlantic 1 mining licence that have consistent sediment packages of above 6m. High gravel volumes or thick sediment packages mainly affect the mining rate of a vessel, as the plant is not able to cope with the high volumes. Mining has to be stopped in order to process material out of the holding bins and this down time is part of the mining time, lowering the mining rate.

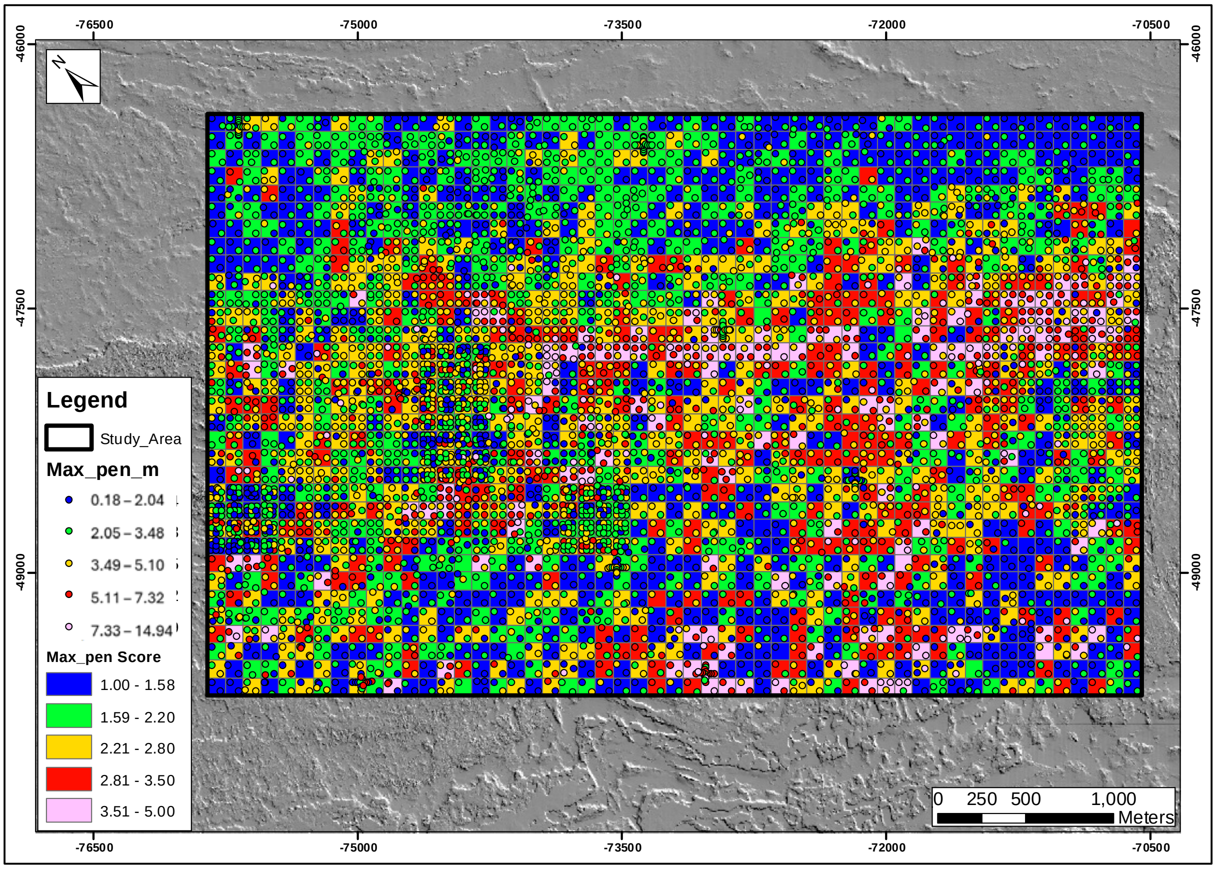

Figure 53: Sampling maximum penetration underlain by maximum penetration score averaged for 100 m x 100 m mining blocks.

The rate of penetration (ROP) essentially provides data about the ease of drilling. Faster rates of penetration mean that it is fast to drill to footwall and the tool did not experience any challenges while engaging with the ground to reach footwall. Lower rates of penetration can indicate the difficulty of drilling to footwall. This could either be because the tool was engaged with competent terrain, prolonging the drilling time to see if the capping can be broken or very coarse gravel texture, hindering fast penetration. The inshore of the study area shows relatively fast rates of penetration, which therefore indicate a low-risk score per 100m x 100m block (Figure 54). This corresponds well with the ease of mining of the inshore parts of the study area. Around the ridge features the rate of penetration increases, which generates higher risk scores of around 1 to 3. On top of the more competent ridges, the rate of penetration is slow, giving rise to higher risks of up to 5 in the model. The extreme northern offshore blocks show a risk between 5 and 6 but these are erroneous, as they show little variation. There were accuracy challenges with the recording of the sampling time in this area (pink blocks).

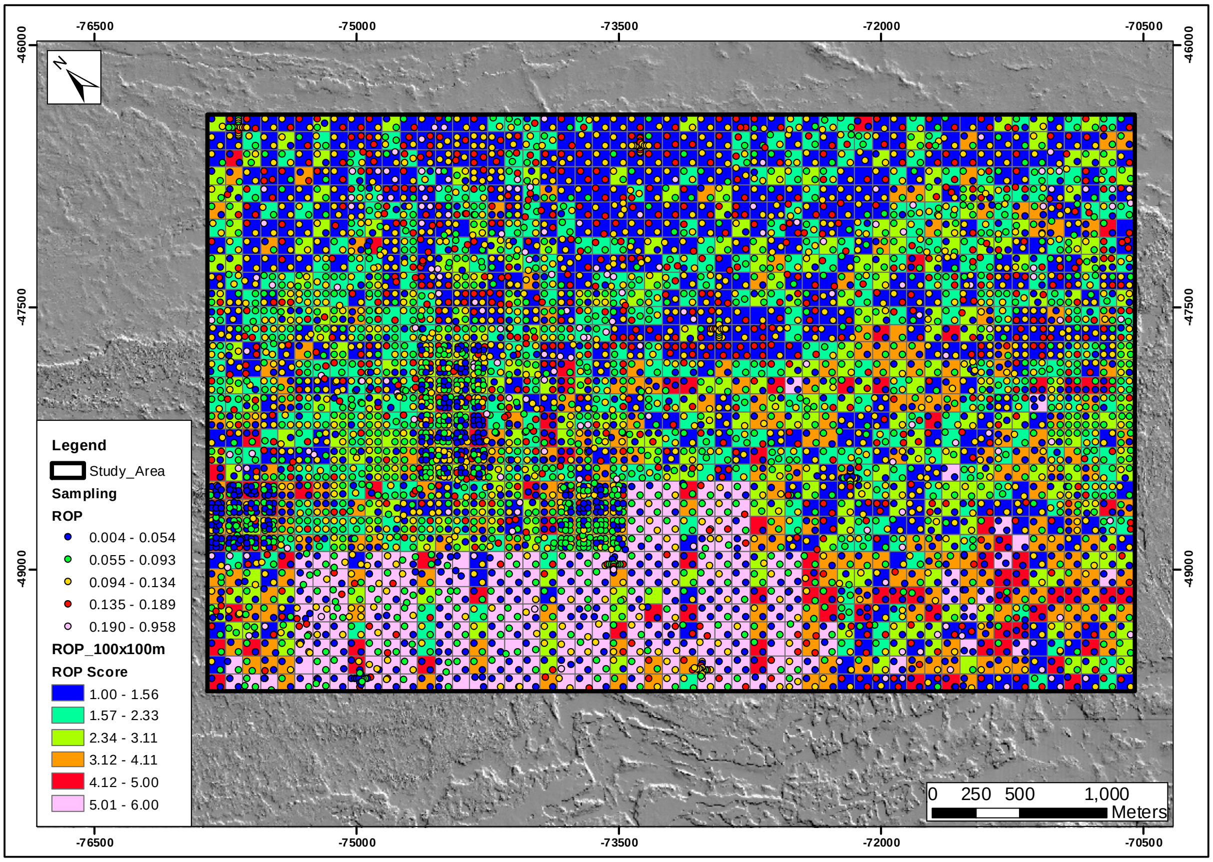

Figure 54: Sampling rate of penetration underlain by RoP score averaged for 100 m x 100 m mining blocks.

Shell volumes in the study area are not of concern as they are mainly low at between 0 to 5% shell in a sample (Figure 55). Small pockets of higher shell volumes are present in the study area, however, they are isolated. Mining a panel with isolated high shell volumes provides a good opportunity for the vessels to alternate between areas of high shell and areas of low shell volumes to manage any plant delays. Shell volumes are visually estimated during sampling and are expressed as a percentage of the plantfeed fraction. Shell often causes full wet bin delays in the plant due to volumes, again affecting the mining rate by lengthening the mining time. No shell related challenges were reported while mining in the study area.

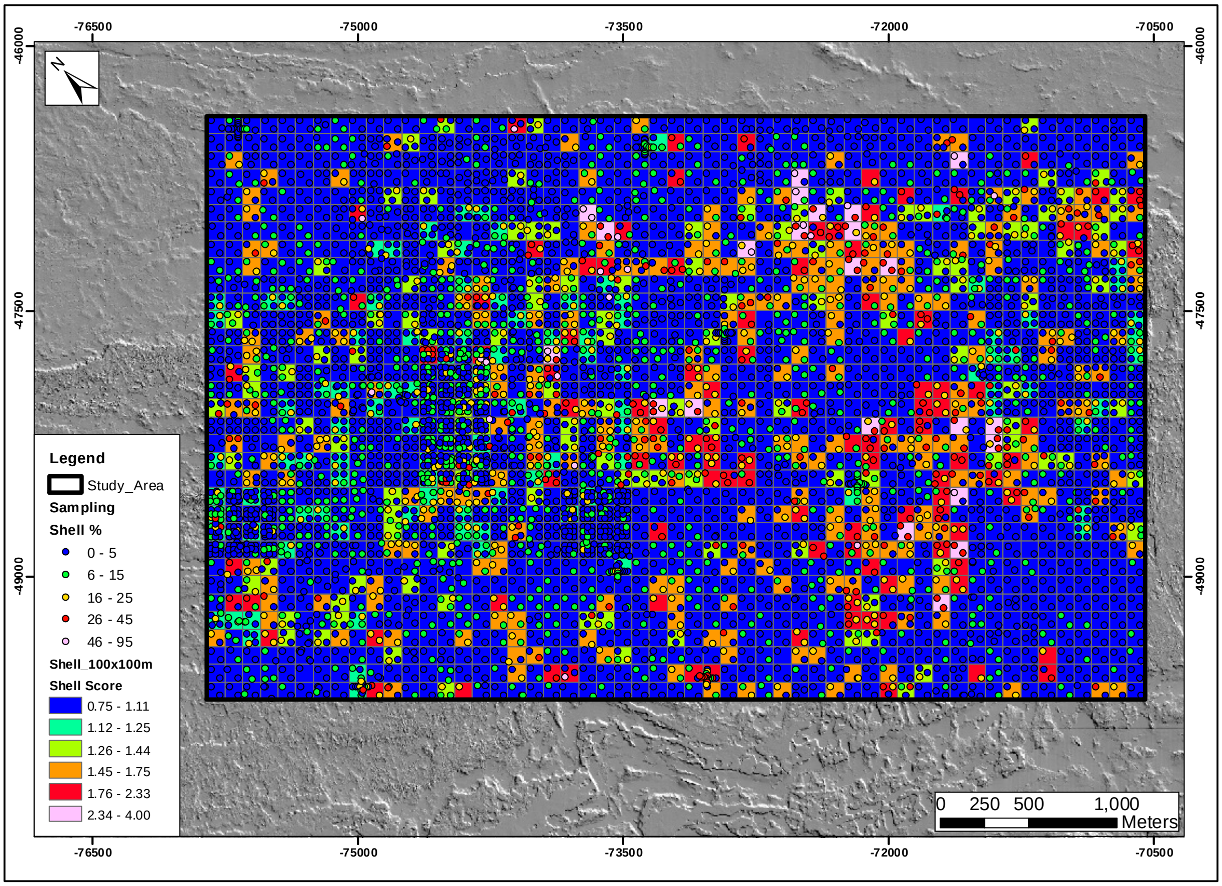

Figure 55: Sampling shell underlain by shell risk score averaged for 100 m x 100 m mining blocks.

The overall risk per 100m x 100m block is split according to the percentages in Table 13 below. The footwall and the rate of penetration are weighted at 25% each, as the footwall and the RoP are crucial in the efficient extraction of gravel. Soft clay footwalls are associated with smooth terrain indicating easy mining ground, while harder footwall types indicate more competent rock, which causes penetration challenges. The rate of penetration shows the ease of mining and gives an indication if the predicted mining rates can be achieved. The mining rates during mining are crucial, as they directly influence the carats per hour that are achieved. Therefore, the rate of penetration is also weighted at 25%. Maximum penetration is weighted as 20% as this parameter has a significant impact on mining when the sediment package is consistently thick. The thicker the sediment package, the more risk there is to exceed the plant capacity, resulting in a lower mining rate. Shell and texture currently are weighted at 15% each of the risk score, as they have a lesser effect on the risk of mining. Figure 56 shows the overall risk index per 100m x 100m block. The inshore parts of the study area were generally assigned a low risk, proved by the ease of mining in these parts. Moving further offshore towards the ridges, the mineability risk increases.

Table 13: Overall Score Split

Sampling Parameter	Split
Footwall	25%
Maximum Penetration	20%
Rate of Penetration	25%
Shell	15%
Texture	15%
Total	**100%**

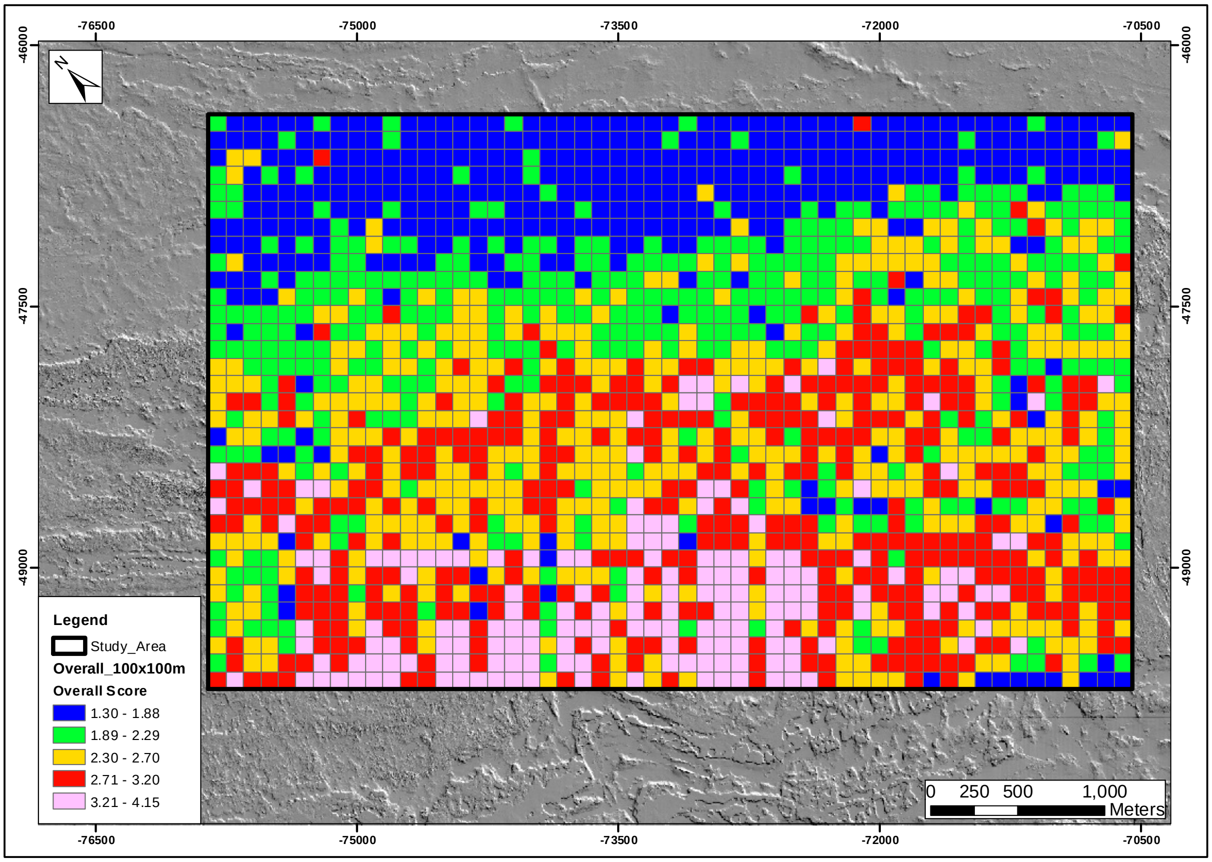

Figure 56: Overall score per 100 m x 100 m block.

Figure 57 is an enlarged part of the area that was mined by the drill bit tools. Mining was done in 2024 in this area, with two panels mined by the GP and one panel mined by the DP. The vessels experienced significant tool stalling in the two offshore panels, as can be seen by the very rough texture from the bathymetry. Weathering of the sandstone has formed a rough textured seabed, with more competent sandstone pinnacles remaining. The inshore panel mined by the DP indicates a lower risk for all 100m x 100m blocks, when compared to the offshore panel. During mining of the inshore DP panel, no major mineability challenges were reported.

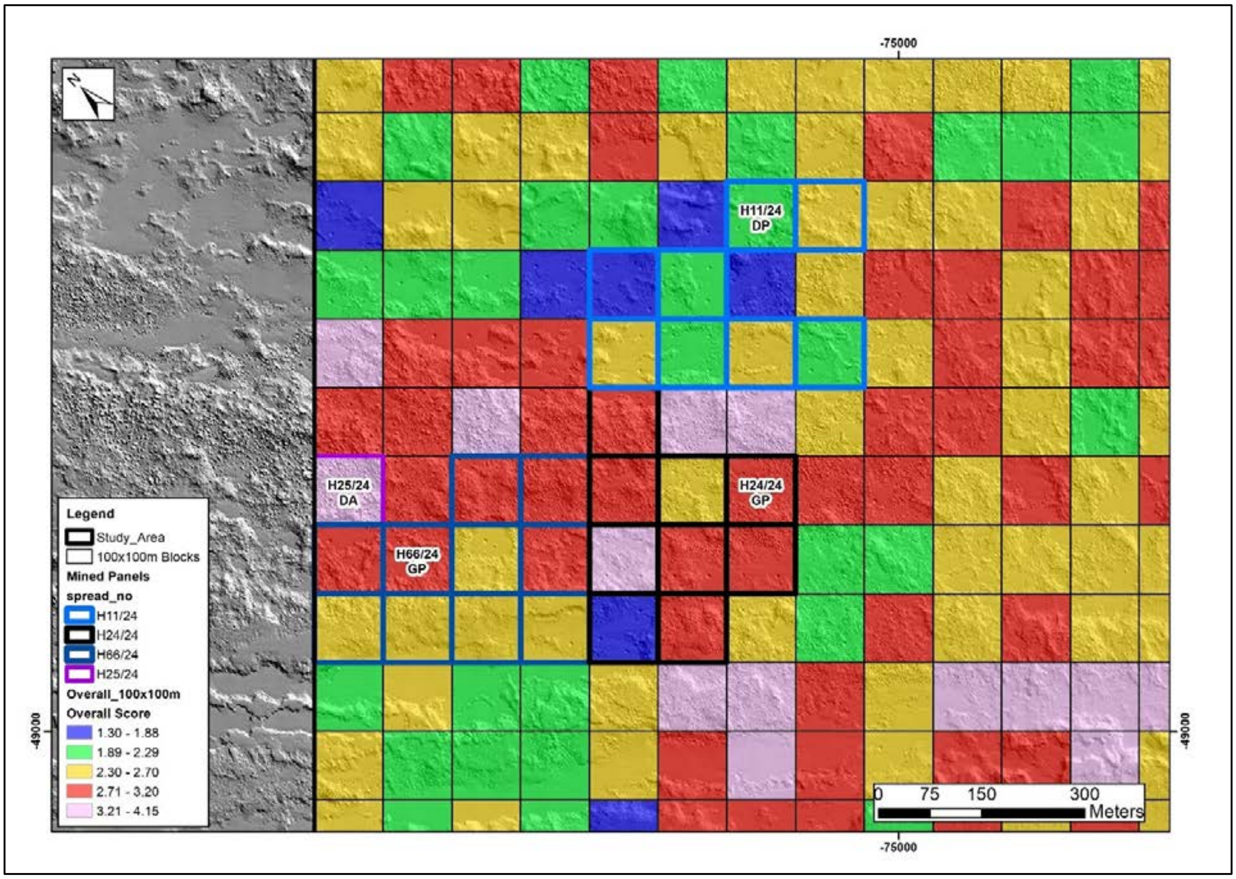

Figure 57: Enlarged area in the northern offshore part of the study area, showing the mined panels as well as the 100m x 100m risk index.

From this study, it can be concluded that the BTM output can be used as an upfront indication of the features within a regional area but would have to be refined by the facies output, as the facies are mapped in more detail. The slope map produced by the BTM is an important parameter, as both the crawlers and the drill bits struggle to mine in areas with a high frequency of steep slopes, although the crawlers are more sensitive to this parameter. The sampling data risk matrix per 100m x 100m block gives a very good reference of the risk of mining a block. As the resource gets estimated and mined on 100m x 100m blocks, the risk per block approach is the most effective. Due to the current limited mining within the study area, the model needs to be further refined, once more mining has taken place. The next steps would be to quantify the slopes into the risk matrix, to have a more comprehensive scoring system. Once the facies are ground truthed with more mining, each facies could also receive a score, and this would then be joined to the 100m x100m mining blocks.

Different groups of vessels should also be assigned different risk thresholds, as already discussed in terms of each vessel's capabilities. From the overall score index in the study area, the highest risk score was 4.15. Other areas in the mining licence will have blocks with higher maximum risks, depending on the geology. Therefore, the risks assigned to the different vessel groups may need to change in different geological environments. For the study area, the risk bracket 3-4 should be avoided by the crawler vessels, especially when coupled with a high frequency of slopes above 10 degrees. The crawlers cannot effectively clean-up the ground sufficiently while tracking over this type of terrain, due to the design of the tool. Tilting or moving up an incline with a depression behind it, will cause the crawler nozzle to not fully engage with the gravel while mining. Big bit mining tools also struggled in this type of terrain, especially with stalling. Blocks located in the depressions of the panels yielded better results by what is believed to be efficient gravel extraction. The small bit vessels have not mined in the study area yet, but could potentially be most suitable for the rougher areas, as the tool itself is smaller and can reach smaller potholes, which could be potentially too small for the big bit drill to reach.

Tables 14 to 16 show the applied risk score for each mining tool. Blocks that score high risk for any mining tool could therefore mean that the mining tool cannot mine the area sufficiently and underperform in terms of grade or could potentially abandon a panel due to the mineability challenges associated with the blocks.

Table 14: Small bit risk

Small bits	**Risk Score**
Low risk	1 - 2
Low risk	2 - 3
Low risk	3 - 4
Medium risk	4 - 5
High risk	5 - 6

Table 15: Big bit risk

Big bits	**Risk Score**
Low risk	1 - 2
Low risk	2 - 3
Medium risk	3 - 4
High risk	4 - 5
High risk	5 - 6

Table 16: Crawler risk

Crawlers	**Risk Score**
Low risk	1 - 2
Low risk	2 - 3
Medium to high risk	3 - 4
High risk	4 - 5
High risk	5 - 6

CHAPTER 7

CONCLUSION

The most important aspect of mining an area efficiently and sustainably is to deploy the right mining tool in the right areas to maximise efficient gravel extraction. The initial design for the crawler was to mine relatively flat and smooth ground, on which the tracks can easily navigate, and the nozzle of the crawler is always engaged with the ground while mining. The drill bit tools were designed to mine different degrees of rough terrain, with the small bits generally better in the rougher areas with smaller potholes, due to the size of the mining tools that could access these potholes. As in any mine, the easier areas with better grades are mined first. More difficult areas remain and once these get mined, the mining tools will have to be stretched to their limits. By doing this, the shortfalls of the tools can be identified, and the technology can be improved.

Region H is a relatively newly unlocked area in the mining licence with commercial diamond grades on Cretaceous footwall. A large number of mining panels were therefore selected in this area during the mine plan development of 2023, 2024 and 2025. This meant that the area was largely untested in terms of mining with both the drill bit tools and the crawler tools. Different tools were therefore deployed in different areas of Region H, to determine the best tool type for every terrain. Good grades were associated with rough terrain, which resulted in several crawler panels not achieving the estimated grades, simply because the gravel was not efficiently extracted. The drill bit tools showed a mix of recoveries, indicating both mineability and possibly grade estimation challenges.

The aim of the study was to develop a more quantitative approach to mineability and vessel applicability, as well as to develop a risk matrix of unmined blocks. This would assist the company in decreasing the time spent on allocating mineability and remove the subjectivity of different people doing the mineability and applicability assignments of an area. The risk matrix on the other hand would give an upfront risk per mining block, which could prevent the wrong vessels from mining an unsuitable area.

In order to define vessel applicability, different geological zones or features needed to be mapped out. These zones or features could then be assigned to the different mining vessels. This was done using two different methods, namely the benthic habitat mapping and creating regional facies across the area. The benthic terrain modeler function used generally for benthic mapping proved to successfully distinguish larger geological features, however, on a generally broader scale (mainly too broad for applicability application). It could therefore be used on a large scale to give an indication of the terrain, however, not useful for the tool applicability determination on a panel scale. The slope maps produced from the benthic terrain modeler are however very useful, especially for the crawler tools, as the crawlers are sensitive to mining on rough undulating terrains.

The facies model provided a more detailed mapping of different geological terrains. The shortfall of the facies model however is the scale at which it is computed. A regional area that is divided into nine different zones can lose detail compared to a local scale facies computation with nine different zones. However, upfront facies creation on a regional scale can assist with applicability determination. However, this will have to be refined with the risk model developed from sampling when the individual 100m x 100m blocks are assigned to different tools. The facies model also needs to be tweaked or adjusted after creating it with the reclassification tool so that it aligns with the geological understanding of the area.

In the study area it was difficult to send the mining tools to the correct areas upfront in an area that was largely unmined, the risks were identified only during the mining process. The mineability risk per block developed in this study can therefore already assist with upfront risk detection before any vessel proceeds to a new area, based on the information received through sampling. Therefore, this tool provides a valuable overview of a new resource area, and the risk associated with each block. In areas already mined in the study area, the risk that materialised during mining is comparable to the risk assigned by the mineability model.

The crawlers are most sensitive to terrain changes. The crawlers currently mine in straight lines, which causes the tools to often mine perpendicular to outcrops/higher lying features. Following a path around outcrops along the contours would potentially cause less mineability challenges as in this way the crawler could avoid steep slopes. To optimise on the mining rate, a simulation would have to be run for a panel to determine an optimised pathway.

The next steps would be to closely monitor and analyse the mining going forward in the study area. This would allow for refining the mapping of the zones done by both the benthic modeler as well as the facies model. The same applies to the risk model in order to see if this model is robust enough to use for upfront risk determination. Different areas and geological settings in the Atlantic 1 mining licence should then also be tested, in order to determine the usefulness of these models.

The current study does have its limitations. Both the benthic terrain modeler as well as the facies model only use the bathymetry data, while there are other geophysical datasets (side scan sonar, analytic signal, first vertical derivative to name a few) available that could assist in the mineability determination. The benthic terrain model seems to miss a lot of the finer details when it comes to determining geological zones and the zones are more broadly assigned. The facies outputs are much more detailed, but also still require manual intervention as they are mainly based on bathymetry elevation.

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APPENDICES:

Classification table developed for the study area to run the Benthic Terrain Modeler function in ArcMap.

Class	Zone	BroadBPI_Lower	BroadBPI_Upper	FineBPI_Lower	FineBPI_Upper	Slope_Lower	Slope_Upper	Depth_Lower	Depth_Upper
1	Slopes larger than 10 degrees					10			
2	Platforms	300	557		1803				
3	Ridges	150	300						
4	Depressions	-250	-150						
5	Transition zones	-150	150						