Mineral Prospectivity Modelling as a Tool for Resource and Mine Development

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Abstract

Prospectivity models in the last ten years have been predominantly used to establish the distribution of potentially mineralised ground over large areas, generally to guide initial exploration programmes in regional and mine camp settings. This approach can also be applied to the mine scale to guide resource estimation, development of reserves, mine and environmental planning, project development and to extend mine life through discovery of new resources.

The Chatham Rise phosphate deposit is used as an example of where the results from prospectivity mapping can be used to guide mine planning, help with resource optimisation and provide constraints for project development. In this example the prospectivity results were combined with environmental modelling to help with environmental planning and the avoidance of sensitive areas, as well as guide mine planning.

Another example compares a feasibility study to a prospectivity model over the same area. Prospectivity is an indicator of potential mineralisation presence, if not necessarily directly correlated to the actual concentration of resource present. Thus prospectivity mapping can be used to guide resource estimation and steer future efforts of resource definition and upgrading. An effective way this can be done is by using the prospectivity equivalent of the resource lower cut-off value to indicate where mineralisation may potentially be present outside the established regions. Confidence and unique conditions grids can then be used to establish what types of data needs to be gathered and where, to increase the reliability of the result.

Keywords: Prospectivity modelling, weights of evidence, fuzzy logic, Chatham Rise, phosphate.

Introduction

Prospectivity modelling has been used for over two decades to spatially analyse regions for the likelihood of certain areas hosting mineral deposits. A number of prospectivity modelling techniques have been developed, including weights of evidence, fuzzy logic and artificial neural networks (Bonham-Carter, 1994). These have been applied to a wide range of mineral deposit types, from prospect to nationwide scales and in data-rich and data-poor study areas. More recently, prospectivity modelling has expanded into the 3D domain. The outputs of these models are mineral potential maps, which highlight areas containing the same geological attributes as known mineral occurrences. Prospectivity modelling is most often used to decrease exploration risk and focus exploration programmes towards smaller areas and using more efficient methods. As such, its use is often perceived to be limited to regional or permit scales. However, it is possible to use the same approach on mine-scale data, utilising the mineral potential maps as a guide for resource estimation and environmental planning.

The example used in this paper is a phosphorite deposit on the Chatham Rise, an east-west trending structural high in the South Island, New Zealand (Figure 1). Water depth over the central Chatham Rise is generally less than 500 m, compared to 3-4 km depth of the seafloor to the north and south. Basement rocks on the Chatham Rise are Torlesse greywacke and argillite overlain by Cenozoic carbonates and marls, mostly Neogene in age.

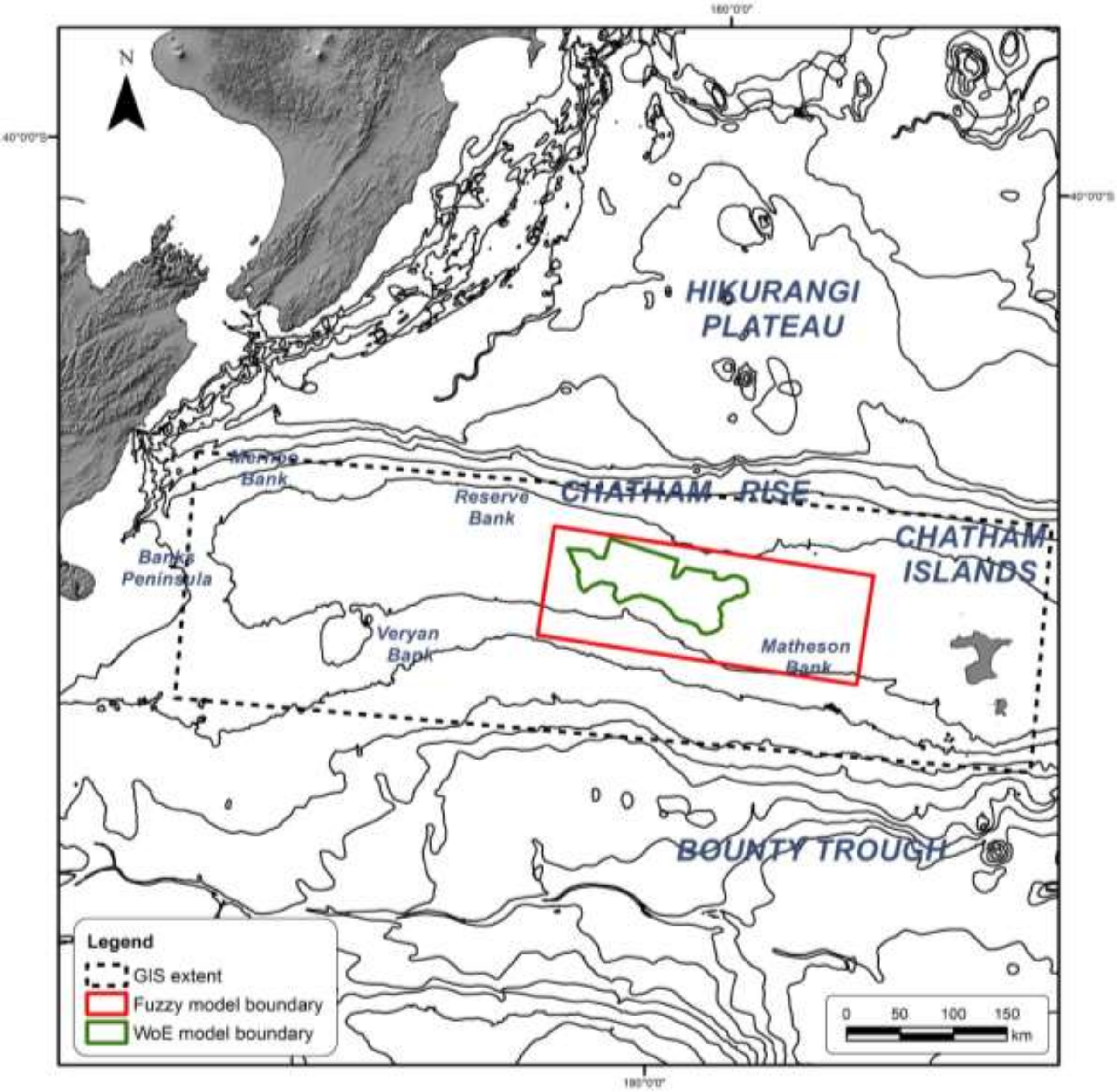

Figure 1. Map of the Chatham Rise, from Nielsen et al (2015).

The central crest hosts a widespread deposit of nodular phosphorite, comprising phosphatised hardground rubble exposed at the sea floor or covered in Pliocene and younger glauconitic silty sand. Phosphate nodules have been known in the area for 60 years after dredging identified the deposit in the 1950s (Reed and Hornibrook 1952). The deposit has since seen episodic yet concentrated exploration efforts in the 1970s and 80s (Pasho, 1976; von Rad and Kudrass, 1984), as well as more recent exploration efforts by Chatham Rise Phosphate Ltd since 2010.

The deposit is attractive for several reasons. It is very low in cadmium, and as New Zealand relies heavily on imported rock phosphate-based fertiliser for farming efficiency, a local source of phosphate could reduce costs and reliance on overseas supply.

Prospectivity modelling of the phosphate deposit on the Chatham Rise relied largely on historical data collected in the 1960s, with additional input of modern multibeam-based bathymetry and grab sampling. Considerable effort was also spent mapping facies of the sea-bed environment using grab sampling and visual inspection using a remotely operated vehicle.

Prospectivity Modelling Versus Resource Modelling

The Chatham Rise deposit is a thin and widespread lag deposit, which makes it unconventional compared to most onshore mines. Still, exploring the Chatham Rise is possible using the usual methodology of establishing the geological setting and building a resource model with the available datasets. In addition, two prospectivity models were built covering the area of greatest historical interest, as well as a larger study area covering the majority of carbonate outcrops on the crest of the Rise.

Mineral prospectivity modelling, or mineral potential mapping, does not provide grade estimates like resource modelling. Rather, the concept predicts where the ground is potentially most prospective based on a number of geological, geochemical and geophysical variables. These variables are tested for correlation with known mineralisation and a subset of those found to have the strongest correlations are combined into a single mineral potential map. Selection of predictive input maps is also influenced by the mineral systems approach (Wyborn et al., 1994), which ensures that variables critical to each stage of the formation of an ore deposit are represented in the model. These processes are the sources of energy and mineralised fluids, transport pathways for fluid migration, structural and chemical trap zones, deposition of minerals and outflow zones for discharge of residual components. If the probability of occurrence of any of the critical processes becomes zero, then no deposit will be present. The scale of prospectivity modelling becomes finer as one moves from source (which can be continental) to the trap environment (which can be deposit scale). Prospectivity modelling study areas can cover prospects, regions or entire countries and, depending on the scale of the model, may identify drilling-scale targets or deposit-scale targets.

A wide variety of resource modelling techniques exists, but all are focused on quantifying the location, grade and continuity of the resource. Being able to do this with confidence optimises productivity and thereby overcomes potential cost barriers associated with mining deposits that operate with small margins. Resource modelling is based on geochemical data, both from surface sampling surveys and drilling programmes, which represents the deposition stage of the mineral systems approach. This data is interpolated into blocks using methods such as inverse distance weighting, nearest neighbourhood statistics or kriging and used in conjunction with the dimensions of the blocks to calculate the total resource and its concentration. Its success depends on a good conceptual understanding of the geology and translation of this into an accurate geological block model. Since interpolation is in essence extrapolation of grades from single sample points into more numerous blocks, the accuracy of resource models also depends on geological continuity or knowledge of the statistical variability. In terms of size, resource estimations are rarely large-scale and extents will cover a single deposit at most.

Chatham Rise Phosphate Model Overview

The Chatham Rise nodular phosphate deposit presents a unique opportunity, with no similar mines existing locally or globally. The Chatham Rise is a structurally simple bathymetric high, elevated compared to the Hikurangi Plateau to the north and the Bounty Trough to the south. It stretches eastwards from the Banks Peninsula as a single structural entity for over

1000 km. The crest of the central Chatham Rise plateaus at 400 m water depth, stepping down to more than 1000 m east of the Chatham Islands (Wood et al., 1989).

In terms of the phosphorite deposit, the basement rocks are early Cenozoic successions of pelagic carbonates overlying indurated greywacke. These carbonates consist of radiolarian ooze and nannofossil foraminiferal chalk, similar to the Amuri limestone of Northern Canterbury. Several hundred metres of Miocene sediment may have been deposited and subsequently eroded, resulting in less than 50 m thickness of Miocene-Pliocene deposits preserved in the study area. This is overlain by a thin veneer of Pleistocene glauconitic-foraminiferal sand containing phosphatised nodules of the eroded Cenozoic limestone (Wood et al., 1989).

Phosphate mineralisation was discovered in 1952 by dredging (Reed and Hornibrook, 1952). In the late 1960s Global Marine Inc. spent several weeks collecting samples on the Chatham Rise (Pasho, 1976), using the results from an initial wide-ranging survey to target a second survey on the area with highest nodule concentrations. Two cruises aboard German vessels, the *Valdivia* in 1978 (Kudrass and Cullen, 1982) and the *Sonne* in 1981 (von Rad and Kudrass, 1984), focussed on the areas previously determined to be most prospective. These sites were revisited in 2011 and 2012 by the *Dorado Discovery*, instigated by Chatham Rock Phosphate Ltd, who provided the most recent sets of data for the models described here.

Data for spatial analysis included bathymetry data, structural interpretations based on seismic surveys, a seismic facies map and sample data from the three main sampling surveys undertaken in the area.

Among the challenges when modelling phosphate prospectivity over the Chatham Rise was to develop input predictive maps that represent the source of the phosphate mineralisation. Many of the predictive maps are derived from highly accurate bathymetric mapping of the seafloor, which can be used to map various features that control mineralisation by using essentially the same variable at a range of scales:

- The source(s) may ultimately be upwelling currents outside the study area, which can be mapped indirectly as regional-scale features carrying nutrient-rich deep-water flows into the mineralised areas.
- Local transport and focussing mechanisms must be active to concentrate the fluids and/or keep the flux of phosphate-rich fluids high, which may be controlled by the presence of subtle variations in slope, terrain offset by faults and the presence of relatively shallow areas with favourable facing slopes.
- Traps appear to have formed according to the availability of carbonate lithology detritus to act as efficient nuclei for mineralisation while phosphatisation occurred.
- The formation and preservation of the phosphate mineralisation is controlled by the lack of younger sedimentary cover, as well as conditions remaining sufficiently calm to prevent removal of nodular, phosphatised gravel.

Other challenges include identifying a suitable training dataset, which conventionally is obtained from mines and prospects with known mineral endowment. Despite extensive exploration, the Chatham Rise contains no mines. Training data was therefore chosen from grab samples of verified quality with high phosphate content.

Prospectivity Modelling Results

The final Weights of Evidence (WoE) model was developed using the Spatial Data Modeller toolbox for ArcGIS 10 (Figure 2) (Sawatzky et al., 2009). Predictive maps selected for their correlation to all aspects of the phosphate mineral systems approach were used to build the model. Important parameters for phosphatisation were found to be deepwater flow paths, the presence of structural highs on large and small scale, water depth and the presence and orientation of slopes.

Following creation of a prospectivity map, targets may be defined by selecting a cut-off value of the probability associated with each grid cell in the model study area. Rather than selecting a relatively high post-probability cut-off for the targeting on the Chatham Rise, the cut-off was set to equal the prior probability value. This maximises the extent of the potential deposit and is sensible given the lag nature of the deposit. As part of the WoE model, maps were also created that display the distribution of model uncertainty and also the influence different model parameters exerted in each grid cell. These maps, in conjunction with the final prospectivity map, are useful tools for resource modelling and mine planning.

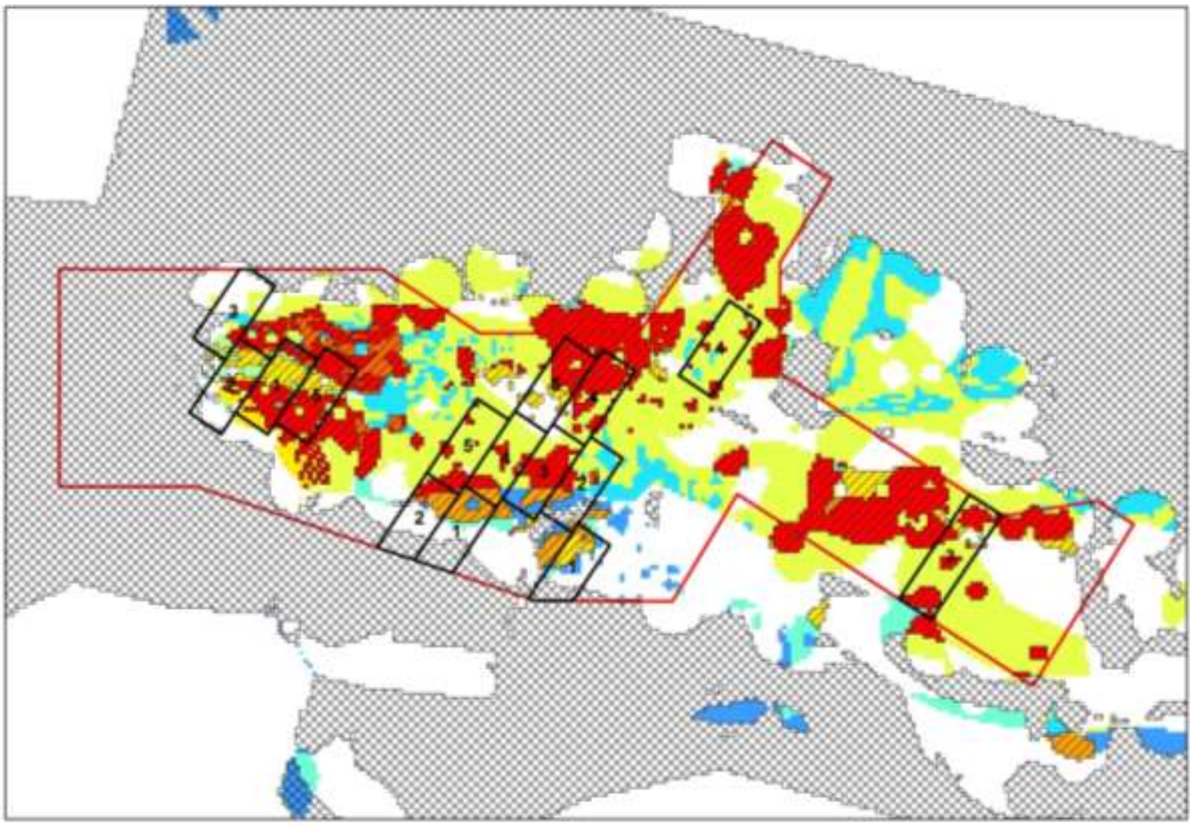

Figure 2. Mineral potential map of the Chatham Rise area, with conceptual mining blocks labelled according to suggested order of activity by year of mining. Warmer colours are higher prospectivity. Cross-hatched areas have low (< 1) data confidence, while diagonally hatched areas have high (> 1.5) data confidence.

Mine Planning

Physical conditions on the seabed heavily influence design of the phosphate mining system (Chatham Rock Phosphate Ltd, 2014), since the drag-head and riser system relies on loosening the surface sediment layers. The mining approach must therefore incorporate environmental factors in the design to ensure (Chatham Rock Phosphate Ltd, 2014):

- Minimised disturbance of the seabed and nodule-bearing sediments during mining.
- Minimised dispersion of fine sediments during return of processed sediments.
- Areas of particular scientific or conservation, identified through a marine spatial planning exercise (Rowden et al., 2014).

The Chatham Rock Phosphate project plans to mine blocks of 5 x 2 km dimensions, leaving a central strip in each block for the repopulation of the bottom-dwelling flora and fauna. The block dimensions are based on optimal efficiency of the proposed mining vessel, while their orientations are based on predominant wind and wave directions recorded over the mining area. The sequence of mining the blocks is chosen based on the predicted distribution of phosphorite and of representative benthic environments. The proposed sequence maximises the ability of the benthos to recolonise as well as maximising economic return in the early stages of the project. Comparing the mine block distribution to the WoE prospectivity model output indicates that the suggested sites generally fall in areas of favourable prospectivity, although there are blocks in years 1-3 that could benefit from additional data to increase confidence and possibly prospectivity (Figure 2).

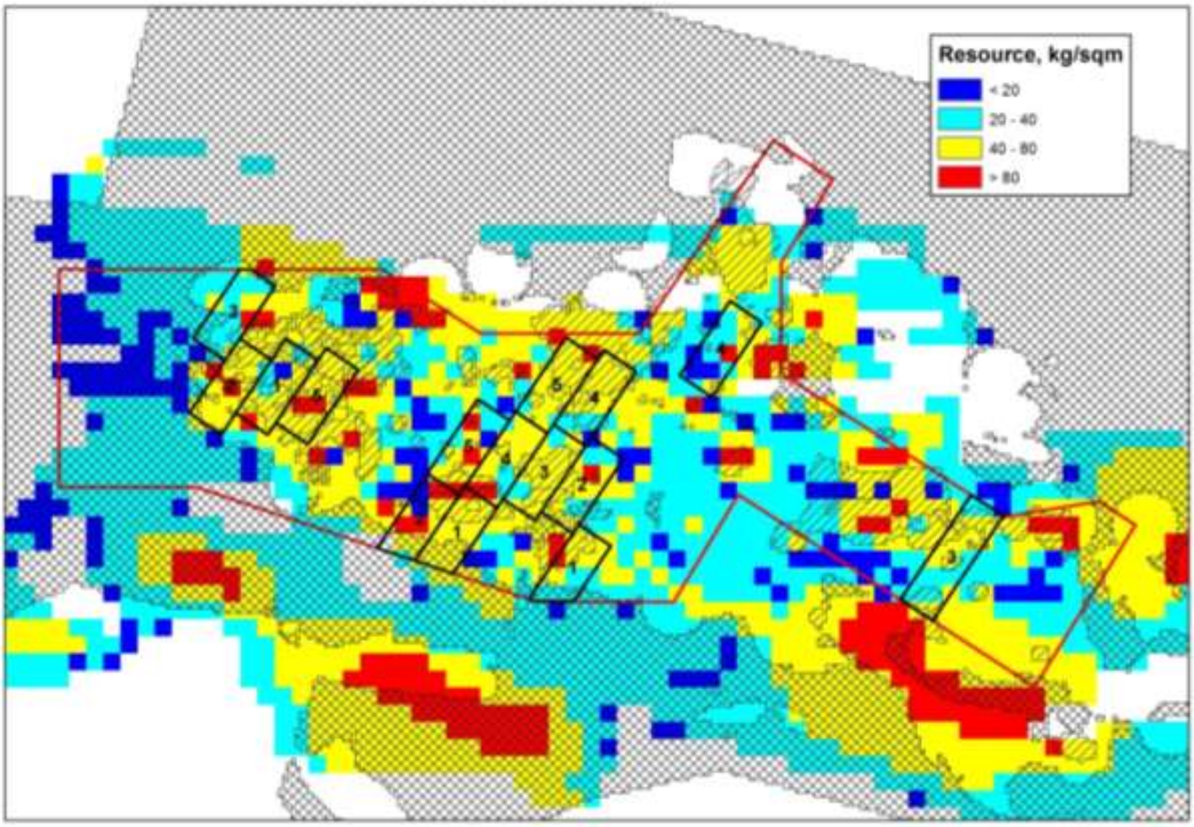

Figure 3. Kenex resource model results compared to prospectivity modelling data confidence values (see Figure 2).

Resource Modelling on the Chatham Rise

Several resource models have been produced for the Chatham Rise phosphate deposit, including one produced by RSC Mining and Mineral Exploration Services (RSC-MME) as an NI43-101 compliant resource estimate in the Mining License Area (Sterk, 2014). Resource estimates are generally completed by interpolating assay values from a number of sample points into a block model. The NI43-101 model data was validated based on quality and levelled based on sampling methodology, but not by geology as there was assumed to be no association with the few and laterally extensive lithological units. However, the high local variability in bathymetry, geology and sample composition was noted.

The resource estimation was limited to areas containing at least two sample points within a 3 km search distance. To compensate for the high local variability in recorded data, the RSC MME resource model may underestimate the resource, as noted by RSC. However, it did enable the resource to be defined outside the relatively heavily sampled central region of the rise. The NI43-101 compliant resource model confirmed results of previous resource models (Kudrass, 1984). Resource models were also produced by Kenex Ltd, using structurally guided domaining and search ellipses, as well as constraining the result with a geological model (Figure 3).

As prospectivity modelling utilises a multitude of data types, areas of high confidence will indicate that further sampling may not significantly improve a resource estimate even if the input data is not the same assay data as was used for the resource estimate. Likewise, areas of low confidence regardless of data type would be areas to focus future resource definition sampling. Areas with prospectivity below prior probability and high data confidence can be excluded from resource models entirely, to avoid smearing grade into areas unlikely to contain mineable grades.

Prospectivity Modelling on the Chatham Rise

Resource Estimation

Prospectivity modelling can be expert-driven (Ranked Overlay and Fuzzy Logic models), data-driven (Weights of Evidence, Logistic Regression) or a combination of the two. The data-driven WoE method has the advantage of being able to handle areas with missing data without classifying them as unprospective and therefore writing them off for future exploration. WoE modelling also produces a number of other outputs in addition to the mineral potential map that add information to the model outcome. The confidence map, the posterior probability of the model divided by the total standard deviation, can be particularly useful.

The confidence is essentially a studentised contrast test. At values above 2, there can be strong confidence in the prospectivity value. At low values (below 1), the user cannot be statistically confident in the result. For the Chatham Rise phosphate deposit, where covered by the WoE model, confidence values > 1.5 coincide with high prospectivity values. This is a result of sampling and surveying being undertaken in areas where phosphate nodules were predicted to exist, which is a perfectly normal (if geostatistically inconvenient) practice that may reduce but not remove the usefulness of the data.

Comparing the prospectivity confidence data with the resource model, it is apparent that south of the mining license area there are several areas where relatively high grades (yellow and red) are not covered with data of high confidence values (Figure 3). Also, areas of low grade are generally not covered with data to satisfy the confidence criteria as well. This is useful to guide resource definition sampling.

Environmental Modelling

In New Zealand, mine planning needs to include an environmental impact assessment as well as a resource assessment. One of the focuses of the most recent survey by CRP was a statistical sampling of the benthic environments by video and bottom sampling.

These newly acquired environmental datasets were the primary inputs to an environmental study by CRP and NIWA (Wood et al., 2012) that used multivariate statistical analyses to identify epifauna and infauna, their characterising organisms, and their spatial distribution. This information was then used to predict the potential extent of suitable habitat for each of these communities.

The environmental study identified two epifaunal and one infaunal community that are closely linked to high-density patches of nodules. The epifaunal communities are patchily distributed in the eastern part of the study region and are dominated by the coral *Goniocorella dumosa*. The infaunal community is mainly found in the west. These distributions were used by CRP to identify areas that could be reserved from mining as part of conditions on a marine environmental consent.

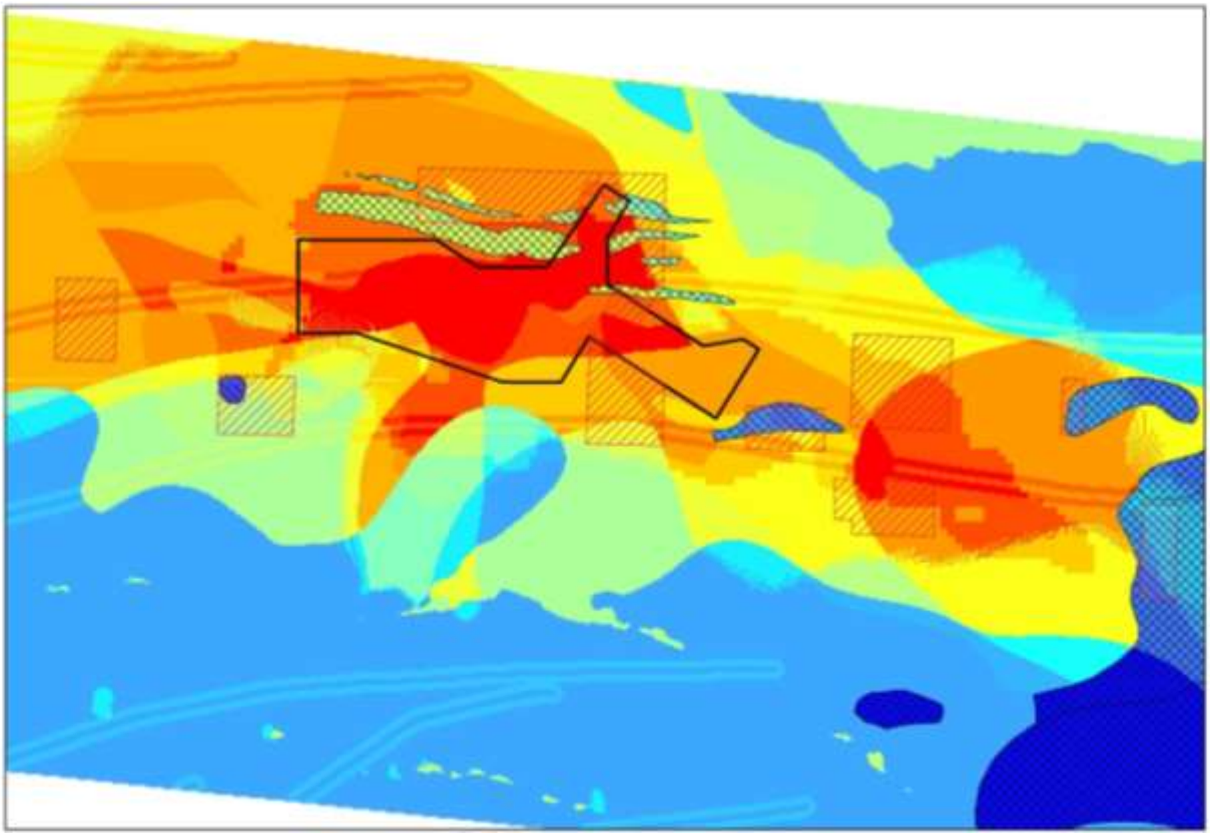

Figure 4. Excerpt of the Fuzzy Logic prospectivity model output (warm colours = favourable prospectivity) versus mine exclusion zones (red hatched areas). Unfavourable geology is cross-hatched in black.

Extending Mine Life

The WoE model was used to determine the input predictive maps to a wide-area fuzzy logic model of the Chatham Rise, with the weights derived from the WoE model steering the rankings given to the fuzzy predictive maps.

The fuzzy logic prospectivity modelling results were used to extend the area of interest for phosphate exploration outside the mining license area. The results of the environmental modelling were included identify not just areas where exploration would have the highest potential for finding phosphate and is least likely to find sensitive habitats. Figure 4 compares the Fuzzy Logic prospectivity output to the selected mine exclusion zones. The areas of greatest prospectivity do not generally coincide with the areas of sensitive habitats, and the mining exclusion areas therefore generally lie in areas of moderate prospectivity.

Conclusions

Two prospectivity models were produced over the Chatham Rise area and their outputs may help guide mine planning and exploration in conjunction with environmental modelling. The prospectivity modelling shows that understanding the geology as well as accurately mapping changes in topography, especially local relief, is important in locating areas with high phosphate potential.

Prospectivity modelling is an on-going process rather than a singular task. It is primarily a way to organise and analyse data, as continued acquisition of new data during mine development will be used to update the prospectivity model and guide future exploration, resource definition and mine planning.

Prospectivity modelling can support exploration planning by indicating areas of high potential as well as areas where additional data can increase confidence in the prospectivity result. The type of data missing from areas of low confidence can also be identified from the modelling through use of unique conditions tools.

Prospectivity modelling can support resource estimation by indicating where additional sampling could have the most impact on the resource model, and by supplying areas of low prospectivity and high data confidence that can be excluded from the estimate to avoid grade smearing into unfavourable ground.

Combining mineral prospectivity modelling with environmental modelling is a powerful way of guiding future exploration and mine planning to optimise exploration value and minimise environmental impacts.

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