Chatham Rise nodular phosphate — Modelling the prospectivity of a lag deposit (off-shore New Zealand): A critical tool for use in resource development and deep sea mining

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A B S T R A C T

After almost five decades of episodic exploration, feasibility studies are now being completed to mine the deep-water nodular phosphate deposit on the central Chatham Rise. Weights of evidence (WofE) and fuzzy logic prospectivity models have been used in these studies to help in mapping the exploration and resource potential, to constrain resource estimation, to aid with geotechnical engineering and mine planning studies and to provide background geological data for the environmental consent process. Prospectivity modelling was carried out in two stages using weights of evidence and fuzzy logic techniques. A WofE prospectivity model covering the area of best data coverage was initially developed to define the geological and environmental variables that control the distribution of phosphate on the Chatham Rise and map areas where mineralised nodules are most likely to be present. The post-probability results from this model, in conjunction with unique conditions and confidence maps, were used to guide environmental modelling for setting aside protected zones, and also to assist with mine planning and future exploration planning. A regional scale fuzzy logic model was developed guided by the results of the spatial analysis of the WofE model, elucidating where future exploration should be targeted to give the best chance of success in expanding the known resource. The development work to date on the Chatham Rise for nodular phosphate mineralisation is an innovative example of how spatial data modelling techniques can be used not only at the exploration stage, but also to constrain resource estimation and aid with environmental studies, thereby greatly reducing development costs, improving the economics of mine planning and reducing the environmental impact of the project.

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1. Introduction

The New Zealand agricultural sector relies heavily on imported rock phosphate-based fertilizer for farming efficiency, resulting in an opportunity for the production of locally based sources of phosphate. Sources of rock phosphate in the SW Pacific region have been depleted over the last 60 years, leading to rising imports of phosphate from further afield and adding to the urgency of exploring the potential of local sources (Cullen, 1979; Von Rad, 1984).

The only known phosphate mineralisation with economic potential in New Zealand is a limestone gravel lag-based nodular phosphate deposit that is located in open waters at a depth of up to 400 m, more than 400 km offshore off the east coast of the Canterbury region of the South Island (Fig. 1). The phosphate deposit is located on the crest of the Chatham Rise, a structurally simple bathymetric high rising over the Hikurangi Plateau to the north and the Bounty Trough to the south. It has been described as a replacement deposit comprising a mix of Late Oligocene and Late Miocene chalk pebbles and hardground rubble phosphatised in the Late Miocene and subsequently concentrated by erosion and selective removal of non-indurated chalk as the crest of the Rise was karstified (Cullen, 1987; Kudrass and von Rad, 1984).

The Chatham Rise stretches due east from the Banks Peninsula as a single structural entity for over 1000 km. The crest of the central Rise plateaus at 400 m water depth, stepping down to more than 1000 m east of the Chatham Islands (Wood et al., 1989). The slope to the north to the Hikurangi Plateau and Trough has a relatively constant gradient, while the southern slope to the Bounty Trough appears as a series of steps into what may be the failed rift arm of the Bounty Trough (Fig. 1).

The Chatham Rise phosphate deposit has been subject to episodic exploration since its discovery in the 1950s (Reed and Hornibrook, 1952). In the late 1960s Global Marine Inc. spent several weeks dredging 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. The bulk of the exploration took place in the late...
1970s and early 1980s by collaborating German and New Zealand scientists onboard the research vessels Valdivia (Kudrass and Cullen, 1982) and Sonne (von Rad and Kudrass, 1984). The surveys focussed on the areas previously determined to be the most prospective.

Renewed interest by Chatham Rock Phosphate Ltd. in the 2010s led to a series of surveys in 2011/2012, revisiting the areas surveyed by the Valdivia and the Sonne. Subsequently, prospectivity and resource studies based on new and historical data were undertaken. A 20-year seabed mining permit was granted in the late 2013, and feasibility studies are in the final stages of completion. The aim of these studies is to integrate geological prospectivity with environmental studies and resource assessment, to effectively develop the resource with minimal environmental impact, as well as plan future exploration where it is most likely to increase the current resource and show a positive economic return.

Computer-based geographical information systems (GIS) provide a variety of tools and statistical techniques that allow the mapping of mineral prospectivity to be carried out and combined with environmental and economic risk analysis. Such techniques and tools have been used by the petroleum industry for a number of years, and the mineral exploration industry has taken this further with the help of spatial data modelling using GIS (Bonham-Carter et al., 1989; Carranza, 2014; Deng, 2009; Harris et al., 2001; Lusty et al., 2012; Mejía-Herrera et al., 2014; Partington and Sale, 2004).

A mineral system model adapted for phosphate deposition on the Chatham Rise phosphate has been developed from the mineral system concept normally applied to a range of hydrothermal and magmatic styles of mineralisation (Hronsly and Groves, 2008; Lord et al., 2001; Wyborn et al., 1994). This adapted model has been used to constrain the modelling of the prospectivity of the central Chatham Rise through the development of a range of predictive maps as proxies for the physical and chemical processes that have been combined to form the phosphate mineralisation. While the factors leading to the formation of phosphatised lag gravels are obviously different from those leading to many metallogenic ore deposits, the components of the mineral system model are similar: There need to be a source of phosphate, a means to transport it to the site of deposition, a trap to allow the phosphate rich fluids to replace chalk pebbles and hardground rubble, and means to concentrate and preserve the deposit.

The mineral system approach used with spatial data modelling differs from conventional ore deposit models by focussing on the similarities rather than on differences between deposit-types. Since the mineral system approach is process based, it is not restricted to particular settings or mineral type, and has here been adapted to a mixed sedimentary and chemical process system. When applied to mineral deposits, the mineral system approach requires identification at various scales of the critical deposit-forming processes that can be mapped and that are

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characteristic of the mineral system in question. The predictive maps developed for the central Chatham Rise area represent aspects of possible source, transport, trap, and phosphate deposition. Developing mineral system concept for a nodular phosphate deposit poses challenges, as unlike most metallogenic deposits, the deposit in question here is surficial and laterally extensive, and may be formed by processes that are not easily recognised or mapped.

The Chatham Rise nodular phosphate deposit is a unique mining opportunity, with no similar deposits known locally. Globally, similar deposits are rare but examples can be found onshore in the Gingin Chalk of Western Australia (Simpson, 1920) and offshore Baja California (D’Anglejan, 1967). While historical data are available open-file from the New Zealand Petroleum and Minerals (NZPAM) database, as well as from the National Institute for Water and Atmosphere (NIWA) and the Institute of Geological & Nuclear Sciences Ltd (GNS Science), surveying on the Rise has been done episodically and without connection or consistency between the exploration programmes. Therefore, the first task and the most time consuming one was to build a digital database of all available geological, geochemical and geophysical data. Also, as the New Zealand outer continental shelf regions are generally underexplored, data are sparse. The resulting GIS covers more than 30,000 km² of the Chatham Rise crest region, with the spread of shallow, high-resolution data limiting quantitative estimation of prospectivity to the central region (Fig. 1).

2. Geology of the Chatham Rise

The oldest rocks of the Chatham Rise are indurated greywacke and argillite of the Jurassic–Cretaceous Torlesse Supergroup affinity. These rocks were later rifted into east–west oriented half-grabens generally hinged to the north during the second episode of the Early Cretaceous Rangitata orogeny (Wood et al., 1989). Minor movement has occurred on the same faults during the Cenozoic. Movement along a second set of north–south trending sinistral transcurrent faults appears to give the Rise the appearance of a gentle bend (Fig. 1). After the Rangitata rifting, the first sediments deposited were basin-fill initiated around 100 Ma, where 1000–2500 m or more of sediments were deposited in newly formed half-grabens, with the thickest accumulations in the western region of the Rise (Wood et al., 1989), leading to a relatively complex east–west oriented crest structure which is generally oriented similarly to the modern crest (Fig. 2).

The geology of the study area is summarised in Fig. 3. The early Cenozoic succession is block faulted and down-thrown 10–85 m towards the north (Falconer et al., 1984). Rocks sampled from this time interval generally come from the Matheson Bank region, and include cross-bedded foraminiferal limestone from a shallow (<100 m) water depth. Radiolarian ooze and nanofossil foraminiferal chert has also been recovered from the study area. The chert appears similar to the Amuri limestone of Northern Canterbury, while the late Cenozoic succession is very thin or absent over large parts of the central Rise (Wood et al., 1989). Several hundred metres of Miocene sediment may have been deposited and subsequently eroded as uplift began in the Late Oligocene with the development of the Alpine Fault plate boundary (Field and Browne, 1989), resulting in less than 50 m of Miocene–Pliocene preserved in the study area. The Oligocene chert may have been locally exposed as well (Kudrass and von Rad, 1984). This is overlain by a thin veneer of Pleistocene glauconitic-foraminiferal sand containing phosphatized nodules of the eroded Cenozoic limestone (Wood et al., 1989).

The paleoceanographic setting of the Chatham Rise is mainly described from scientific deep sea drilling reports and based on sediment cores on the deep southern flank south of Mernoo Bank (DSDP Site 594, Kennett et al., 1983) and northern flank north of Matheson Bank (ODP Site 1125, Carter et al., 1999). The Chatham Rise is situated in a transitional region between oceanic and terrigeneous influences (Kennett et al., 1983). It is described as a significant barrier to ocean circulation, with a crest that corresponds with the Subtropical Front, a convergence zone between Subtropical Water flowing around northern New Zealand as the East Cape Current, and Subantarctic Water flowing around southern New Zealand as the Southland Current (Heath, 1976). A slow (0.08 m/s on average) northwards net drift rises from 700 m depth to flow over and across the deeper parts of the saddle (Heath, 1976). A zone of high productivity lies over the Rise following the Subtropical Front (Fig. 1) adding a significant biogenic component to the many sources of sediment to the crest of the Rise, namely (Carter et al., 1999): biopelagic snow from vigorous water mixing along the Subtropical Convergence; suspended terrigeneous sediment supplied by rivers feeding into the East Cape and Southland Currents; distant airfall tephra from central North Island volcanic eruptions; and occasional ice-raftered debris from icebergs.

The position of the Subtropical Front likely remained fixed during glacial/interglacial changes. However, during glacial periods, more
The phosphate nodules display two phases of boring and burrowing activity that riddle the phosphatised limestone of most nodules, while a later phase of boring is reflected in the open tubular cavities that penetrate and define the outline of larger nodules (Cullen, 1987).

3. Mineral system model for phosphate deposition on the Chatham Rise

3.1. Source of phosphate

In the Chatham Rise region, a component of the phosphate along with carbonate may be sourced from sluggish dysoxic deepwater flow in a highly productive, stratified ocean before the establishment of the modern frontal system and ocean circulation system (Fig. 4; Hayward et al., 2004). Such warm conditions with sluggish deep-water flow may have persisted throughout the Eocene and during the Early Miocene (Hayward et al., 2004; Nelson and Cooke, 2001) and allow phosphate to become super saturated in the warm water.

In recent phosphate forming environments there is low sedimentary input and high organic productivity associated with seasonal upwelling of nutrient-rich deepwater (Waples, 1982). Today, upwelling is associated with the Subtropical Front, which is situated over the Chatham Rise and the deflection of the southern Southland Current and the northern East Cape Current towards the east (Fig. 1). The presence of such front leads to increased turbulence and mixing of surface waters leading to increased organic production and higher influx of phosphate-bearing organic matter to the Rise. The past presence of a front is indicated from latitudinal differences in benthic foraminifera assemblages on either side of the Rise from at least early Late Miocene onwards (Hayward et al., 2004), although a proto-front may have been present during the first Antarctic glaciation in the Late Eocene and Early to mid Oligocene (Nelson and Cooke, 2001). Since decreased oxygen levels and increased input of organic matter may be linked to times of vigorous frontal activity on the Rise, it may be that the main phosphatising events are limited to global cooling events and Antarctic glaciations (Nelson and Cooke, 2001).

The source of phosphate may ultimately be upwelling systems that may not easily be mapped as regional-scale features that focus nutrient-carrying deep-water flow into the phosphatised areas. What can be mapped as a proxy instead are regions where the bathymetry allow larger volumes of organic-rich deep water to pass such as regional saddles where slow deepwater flow has been suggested (Heath, 1976).
Such areas are suggested where the width of the crest is reduced (Fig. 1).

3.2. Transport of phosphate from the source to the trap site

If the source of phosphate can be viewed as the deep currents bringing organic matter from upwelling zones at the sea surface to the Chatham Rise, the bottom contour-following currents are believed to be the mechanism for redistributing the organic matter to the trap sites where the phosphate replaces the lag gravel on the Rise. The direction and relative intensity of these currents depend on the grade of slope and the presence of features that may constrict flow such as fault scarps and incisions. While the Rise in general may have been relatively stable since the Late Cretaceous to early Palaeogene rifting ceased (Cook et al., 1989), Oligocene faulting indicated in seismic profiles (Falconer et al., 1984) would have created seabed relief for currents to follow and exposed high ground for hardground formation and phosphatisation (Kudrass and von Rad, 1984). Regional faults are mapped from relatively low-resolution industrial seismic surveys (Wood et al., 1989) showing a general east–west trend of the major lineaments (Fig. 2). A higher resolution fault and lineament set was derived from the 1984 Sonne shallow seismic data (Falconer et al., 1984; Falconer, pers. comm.) and recently acquired high-resolution multibeam bathymetry (Wood, 2012; Wood et al., 2012) (Fig. 2).

In times of sluggish ocean circulation and/or sea level highstands, bottom currents may be weak enough to allow transport and draping of fine sediment on exposed highs. During times of more intense ocean circulation and/or sea-level lowstands, these flows may be strong enough to waft unconsolidated fine sediment away especially from slopes and high ground.

3.3. Formation of trap

The Chatham Rise has been covered by subsequently lithified and eroded Late Eocene, Oligocene and Early Miocene chalks and foraminiferal limestones (Fig. 3), which are the host-rocks for phosphatisation since nodules contain remnants of chalk and foraminifera from the age and environment represented by the chalk deposits (Cullen, 1987; Kudrass and von Rad, 1984). In marine carbonate shelf environments, extensive deposits of nodular phosphate are associated with pauses in sedimentation and consequent hardground formation (Pedley and Bennett, 1985). In addition, oxygen-starved conditions are necessary for phosphate replacement and nodule formation (e.g. Arning et al., 2009). The time-equivalent and laterally extensive Amuri Limestone of Canterbury contains horizons of – and is overlain by – phosphatised nodules (Morris, 1987), suggesting episodes of region-wide dysoxic bottom conditions allowing extensive phosphatisation. The Oxygen Minimum Zone is today situated at about 1000 m depth (Fig. 4; Hayward et al., 2004), indicating that extensive phosphatisation has not been possible on the Chatham Rise since the modern water column structure was established.

The presence of phosphorous rich bottom water and oxygen minimum conditions may pass over an area without a trace in the geological record except for the subsequent presence of phosphate mineralisation. The intervals of phosphate production may be brief, and possibly alternating with periods of sediment bypass and winnowing away the matrix sediment, further concentrating the phosphatised hardground rubble (Pedley and Bennett, 1985).

During the Eocene and Early Miocene times of sluggish, dysoxic deep-water flow, conditions were optimal for deposition of chalcy ooze that would dilute deposited phosphate. Cooling of the surface water and intensification of upwelling at Subtropical Convergence would halt carbonate production leading to sediment starvation and hardground formation at the sea bed. When bottom current intensified, removal and dissolution of soft chalk would concentrate resistant and phosphatised hardground formations. Episodes of intense upwelling at the surface would increase organic matter contribution, leading to pulses of organic matter to the sea bed and widespread replacement of the exposed chalk and hardground by phosphate, and subsequent redistribution and removal by bottom currents. Major periods when this is likely to have happened repeatedly are during times of rapid changes in oceanic climate, such as the Eocene/Oligocene glaciation, the Late Oligocene warming and the late Early Miocene end of the Miocene Warm period (Zachos et al., 2001).

Since phosphate mineralisation straddles the crest and required dysoxic waters to form, the time of formation may be limited to the
time before the modern well stratified water column was established, when sluggish, dysoxic waters were able to flow through saddles on the crest of the Rise (Hayward et al., 2004; Heath, 1976) (Fig. 1). The lower age limit is determined by the earliest deposition of carbonates on the Rise, while oxygenation of shallow and intermediate water masses would not be established until the modern ocean currents came into play in the Late Miocene when Antarctic Intermediate Waters first flooded the Chatham Rise. This sets an upper age limit on the phosphate entrapment on the Crest of the Rise to be no younger than the Late Miocene. Predictive map themes of trap formation should therefore be based on the extent of chalk facies of Eocene to early Late Miocene age.

3.4. Deposition and exposure of phosphate nodules

The physiochemical processes leading to phosphatisation by replacement of hardgrounds depend regionally on the presence of rapid physiochemical changes in conditions to allow phosphate to be deposited, exposed carbonate to be replaced, and locally on high surface area to volume ratios for effective adsorption of phosphate from the mineralising bottom waters. Irregularities in the karst surface would lead to more exposed areas becoming more phosphatised than others. Since the phosphatised carbonate is resistant to weathering, the effect would be self-reinforcing leading to protruding highs that would break down mechanically through increased slope instability or, unique to this deposit, by the impact of iceberg keels during the Pleistocene glaciations. There are no indications of lateral transport otherwise with currents not being strong enough to move the phosphate nodules (Kudrass and von Rad, 1984). The basins between the protruding karst surfaces are traps for fine siliciclastic cover sediment, leading to the presence of karst and deposits of phosphatised nodules to stand out as areas of mappable local rough relief.

Another factor in the surface distribution of the deposit is the water depth and slope orientation. Deeper waters are likely sites for accumulation of siliciclastic sediments as deep currents would slow down as the accommodating water column volume increases, and slides and slumps tend to move sediments downhill. The flanks of the Rise would be host to sediment drapes as well. Orientation of slopes will preferentially facilitate or hinder sedimentation depending on their facing in relation to dominating bottom current directions, leading some slopes to be potential traps for cover sediments while other would be swept clean frequently.

4. Spatial analysis methodology

Two prospectivity models were produced. In order to quantitatively define the most important predictive parameters for phosphate mineralisation, a WofE model was established over the area of highest data concentration (Fig. 1) and which covers the most sampled seabed sedimentary units. The results of this model were applied to more extensive fuzzy logic model covering all of the seismically mapped area of the Chatham Rise (Fig. 3).

4.1. Weights of evidence spatial data analysis

The WofE spatial modelling technique relies on the spatial analysis of each predictive map representing different aspects of the mineral system model using a set of training points of known areas of phosphate mineralisation. It was originally developed for medical diagnosis (Spiegelhalter and Knill-Jones, 1984), but has been adopted for mineral prospectivity modelling (Bonham-Carter, 1994; Bonham-Carter et al., 1989). The predictive maps are commonly binary, divided simply into areas of favourable and unfavourable conditions (Deng, 2009). The spatial correlation is calculated based on the area covered by the data variable tested and the number of training points falling within that area. A contrast value (C) is then calculated based on the ratio between the areas of the favourable and unfavourable conditions. A simple student test (StudC) is the ratio of C over its standard deviation (Cs). In this study C values >2 and StudC values >1.5 are considered significant positive correlations (Bonham-Carter, 1994; Peters and Partington, 2008).

The modelling was carried out using the Spatial Data Modelling tools for ESRI’s ArcMAP 10 GIS software (Sawatzky et al., 2010). The study area grid was set up at a 250 × 250 m resolution, the finest resolution the model should be viewed at based on data availability and coverage. The grid covers the parts of the seismic facies map of Falconer et al. (1984) that intersected the majority of the available exploration data, spanning a total area of 6539 km². Although the phosphate may originally have been a single extensive deposits, subsequent erosion and deposition of cover sediments have resulted in irregular surface distribution of phosphate nodules (Kudrass and von Rad, 1984). Therefore, based on observations of deposit irregularity and the geostatistical analyses underlying resource estimates (Kudrass, 1984; Sterk, 2014), a unit cell size of 2 km² was chosen for the analysis and modelling. This resulted in a prior probability of 0.01407 or a 1.4% chance of randomly finding mineralisation within any single 2 km² area before additional evidence is applied to the study area.

No phosphate mines exist in the area, so a set of training points was developed from sample points with high concentrations of phosphate nodules. All points with phosphate coverage calculated to be above 50 kg/m² were initially chosen. From these 424 points, 46 training points were chosen by filtering out points that were a unit cell radius or less from other points, while ensuring a good geographical spread of training data.

4.2. Fuzzy logic data analysis

The fuzzy logic spatial data modelling technique is an easily understood and effective method used for prospectivity modelling in less data rich study areas (Bonham-Carter, 1994; Carranza, 2008). Fuzzy logic does not rely on training data, but uses expert knowledge rather than spatial statistics to map prospectivity. This knowledge is often expressed in useful but imprecise terms such as near, sometimes, and maybe. Fuzzy logic provides a means to convert such semantic descriptions into a numerical map. Instead of simple Boolean logic True and False situations, fuzzy logic allows degrees of truth expressed as a membership function between 0 (no membership) and 1 (full membership). Membership values below 0.01 will exclude the predictive map in question; at 0.1 the map will only be included if all other maps give high weights to the cell in question. Values of 0.1–0.5 will deem a region somewhat unfavourable depending on the total value. A membership of 0.5 indicates a perfectly ambiguous situation and the map will have no impact on the final probability value. Values of 0.5–0.9 will weigh a map favourable in the final prospectivity map.

The Overlay Spatial Analyst Tools that are part of ESRI’s ArcGIS software (Sawatzky et al., 2010) were used to create the fuzzy logic model. The fuzzy logic model study area covers the entire central Chatham Rise region from the east side of Reserve Bank to the northwest of Matheson Bank near the slope and shelf region of the Chatham Islands (Fig. 1). The total area is 30,993 km², covering the full extent of the Falconer et al. (1984) seismic facies as well as the majority of the area samples by the 1960s surveys by Global Marine (Pascho, 1976) (Fig. 3).

5. Weights of evidence spatial analysis of predictive maps representing proxies of the mineral system model

5.1. Analysis of predictive maps representing phosphate source

Deep water currents carrying phosphate-rich waters from surface upwelling are here considered the source of phosphate for mineralisation. The paths of general deepwater flow can be mapped based on the general shape of the Chatham Rise. The Viewshed tool of ArcMap was used to...
define areas lying within and facing the broad north–south trending saddles that cross the central and eastern Rise (Fig. 1). For the WoE model, 95% of the training points occur in the broad area that is either within or facing the central saddle, giving a C value of 2.7 and a StudC value of 3.7 (Table 2). This result was applied to the fuzzy logic model, in which areas facing the saddles were given a weight of 0.7, and areas outside were weighted 0.3 (Table 3). The regional bathymetric dataset was not of good quality, and it is recommended to update this if more detailed studies are needed.

5.2. Analysis of predictive maps representing phosphate transport

Structural features are a very important control on the transport and deposition of mineralisation in a majority of mineral systems, for example by channelling and focussing mineralising fluids along faults. However, as the mineral system model here involves a surficial deposit formed through surface exposure and deposition, transport mineral system processes must be mainly controlled by topography and interaction with bottom water currents. These features have some overlap with trap mineral system processes. Faults create topographic relief and can act as a major influence on geomorphology, which on the Chatham Rise can promote exposure to phosphate rich waters (trap feature) as well as create gradients for bottom currents to follow (transport feature). Fault data were compiled from regional and local seismic mapping and found to have highest spatial correlation with a 1400 m distance buffer, capturing 93% of the training data with a C value of 2.7 and StudC of 5.6 (Table 2). This result confirms that although the mineralisation is formed by surface processes, underlying geological structures still have a significant control on the distribution of the phosphate. This was extended to the fuzzy logic model using the regional fault data only and assuming that the fault zone itself as well as terrain distant to faults would have no significant impact on prospectivity; 0–400 m distance and distances over 1400 m were given a weight of 0.5 (neutral), while 400–1400 m was given a weight of 0.7 (Table 3). As the fault set is rudimentary with detailed work only in the central WoEs model area (Fig. 2), no other aspects of faulting such as age, orientation or intersects, were considered.

Water depth and orientation of slopes are important controls on the direction and strength of dominant bottom current flow directions, which facilitate hardground formation, phosphatisation and nodule exposure. These factors overlap somewhat with the trap predictive maps, as water depth and orientation of slopes control the intensity and direction of bottom currents. The actually precipitation of phosphate depends on the convergence of surface processes, underlying geological structures still have a significant control on the distribution of the phosphate. This was extended to the fuzzy logic model using the regional fault data only and assuming that the fault zone itself as well as terrain distant to faults would have no significant impact on prospectivity; 0–400 m distance and distances over 1400 m were given a weight of 0.5 (neutral), while 400–1400 m was given a weight of 0.7 (Table 3). As the fault set is rudimentary with detailed work only in the central WoE model area (Fig. 2), no other aspects of faulting such as age, orientation or intersects, were considered.

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Sloping terrain facilitates bottom current flow which keeps the hardground surface sediment free and transports the elements needed for phosphatisation. Flat terrain is detrimental to nodule prospectivity as this indicates sediment-filled basins. Too steep slopes may also be detrimental as these may be drifts or sediment wedges at scarps, or on the regional scale it indicates terrain on the actual flanks of the Chatham Rise in deeper water and covered with sediment drapes. This was reflected in a categorical analysis of a reclassified slope map, which gave a poor correlation with the shallowest slope angles and negative correlation or no training data in areas with relatively steep slopes. Slopes based on the regional bathymetry datasets had good correlation with 84% of the training data at angles below 0.1° (C = 1.7, StudC = 4.5). This was extended to the fuzzy logic model but using a maximum angle of 0.2° with a weight of 0.8, while steeper slopes were considered unprospective with a weight of 0.1.

5.3. Analysis of predictive maps representing phosphate traps

The actual precipitation of phosphate depends on the convergence of several factors including low oxygen levels, increased phosphorous concentration and/or flux to the area (for example from mixing upwelling cold and P_2O_5 saturated deep water with relatively warm surface water at a front), paths of local bottom water currents, and lack of other sedimentation. The phosphate nodules were formed as a replacement and growth around carbonate hardground gravel clasts on or near the seabed. The predictive maps created outline the distribution of carbonate on the seabed as well as the distribution of local ridges. A categorical test of the seismic facies from Falconer et al. (1984) resulted in a strong positive correlation between training data and the extent of Oligocene chalk as well as with Miocene chalk on the south side of the crest. A negative correlation was found with Late Eocene chalk and chert, while a negative correlation with Miocene chalk north of the crest may be the result of the facies map being oversimplified. Combining the Oligocene and southern Miocene facies with logic OR resulted in a predictive map covering 96% of the training data with a C of 3.5 and a StudC of 4.9. For the fuzzy logic model, facies older than Late Eocene were given a very low weight of 0.01. The Late Eocene marl was weighted neutrally at 0.5. Early Oligocene chalks were weighted 0.8, while the softer Miocene chalks were weighted slightly lower at 0.6. Pleistocene cover sediments were weighted 0.1.

Local highs were mapped at a finer resolution from the bathymetric data than was done for the transport process predictive maps. The analysis used the Flow Focus tool of ArcMap, which assigns a value to a cell based on how many of the neighbouring cells have higher values than the centre cell. In a bathymetric grid, the cells with the lowest Flow Focus are located near the centre of a basin or on the central crest. A categorical test of the reclassified depth intervals found that 81% of the training points are found in shallow water, but not the shallowest interval as this is outcrops of siliciclastic basement.

Sloping terrain facilitates bottom current flow which keeps the hardground surface sediment free and transports the elements needed for phosphatisation. Flat terrain is detrimental to nodule prospectivity as this indicates sediment-filled basins. Too steep slopes may also be detrimental as these may be drifts or sediment wedges at scarps, or on the regional scale it indicates terrain on the actual flanks of the Chatham Rise in deeper water and covered with sediment drapes. This was reflected in a categorical analysis of a reclassified slope map, which gave a poor correlation with the shallowest slope angles and negative correlation or no training data in areas with relatively steep slopes. Slopes based on the regional bathymetry datasets had good correlation with 84% of the training data at angles below 0.1° (C = 1.7, StudC = 4.5). This was extended to the fuzzy logic model but using a maximum angle of 0.2° with a weight of 0.8, while steeper slopes were considered unprospective with a weight of 0.1.

5.4. Analysis of predictive maps representing phosphate deposition

Since the phosphate mineralisation is uniform and distinctly different from the host sediment, phosphate content has generally been
derived from the relative proportion of the coarse sediment fraction (>1 mm), extrapolated from analysis of chemical phosphate on size fractions of bulk samples. Consequently, phosphate grade is calculated as the mass of nodules per square metre, based on the weight of the coarse fraction modified by the percentage of phosphate nodules in the fraction and the size of the area sampled. The phosphate nodule grade maps were not used in the WofE model because the four main sampling programmes used at least four different sampling methodologies as well as different sample processing techniques and a thorough analysis of the implications were not available at the time of modelling. Instead, observed percentage of nodules in samples, generally observed shipboard, was used as an indicator of economic nodule abundance. The point data interpolated to an area grid using inverse distance squared weighting with a 5 km search radius, using circular search similar to the procedure used for resource estimation of the Chatham Rise phosphate (Kudrass, 1984; Sterk, 2014). Cut-offs were selected from the sample value histogram. Combining nodule abundances by weight >15% captured 93% of the training data with a C of 3.7 and a StudC value of 6.1 (Table 2).

For the fuzzy logic model, the Global Marine dredge sample set was added to the sample data, which were also converted to kg/m² grade estimates, constrained by a new resource estimate (Sterk, 2014). Based on the structural orientation inferred from the Flow Accumulation analysis described above, the study area was divided into five sectors with distinct structural orientations. These were used to guide inverse distance squared weighting interpolation of the grade data using oriented 12 km by 6 km search ellipses. A cut-off grade was assumed to be 20 kg/m² and to maintain the robustness of the interpolation only areas interpolated from at least 5 sample values were included. The grid was also clipped by unprospective geology (outcrops of basement and Palaeogene clastic sediment, as well as Pleistocene cover sediment). Robust estimates of >20 kg nodules/m² were given a weight of 0.8, while samples outside of this were given a neutral weight of 0.5 (Table 3).

6. Weights of evidence and fuzzy logic modelling

The spatial analysis of each predictive map is as important for exploration targeting as the spatial data modelling itself, as the analysis identifies data that best predicts mineralisation as well as interrelationships between datasets that can improve exploration targeting and improve future data acquisition (Partington, 2010). The analysis also highlights where more research may be needed and where additional data can be collected to improve the model. For example, what is the spatial relationship between the inferred ridges on the Chatham Rise crest and the extent of mineralisation? Are there deposits associated with past ridges when the Chatham Rise had a different configuration from today? The most important variables that can be mapped for predicting nodular phosphate deposits on the Chatham Rise based on the WofE spatial analysis are listed in Table 1.

A WofE prospectivity model was created using the predictive maps described above, representing all stages of the phosphate nodule mineral system model (Table 2). For example, spatial association with saddle areas provides information on source; associations with faults, geology and features of crest architecture provide information on transport pathways and traps; and distribution of phosphate nodules provides information on the efficiency of deposit formation. The final predictive maps were chosen as having the best regional coverage, a significant association with the mineral system model considered, being useful for establishing parameters and weights to use in the fuzzy logic model, and with minimal duplication of the predictive map patterns. The predictive themes were added to the final model after their spatial correlation values were calculated (Table 2).

Based on the WofE map themes, similar maps were developed for the laterally more extensive fuzzy logic model. Weights were constrained by the C values derived from the weights of evidence model as well as on the impact of the variable in question missing from an area (for example not being close to a fault does not preclude phosphatization, while being in areas of basement outcrop do). The fuzzy logic predictive themes and their weights are summarised in Table 3.

<table>
<thead>
<tr>
<th>Exploration variable</th>
<th>Chatham Rise nodular phosphate deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathymetry</td>
<td>Shallow water depth, eastern and south-eastern slope aspects, local highs, association with regional saddle features.</td>
</tr>
<tr>
<td>Seismic facies</td>
<td>Chalk-containing surface facies (Oligocene and Miocene units). Pleistocene cover is negatively correlated, as is Eocene and older, generally siliciclastic facies.</td>
</tr>
<tr>
<td>Lithology</td>
<td>Proportion of phosphate nodules in the coarse sediment fraction</td>
</tr>
<tr>
<td>Faults and lineaments</td>
<td>Exposure from fault offsets, seabed tilting, linear zones of weakness, iceberg scouring likely too young to influence overall phosphate nodule distribution.</td>
</tr>
</tbody>
</table>

6.1. Weights of evidence model results

The final WofE model was developed using the Arc-SDM toolbox developed for ArcGIS 10 (Sawatzky et al., 2010). Inputs to the model are the selected predictive maps, their spatial statistics and the training data. The modelling produces up to five grids that measure geological potential and uncertainty. To be able to query the combinations of inputs that produced the prospectivity result, a grid response map was produced which contains the intersection of all of the input themes in a single integer theme, called a unique conditions grid. Each row of the attribute table contains a unique row of input map values, indicating which predictive maps contributed to the final prospectivity value of a given grid cell. Any combination of map variables can thereby be queried to assist the user in establishing the final targets. Especially important for exploration, the areas missing different types of data can also be identified. The unique conditions grid can be combined with other maps, for example of exploration expenditure, to simplify cost analysis of future exploration needs (e.g. Kreuzer et al., 2014).

A confidence map was also produced, showing the confidence that the reported post-probability is not zero for a given grid cell. This is achieved by dividing the post-probability with the total standard deviation, an approximate Student T test (Sawatzky et al., 2010). The variances of the weights and variance due to missing data are summed to give the total variance of the post-probability in these maps. Combining the unique conditions grid with the confidence maps produced during the weights of evidence modelling allows areas where the confidence in the result is low and where data are missing to be mapped. Thereby the model can be used not only to target new prospective ground, but also to plan new exploration programmes where new or additional data are required.

The final stage of the modelling involved reclassification of the post-probability maps to define areas of high-priority targets for phosphate mineralisation for sampling and resource estimation studies. Unique to this model is the presence—absence nature and extensive coverage

Table 2

<table>
<thead>
<tr>
<th>Map</th>
<th>Variable</th>
<th>W⁺⁺⁺</th>
<th>W⁺⁺</th>
<th>W⁺</th>
<th>W−</th>
<th>W−−</th>
<th>C</th>
<th>StudC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saddle region</td>
<td>Source</td>
<td>0.5</td>
<td>2.2</td>
<td>2.7</td>
<td>3.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shallow bathymetry and slope aspect</td>
<td>Transport</td>
<td>0.3</td>
<td>0.9</td>
<td>1.3</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gentle slopes</td>
<td>Transport</td>
<td>0.6</td>
<td>1.1</td>
<td>1.7</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity to faults</td>
<td>Transport</td>
<td>0.9</td>
<td>1.8</td>
<td>2.7</td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oligocene and Miocene chalk near surface</td>
<td>Trap</td>
<td>0.9</td>
<td>2.6</td>
<td>3.5</td>
<td>4.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximity to local highs</td>
<td>Trap</td>
<td>1.6</td>
<td>2.9</td>
<td>4.5</td>
<td>6.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area with significant nodule abundance</td>
<td>Deposit</td>
<td>1.2</td>
<td>2.4</td>
<td>3.7</td>
<td>6.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Please cite this article as: Nielsen, S.H.H., et al., Chatham Rise nodular phosphate — Modelling the prospectivity of a lag deposit (off-shore New Zealand): A critical tool for use i., Ore Geol. Rev. (2014), http://dx.doi.org/10.1016/j.oregeorev.2014.10.013
of the nodular lag deposit in focus, which differs significantly from the generally narrow, highly concentrated targets in metallogenic prospectivity modelling. To achieve maximum target coverage, the prior probability of 0.01407 was set as a lower cut-off, as the broadest area the prospectivity model can validly target. Within the prospective area the model has identified 67 target areas covering 891 km², or 13.6% of the 6538 km² study area (Fig. 5), with 93.5% of the training points located within the prospective part of the study area. The prospective areas of the model occur on local topographic highs near the central saddle, along the strike of major faults and where the terrain is generally flat. 727 km² (81.6%) of the target area is also covered by a resource with >20 kg/m² nodule coverage, indicating that the prospectivity model adds 164 km² of new potentially prospective ground (Fig. 5).

The model does have issues of conditional dependency, as several of the predictive maps used have been derived from similar data sources and have similar map patterns. Probability values may therefore be overestimated and should not be used as actual statistical probability of finding phosphate mineralisation. The conditional dependence issue can be minimised by excluding or combining dependent predictive maps. However, this could remove important information from a dataset that is already sparse. The probability values can instead be used to objectively rank the targets by ordering the posterior probability values of the target areas.

Statistically testing the predictive capacity of the prospectivity model required creating a set of measured data points with known high nodular phosphate concentrations. From the phosphate coverage dataset, all points with phosphate coverage value above 50 kg/m² within the study area were chosen to test the predictive efficiency of the model (424 points). The curve for the 46 points of the training data gave a Success Rate value of 96.7% and the efficiency of prediction based on the 424 high nodule concentration points is 93.5%. These measures confirm that the model has high predictive efficiency.

### 6.2. Fuzzy logic model results

The fuzzy logic prospective modelling was completed to produce targets based largely on predictive map derivatives of bathymetry and geology, using the fuzzy logic modelling tools of the Arc-SDM toolbox for ArcMap 10. A cut-off of 0.51 was used for targeting, based on a comparison with mineralised target areas from the WofE model. The highest prospectivity was indicated for targets that included the > 20 km² resource estimate based on all available sample data as well as proximity to faults, marked with red in Fig. 6.

In addition to the resource estimate data and fault map, the model used low slope angles, entrainment in the saddle regions, and shallow bathymetry with SE-facing slopes as important parameters for nodule deposition on the Chatham Rise. The most prospective regions are likely to be found in the vicinity of major faults and within the very prospective Early Oligocene chalk facies. Importantly, the model also maps areas that are less likely to be mineralised: i.e., areas containing outcrops of basement and areas with thick cover of Late Neogene, especially Pleistocene, sandy sediments. Prospectivity is also likely to decrease as one searches north or south away from the central crest where slope angles are steeper, young sediment drapes are thicker, and water depth likely to have been too deep to favour extensive phosphatisation in the past.

The targets cover more than 9600 km² or 30% of the model area (Fig. 6). 57 targets were defined with areas greater than 1 km². The 10

| Table 3 |
|---|---|---|
| Map               | Variable              | Fuzzy class | Fuzzy weight |
| Saddle region     | Source                | 2 (inside)  | 0.7          |
|                   |                      | 1 (outside) | 0.3          |
| Bathymetry and aspect | Transport          | 2 (favourable) | 0.7         |
| Slope             | Transport            | 2 (<0.2°)  | 0.8          |
| Slope             | Transport            | 1 (<0.2°)  | 0.1          |
| Proximity to faults | Transport          | 3 (400–1400 m) | 0.7     |
|                   |                      | 2 (0–400 m) | 0.5          |
|                   |                      | 1 (<1400 m) | 0.5          |
| Seismic facies    | Trap                 | 6 (no data) | 0.5          |
|                   |                      | 5 (Pleistocene chalk) | 0.1     |
|                   |                      | 4 (Miocene soft chalk) | 0.6     |
|                   |                      | 3 (Oligocene chalk) | 0.8          |
|                   |                      | 2 (Cenozoic marl) | 0.5          |
|                   |                      | 1 (Basement) | 0.01         |
| Nodule grade      | Deposit              | 2 (>20 kg/m²) | 0.8       |
|                   |                      | 1 (>20 kg/m²) | 0.5          |
targets with >100 km² area make up 90% of the total target area. The highest prospectivity targets (red in Fig. 6) are based on the resource and fault predictive maps especially, and cover 2400 km² or 13% of the total model area.

7. Predictive mapping and resource modelling

Resource modelling requires evaluation based on statistics and sample distribution. Because the Chatham Rise deposit is essentially a 2-dimensional resource resulting from multiple inputs, there is no simple way to constrain the resource distribution. The prospectivity model, on the other hand, takes into account the varying mappable geological parameters that control deposition and can be used to more accurately constrain the resource estimation interpolations and prevent grade smearing into less or more importantly non-prospective areas.

Using the weights of the different facies, a map can be produced that compares grade estimated using resource modelling to the facies model (Fig. 7A). This can then be used to exclude areas of phosphate grades projected into unfavourable geology, as a hard boundary for resource distribution in addition to other limiters such as an economic grade cut-off (Fig. 7B). However, the most effective approach to resource modelling may be to base it on the post-prospective map, thereby including all the variables that are favourable for deposit occurrence. This would allow grade to occur over basement facies, for example, if other variables were in favour and the presence of a nodular lag deposit on a basement outcrop was due to the removal of younger, finer-grained deposits by bottom currents.

8. Data confidence and exploration planning

As important as the assessment of prospectivity for phosphate may be, the ability of the WoF technique to quantify data uncertainty is also significant for this project. This enables the distribution of data involved in the estimates to be mapped and quantify where the data coverage is too sparse to ensure confidence in the result. This is not possible for the expert opinion-driven fuzzy logic modelling.

The fuzzy logic model output can be used to aid future exploration planning, by highlighting areas most likely to be prospective. For the Chatham Rise model, the WoF targets generally fall within the area of high confidence in the data. This is common for most prospectivity models and may be an artefact of historical surveying generally focusing on areas of known mineralisation (Fig. 8). Targets that are outside the area of statistically convincing results may be prioritised for exploration if they overlap fuzzy logic targets. Likewise, areas without WoF-based targets that are in regions with low confidence can be prioritised for follow-up exploration especially if the fuzzy logic model shows prospective ground there. Likewise, areas shown with confidence to have no targets can be avoided.

Combining the confidence map with targets and resource estimates, which are generally calculated simply based on grades from sample data, can likewise guide exploration towards adding data where the return will be the greatest: Areas with WoF targets and high data confidence can be assumed to be valid, lending validity to resource estimates from these (compare Figs. 7b and 8). Areas with fuzzy logic targets but not high WoF data confidence are prime subjects for further exploration, including data acquisition, and resource estimates from these will need to be treated with caution. Areas with high data confidence and no targets are effectively sterilised, barring changes to the mineralisation model or geology.

9. Predictive maps and environmental modelling

The final prospectivity maps and associated predictive maps can be combined with cadastral and environmental maps to define where mining is possible. This way, the Chatham Rise predictive model results can be applied to environmental modelling since part of the modelling outlines the extent of hardground formation; hard substrates provide living space for a specialised subset of benthic organisms, which will be impacted when the hardground rubble is removed from the seabed as part of the mining process. Model output can be used to map out and evaluate the impact of the planned mining on hardground dwellers (area mined compared to the total area of living space). Conversely, mapping the distribution of hardground dwellers and animals that feed on them may be added to the phosphate model as potential predictive layers.

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10. Conclusions

Spatial data modelling techniques were applied to the offshore Chatham Rise phosphate nodule deposit. Challenges to the modelling include inconsistent data formats, scarcity of data and uncertainty of locations of especially older data. Two models were produced, both combining individual predictor themes of geology, geochemistry and geophysical data into singular predictive maps. A weights of evidence (WofE) model was first produced that covers the area of highest data density. The result from the WofE modelling was then used to guide a fuzzy logic model that covers a wider if less well explored region.

The models confirm that aspects of the topography and especially change in relief (nearness to local highs, faults) are as important as understanding the geology. For future exploration, collecting good quality, high-resolution bathymetric data should be a primary concern, as is mapping near-surface structures using sub-bottom or shallow-seismic profiling. Having good coverage of samples tested for the presence of phosphatised hardground nodules is also important.

The benefits of this type of analysis include a need for quality-controlled input data, effective data compilation and through the production of unique conditions and confidence grids, a guide for future exploration programmes. Since the deposit is a lag deposit, the output of the models is relevant for showing where the deposit can be found as much as where it is absent. Combining the WofE and fuzzy logic models post-probability maps with a map of statistical confidence in the results can be used to limit exploration to areas where exploration will give the most return, limiting expenditure as well as environmental impact. The models can therefore be integral to exploration and mine planning as well as to resource and environmental modelling over the central Chatham Rise.

Fig. 7. A. Facies prospectivity from Table 3 compared with a grade map. B. Grade map, cut by unprospective lithologies and with < 20 kg/m² cut out.
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