You're going to do What? Where? Challenges for resource estimation on the Chatham Rock Phosphorite Project

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Abstract

The Chatham Rock Phosphorite project is situated 450 km east of New Zealand at approximately 350 to 450 m water depth. The deposit occurs as a thin layer of phosphate-bearing glauconitic sand at the surface of the sea floor and has a thicknesses typically ranging from 0 to 1 m. The sand layer consists of mainly silt and sand-sized sediments, with phosphatised chalk nodules up to 15 cm in diameter.

Phosphate nodules were first discovered on the Chatham Rise in the 1950s by a New Zealand Government survey. During the 1960s to 1980s several private and government sponsored cruises explored the Chatham Rise and surrounding seafloor area. A total of 1174 samples were collected over a 600 km2 area with the majority of the samples collected using a pneumatic -or large Van Veen-style grab-sampler.

Since acquiring the licence in 2010, Chatham Rock Phosphate Limited has conducted six cruises in two programs in the Project area. A total of 261 samples were collected using a Van Veen grab, box core and grab samples.
Sample quality and QA/QC measures varied considerably between the cruises and within each cruise. A critical part of the assessment of the data collected in the Project area was to determine what quality thresholds to use to allow or disallow data to enter into the estimation process. As part of the data verification process, the relative and absolute quality of the data was assessed in as much detail as practically possible. The best samples were those that were collected using the pneumatic grab, sampled the full sand horizon, had a small location survey error and had no other apparent data ambiguities.

This paper describes the challenges for mineral resource estimation for an unconventional style of mineralisation using unconventional sampling techniques.

Keywords: Chatham Rise, Phosphorite, Rock phosphate, Seabed mineralisation, Seabed nodules, Resource estimation.

Introduction

The Chatham Rock Phosphorite project is situated 450 km east of New Zealand at approximately 350 to 450 m water depth (Fig. 1). Phosphate nodules were first discovered on the Chatham Rise in the 1950s by a New Zealand Government survey. Several exploration campaigns have since been completed. CRP holds 100% of Mining Permit 55549 (820 km^2) and the 3,906 km^2 (formerly 4,726 km^2) Continental Shelf Licence MPL 50270. CRP's long-term strategic focus is to mine phosphorite from the Chatham Rise in order to supply phosphorite to the fertiliser industry. This paper describes the challenges for mineral resource estimation for an unconventional style of mineralisation using unconventional sampling techniques.

This paper contains a number of terms, denominations and calculation methods that are specific to this type of deposit (Table 1).

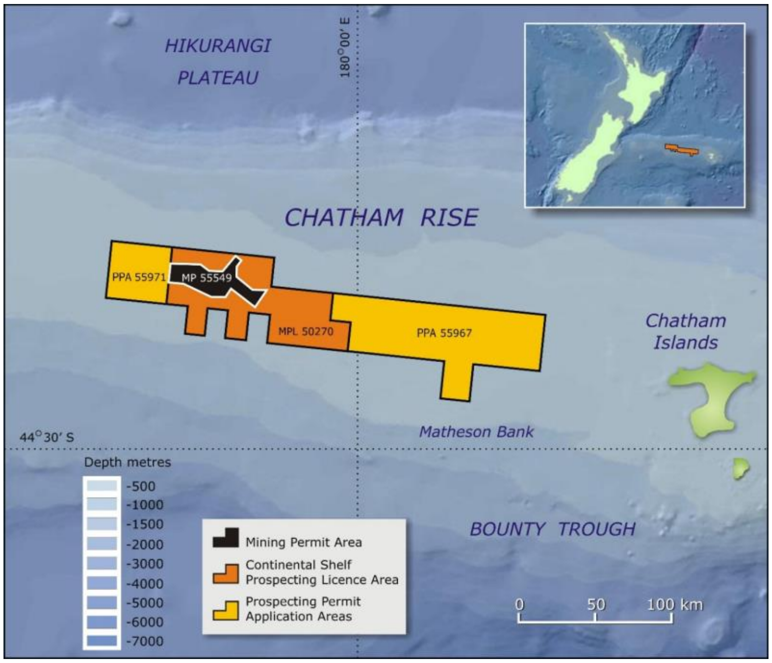

Figure 1. Chatham Rise Phosphorite Project location.

The deposit has been assessed, both at present and in the past, using measurements and estimations of the weight of phosphorite nodules relative to sample volumes collected from the sea floor. These measurements have either been expressed as phosphorite grade, expressed as weight per volume (kg/m^3), or as phosphorite coverage expressed as weight per area (kg/m^2).

Table 1. Phosphate mineral nomenclature use in the paper.

Definition	Grade	Description
P	%	The element phosphorus. It is a non-metallic chemical element and occurs in phosphate minerals in phosphate rocks.
P_2O_5	%	Phosphorus pentoxide (chemical compound).
Phosphorite		Synonym: "rock phosphate". A non-detrital sedimentary rock or nodules which contain high amounts of phosphate-bearing minerals.
Rock phosphate		A general term that refers to a rock with high concentrations of phosphate minerals.
Phosphorite minerals		The phosphate class of minerals is a large and diverse group; however, only a few species are relatively common.
Phosphorite grade	Ph kg/m^3	The weight of phosphorite nodules per cubic metre.
Phosphorite coverage	Ph kg/m^2	The weight of phosphorite nodules per square metre of sea floor.
Penetration depth	m	The thickness of the mineralised sediment component in a sampling bucket.
True depth	m	The true depth of the mineralised sediment.

The determination of this grade and coverage is carried out using conventional methods (weighing and simple measurements of volume) and does not involve a chemical analysis in a laboratory to determine P_2O_5 content. Therefore, typical industry sample quality control measures such as inserting certified reference materials (i.e. "standards" and "blanks") do not apply.

Geology

The Chatham Rise phosphorite is comprised of phosphorite nodules that are loosely distributed within a layer of Neogene-age glauconitic sand commonly about 20 cm thick but locally over 1 m thick (Fig. 2). This sand is a pelagic lag deposit comprised of 20% to 40% silt and 30% to 60% fine to very fine-grained sand. Thickness of the glauconitic sand varies over distances of tens of metres or less. The concentration of phosphorite nodules varies both vertically and laterally.

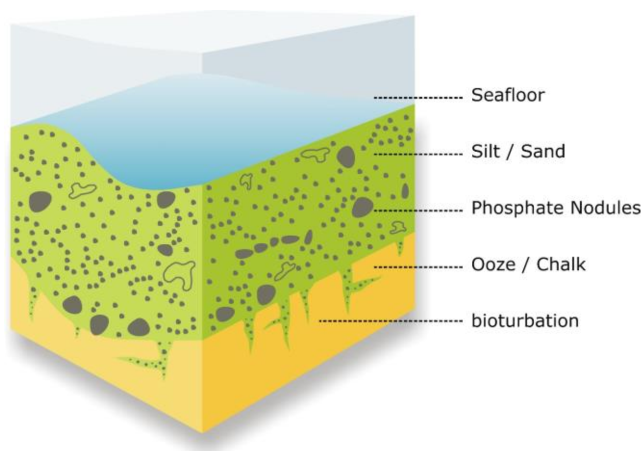

Figure 2. Schematic cross-section of phosphorite-bearing sand zone (adapted from CRP (2012)).

Kudrass and von Rad (1984) suggested two possible modes of phosphatisation resulting from diagenetic processes.

1) Replacement of CaO in pore water of org anic-rich anoxic sediments, with phosphorus released through bacterial activity (Fig. 3). This process is common on the upper continental slopes and outer shelf areas with upwelling nutrient rich water.
2) Replacement of CaO by direct uptake of phosphorus dissolved in seawater (Fig. 3). Absorption of phosphorite onto organic coating of the chalk may enhance this process. The process seems to be limited to areas with phosphorus-rich seawater, but recent examples have not been found.

Kudrass and von Rad (1984) suggest phosphatisation during burial is the most likely option, but that further studies were required (Fig. 4).

Phosphatisation was followed by glauconitisation and silicification of the nodules. Sand and mineral-filled fractures and borings on the surface of nodules were subsequently cemented by later stage diagenetic processes (Fig. 3).

The present composition of the phosphorite nodules originated during the late Miocene by diagenetic replacement of the chalk pebbles (Fig. 3; Kudrass and von Rad (1984)). Apatite based cement replaced pre-existing glauconite suggesting that the main Late Miocene phosphatisation event was followed by minor authigenic phosphatisation which mainly cemented fractures and bore holes (Kudrass and von Rad, 1984).

Later modification by icebergs resulted in the reworking of phosphorite material to create a highly irregular distribution. It is possible that the gouging icebergs removed the phosphorite in the furrows and created higher grade phosphorite accumulations along parallel ridges beside the furrows (Fig. 3).

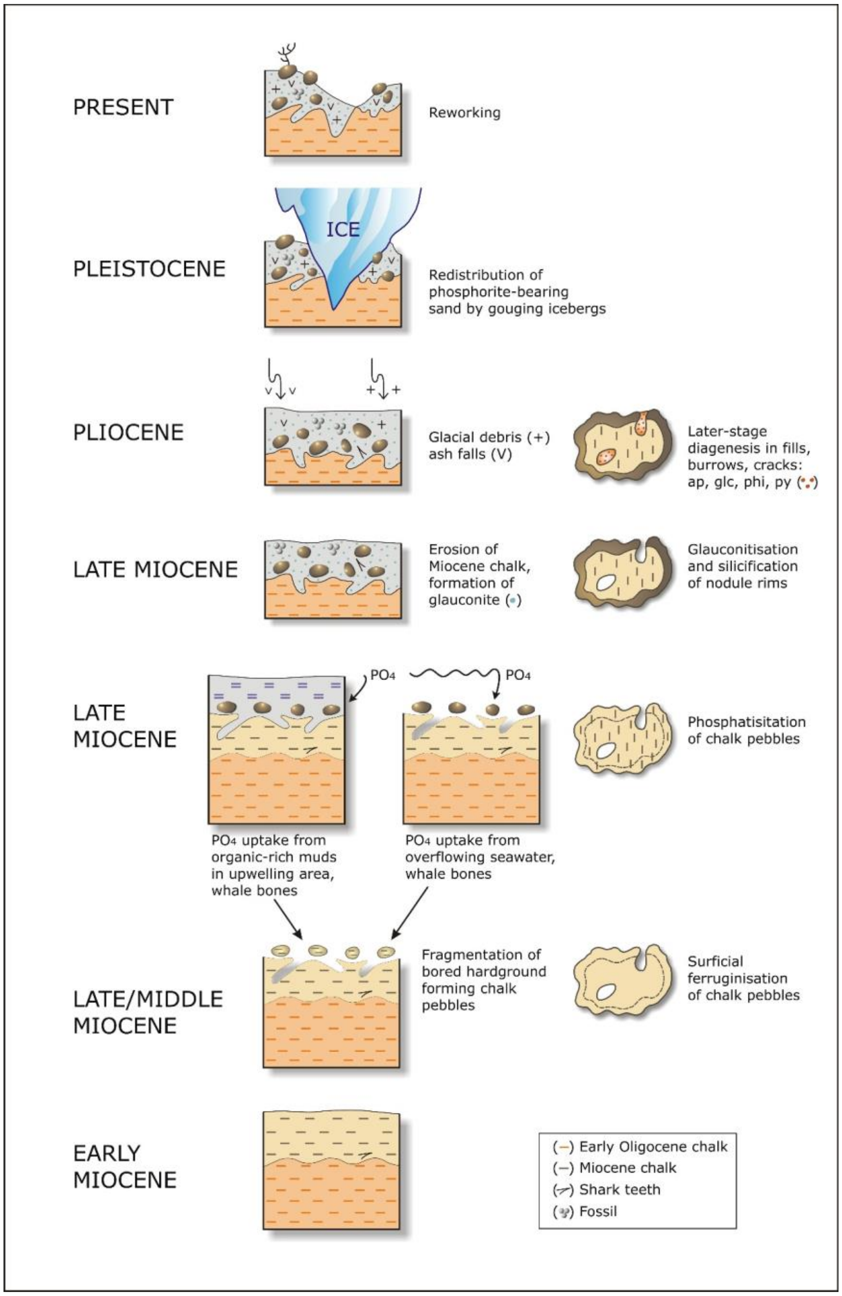

Figure 3. Evolution of the Chatham Rise phosphorite deposit and associated sediment with alternative models for the phosphatisation process (adapted from Kudrass and von Rad (1984)).

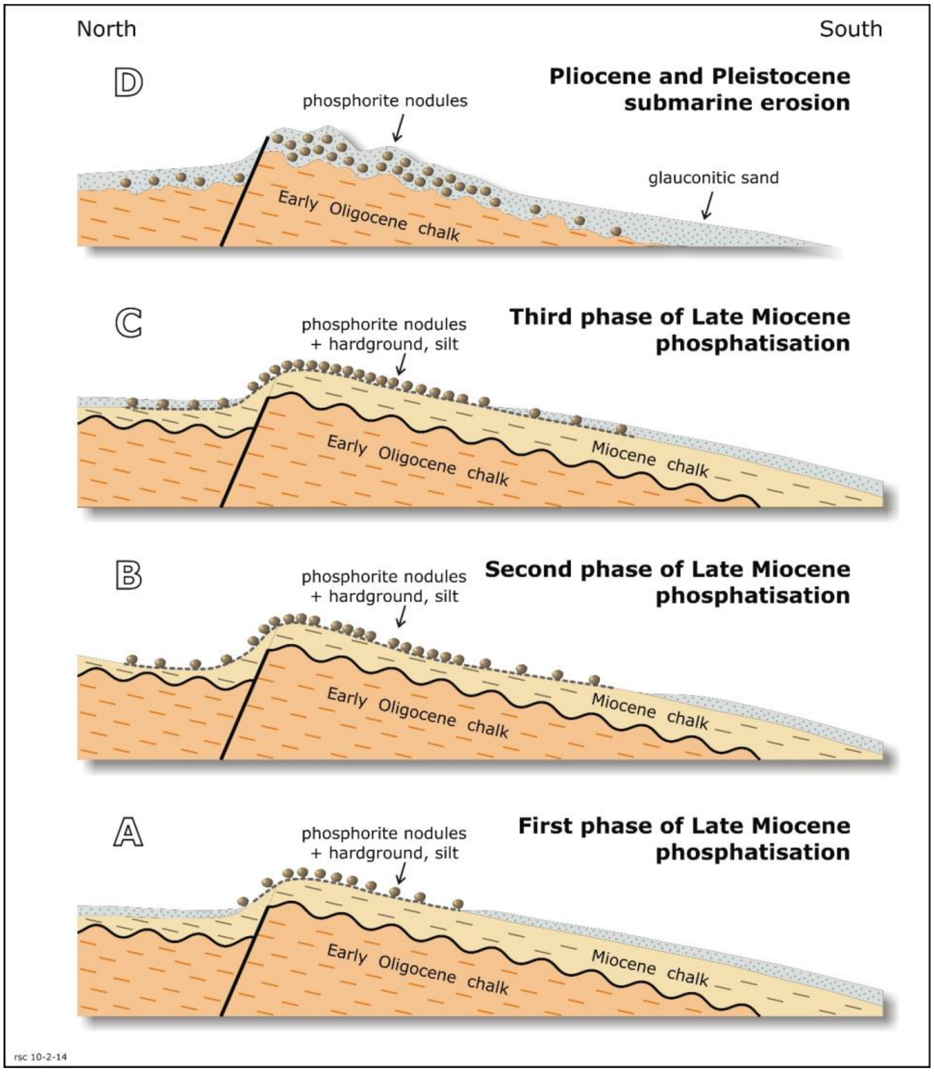

Figure 4. Schematic illustration of probable morphological control of phosphatisation with repeated cycles of partial burial, phosphatisation, erosion, and hard ground formation (adapted from (Kudrass and von Rad (1984)).

Analyses by x-ray diffraction show that apatite and calcite are the main mineral constituents. Analyses on separated Sonne samples show apatite contains P_2O_5 up to 30.05% (Johnston, 2013). The apatite mineral is assumed to be francolite (carbonate-fluorite-apatite) (McClellan and Gremillion, 1980). The assays and geochemistry discussed here are not necessarily representative for the Mineral Resource and further work is required to establish more accurate phosphate grades for the Chatham Rise deposit.

Mapping of the seafloor sediment units was undertaken on the R.V. Sonne using a Huntec high-resolution seismic system. The seismic facies are based on seabed morphology, amplitude of bottom reflection, distinct sub-bottom reflectors, and seismic stratigraphy of the sub-bottom geology (Falconer, von Rad and Wood, 1984). There is a wide variety of seismic character even over short (100 m) distances, with boundaries showing both abrupt and subtle changes. Ten facies domains were established.

Exploration

The work conducted on the Chatham Rise has been completed by a mixture of private and government funded organisations. Various programmes have been undertaken since the 1950s and a total of 1787 successful samples were collected by explorers, including CRP itself. An overview is shown in Table 2.

Given the rare nature and poor accessibility of the deposit, standard sampling techniques did not exist. Hence, most of the sampling campaigns were built around a trial-and-error approach and customised sampling tools. Most of these methods also had unique sample positioning techniques as well as sub-sampling and grade determination methods. The various approaches to sampling of the seabed are described below, however, a detailed description of each method and its associated problems is outside the scope of this paper.

Table 2. Overview of sampling at the Chatham Rock deposit

Operator	**Global Marine**	**Tangaroa**	**Valdivia**	**Sonne**	**Tranquil Image**	**Dorado Discovery**
Year	1967	1976	1978	1981-1982	2011	2012
Sample Type						
Pipe Dredge	334	0	0	0	0	0
Chain Bag Dredge	0	0	0	2	0	0
Box Core	0	25	0	8	0	117
Box Grab	0	0	8	0	0	0
Clamshell Grab	0	0	0	0	0	50
Large Grab	0	0	527	0	0	0
Van Veen Grab	0	0	109	0	45	0
Pneumatic Grab	0	0	0	517	0	0
Gravity Core	0	4	0	0	0	0
Piston Core	0	21	3	3	0	0
Vibrocore	0	0	0	0	0	14
TOTAL	334	50	647	530	45	181

To estimate a Mineral Resource to an appropriate degree of quality therefore required an in-depth analysis of each sampling technique with a matrix-based assessment and comparison of each method. Each sample was scrutinised and given a quality ranking ("SQR") based on a variety of factors. Below follows a summarised description of the sampling techniques deployed on each campaign.

Moray Rose and M.V. Taranui (1967-1968) sampling was conducted using a custom built pipe dredge with a diameter of 45 cm. Upon reaching a sampling station, the ship’s engines were stopped and the pipe dredge lowered to the bottom at a moderate rate to prevent fouling of the 1.27

cm (1/2 inch) gauge wire line. The pipe dredge was then towed behind the slow moving vessel in the case of the *M.V. Moray Rose*, and dragged behind the drifting vessel in the case of the *M.V. Taranui*. Once on board the pipe was upended and its contents dumped on the deck of the ship. A subsample was taken (the method of subsampling is not recorded) and the remainder of the material was washed overboard using a fire hose (Global Marine Inc., 1968).

Between 1975 and 1978, the R.V. Tangaroa collected cores from 53 stations, comprising 21 piston cores, 4 gravity cores and 28 box cores. Piston core were collected initially using a 5.5 m long, 76 mm diameter barrel, with 340 kg of lead weights, then a 1.8 m barrel with 681 kg of lead weight in an attempt to better penetrate phosphorite-bearing sediments. Penetration depth of the piston cores ranged from 0.32 to 4.67 m.

The gravity corer, with a 0.6 m long barrel and internal diameter of 76 mm, was weighted with 91 kg of lead but never exceeded 0.25 m penetration depth. Box cores were collected using a Friedrech Leutert designed corer with internal dimensions of 0.225 m (width) x 0.295 m (length) x 0.47 m (height) and effective height of 0.3 m. Maximum penetration obtained was 0.22 m and reported phosphorite weight percent data from the box cores ranges from 0.9% to 69.9%, with an average of 19.6% (Cullen, 1978).

The majority of the Valdivia (1978) samples were collected using a large Van Veen-style grab of 0.12 m^3 volume, weighing approximately 400 kg, and having a sampling area of approximately 66 cm x 66 cm (Figure 5). Other methods of collecting sediment samples were trialled, including: a smaller Van Veen grab with a sampling area of approximately 45 cm x 45 cm, a box grab sampler, a 3 m piston corer equipped with a pilot corer, a box core sampler and chain bag dredge. The main issues with these methods were poor sample penetration and sample recovery. The large Van Veen-style grab had its shortcomings, including lower penetration power into nodule-rich sediment and insufficient jaw closing power resulting in large nodules occasionally getting caught between the jaws, preventing complete closure of the grab and causing sediment loss. However, despite these shortcomings, it was regarded as the best of the sampling systems available on the market at the time (Kudrass, 2014), and was utilised up until it was lost overboard.

Figure 5. Large grab sampler (left) and smaller Van Veen grab sampler (right) used to collect sediment samples aboard the *R.V. Valdivia.*

Sampling using both the large Van Veen-style grab and smaller Van Veen grab sampler involved lowering it to the sea floor and on contact with the sediment, the slackening of the cable disengaged the mechanism holding the grab jaws open. Recalling the cable would raise the outer arms of the jaws, pulling them closed before retrieving the grab to the ship. This process relies on the weight of the grab both to penetrate the sediment and to force the jaws to close. Weights were added to the grab during the programme to improve penetration of the sand. Flaps at the top of the large grab prevented the development of a bow wave as the grab was lowered and protected the sample from being washed out as it was retrieved.

Most of the *R.V. Sonne* samples (1981) were collected using a 0.8 m^3, 1.8 tonnes pneumatic grab sampler which was specifically designed for the *R.V. Sonne* cruise. The heavy weight of the grab allowed the grab to penetrate deeper into the nodule-bearing sands than grabs used on previous surveys. The coarse nature of the phosphorite deposits means that lighter grabs have difficultly penetrating past the larger nodules and consequently have reduced sample penetration and recovery; the weight and additional pneumatic closing power of 1.5 tonnes of the *R.V. Sonne* grab meant that many samples were able to be collected over the full depth of the phosphorite-bearing sand horizon and into the top of the chalk unit. However, the data show that even the pneumatic grab experienced a reduction in penetration depth where the percentage of phosphorite nodules in the sediment exceeded 30%, though this affect was less pronounced than the with the *R.V. Valdivia* grab (Von Rad, 1984). The closing power of the *R.V. Sonne* grab did eliminate the problem of having large nodules wedging the jaws of the grab open and causing sediment loss, as had been previously encountered with the *R.V. Valdivia* grab samples.

Once the pneumatic grab was closed the sample was fully enclosed and not exposed to water movement as it was retrieved from the sea floor and onto the deck of the boat. Sediment loss at the retrieval stage is not considered to be a significant issue and consequently recovery in the grab is generally considered to be 100%, except where the bucket was observed to be completely full of sediment. In these instances it is possible the bucket penetrated the sediment to a depth of up to 70 cm, but due to its volume capacity of 0.8 m^3 it could not have collected all sediment contained within its sampling area beyond a depth of 38 cm as the volume of in situ sediment exceeds the volume of the bucket. Consequently it is inferred that all full bucket samples have an unknown sediment recovery of <100%. In addition, Kudrass (1984) notes that with increasing penetration depth the grab's own closing force caused it to lift by up to 30 cm during closure. For these reasons it is impossible to determine true penetration depth and sample recovery for full grab samples.

The Van Veen grab sampler used for the Tranquil Image programme (2011) was small and had a surface area of 0.25 m^2. The range of total sample weights varied from 2 to 40 kg. Due to the Van Veen grab's limited weight and non-powered jaws it had a maximum sample depth of 30 cm. As with the *R.V. Valdivia* the grab also had issues with stones and nodules being caught in the jaws and allowing sample loss. Sample volumes have not been evaluated as penetration depths for the samples were not recorded. The shallow depth of the sample penetration and lack of chalk or ooze in samples indicate that the Van Veen grab has generally failed to test the full thickness of the glauconitic sand layer.

Seafloor sampling on the Dorado programme (2011-2012) was conducted using the large clamshell grab and box corer. Despite its size and weight, the large clamshell grab sampler had poor penetration power, especially in nodule-rich sediment. It was lowered to the sea floor and closed by recalling the cable, causing the hinge of the bucket to rise and the jaws to close under their own weight (Figure 6).

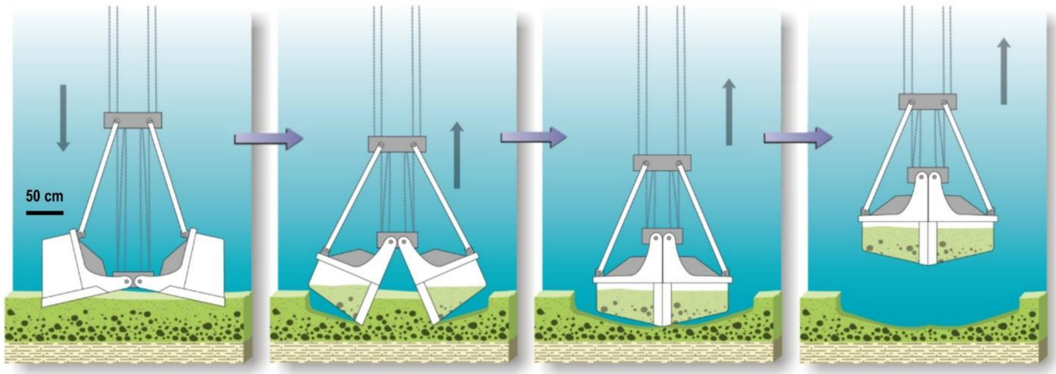

Figure 6. *Dorado Discovery* clamshell grab sampling process.

The grab was an "ex-junk yard" grab and not specifically designed for undersea sampling. In addition to poor penetration power relative to its size, the main drawback of the clamshell grab as a sampling tool is that it was not enclosed, resulting in washing of the contained sediment when the grab was retrieved, particularly at the sea surface where it was exposed to wave action. Most samples were noted as having some degree of washing, and this was more pronounced when the grab contained smaller volume samples (Nielsen, 2014). How much material was lost to washing is unknown. In addition, geometry of the grab, 2.03 x 1.42 m when open and approximately 1.4 x 1.42 m when closed, indicate that the sampled sediment in the clamshell grab undergoes compression as the bucket closes (in a similar way to the sediment in the *R.V. Sonne* grab, which has implications for the determination of true sample depth of the grab samples.

A general overview and comparison of sampling footprints is shown in Figure 7.

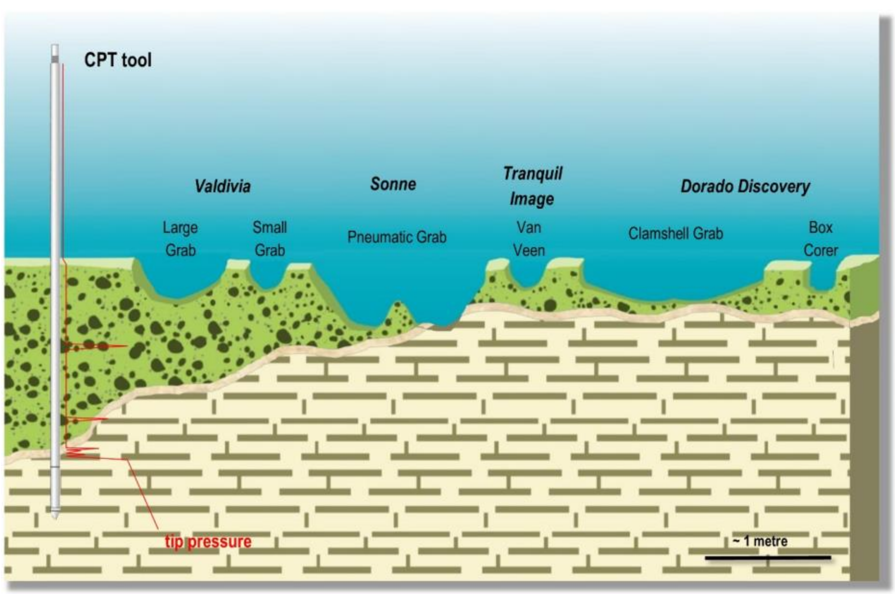

Figure 7. Schematic sand and chalk profile showing potential tonnages below the grade sampled depth.

Results

Data Validation

As part of the data verification process, the relative and absolute quality of the data was assessed in as much detail as practically possible. This is a critical part of the assessment of the data as it depicts what the quality threshold is to either allow or disallow data to enter into the estimation process. Quality assurance and quality control measures varied significantly between the various campaigns. Across and even within the various sampling campaigns, different sampling, sub-sampling, logging, volume and depth measurements, grade calculations, and location measurements have occurred and a matrix was constructed to rank the impact of all these factors (

Table **3**).

All original log sheets were checked in detail, re-digitised and grades were recalculated using the original data only. Volumes were re-calculated by modelling the sampling buckets in 3D and determining best-fit fill-volume curves. Only data with an SQR of 1-4 were determined to be of high enough quality to be included in the resource estimation process.

Resource Estimation

Estimation was performed using 2D accumulation Ordinary Kriging ("OK") on the parameters Ph kg/m^2 (i.e. grade x thickness), Depth and SQR. Two-dimensional accumulation estimation is considered appropriate because there is no correlation between thickness and grade, and variability in the vertical direction is disregarded as selective mining is not possible.

Each of the ten geological facies domains was estimated in isolation, i.e. neighbouring data from other seismic facies domains were excluded from the estimation process. Each block therefore ended up with an estimated value for Ph kg/m^2, Depth and SQR. The grade (Ph kg/m^3) was then calculated by dividing Ph kg/m^2 by the estimated Depth for each block.

Investigation of cumulative frequency, histograms, and mean/variance vs. top-cut plots indicated that top-cutting was warranted for the distribution in domain 9. A grade cap of 150 kg/m^2 was chosen which caps two outlier samples to this value and lowers the mean of the domain from 35 to 32 Ph kg/m^2. The depth was not capped as it was limited to the depth of the sampling tool used.

Geological knowledge is the best guide to define directions of grade continuity. However, for this analysis they cannot be determined. A simple visual thematic representation of the grades within each of the established geological domains in plan view doesn't indicate any consistent or coherent trends or directions. Two-dimensional directional variography confirms this, showing several short-range directions of increased coherence, mixed within each of the ten domains. This may indicate a lack of high resolution geological control on the mineralisation and that further sub-domaining is required. However, this is not possible at this stage. This result has been taken into account when classifying the Resource.

Table 3. Sample quality ranking.

SQR	CATEGORY DESCRIPTION	NUMBER OF SAMPLES					
		GLOBAL MARINE	TANGAROA	VALDIVA	SONNE	TRANQUIL IMAGE	DORADO DISCOVERY
1	SONNE only; ATNAV, grab samples, chalk present (sampled full profile); not full bucket (assume ~100% recovery)				221		
2	SONNE: grab sample, ATNAV, no chalk (not sampled full profile); not full bucket (assume ~100% recovery) VALDIVIA: large grab sample, ATNAV, <5% difference in volume from modelled, not subsampled for sieving			37	50		
3	SONNE: grab sample, ATNAV, full bucket (possible sediment loss/sampling bias) or minor data inconsistencies VALDIVIA: large grab sample, <10% difference in volume from modelled, not subsampled for sieving; OR small grab sample, ATNAV, <5% difference in volume from modelled, not subsampled for sieving			67	119		
4	SONNE: grab sample, SATNAV, chalk present or absent, partial or full bucket VALDIVIA: large or small grab sample, ATNAV or SATNAV, <15% difference in volume from modelled, subsampled for sieving or not			102	115		
5	SONNE: grab sample, SATNAV, data inconsistencies VALDIVIA: large or small grab or box core sample, ATNAV or SATNAV, >15% but <40% difference in volume from modelled DORADO DISCOVERY: box core sample, GPS, average PH% factored fraction weight			278	2		21
6	SONNE: any kind of sample, washed out sample, ATNAV or SATNAV VALDIVIA: large or small grab sample, washed out sample or >40% difference in volume from modelled, ATNAV or SATNAV TRANQUIL IMAGE: grab sample, PH% > 2mm fraction recorded DORADO DISCOVERY: box core sample, visually estimated PH% only; OR grab sample GLOBAL MARINE: dredge sample, non-validated data, estimated PH% TANGAROA: box core sample, non-validated data measured PH weight % or visually estimated PH%	337	26	136	4	45	129
7	ALL: successful samples with non-usable data (no PH% recorded, no location data); OR samples that failed due to technical failure	0	27	69	38	10	56
TOTAL SAMPLES:		**337**	**53**	**689**	**549**	**55**	**206**

For this reason, a circular search was adopted on each domain. An omni-directional normal scores variogram was constructed on facies domains 4 and 9 as well as the entire data set, and capped at a SQR of 4, to investigate the nugget effect and the variogram ranges as input parameters for the 2D OK estimation process. Nested spherical structures were used in normal score transform to deal with the skewed dataset. Data was declustered and top-cut before processing for smoother results.

A block model was constructed that covers the main sampled area. A block size of 1 km x 1 km x 1 m was chosen, based on the average data spacing in the main sample areas, hereby attempting to maintain a balance between the sparsely sampled and densely sampled areas. The more densely sampled areas may statistically require a smaller block size for optimum estimation parameters but the 1 km^2 was considered applicable given the proposed mining method. The model was brought into two dimensions (only one block in the z-direction) and all the samples given an elevation of 0.5 m RL.

The block model was checked for representativeness by comparing the raw data with the block data for each domain. This showed several instances in a densely sampled area, a zero-grade sample surrounded by several high grade samples. This high local variability is also clear from the variogram and has been included into the blocks by the estimation process.

A trend analysis in east direction plot (Figure 8) shows that the resource blocks represent the sample grades well. Only for the section between 70,4000E and 71,4000E do the samples show a higher average grade than the blocks but this area is poorly informed (low number of samples).

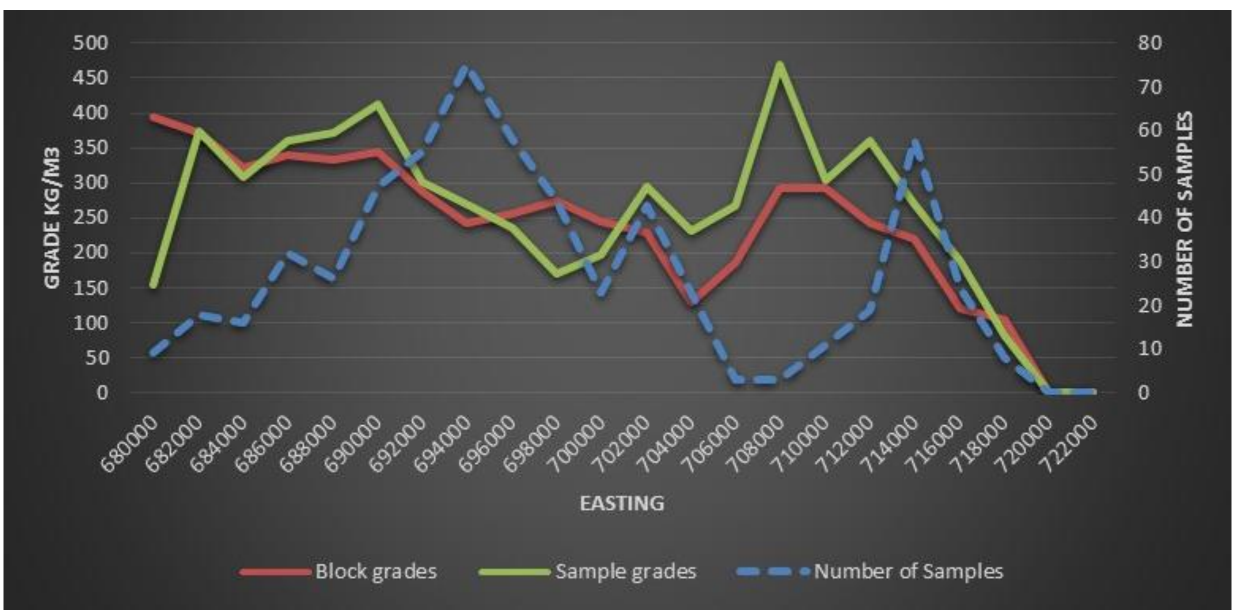

Figure 8. Trend analysis showing validation of block grades versus the input samples from west to east (left to right)

Given that no similar deposits exist that are currently in production and from which economic parameters can be derived to evaluate the deposit, CRP has carried out extensive work to assess mining, market and environmental concepts. These concepts are important to determine whether the deposit is "potentially economically extractable".

After considerations for potential economic extraction, RSC reported a Mineral Resource of 80,000,000 m^3 at an average grade of 290 kg/m^3 within Mining Permit 55549. The Mineral Resource was classified as an Inferred Mineral Resource at a cut-off grade of 100 kg/m^3 for a total contained 23.4 Mt of phosphorite (Table 4). There are no resources classified in Indicated or Measured categories.

Table 4. Statement of Mineral Resources (Phosphorite) for Mining Permit 55549, Chatham Rise. Estimates are rounded to reflect the level of confidence in these resources at the present time.

Classification	Volume	Thickness	Phosphorite Grade	Contained Phosphorite
	m^3	**cm**	**kg/m^3**	**Mt**
Inferred	80,000,000	20	290	23.4

Notes:
1. *The Mineral Resource is reported in accordance with the JORC Code, 2012 edition*
2. *The Mineral Resource is contained within MP 55549*
3. *All resources have been rounded to the nearest 0.1 million tonnes*
4. *Ph kg/m^3 is the weight of phosphorite per cubic metre*
5. *Contained Ph Mt is contained weight of phosphorite per million tonnes*
6. *Mineral Resource is reported at 100 kg/m^3 cut-off grade*

SUMMARY & CONCLUSIONS

Estimating a Mineral Resource at the Chatham Rock Phosphate project, using mostly historical data requires a good understanding of the geological controls on mineralisation, a thorough assessment of the sampling data, and a study of factors that affect the potential economic extractability (mining, environmental, market research, etc).

The geology and controls on mineralisation have been well documented and researched, and lead to the delineation of ten estimation domains based on varying geological properties for each domain. Geological continuity is well understood.

Most of the sampling campaigns were built on using customised sampling tools. Most of these methods also had unique sample positioning techniques as well as sub-sampling and grade determination methods. Across and even within the various sampling campaigns, different sampling, sub-sampling, logging, volume and depth measurements, grade calculations, and location measurements have occurred and a matrix was constructed to rank the impact of all these factors.

Given the rare nature of the deposit, mining, market and environmental concepts were reviewed in order to assess potential for economic extractability as a prerequisite for classifying a Mineral Resource, showing positive results.

By using a simple 2D accumulation Ordinary Kriging estimation approach, and by using only the best quality data, a Mineral Resource was classified into the Inferred category.

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