Genesis of the Chatham Rise Phosphorite; an interpretation from current literature.

S.L.M Hughes-Allan
Exploration Geologist
Kenex Ltd
16 Oroua Street, Eastbourne, Lower Hutt
sally@kenex.co.nz

Acknowledgements

The information presented is done so with the support of Kenex Limited and the permission of Chatham Rock Phosphate Limited. The author would like to thank Tim Allan for undertaking technical reviews of the paper and providing information on the recent findings in the Great South Basin. Gondwana animation figures are reproduced with the permission of Rupert Sutherland, GNS.

Abstract

A synthesis of new ideas from papers relating to the genesis of the Chatham Rise phosphorite deposit is presented.

Since the Sonne and Valdivia Cruises in the late 1970's and early 80's, little has been contributed to further define, quantify or explain the Chatham Rise phosphorite deposit. There have been, however, many advances in geochemistry, paleo-geography, paleo-oceanography and paleo-climatology which have contributed to understanding the genesis of phosphorite deposits worldwide.

Recent oil and gas exploration in the Great South and Canterbury Basins has resulted in increased seismic coverage which has yielded in new insights into the deformation sequence on New Zealand's continental shelf marginal out in to the adjoining deep water basins.

It is proposed that the Miocene southern ocean, open shelf, replacement type phosphorite deposits (which include the Chatham Rise phosphorite) were formed in response to tectonic movements, the subsequent erosion of the ancient super continent of Gondwana and the migration of ocean fronts in response to changing ocean topography.

It follows that a reconstruction of paleo-geography and paleo-oceanography adjacent to the Gondwana supercontinent will provide insight into the development of this large phosphorite resource in time and space.

***Keywords**:* phosphorite, paleo-geography, paleo-oceanography and paleo-climatology, Gondwana, Great South Basin.

Introduction

Based on 960 grab samples from the Valdivia and Sonne cruises (1978 and 1981), the Chatham Rise phosphorite deposit (CHPD) has been estimated at 30 million tonnes of phosphorite averaging 9.4%P (21.5% P_2O_5) and concentrated at 66kg m^{-2} over an area of 378km^2 (Kudrass & Cullen, 1982). The locus of the area is between 179°08'E and 179°42'E, along the crest of the Chatham Rise, in about 400m water depth (Kudrass & von Rad, 1984).

Phosphorite deposits are known to occur in ocean basins around the globe. Several of these, including the Chatham Rise deposit have been dated between 23 to 5 million years ago (Ma) (Shields, Stille, & Brasier, 2000). These authors attribute the formation of the Miocene southern ocean, open shelf, replacement type phosphorite deposits (which also include those of Peru and Namibia) to a complex interplay between source, ocean chemistry, global temperature changes and ocean circulation.

Morphology

The Chatham Rise phosphorite deposit occurs as a surficial or subsurface uncemented gravel of hard subangular to subrounded "nodules", enclosed in a matrix of unconsolidated, glauconitic sandy mud (Cullen, 1987). An identical fine sediment layer, up to 1m thick and containing sparse granules of phosphorite, overlies the nodule rich layer. Frequent exposure of the nodule-bearing layer at the seafloor indicates very low sedimentation rates and very

gentle current winnowing. There is virtually no evidence of sorting by ocean currents (Cullen & Singleton, 1977); (Cullen, 1987).

Where present on the Chatham Rise, the nodule layer is up to 0.7m thick. The nodules vary in size from 2-150mm and are composed of indurated and phosphatised, light coloured pelagic oozes. Phosphorite clasts display two distinct phases of boring and burrowing, the latter phase playing an important role in providing access routes for phosphatising solutions (Cullen, 1987).

The patchy distribution of the nodules on the Chatham Rise is believed to reflect the irregular development of an original phosphatic "duricrust" wherever the calcareous pre-cursor was exposed at the seafloor (Cullen, 1987) with some modification from original locus of deposition by iceberg scouring during low stands of sea-level (Kudrass & Cullen, 1982); (Kudrass & von Rad, 1984).

Geochemistry

Phosphorites are defined as those rocks containing more than 50% apatite (+/- fluorapatite & francolite). Literature searches favour two modes of phosphorite deposition;

1. Authigenic: caused by direct precipitation, interstitial growth or pelletal accretion in reducing environments and usually restricted to lagoon or estuarine environments and
2. Diagenetic: via replacement of a calcareous precursor and located on offshore topographic highs, banks, ridges and seamounts.

Cullen (1987) assigned the Chatham Island phosphorites to the latter category when he observed the "*crudely concentric structure observed in many individual nodules*" reflects the diagenetic origin of the phosphorite.

Phosphorous is delivered to the oceans via continental weathering and fluvial transport (Föllmi, 1996); (Delaney & Filipelli, 1994); (Compton, Snyder, & Hoddell, 1990). It is processed by plankton and liberated to the sediments by the decay of marine organisms. The initial step in the formation of phosphorites is the super saturation of pore water in organic matter-rich sediments (Arning, 2009) at the sediment/sea-water interface. In the case of the Chatham Rise, this occurred where sediments of the calcareous Oligocene to Plio-Pleistocene Penrod Group (Cook, Sutherland, Zhu, & others, 1999) were exposed at the sea floor (Figure 1).

Replacement of the calcium carbonate precursor by calcium phosphorite occurs in areas of ocean upwelling and high organic productivity (Baturin, 1989), (Burnett, 1977), (Burnett & Riggs, 1990).

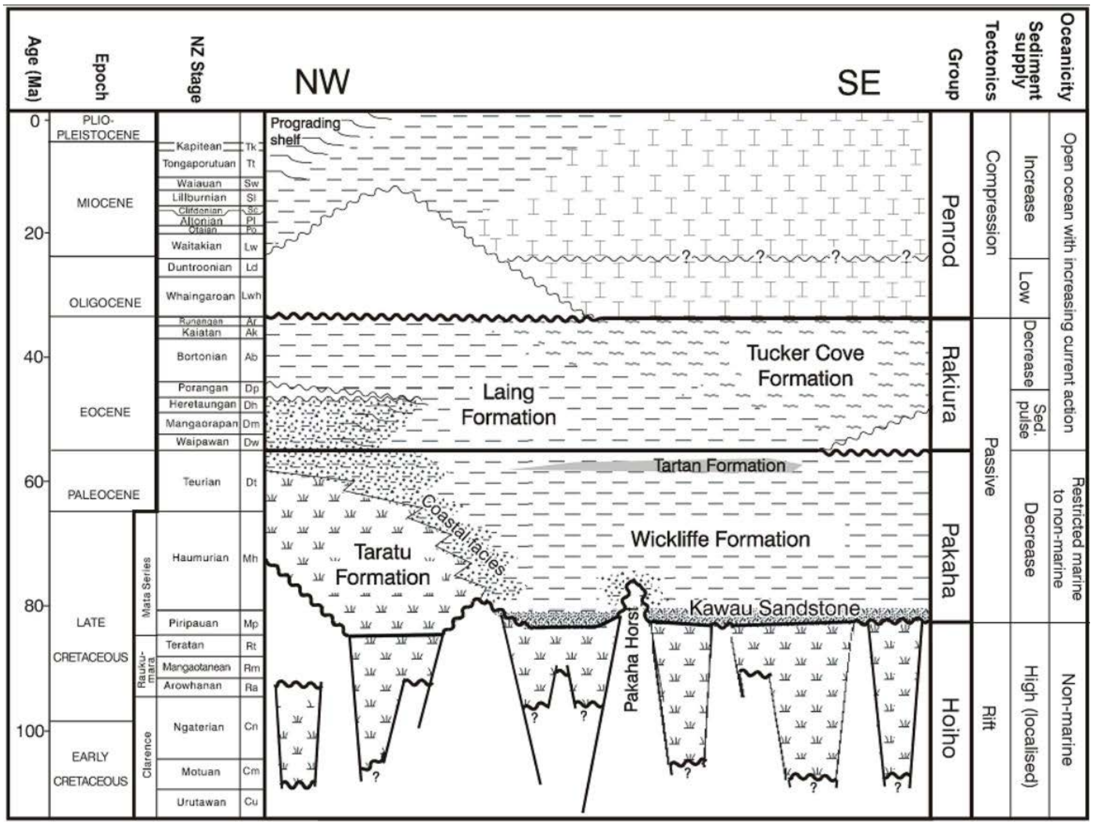

Figure 1: Generalised stratigraphy of the Canterbury and Great South Basins (Cook et al, 1999).

Age

Along most of the Chatham Rise, the phosphorite rests on a substrate of Upper Eocene-Lower Oligocene chalky limestone. At its interface with the nodule bearing "superficial lag" deposits, the topmost 15cm of the limestone is softened to the consistency of sticky cream cheese (Cullen, 1987). Close examination of this layer has failed to reveal the presence of any post-Oligocene microfossils and may correlate to the Miocene erosion feature, the Marshall Paraconformity (Carter, 1985) and the glacio-eustatic lowstand of sea level described by Fulthorpe et al (1996).

The youngest reliably dated limestone to have been phosphatised is 12-15Ma (Middle Miocene). Potassium-argon dating of the outer glauconite coatings (Cullen, 1987) put the upper age limit of the nodules between 5.7 and 11Ma.

McArthur (1990) pushed this date to 4.90$\pm$ 0.35Ma with strontium isotope measurements ($^{87}Sr/^{86}Sr$ captured from ambient pore water at the time of formation).

Paleogeography and Gondwana

The earliest identified sediments on the Chatham Rise are Permo-Triassic in age. A thick sequence of marine muds (flysch) was lain down in a subsiding trough at the Pacific margin of Gondwana (Spörli, 1980). These sediments were folded and metamorphosed during the Jurassic-Cretaceous Rangitata Orogeny (~140Ma). During the Mid Cretaceous, the first phase of Gondwanan break-up resulted in the regional formation of isolated lacustrine depo-centres (T. Allan, *pers comm* 2010). In the Late Cretaceous a second, more widespread phase of rifting occurred at ~30°clockwise relative to the first and was associated with subsidence in the Canterbury and Great South Basins. The second phase is seen on the Chatham Rise as extensional (basement) half-grabens. Initial terriginous graben fill was followed by shallow marine sediments, as thermal erosion and the onset of major normal faulting (on the western margins of the Canterbury and Great South Basins) allowed marine incursion from (what is now) the north east (T. Allan, *pers comm* 2010).

The Wishbone Scarp, which was also active through the Cretaceous, formed the northern margin of the Chatham Rise. The Bounty Trough (BT Figure 2 below); a failed extension of the New Caledonia and deep-water Taranaki basins, formed what is now the southern margin of the Chatham Rise (Sutherland, King, & Wood, 2001).

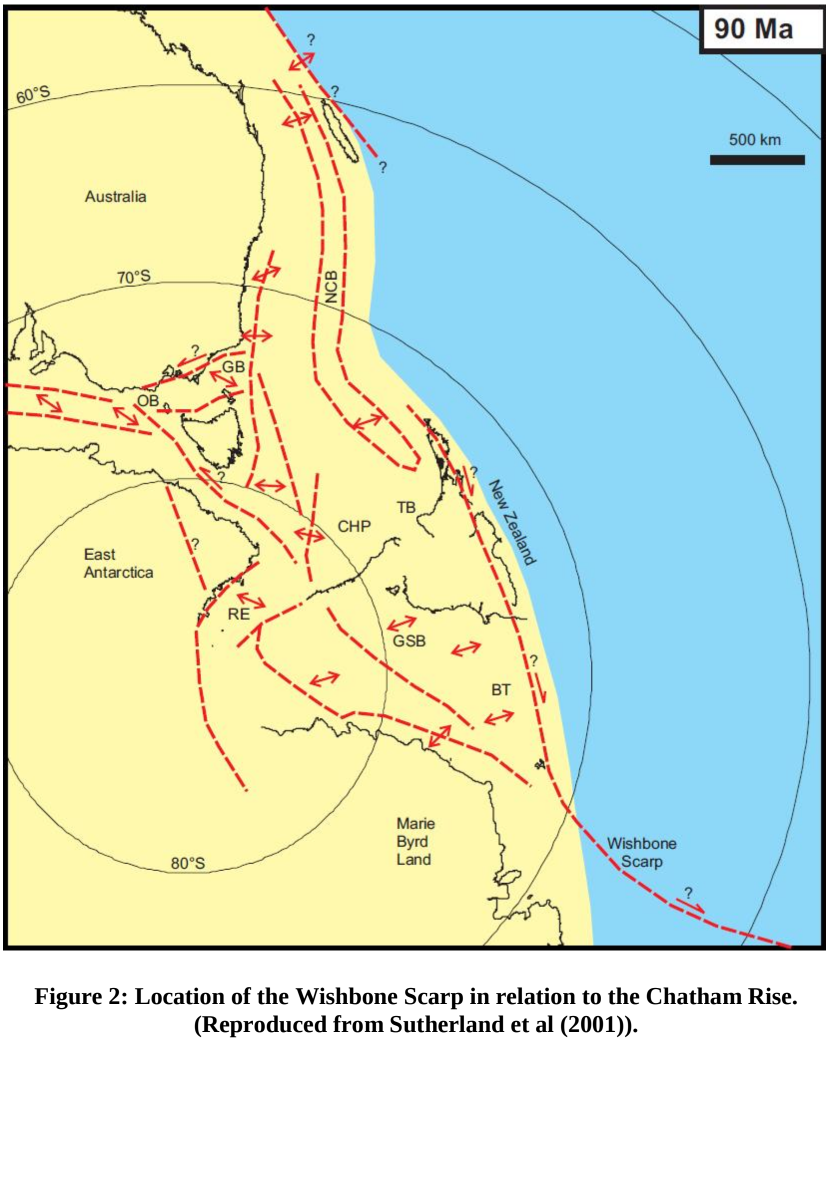

Figure 2: Location of the Wishbone Scarp in relation to the Chatham Rise. (Reproduced from Sutherland et al (2001)).

Rifting had essentially ceased by the end of the Cretaceous (66Ma) (Figure 3b) and during the Paleocene (65-55Ma, Figure 3c) was replaced by land emergence and shallow marine deposition punctuated with shallow marine volcanism (Wood et al (1989)).

Some faults were re-activated during the Eocene (55-33Ma Figures 3d and 3e) giving rise to local depo-centres, and regional subsidence occurred on the flanks of the Chatham Rise. Formation of the modern plate boundary was preceded in the Late Oligocene/Early Miocene by long wavelength uplift of eastern regions of the Canterbury and Great South basins (T. Allan, *pers comm* 2010), on trend with erosion of Oligocene sediments on the Chatham Rise.

Middle to Late Oligocene (35-25Ma Figure 3f) was a period of erosion, intense bio-turbation and non-deposition in many parts of New Zealand (the Marshall Paraconformity of Lewis et al (1986) and Carter (1985)). Along the crest of the Chatham Rise, phosphatised and glauconised fragments of Early Miocene limestone buried the Mid-Oligocene erosion surface and thin sequences of glauconitic sand and silt, marl and foraminiferal ooze accumulated. Later erosion commonly removed the Miocene section though it is preserved in the more phosphatised lag gravels and increasingly down the flanks of the rise (Wood et al (1989)).

West of the Chatham Islands, a broad, gentle saddle separates the Chatham Islands from the Matheson Bank. The Late Cenozoic (Miocene to Recent) sedimentary sequence is absent or very thin with chalk and chert exposed at the sea-floor (Kudrass & von Rad, 1984). In the vicinity of Matheson Bank, Paleogene rocks and Chatham Island Schist are widely exposed. Work by Zobel (1984) suggests that patches of Oligocene sediments have remained exposed on the crest of the rise since their deposition some 30 million years ago.

On the flanks of the rise west of 179°E, there is an increase in thickness of the Late Cenozoic (<10Ma Figures 3g and 3h) sequence culminating dramatically in the thick clastic wedge of the Canterbury continental shelf and contiguous outwash plain. Subsurface stratigraphy confirms that a substantial proportion of this sediment build up is from the west (Wood et al (1989)) and coincides with the inception of the Alpine Fault. Contemporaneously, the western edge of the Chatham Rise was down-warped west of Mernoo Bank (Mernoo Gap).

Most late Cenozoic faulting is restricted to the western end of the rise (as the effects of the developing plate boundary were increasingly felt) and are reactivated Cretaceous faults. The Late Neogene (<5Ma) sequence is not offset in the vicinity of Mernoo Bank (Herzer & Wood, 1988) but the seismic sections show that the reactivated Cretaceous half-grabens of the North Mernoo Fault Zone display repeated steepening of the north slope of the rise. Here, the late Cenozoic sequence consists of slump and fault disturbed material (Lewis, Bennett, Herzer, & von der Borch, 1985) but there is little seismic activity recorded on the rise today (Wood, Andrews, Herzer, & al, 1989).

Figure 3: The break-up of Gondwana

Images reproduced from an animation by Rupert Sutherland - http://www.teara.govt.nz/en/native-plants-and-animals-overview/1/1

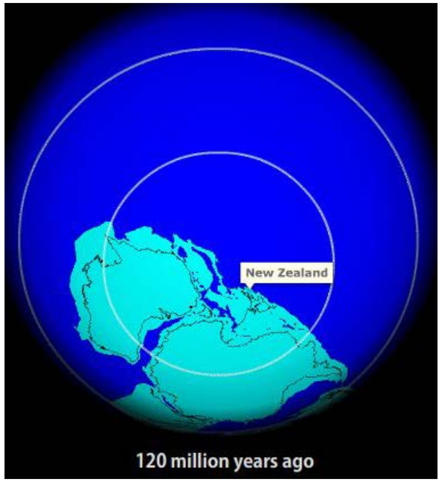

Fig3a: Permo-Triassic to Early K. *Deposition of sediments at Gondwana margin – Rangitata Orogeny ~140Ma.* **Latitude of CR~80°S.**

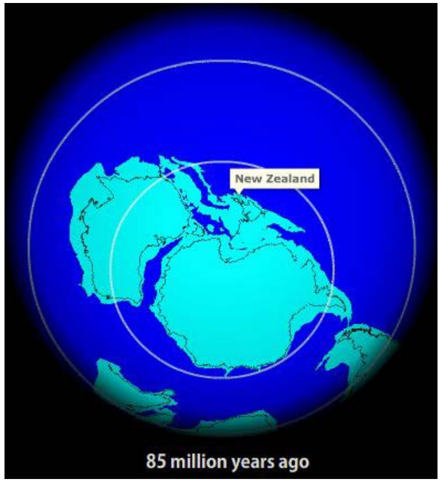

Fig 3b: 85Ma: Late Cretaceous, New Zealand splits from Gondwana. **Latitude of CR ~65°S.**

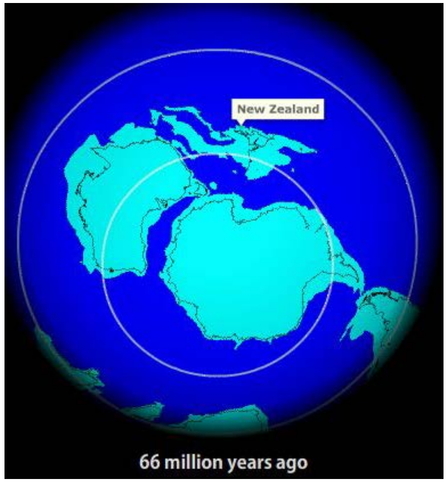

Fig 3c: 66Ma: K-T boundary. Rise is sub-aerial (Stillwell, et al., 2006). **Latitude of CR ~56°S.**

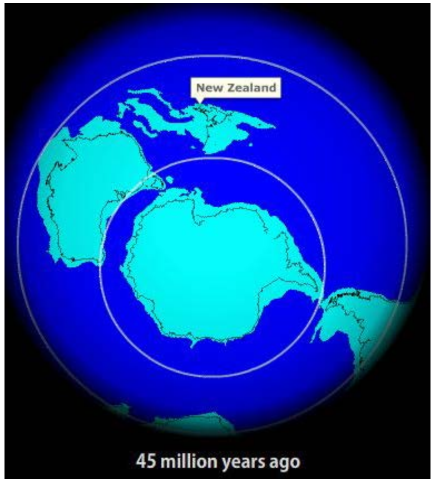

Fig 3d: 55-45Ma – mid Eocene: Australia and South America still joined to Gondwana. **Latitude of CR ~54-52°S**

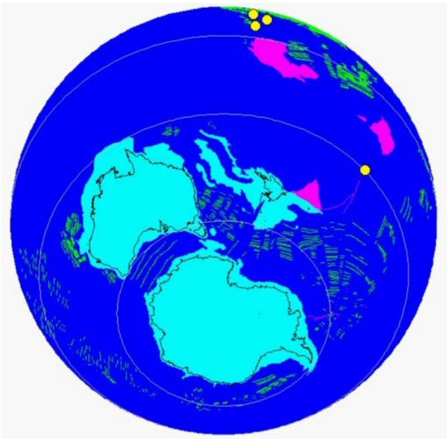

Fig 3e: 45-35Ma - Latest Eocene Tasman Sea leaking?

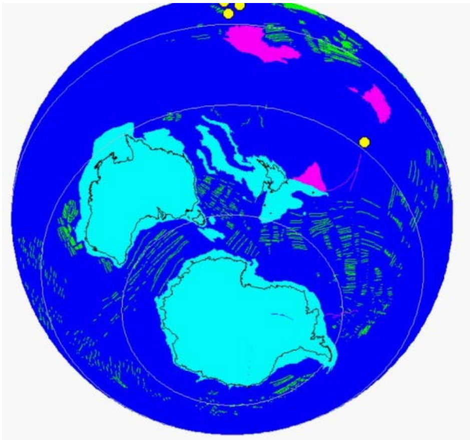

Fig 3f: 35-25Ma – Mid to Late Oligocene Marshall Paraconformity. **Latitude of Chatham Rise ~49°S**

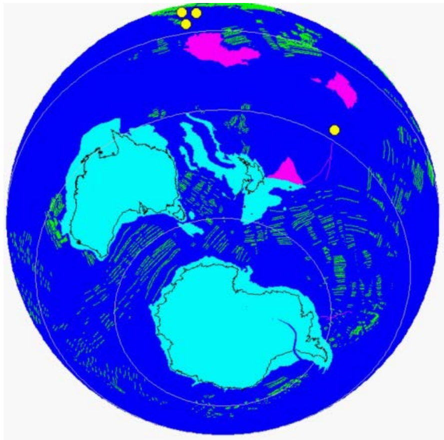

Fig 3g: 25-15Ma Early to Mid Miocene. Inception of Alpine Fault, opening of Drake Passage.

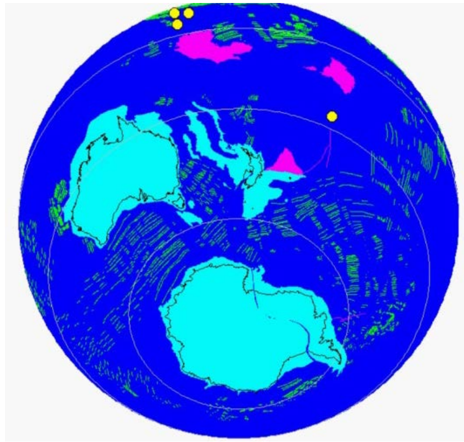

Fig 3h: 12Ma – Mid-Miocene Formation of the Chatham Rise phosphorite. **Latitude of CR ~46°S.**

Palae-oceanography and ocean fronts

Shields et al (2000) use advanced isotope analysis to examine two giant sedimentary phosphorite generation episodes in the earth's history; one in the Pre-Cambrian to Cambrian and one during the Cretaceous-Recent. They relate increases in seawater $^{87}Sr/^{86}Sr$ to changes in seafloor spreading rates and link orogeny and global weathering rates to P-input and P-formation. They also use Nd isotope ratios to track palaeo-currents in the role of phosphorite formation and note that there are no major phosphorite deposits from the Oligocene (an interval of at least 10Myrs).

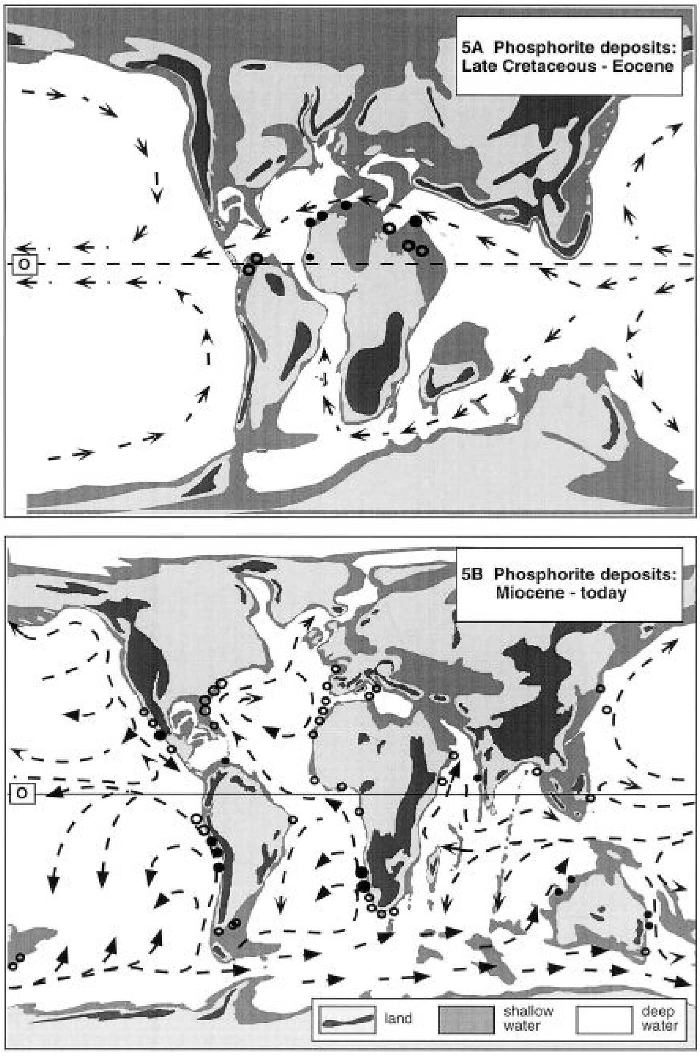

Figure 4: Global paleo-currents from the Late Cretaceous to today (after Shields et al, 2000.)

Of importance to the Chatham Rise deposit is towards the end of the Oligocene (25Ma), as glaciations began in Antarctica, contemporaneous phosphogenesis began in the Mediterranean, off California, in Brazil and the Eastern United States, Peru and Namibia.

The switch in location of phosphorite formation from the Middle East (in the Late Cretaceous to Eocene) to the western seaboards and Eastern United States was in response to the glacially related up-welling and a change in ocean circulation patterns from predominantly E-W to dominantly N-S (Shields, Stille, & Brasier, 2000) (see Figure 4).

In times of cooling, the increase in latitudinal temperature gradients may lead to more intensified oceanic circulation and increased coastal upwelling, which itself may lead to a greater phosphate flux to outer-shelf sediments (Vincent & Berger, 1985).

Zachos (2001) utilises techniques developed to resolve deep-sea oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes from cores (Figure 5). This information provides both climatic and stratigraphic data on a variety of geologic time scales (millennial to tectonic). Zachos (2001) concludes that the opening of the Tasman Sea and Drake Passage were tectonically driven events that had profound effect on the dynamics of global climate.

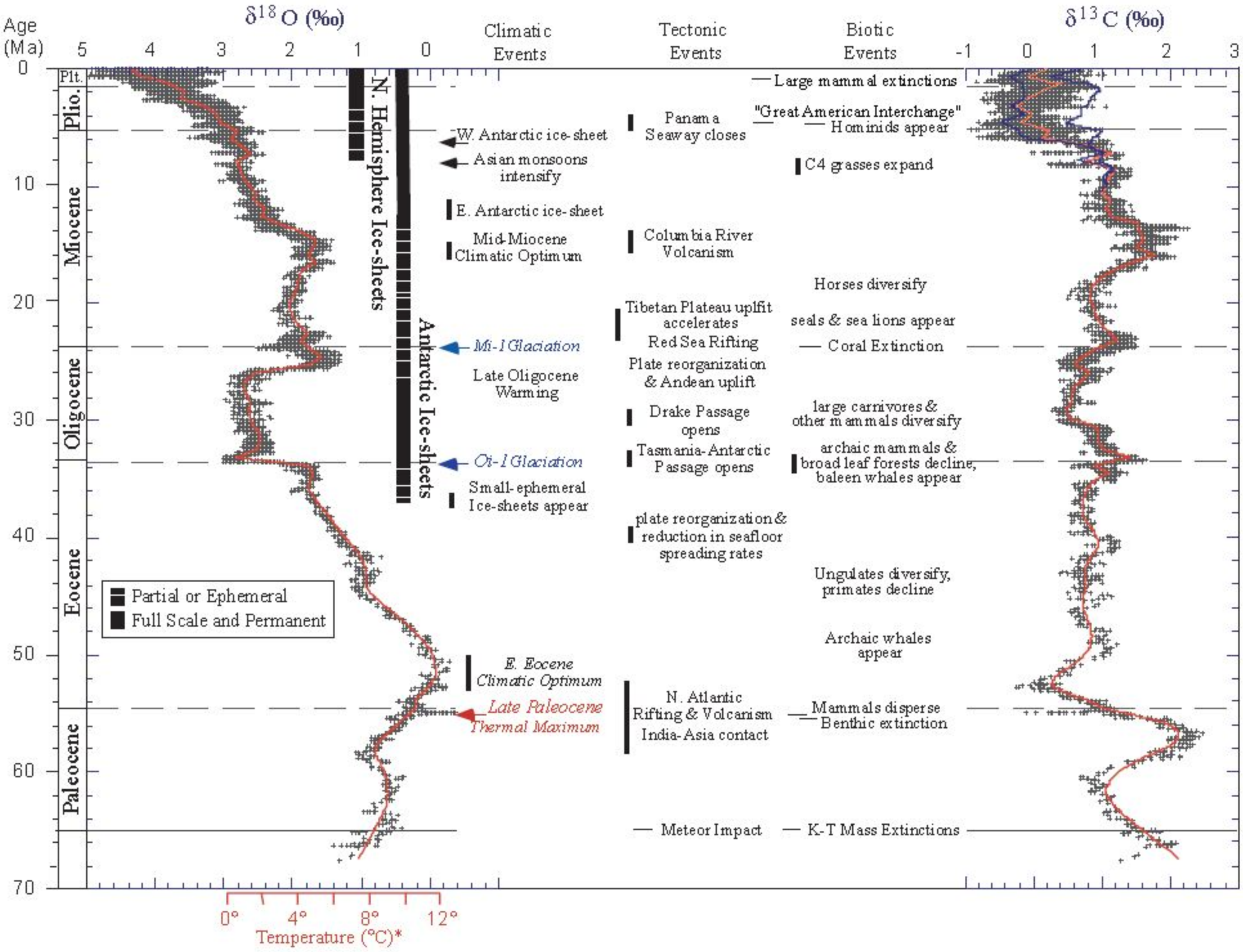

Figure 5: Global deep-sea oxygen and carbon isotope records based on data compiled from 40 DSDP and ODP sites. Note development of the Antarctic ice sheet corresponding with the Tasman Sea and Drake Passage openings despite climatic optimums at Early Eocene, Late Oligocene and Mid-Miocene. Reproduced from Zachos et al, (2001).

Using lithological, paleontological and geochemical properties of New Zealand's sedimentary sequence, Nelson and Cooke (2001) further refine Zachos's theories and apply them to the New Zealand Sector of the Southern Ocean (NZSSO).

Figure 6 illustrates the evolution of the NZSSO from the Eocene (Fig 6a) through to the present (Fig 6f) and shows the change in sea-water temperatures over the Chatham Rise and the propagation of the cold Antarctic front northward.

Figure 6: Evolution of ocean fronts in Cenozoic time (after Nelson and Cooke (2001)). Data derived from analysis of deep-sea drill cores (numbers on figures).

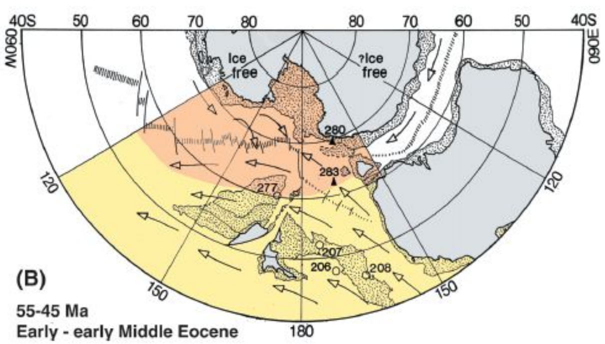

Fig 6a: Ocean temperature high (Early Eocene climatic optimum). Deposition of bio-calcareous oozes.

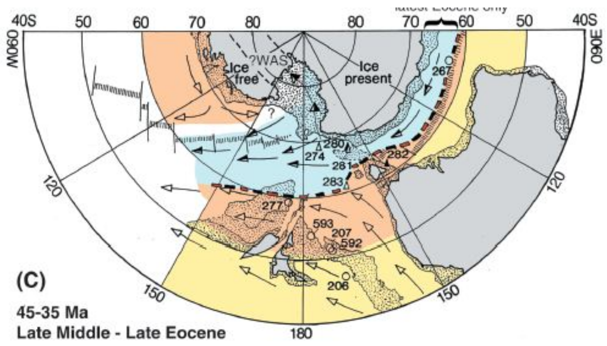

Fig 6b: Cool water flow in Latest Eocene (35Ma) as ice develops in West Antarctica. Tasman Sea begins to leak.

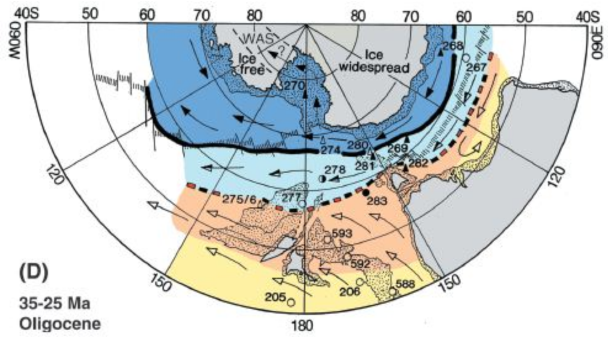

Fig 6c: Ocean temperature over CR still high (Late Oligocene warming). Marshall Paraconformity, island dotted carbonate sequence strong current flows across portions of plateau.

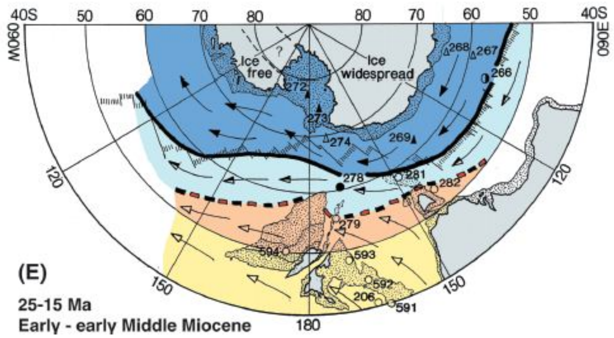

Fig 6d: Opening of the Drake Passage. Ocean temperature high (Mid-Miocene (16Ma) climatic optimum. Proto-subtropical front lies south of CR.

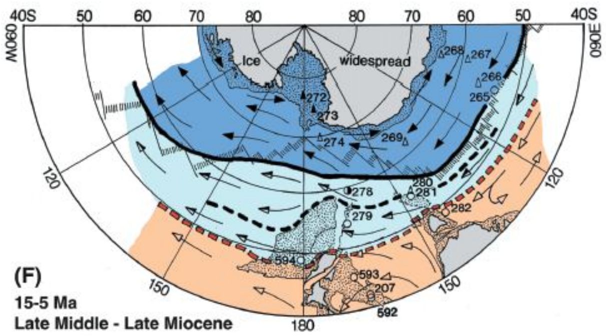

Fig 6e: Chatham Rise becomes zone of intense up-welling. **Formation of the Chatham Rise phosphorite.**
Cool Antarctic current moves northward.

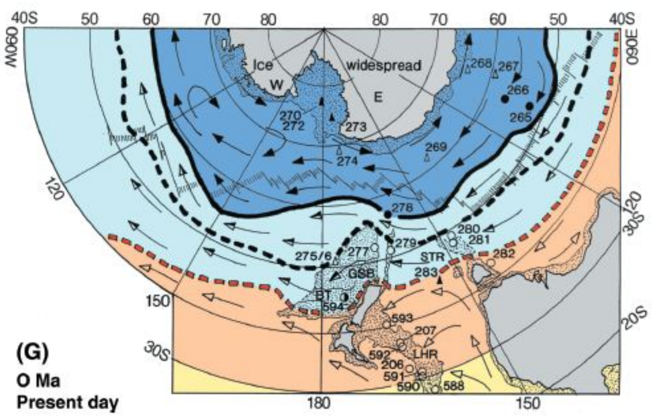

Fig 6f: Ocean temperature configuration essentially unchanged from Miocene.

Conclusions

All Miocene-Recent phosphorites formed in areas of up-welling related to changes in ocean circulation currents and glaciations (Shields, Stille, & Brasier, 2000).

In the case of the Chatham Rise, Late Cretaceous rifting established a block of stable E-W trending landmass which was dominated by warm seas temperature at least since the Eocene (warm water favours the initiation of diagenetic phosphate).

It is proposed that opening of the Pacific sector of the Southern Ocean in the Mid-Oligocene generated a sea-level fall and initiated changes in ocean chemistry and current flow directions south of the Chatham Rise during this time.

A 2–4 Ma hiatus in sedimentation during the mid-Oligocene saw the regional development of the Marshall Paraconformity. This period in New Zealand's geological history is marked by intense biological activity (bio-turbation) and resulted in to low oxygen availability at the sediment/water interface on the Chatham Rise. Pore spaces within the uppermost Oligocene limestone layer became a locus for concentrations of phosphorous as marine organisms metabolised and decayed.

Opening of the Drake Passage in the Early to Mid-Miocene saw the development of the 'polar ocean front' which advanced towards the Chatham Rise as ice sheets developed in the Antarctic.

By Mid-Miocene, the topographic high of the Chatham Rise became a locus for ocean up-welling of the polar waters. This coincided with the Mid-Miocene (16Ma) climatic optimum.

More phosphate was added to the Chatham Rise system as dissolved inorganic phosphate (from weathering of aerial landmasses) was re-introduced to the photic zone by the polar up-welling. The ascent of phosphate-rich waters in regions of upwelling involves a decrease in partial pressure of CO_2, with a consequent rise in the pH, resulting in super saturation of sea water relative to carbonate fluorapatite, and direct inorganic precipitation (Kasakov, 1937). Mineralization can occur at the sediment/water interface or in interstitial pore waters and the concentration of apatite into indurated phosphate nodules was brought about by winnowing and reworking processes (Burnett & Riggs, 1990).

By the Late Miocene, the cool waters of the Antarctic current had propagated northwards over the Chatham Rise and phosphate sedimentation ceased as a response to a cooler, temperate ocean regime which has persisted into recent geologic time.

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