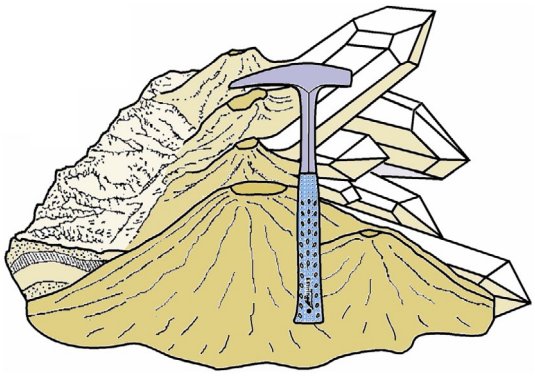


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Editor – This issue of Geocene has been updated. Some images on pages 21–24 have been removed to minimise possible copyright issues. An explanation and reference to each deleted image has been added to its vacant space.

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Geocene is a periodic publication of Auckland Geology Club, a section of the Geoscience Society of New Zealand’s Auckland Branch.

Contributions about the geology of New Zealand (particularly northern New Zealand) from members are welcome. Articles are lightly edited but not refereed.

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REVISITING THE OCCURRENCE OF PALYGORSKITE CLAYS ("MOUNTAIN LEATHER") WITHIN JOINTS IN KING COUNTRY OLIGOCENE LIMESTONES, NORTH ISLAND, NEW ZEALAND

Cam Nelson[1] and Orla Hansen[2]

Palygorskite

Named from the type locality Palygorskaya in the Palygorsk Range, Urals Mountains in Russia, palygorskite is globally a rather uncommon fibrous clay mineral that is reported occasionally within rock tension joints and fault zones, in secondary cave deposits, in alluvial terrace deposits, and in soils with calcic or petrocalcic horizons ("calcretes") (e.g. Singer 1979; Post & Crawford 2007; Churchman & Lowe 2012; Bosák & Zupan Hajna 2018; Soil Survey Staff 2022; Mindat.org 2024). Chemically, it is a hydrated magnesium aluminium phyllosilicate mineral, in its purest form $(Mg,Al)_2Si_4O_{10}(OH).4H_2O$, but like all clay minerals, it can show quite a wide variation in its elemental make up (e.g. Soong 1992; Post & Crawford 2007). Physically, it is distinctive because it forms tough, but flexible and absorbent sheets or mats, a few to ten or more millimetres thick, constructed of asbestos-like, tightly intertwined fibrous crystals. Historically called attapulgite, a name no longer favoured (e.g. Murray *et al.* 2011), and often popularly referred to as 'mountain leather', the mats have a waxy or earthy lustre, and are usually white to grey in colour, sometimes iron-stained pale yellow to light brown on their exterior surfaces. Impurities of other crystals or associated rock minerals and fragments can be incorporated within the palygorskite mat. When in large quantity, the high adsorption, absorption, and thickening properties of palygorskite give it a wide range of environmental, industrial, agricultural, and other economic applications (e.g. Fuchs 2005; Murray *et al.* 2011).

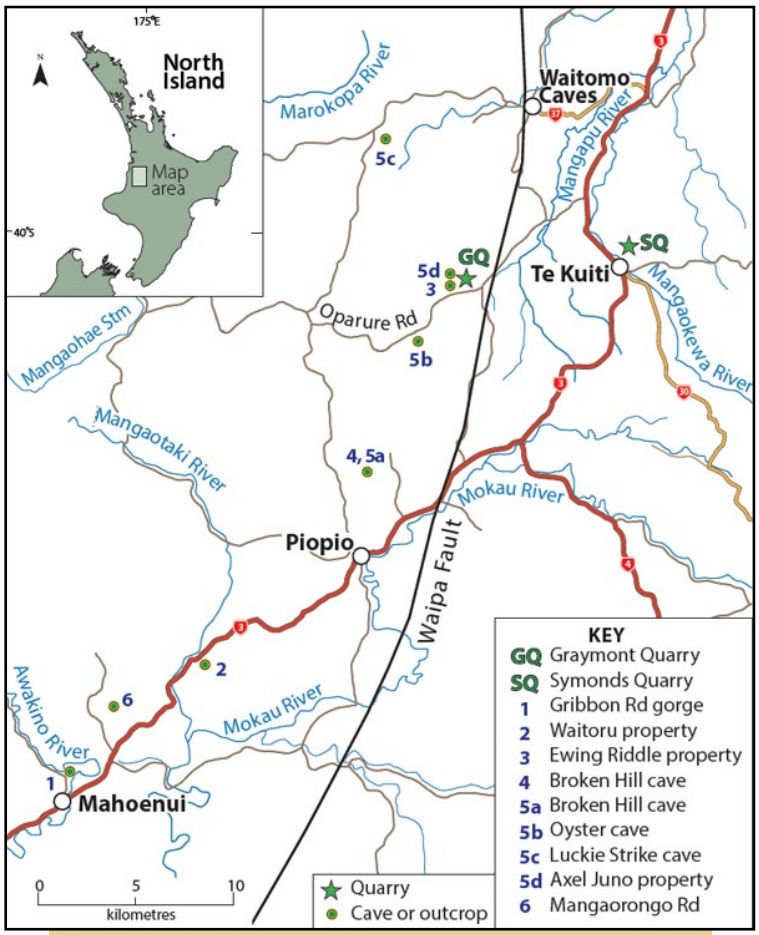


Fig. 1. Locality map for Graymont (GQ) and Symonds (SQ) limestone quarries, and the cave and other locations mentioned in **Table 1**.

Association of New Zealand palygorskite localities with limestones

Reported occurrences of palygorskite in New Zealand are very few and usually associated with carbonate-rich host rocks, such as limestones (Henderson 1921 - who used the now obsolete synonym 'pilolite'; Morgan 1927, p. 80; Hunt 1960; Laird & Donald 1961; Lowry 1964; Soong 1992; Kirkman & Wallace 1994). Minor amounts have also been noted within fault gouge in greywacke at a single Wellington locality (Soong & Perrin 1983) and in schist at Cromwell Gorge, Central Otago (Soong & Bryant 1988).

Of the above seven referenced New Zealand carbonate-associated occurrences, only one is from the South Island, in Northwest Nelson, where small amounts of palygorskite occur sporadically in veins and cavities within the Ordovician Mt Arthur Marble and pink marble lens of the Onekaka Schist Formation (Soong 1992). The other six reported New Zealand carbonate-related palygorskite localities (**Table 1**) are all from Oligocene limestones of the Te Kūiti Group in the King Country region of central western North Island (**Fig. 1**), namely the Orahiri and Ōtorohanga Limestone formations (Nelson 1978a), which are the host rocks for many underground caverns, including the world-renowned Waitomo Caves (e.g. Williams 2004). None of the six published records in **Table 1** give field illustrations of the palygorskite occurrences in the Te Kūiti limestones, although Kirkman & Wallace (1994) did include an image of a small, corrugated sheet of palygorskite from the regolith atop an Orahiri Limestone exposure, which they suggested was tightly buckled because of volume reduction of the limestone associated with calcite leaching in the soil zone. They also included two SEM pictures that demonstrated the fibrous morphology of the palygorskite crystals.

Here we note the geological setting, nature, and possible origin of the palygorskite clays that occur within some of the joints observed in both outcrop and boxed drill-core

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Table 1. Published mentions of palygorskite occurrences in limestones in the King Country region of North Island. Localities 1 to 6 shown on **Fig. 1**. We emphasise that given the scattered expanse of these localities throughout the region it is inevitable that the occurrence of palygorskite in joints within the Te Kūiti Group limestones is far more common than recorded here, and largely subsurface and hidden.

Authors	Locality	Comment
1. Henderson 1921	About 2 km north of Mahoenui in limestone gorge of Awakino River on Gribbon Rd	Suggested the name 'pilolite' – new to NZ
2. Morgan 1927	As for 1; also "Waitoru" property of Mr J Wall, near SH3 about 10 km SW of Piopio	In both cases, used the name pilolite (following 1)
3. Hunt 1960	Cave on Ewing Riddle property opposite Troopers Rd (near present Graymont Quarry site)	Suggested a variety of asbestos called 'mountain leather'
4. Laird & Donald 1961	Broken Hill Cave on Mangakowhai Rd, north of Piopio (approx. N83/558687)	Used the name 'mountain leather'
5. Lowry 1964	Broken Hill Cave (as for 4); also mentions Oyster Cave (50 m N of junction of Waitepipi Rd and Oparure Rd), Luckie Strike cave (W of Waitomo Caves), and cave on Axel Juno property (on present Graymont Quarry site)	First to use name palygorskite as belonging to the 'Palygorskite (Attapulgite) group' of clay minerals
6. Kirkman & Wallace 1994	Bulldozed regolith over limestone about 6 km north of Mahoenui between SH3 and Mangaorongo Rd (approx. N91/402561)	Used name palygorskite

samples of the Ōtorohanga Limestone at the Graymont Ōparure (formerly McDonald's) Lime Quarry, New Zealand's largest (67 ha) single lime quarry, located off Ōparure Road (NZ Topo 50 BF33 1:50 000 Te Kūiti - Grid ref BF33/807547), due west of Te Kūiti township (**Fig. 1**). We mention also another similar palygorskite occurrence at nearby Symonds (Lime) Quarry (BF33/885565) sited next to the southern portion of Sommerville Road, immediately north of Te Kūiti township (**Fig. 1**). Compared to most natural and vegetated karstic landscapes and underground cave situations, actively working quarries afford excellent fresh and accessible exposures of a limestone body and its fracture and joint patterns, and so provide a clearer overall picture of the geological/stratigraphic setting of the rocks containing occasional palygorskite examples.

Limestone joints and their infills

Joints are natural fractures in rocks resulting from tensional tectonic movements associated particularly with their post-burial uplift. Unlike faults, joints do not show offset of strata either side of a fracture surface, and in sedimentary rocks like limestones most are developed roughly perpendicular to bedding directions.

Master joints in the 60–90 m thick Ōtorohanga Limestone at the Graymont Quarry appear as near vertical, seemingly continuous fractures spaced about 1–5 m apart, partitioning the limestone body into *in situ* sub-blocks, while more minor joints might occur at about 0.1–0.5 m spaced intervals (**Figs 2A, 3A**). Their orientations approximate that of a significant fault through the quarry, sub-parallel to the nearby major Waipa Fault (**Fig. 1**), suggesting they are all likely to be part of the same tectonic stress field accompanying uplift (Hansen 2008). While many of the joints are quite tight and lack any obvious infill material other than a superficial rusty wall stain of hydrated iron oxide ("limonite"), others include combinations of clay to sand-sized material comprising highly variable amounts of the minerals smectite, palygorskite, calcite, quartz, and feldspar, as identified in X-ray diffractograms (XRD; Hansen 2008). A broadly similar situation exists at the Symonds Quarry locality (**Fig. 2B**).

The palygorskite of interest here appears as papery to mat-like sheets on some of the vertical joint surfaces (**Fig. 3B**) and is positively identified in short XRD scans of air-dry powder samples by diagnostic peaks at about 10.4–10.5 Å (1.04–1.05 nm) and 6.4 Å (0.64 nm) (Soong 1992; Hansen 2008; Mindat.org 2024). Hansen (2008) determined the palygorskite abundance infilling selected joints, logged in seven sections of boxed drill cores at Graymont Quarry, to range from a few to about 40 wt% (av. 11 wt%). Examples of palygorskite sheets extracted from outcrop joint surfaces are shown in **Figs 4A & C**, while an SEM image in **Fig. 4B** reveals a chaotic tangle of palygorskite fibres building the mat shown in **Fig. 4A**. We have not conducted a full chemical analysis of the palygorskite from the Oligocene limestone joints, but an SEM energy dispersive analyser yielded for one sample strong elemental peaks for Ca, Si, Mg, O, S and Fe (Hansen 2008, p. 435), while partial palygorskite analyses from other King Country cave and outcrop limestone

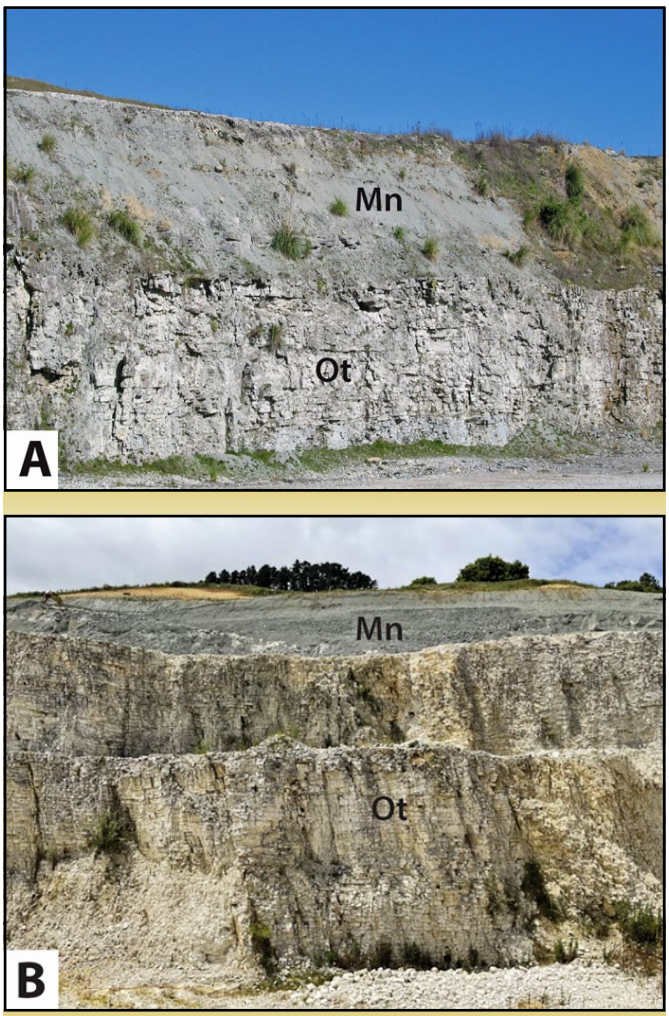


Fig. 2. The upper portion of the Ōtorohanga Limestone (Ot) and the overlying Mahoenui mudstone (Mn) at the Graymont **(A)** and Symonds **(B)** quarries. Note the prominent master joints in the limestones, the occasional hosts of mats of palygorskite clays.

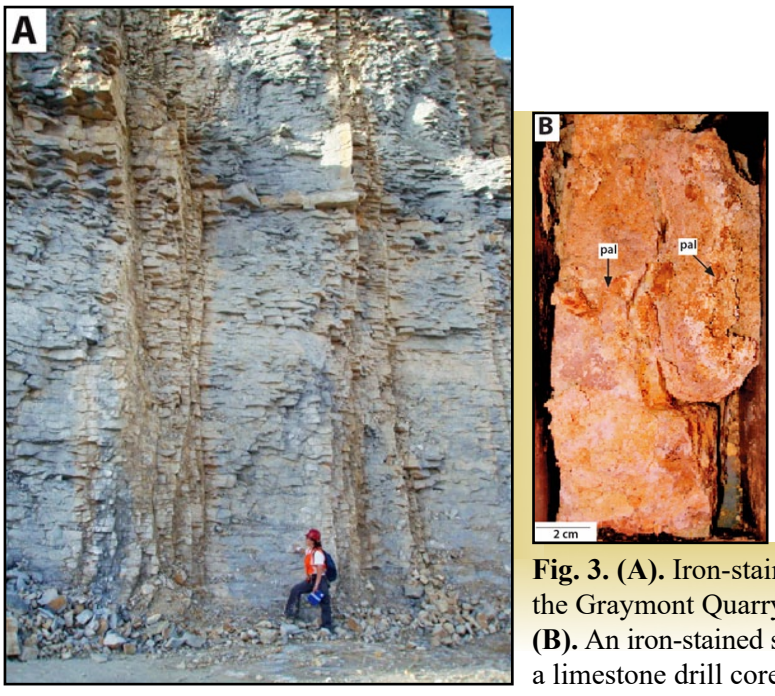


Fig. 3. (A). Iron-stained master joints in the flaggy Ōtorohanga Limestone at the Graymont Quarry.
(B). An iron-stained sheet of palygorskite (pal) on the face of a joint surface in a limestone drill core (BH503, box 21, 64 m depth) from Graymont Quarry.

localities reported by Henderson (1921), Lowry (1964), and Kirkman & Wallace (1994) confirm their anticipated elevated MgO content, in the range of 6.4–9.5 wt%.

Discussion

Oligocene host limestones

The King Country limestones of the Te Kūiti Group began life as bryozoan-bivalve-echinoderm-foraminifera-rich skeletal carbonate sediments that accumulated in the late Oligocene at temperate latitudes in a tidal current-dominated seaway (Anastas *et al*. 2006). Nelson *et al*. (1988a) showed that the lithification of these skeletal-rich temperate carbonate sediments into hard limestones occurred mainly from the precipitation of calcite cement in pore spaces during their burial from about 600–1100 m below the sea floor. This was the sub-bottom depth range over which pervasive pressure-dissolution of calcitic skeletons in the deposits took place, releasing dissolved carbonate available for calcite cementation (Nelson *et al*. 1988a). The post-Oligocene subsidence and burial of the Te Kūiti Group deposits was accomplished throughout the Miocene by accumulation of very thick (1,000–2,000 m) sequences of mainly deep-water terrigenous sediments, dominated by slope mudstones and redeposited sandstones (e.g. Nelson & Hume 1977; Kamp *et al*. 2004). Of these, it is the several 100-m-thick mudstones of the Early Miocene Mahoenui Group that stratigraphically directly overlie the Te Kūiti Group limestones in the King Country (e.g. **Fig. 2**).

Limestone joints

The joints in the Oligocene limestones formed during their post-lithification uplift and exhumation, long after burial cementation. Kamp *et al*. (2004) suggested that uplift was a consequence of tectonic doming of central North Island that began and continued throughout the Pliocene (5.3–2.6 Ma) and amounted to a maximum uplift of about 2000 m across the King Country region. During the Quaternary the uplifted Mahoenui and Te Kūiti Group rocks would have become progressively subjected to the influence of increasing incursions of subsurface meteoric waters, especially so along fractures like joints, and eventually to variable degrees of full subaerial exposure and erosion (e.g. Williams 2004).

Age of palygorskite formation

The sheet-like form of the sporadic palygorskite mats within some joints indicates their formation post-dates both joint development in, and therefore lithification/cementation of, the limestones. An early suggestion from Nelson (1978b) that cementation of these kinds of New Zealand limestones occurred mainly in the shallow subsurface under low-burial conditions led Kirkman & Wallace (1994) to postulate that the joint palygorskite in the Te Kūiti limestones could have

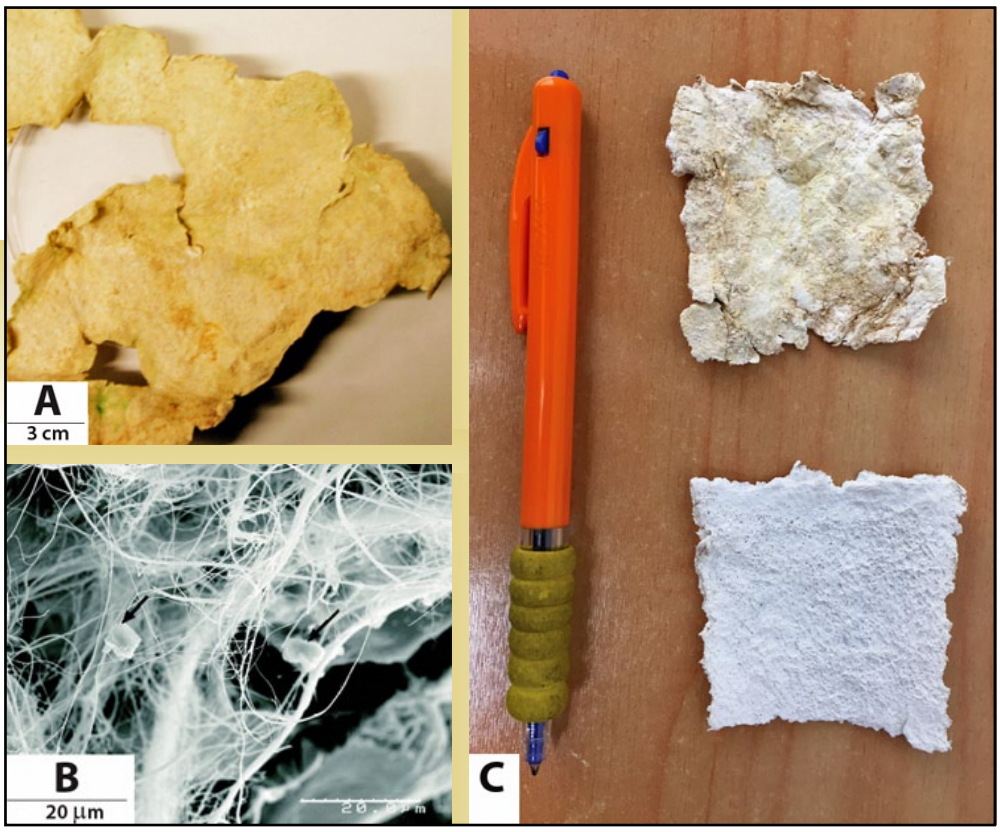


Fig. 4. Portions of palygorskite mats extracted from joints in the Ōtorohanga Limestone at Graymont (A) and Symonds (C) quarries, and an SEM image (B) of entangled palygorskite fibres including a pair of calcite crystals from the mat in A.

developed very soon after this and prior to uplift, implying an early Miocene age for the palygorskite. But Nelson *et al*. (1988a) subsequently revised the shallow burial lithification scenario to a much deeper burial one, as noted above, and we postulate that palygorskite development is solely a Quaternary phenomenon that followed Pliocene uplift of the limestones into the subaerial realm. We know that karstification and cave formation in the limestones was underway by the early Pleistocene, as shown by the preservation in some caverns of dated pyroclastic deposits, including the 1.55 Ma Ngaroma Ignimbrite and 1 Ma Kidnappers ash (Williams 2023; Suresh *et al*. 2025). Other younger tephra accumulations (e.g. Rangitawa Tephra 349 ka) and a wide range of speleothem ages (535 ka to mainly <200 ka; Suresh *et al*. 2025) indicate that freshwater incursions and cave developments continued throughout the mid- to late-Pleistocene. Consequently, we favour that the localised formation of palygorskite in joints is associated with the Quaternary incursion of freshwater into the limestones.

Required Mg source

Kirkman & Wallace (1994) suggested that the necessary source of Mg for palygorskite formation in the Te Kūiti Group limestones could have come from the alteration in the carbonate deposits of diagenetically unstable high-Mg calcite skeletons to stable low-Mg calcite ones. But in temperate-latitude shelly carbonates such as the Te Kūiti Group deposits (e.g. Nelson 1978b), low-Mg calcite skeletons most likely already dominated the primary skeletal mineralogy. Also, diagenetic degradation of any high- to low-Mg calcite via incongruent dissolution of Mg typically occurs in non-tropical carbonates soon after their deposition, on or close below the sea floor (e.g. Nelson 1978b; Alexanderson 1979; Lewy 1981; Nelson *et al*. 1988b; Smith & Nelson 1994; James 1997), certainly well before wholesale burial lithification of the sediments into cemented limestone. So, at least in our case, a Mg supply for palygorskite formation from the conversion of high- to low-Mg skeletal calcite is highly improbable.

Unless now removed by subaerial erosion, everywhere throughout the King Country the Oligocene limestones are overlain directly by thick deep-water mudstone deposits of the Early Miocene Mahoenui Group (**Fig. 2**). The Mahoenui mudstones are clay mineral-rich (40–50 wt%) and overwhelmingly dominated by expandable smectite (montmorillonite) clays (Nelson & Hume 1977; Hume 1978). Swelling and shrinking of these clay minerals during wetting and drying climatic conditions is responsible for significant cracking and frittering of the host Mahoenui mudstones in field exposures, which are consequently very prone to water infiltration and slumping (e.g. Chandler 1978; Basher 2013). Hume (1978) showed that the smectites are dioctahedral varieties having Ca and/or Mg as their main exchangeable cations, and a chemistry dominated by SiO_2 (59.8 wt%), Al_2O_3 (19.1 wt%), $FeO+Fe_2O_3$ (8.3 wt%), MgO (2.9 wt%) and CaO (1.5 wt%). We speculate that the Mg and other soluble elements (such as Si, Al, Fe) required for palygorskite formation (e.g. Singer 1989, 2002) could have come from the selective leaching and breakdown of mineral constituents, including especially smectite, by subsurface waters percolating down through the thick sequences of Early Miocene mudstones overlying the limestones (Nelson & Hume 1977; Hume 1978). Notably, an associated cause-and-effect relationship between smectite

transformation and palygorskite development is reported from many calcic-dominated soil profiles (e.g. Khormali & Abtahi 2003; Owliaie *et al*. 2006; Bouza *et al*. 2007; Kadir & Eren 2008).

Environmental setting for palygorskite development

The formation and persistence of palygorskite is favoured from solutions characterised by having an alkaline pH, high concentrations of Mg and Si, and low Al activity (e.g. Singer 1979, 1989). Reported environmental settings experiencing such conditions can be diverse and include: (a) in shallow marine deposits adjacent to landmasses experiencing intense chemical weathering or associated with hydrothermal activity; (b) in inland lake deposits and soils from semi-arid and arid regions; and (c) associated with cave deposits or carbonate rocks of various kinds (e.g. Callen 1984; Singer 2002; Bosák & Zupan Hajna 2018). Of these, only (c), the carbonate setting, accords well with our situation for the partial fills of palygorskite in some of the joints in the Ōtorohanga Limestone at the Graymont and Symonds quarries, as well as the limestone cave occurrences elsewhere in the King Country (**Table 1**, **Fig. 1**).

Discussing overseas carbonate host-rock situations, Bosák & Zupan Hajna (2018) noted that palygorskite in limestone fissures could either be blown or washed into the fissures (i.e. allogenic or detrital palygorskite) or result from *in situ* chemical precipitation from percolating meteoric solutions with suitable pH and redox conditions and chemical composition (i.e. authigenic or neoformed palygorskite). In our case we are dealing solely with the latter situation of chemically precipitated authigenic palygorskite.

Interestingly, one of the conditions apparently favouring palygorskite development, certainly in petrocalcic-bearing soils, relates to the accumulation of water at strong textural transitions in a profile, thereby maintaining a saturated solution that fosters precipitation of palygorskite at and close below such boundaries (e.g. Singer 2002; Churchman & Lowe 2012). Regionally, the contact between the hard Te Kūiti Group limestones and the overlying soft Mahoenui Group mudstones fits well the definition of a strong textural transition. In the field (e.g. **Fig. 2**; Nelson 1977), the boundary is striking, typically sharp and often recessed a bit because of easier erosion of the mudstone, and the basal zone of mudstone is often damp from the downward percolation, accumulation, and slow seepage of groundwaters. We conclude that the primary source of chemical elements required for the selective precipitation of authigenic palygorskite has come from Quaternary ground waters seeping into some of the more permeable limestone joints after becoming charged with the necessary soluble constituents, including Mg, Fe, Al, and Si, derived from leaching and breakdown of especially smectite clay minerals in the overlying Mahoenui mudstones.

Acknowledgements

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HOCHSTETTER WAS UNIMPRESSED – COAL AT WHANGAPARĀOA

Bruce W. Hayward

In early January 1859, Ferdinand Hochstetter was requested by the New Zealand Government to stay on in New Zealand, and particularly in the Province of Auckland, to "*extend his researches for a few months longer*" and the government would provide the required financial support (Hochstetter 1867, p. 28). He recognised he would not have time to visit and map the geology everywhere, and so on January 10 he had a notice placed in the papers, calling for settlers to send in rock specimens for him to examine (Nolden & Hayward 2023). As a result, on February 15, a Mr McMillan brought in large lumps of coal from Whangaparāoa.

Hochstetter had his heart set on taking a major expedition to the centre of the North Island to see the large volcanoes that Sir George Grey had told him about when Hochstetter had been visiting the Cape of Good Hope, where Grey was Governor. He was desperate to get away as cooler months were coming, but on March 1 he wrote in his diary (Nolden & Hayward 2023) "*I was at Whitaker's in the morning with my maps; the minister expressed his wish to visit Whangaparaoa before my journey south, to report on the coal McMillan had brought from there. I had to agree to this and the trip south was thus postponed for a few days.*" Frederick Whitaker was Attorney General of New Zealand (based in Auckland) and the minister was particularly keen that Hochstetter assess the resources around Auckland in the hope of finding valuable rocks, like more coal. Hochstetter's first task on arrival in Auckland had been to assess the coal resources at Drury.

On the following day (March 2), Hochstetter sailed on Captain Burgess's cutter from Auckland to the south side of Whangaparāoa Peninsula. In his diary Hochstetter wrote "*We walked across the peninsula, then along the beach, and found very hospitable quarters at noon in Mr Campbell's house - a simple thatched house. Captain Burgess returned to Auckland that evening … we slept in the small settler house.*" There is no mention of what he did in the afternoon but I suspect the tide came in and that prevented access to where McMillan had found the coal lumps.

Next morning, when the tide was low (March 3), "*Mr Campbell accompanied us to the spot on the north shore of Whangaparāoa from where Mr McMillan brought the coal.* ***I convinced myself that there was nothing here but driftwood turned into coal*** *... From there only eight miles to Mr Kelly's Farm on the Great Northern Road, but I have never found so difficult a walk of such insignificant distance, nothing but beach, and from the beach across the poorest fern steppes.*" (Nolden & Hayward 2023).

In his diary, Hochstetter made no other comment on the geology of the area, but in his 'Geology of New Zealand' (Fleming 1959, p.47) he gave a brief account and interpretation of what he saw: "*many large and small angular fragments of fine glossy brown coal that are found on the tidal platform at the foot of the cliff, enclosed in a fine-grained muddy sandstone. These occurrences have given cause for the erroneous opinion that a coal seam crops out here. Near the coal fragments were found several pieces of driftwood altered to coal. What is preserved here is not a continuous coal seam but only pieces of a shattered seam interbedded in younger marine sediment.*" This suggests that Hochstetter must have also kept notes on the geology he saw in addition to his diary.

Gregory (1969), who studied the geology of Whangaparāoa Peninsula, made no mention of this exposure. Auckland Libraries Research posted on their Facebook Page on 18 October 2021: "*Around 1860, surveyors discovered brown coal deposits along the bay. They made several bores, but not enough coal was extracted to justify investment. By 1900, the coal had fallen into myth and some locals didn't believe it had ever existed. However, James Graham of the Kia Ora House at Arkle's Bay brought a sample to the Auckland Star's offices in 1909. The staff was impressed. They speculated that several seams must crisscross the Whangaparaoa Peninsula and noted other discoveries in the area. Yet coal was never commercially mined on the peninsula.*"

Auckland Geoclub has taken two field trips to Coalmine Bay (in 2008 and 2026) (**Figs 1 & 2**) to look for and examine the exposure described by Hochstetter where McMillan collected his coal lumps. This occurs at the east end of the Coalmine Bay beach. We saw nothing that convinced us that there was any coal seam or even "*a shattered coal seam broken into pieces*". Many lumps

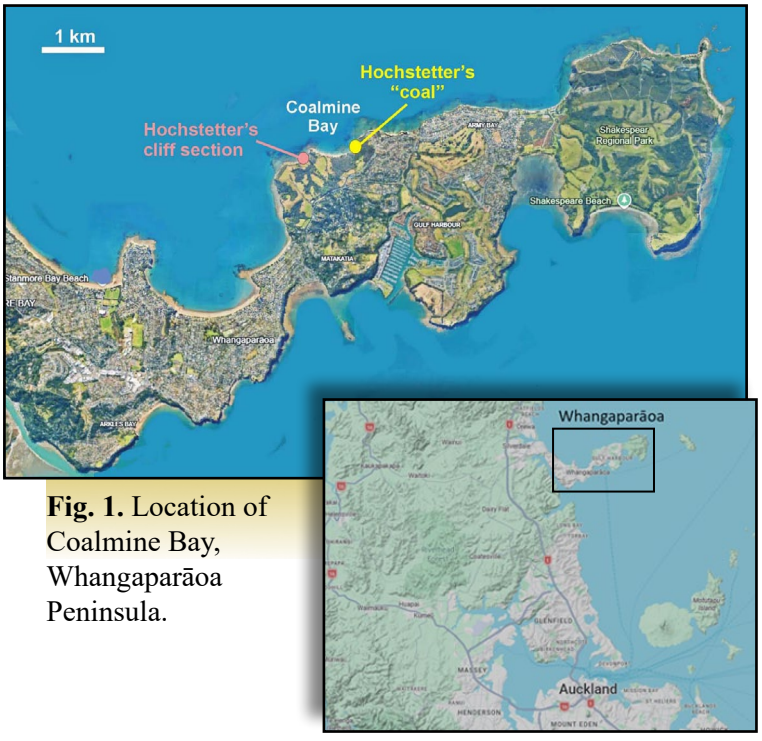


Fig. 1. Location of Coalmine Bay, Whangaparāoa Peninsula.

looked like slightly flattened, elliptical sections through black carbonised logs (**Fig. 3**), and pieces of branch and twig (**Fig. 4**) buried within the upper parts of a ~1 m thick sandstone turbidite (**Fig. 5**). The largest logs and pieces of carbonised wood occur in the upper 20–30 cm of the sandstone, whereas most of the smaller branches, twigs and pieces of wood occur in a ~5–10 cm-thick layer on the top of the sandstone bed (**Fig. 6**).



Fig. 2. East end of Coalmine Bay where the layer of carbonised wood (Hochstetter's "coal") occurs in a sandstone bed just beneath this distinctive sandstone with rippled mudstone horizons. Photo width 4 m.



Fig. 3. Elliptical sections through two party squashed carbonised logs at the top of the sandstone turbidite, Coalmine Bay. Width of photo 1 m.



Fig. 4. 5–10 cm-thick layer of short pieces of branchlets at top of sandstone turbidite bed. Width of photo 60 cm.

The modern interpretation of the sandstone beds in the Waitematā Sandstones around Auckland is that they were deposited by turbidity currents that flowed down the submarine slopes of the Waitematā Basin from shallow water and were deposited in deep water on the floor of the marine basin (Ballance 2017). Black carbonised fossil plant material occurs sporadically throughout the Waitematā outcrops and almost everywhere it is located in the uppermost parts of a sandstone turbidite bed. From this, I infer that the carbonised wood in the Waitematā Sandstones was predominantly carried down into deep water within the turbidites. One possibility is that this wood material was already water-logged and had sunk to the seafloor in shallow water and possibly had been buried within the loose sediment prior to triggering of the turbidity current. Another possibility is that much of the wood material had been carried into the sea by rivers during a large rainstorm and may have been incorporated into a turbidity current that might have been triggered by the storm.



Fig. 5. Upper portion of sandstone turbidite bed, Coalmine Bay, showing larger wood chunks below a layer of smaller woody branches and twigs at the top of the bed. Width of photo 1.5 m.



Fig. 6. 1 m-thick sandstone bed (lower half of photo) with carbonised wood at the top and overlain by laminated sandstone turbidite bed.

No matter what the time relationship was between the wood delivery and turbidity current, the presence of the wood in the upper parts of the sand turbidite deposit can be explained by the wood having a lower density than the sand and therefore it dropped out from the turbidity current later than most of the sand. The larger logs dropped out first and the smaller pieces possibly stayed in suspension for some time after the turbidity current carried them down before they became sufficiently waterlogged to fall to the deep sea floor.

There are a few larger single carbonised logs elsewhere within the Waitematā Sandstones in places like Takapuna Head, but the Coalmine Bay locality probably has the largest concentration of large and small pieces of wood in a single turbidite than anywhere else in the Waitematās. I agree with Hochstetter's interpretation of some of the wood being driftwood except that I would infer that all the black lumps at Coalmine Bay was at some point driftwood (**Fig. 7**).



Fig. 7. Plan view of part of the carbonised wood horizon within the sandstone turbidite bed at Coalmine Bay. All these large pieces are clearly wood but they could be mistaken for parts of a thin coal seam as was done by Hochstetter. Width of photo 2 m.

In his 'Geology of New Zealand' (Fleming 1959, p. 46), Hochstetter figured a section of cliff on the north coast of Whangaparāoa Peninsula (**Fig. 8**). This is not the cliff section in which the "coal" occurred but it appears to be a stylised interpretation of the cliff section located about 800 m to the west (**Fig. 1**), around the point and out of sight from Coalmine Bay.

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Fig. 8. Ferdinand Hochstetter's field sketch of Waitemata Group strata on the north side of Whangaparaoa Peninsula, visited by him on 3 March 1859.

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FIRST RECORD OF A FOSSIL LICHEN FROM NEW ZEALAND

Ian J. Geary[1] and Bruce W. Hayward[2]

A small fossil foliicolous (grows on leaves) lichen belonging to the family Strigulaceae is reported from Late Pliocene (3.8–2.9 myr) leaf beds at Beachlands, Auckland. This is the first recorded fossil lichen from New Zealand.

Introduction

Soft, fossil-plant-rich estuarine sedimentary rocks are exposed in the low cliffs and foreshore at Beachlands, east Auckland, opposite Motukaraka Island (**Figs 1, 2**). These plant fossils (especially leaves, fruits, mosses and fungi) were the subject of recent Honours and PhD theses

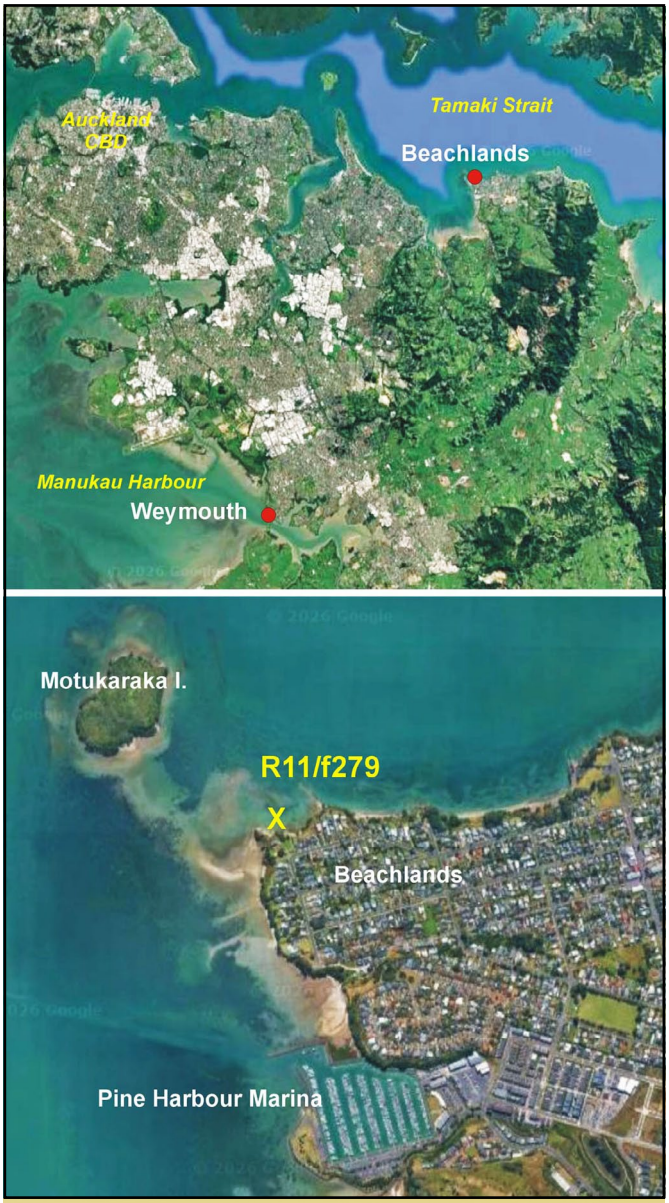


Fig. 1. Upper. Location of Late Pliocene fossil localities at Beachlands and Weymouth.
Lower. Map of Beachlands area showing location of the fossil site (R11/f279) where the fossil lichen was collected.



Fig. 2. Source area (circled) for Late Pliocene leaf beds containing the fossil lichen at Beachlands Beach, Auckland.

by one of us (Geary 2015, 2022). While undertaking lab work in 2017, I.J.G. came across a small piece of fossil plant among leaf beds from Beachlands (NZ Fossil Record File site R11/f279). He did not recognise the material and so photographed it (**Fig. 3**) and sent the image to several botanists plus his doctoral advisor B.W.H., who immediately recognised its similarity to the foliicolous lichen genus *Strigula* (**Fig. 4**), which he had collected many times during his lichen studies around New Zealand over many decades, particularly in the 1970s–1990s.

Fossil lichen

The fossil (University of Otago, Geology Museum, OU36643) was ~2.5 mm across and embedded in fine sandstone. It consisted of seven black, hemispherical bodies, some



Fig. 3. View of the underside of the inferred fossil foliicolous lichen of *Strigula* s.l. from the Late Pliocene.

[1] University of Otago, 362 Leith St, Dunedin North, Dunedin
[2] Geomarine Research, 19 Debron Ave, Remuera, Auckland

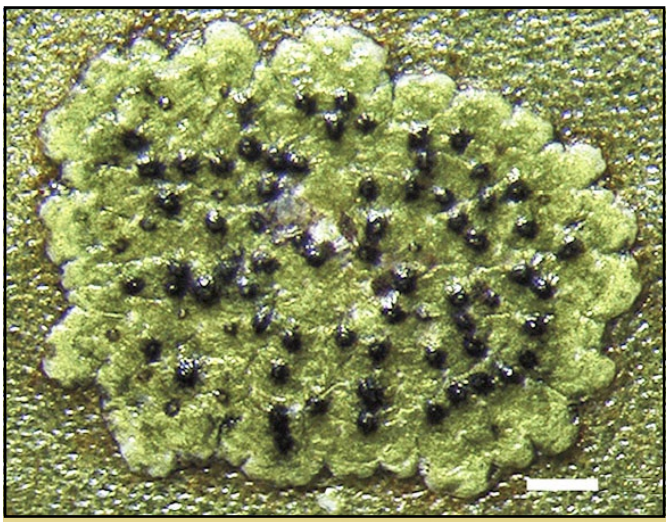


Fig. 4. A large live foliicolous lichen *Strigula* attached to a leaf. Scale 1 mm. Photo: Wikicommons.

with an open pore (probable ostiole) at the apex. They are clustered tightly together similar to the perithecia in some specimens of *Strigula*. There is a hint of possible brown thallus between and around some of the perithecia. This specimen seems to be the underside of the perithecia and this would be consistent with it having been attached to the surface of a leaf, which has peeled off before or during examination. The fact that this fossil comes out of beds packed full of fossil leaves, many of which are identified as extinct-large leaved southern beech of the *Nothofagus* subgenus, *Brassospora*, would be consistent with the identification of this fossil as a foliicolous lichen. Unfortunately, attempts to dissect a perithecium in the hunt for confirmatory structure and spores was unsuccessful as the specimen was too hard and brittle.

Discussion

Obtaining an age for these carbonaceous sedimentary rocks has been challenging as most spores and pollen extracted from the sediment (Fossil Record Numbers R11/f259, f260) are reworked from the underlying early Miocene Waitematā Group sediments that were eroding at the time. A near identical suite of mostly extinct plant fossils has also been worked up from Weymouth Beach, Auckland (Geary 2022). Here the estuarine plant-rich beds interfinger with shallow marine sediments containing a rich molluscan fauna (as casts and moulds). The presence of distinctive molluscan taxa at Weymouth dates the strata as Late Pliocene (New Zealand Waipipian Stage, 3.8–2.9 myrs old, Clowes *et al*. 2026) – the same as a similar even richer molluscan fauna obtained from subsurface excavation nearby at Māngere (Hayward *et al.* 2023).

Fossil lichens are extremely rare globally with more than 95% of the ~170 unambiguous lichen fossil taxa having been preserved in amber from Europe (e.g. Kaasalainen *et al.* 2017). The present specimen appears to be the first fossil lichen from New Zealand and possibly the second recognised fossil foliicolous lichen recorded anywhere. Sherwood-Pike (1985) argued that the Eocene foliicolous fungal genus *Pelicothallos* from the USA is most probably a junior synonym of the lichen genus *Strigula*. Today there are sixteen extant species of *Strigula* s.l. in New Zealand and they are relatively common growing on the leaves of a number of native trees, especially tawa, taraire and titoki (*Beilschmiedia tawa, B. tarairi, Alectryon excelsus*) (e.g. Hayward *et al*. 1986; Sérusiaux 1998; Galloway 2007). No *Beilschmiedia* leaves have been recognised in the fossil leaf beds from Beachlands but some *Alectryon*-like cuticle has been identified (Geary, 2022).

Recently, Jiang *et al.* (2020) have used molecular sequencing and morphological characters, especially of the fungal spores and thallus, to subdivide the global foliicolous species of *Strigula* s.l. into six clades, which they formalised as genera. Since our fossil lacks spores or much thallus, we are unable to assign it to any of these genera and it is best referred to as Strigulaceae or *Strigula* s.l.

Acknowledgements

I.J.G. thanks his supervisors Daphne Lee, John Conran and Janice Lord for their encouragement and advice during his PhD research. We thank Jennifer Bannister for comments that have improved the MS.

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REMUERA FEAST REVISITED

Jill Kenny

Flicking through the New Zealand Listener (April 11, 2026), I came across an article by Eric Frykberg (Frykberg 2026) with a painting that I instantly recognised – or thought I did. I remembered that many years ago, Geoclub member, Malcolm Simpson – well known as the discoverer of Cobb Valley's Trilobite Rock (Mason & Watters 1999, Hayward & Grenfell 2024) – had written an article about a painting of a Māori feast in Remuera, Auckland. I found it in Geocene 12 - Simpson (2015) with an additional note in the Geocene Index – (conundrum on the location of a Māori feast, determined by positions of volcanoes in the background of a lithograph).

I investigated the article and found the familiar painting at the bottom of the first page (**Fig. 1**). But it was different.

Quickly scanning the text, I realised that the painting in his figure 1 was an enhanced lithograph, whereas the painting in the Listener is what Simpson referred to as – but did not show – 'the original watercolour sketch'.

As Geocene Editor, even back then, I remember puzzling over this lithograph for some time, trying to reconcile the position of the feast. In the end, I went with what Malcolm Simpson had decided. Back then, I didn't have the luxury of the greatly improved Google Maps oblique views available today, and I didn't see the original watercolour – I had assumed it was more-or-less identical to the lithograph.

But they are not the same at all. **Fig. 2** shows a clear contrast. I include (below) excerpts from Malcolm's analysis

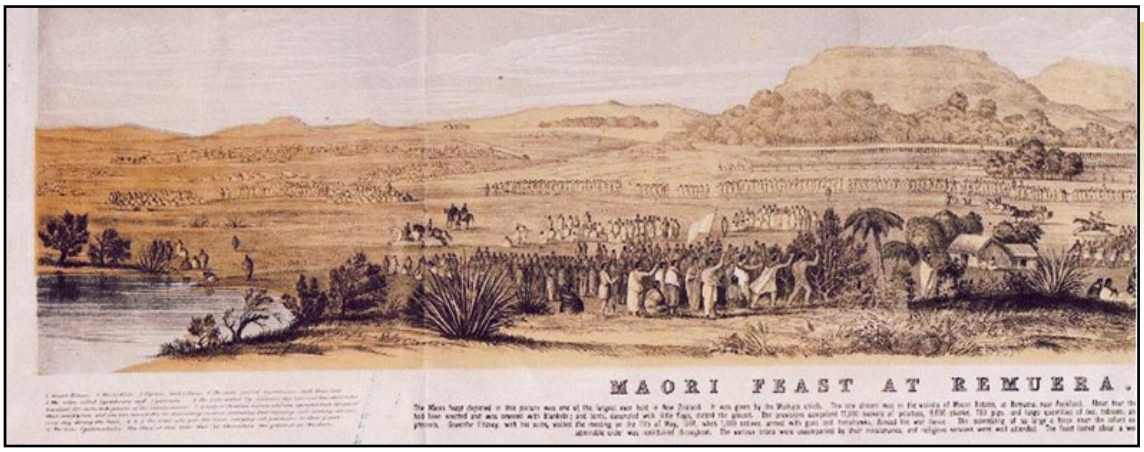


Fig. 1. Figure 1 from Simpson (2015) with caption - "*Brett's Almanac 1890 enhanced* ***lithograph*** *of the Feast (detail) showing prominent hill, named Mt Hobson, with Mt Eden in rear right.*" Labels are not visible at this scale.

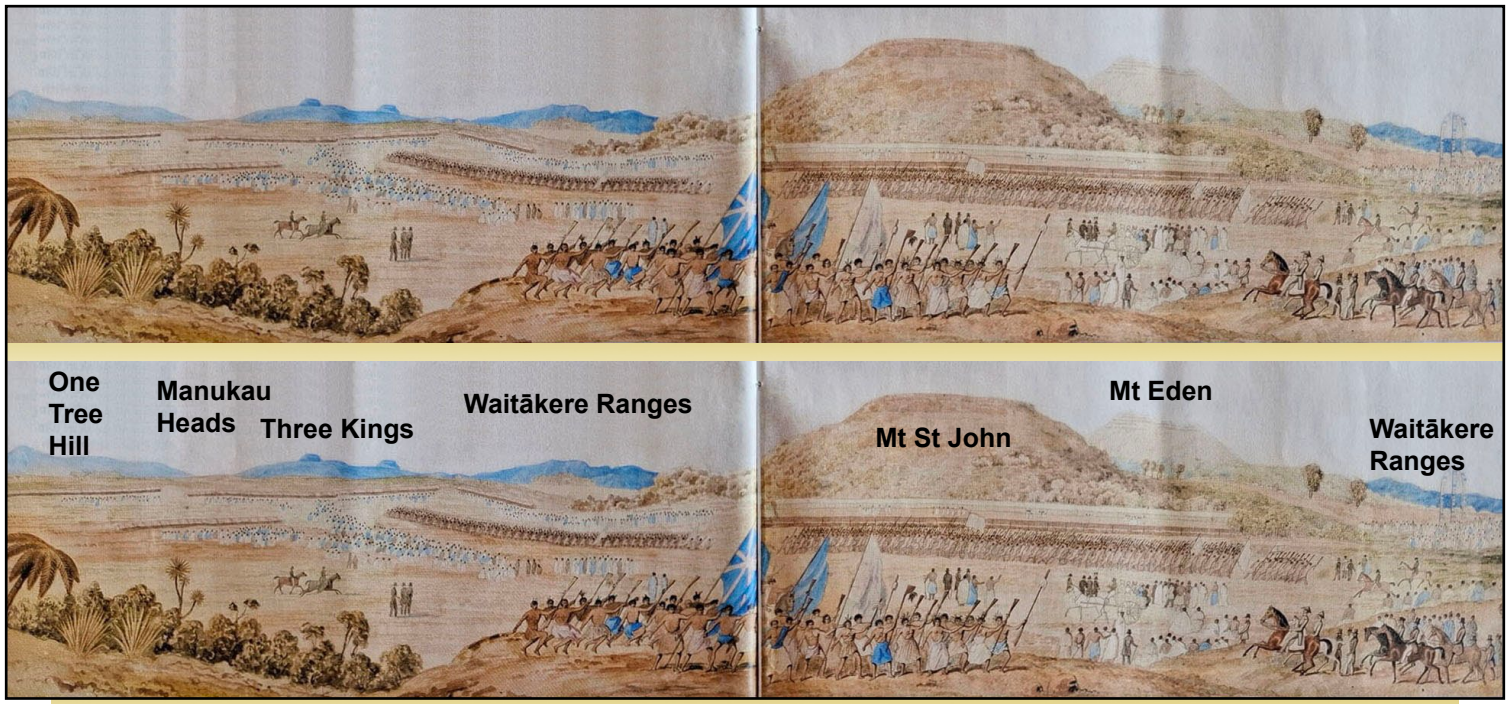


Fig. 2. The **original watercolour**, as included in the Listener article (Frykberg 2026) (upper), and the same painting that I have labelled (lower). Notice that this wide painting shows that the **lithograph** in Fig. 1 is only part of the scene, being somewhat truncated at both the left and right hand ends. Despite this, the foreground is also very different.

(Simpson 2015), taking up this whole page and indented to contrast it from my current article -

"On the 10th May 1844 the European inhabitants of the fledgling town of Auckland witnessed a gathering of some 3000 – 4000 Maori from tribes in central and northern New Zealand. The gathering was hosted by the prestigious Waikato chief Te Wherowhero and chief Wetere Te Kauae. ..."

"Governor Fitzroy, visiting the Feast with his staff, described the scene taking place in a "natural amphitheatre" and an eye witness ascended Mt St John from which he obtained a view of the whole scene. Also observing the happening was artist Joseph Merrett. He made a watercolour sketch, later filling in with pen finer detail to produce a panoramic view 840mm wide. During the year following, the sketch was transferred to a lithograph, which, while retaining the general layout as shown in the original sketch incorporated some embellishments and a series of numbered points of interest annotated at the base of the picture. Of significance were the hills numbered Mt Hobson-1, Mt Eden-2, and Three Kings-21. These annotations were to provide a conundrum the solution of which is still unclear."

"... the "Auckland Star" newspaper produced Bretts 1890 Almanac (Brett was the proprietor of the Star) with an insert of the 1845 lithograph enhanced with two tints and named "Maori Feast at Remuera" (Fig. 1 *[of Simpson 2015, **Fig. 2** of this article]*). It is likely that the circulation of this lithograph stimulated an interest as to where in Remuera the scene took place. Given the elapse in time from 1844, there would have been very few of the eye witnesses still alive in 1890 to assist in resolving the question."

"Sometime before 1908, Dr Hocken of Dunedin, a prominent art collector, bibliographer and researcher, acquired the original watercolour sketch and a copy of the 1845 lithograph. ... As part of the Collection record relating to the two pictures is the following ... in Dr Hocken's hand:

> "*... the artist of this primitive watercolour was Joseph Merrett,* [1816? –1854] *a former resident of NSW and interpreter. It was lithographed at home with some alterations which are an improvement on the original. Judging from its rarity, this lithograph must have made a scanty sale….N.B. The site of the Feast being quite forgotten & frequent inquiry failing to locate it, I devoted some time in 1908, aided by Mr Allom of Auckland to its discovery. The hill in the foreground of the picture is the foot of Little Rangitoto* [Maunga Rahiri] *now reserved for quarry purposes. Mountain Road* [now named Upland Rd] *runs through it thus forming an additional landmark. This gives a sufficient key to the position…*"

"This assertion as to locality was based upon the relative positions of Mt Hobson and Mt Eden in the lithograph and Dr Hocken (and others) used these geographical positions to postulate the site of the observer (artist). Hence the site of the Feast lay between Little Rangitoto and the eastern slopes of Mt Hobson two kilometres away crossing two deep gullies. Hardly the natural "amphitheatre" described by Fitzroy."

"Consideration has to be given to the possibility that the identification of Mt Hobson in the lithograph is incorrect. If we assume the prominent cone in the middle of the lithograph is *Mt St John*, which follows that the artist was viewing the scene of the Feast from the lower slopes of Mt Hobson, we then have a better approximation of the relative position of Mt Eden and the view of the "amphitheatre" stretching just over 500 metres to Mt St John (Fig.2 [of Simpson 2015, **Fig. 3** in this article]). Unfortunately, what appears to be a nice solution to the enigma is compromised by the position of the Three Kings in the lithograph, shown as two distant hills to the far west. From Mt Hobson the Three Kings lie to the south west. Furthermore, from Mt Hobson the view of the Three Kings is blocked out by the bulk of Mt St John."

"So there does not appear to be any realistic explanation of the artist's placement of the three mountains. Was the picture a composite, the background of the cones just added to give verisimilitude to the view? Art historian, Leonard Bell, has drawn attention to the differences between the watercolour and the lithograph as far as the grouping of the Maori and Governor Fitzroy are concerned, moving from a spectacle of force by the Maori in the watercolour to a more benign view in the lithograph "downplaying the sense of animation of the Maori figures in favour of a more orderly and calmer scene, in which attention is directed towards Fitzroy, as if he was presiding over the event". Thus the lithograph becomes a political statement."

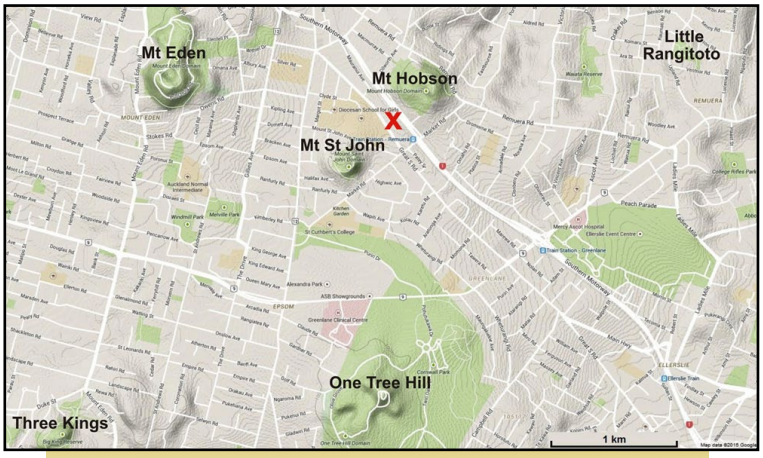


Fig. 3. Figure 2 from Simpson (2015) with caption - "*Map from Google Maps of the relative positions of volcanic cones mentioned in the text. Red X marks the location of the Feast.*"

Returning to my article – The Listener caption for the original watercolour version reads – "*Joseph Merrett's depiction of the 1844 Great Feast in Remuera, Auckland, attended by iwi from Tāmaki Makaurau, Waikato and Bay of Plenty and colonial observers. It was intended to showcase wealth and cement alliances, but within a few decades Māori would face economic annihilation.*" This caption was the only part of Frykberg's (2026) article that was helpful to me. With a heading "*Not there yet*" and under the cover story heading "*It's the economy, stupid*", the article was all about politics and New Zealand's history of 'hard times', and although interesting, it didn't discuss the painting. Only in part of the section under the subheading "*Māori Expropriation*" did his analysis relate to dates covering the 1844 painting of The Feast. Discussing New Zealand's history between 1840 and 1900, Frykberg quotes historian Vincent O'Malley as saying - "*Prior to the wars of the 1860s, Māori were, in many respects, the key drivers of the New Zealand economy. And that very productive economy was destroyed almost overnight in the 1860s, which had consequences that resonated over many generations.*" There was no attempt to describe the painting.

Members from Remuera Heritage have investigated the position of the paintings, and have written a comprehensive article (Cooper & Batistich 2020). They acknowledged Bruce Hayward's suggestions that the feast was held approximately where Dilworth School is now, between Great South Road and Mt St John Road, and that the painter was positioned on the slightly higher ground at Market Road near its intersection with Patey Street, a small street sandwiched between Great South Road and the Southern Motorway. It had to be near here to get the peaks of Three Kings maunga in the correct positions, and the lake on the left of the lithograph would have been the wetland that existed just south of Market Road, down towards an old ice cream factory.

Cooper & Betistich (2020) also point out that the feast was not "hosted by the prestigious Waikato chief Te Wherowhero and chief Wetere Te Kauae. ...", but rather by Ngāti Whātua of Auckland.

So where was the vantage point? Using Google Maps oblique view (**Fig. 4**), I could not mimic the watercolour view, nor the lithograph view when lowering myself (figuratively speaking) on to any of the flanks of Mt Hobson, as Malcolm favoured. I agree with his suggested Mt St John as the foreground maunga but is not quite at the correct angle.

To position the volcanoes according to Joseph Merrett's watercolour, I had to stay in Google Maps oblique mode and back away slightly. When I was satisfied with the image and with the configuration of the volcanoes, I found myself hovering over a slight mound in Patey Street. This position coincides with #7 Patey Street, now occupied by an old house that would have had a wonderful view in all directions, but especially to the southwest – a great vantage point from which to view a feast. This direction coincides with a retaining wall supporting a steep slope above Great South Road.

It might be pedantic, but my slight repositioning along Patey Street makes a marked difference in the view of Mt St John and Mt Eden. From the corner, there is a gap between

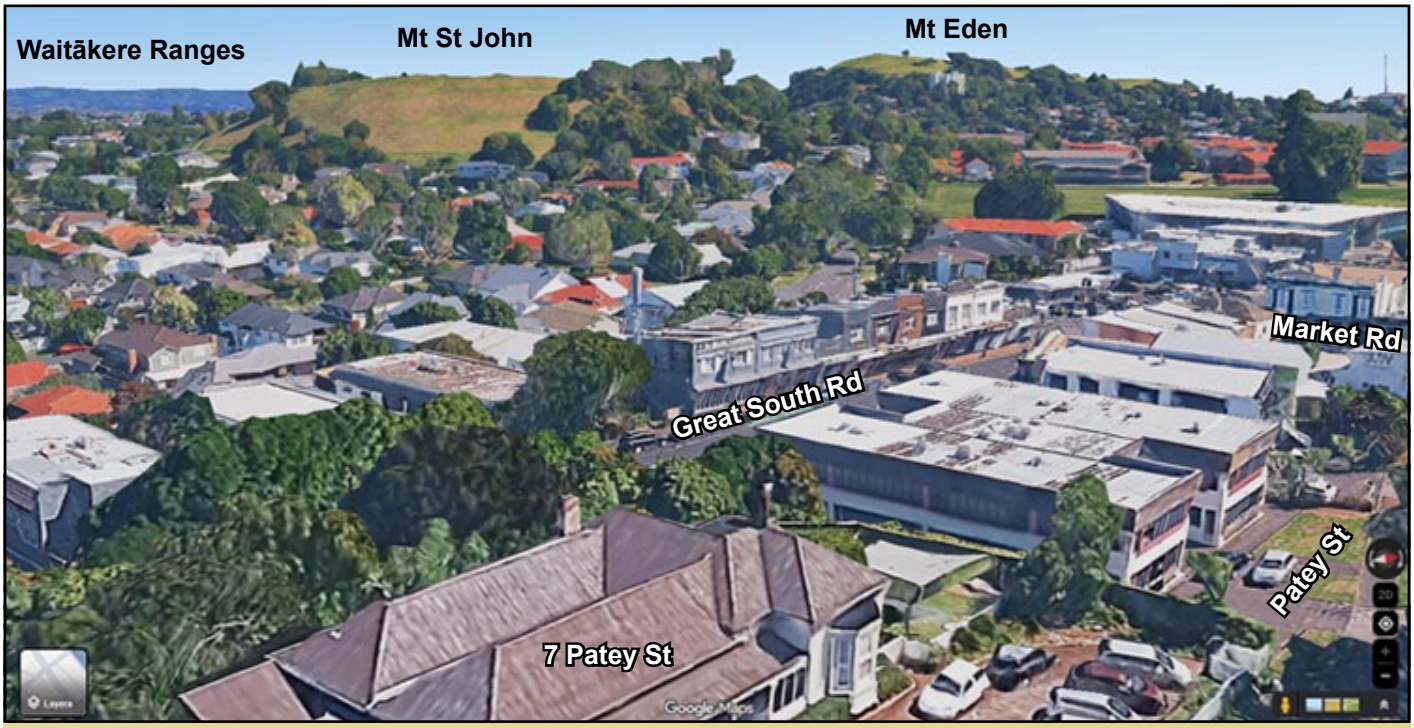


Fig. 4. Google Maps oblique, hovering above #7 Patey St, looking towards the west at as low an angle as possible that still enables the Waitākere Ranges to be visible in the distance.

the two maunga. This gap is not shown in the paintings – there is more of a V-shape in the profile. This is corrected by moving to a position about half way along Patey Street, outside #7. Although I could not get the Google Maps oblique view (**Fig. 4**) to extend around to the southwest sufficiently, as in **Fig. 2**, the sole remaining Three King's peak is still the same with this slight change of location.

In the lithograph, apart from the difference of the "more benign view", the foreground has shifted and incorporated a lake, and has become more of an amphitheatre suitable for a large feast, in the vicinity of Great South Road, Greenlane. I suggest that Malcolm's red **X** is not correct. I choose to mark the spot with a blue **X**, half way along Patey Street (**Fig. 5**). Suburban buildings conceal views to the maunga, and without access to a drone, it was impossible to ground truth my suggestion that the vantage point was approximately 7 Patey Street.

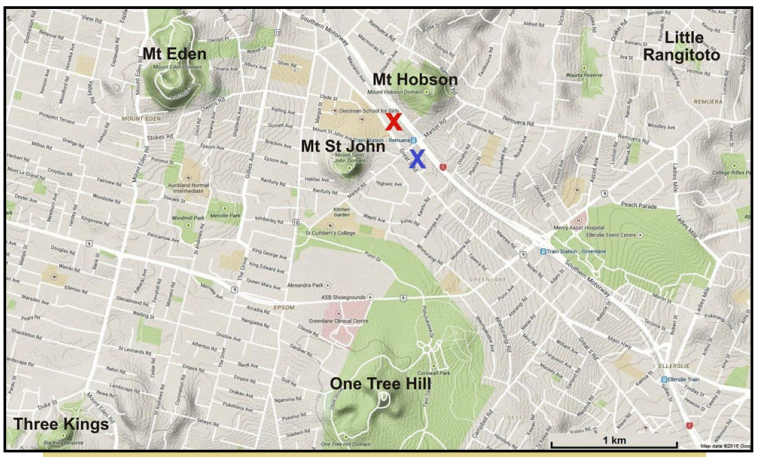


Fig. 5. Using the map from **Fig. 1**, and still showing Malcolm's red **X**, I now indicate my preferred position half way along Patey Street (blue **X**).

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WHAT A JAMMY FIND – EXTREMELY RARE SINISTRAL LINED WHELK

Bruce W. Hayward

I don't have a shell collection but we do have three grandchildren in the USA who live 400 km from the sea. One has a current sea shell interest, so I took our USA-based daughter to the North Shore to collect a few shells from Takapuna Beach, just a day after a significant ex-tropical storm shell wash-up. I knew that the boat ramp carpark at the northwest end of the beach often traps a diversity of shells on its northern side by the fossil forest.

We spent about 15 minutes looking for shells. I found several pieces of broken lined whelk *Buccinulum lineum* and thought a whole specimen would be a nice addition to the dominantly bivalve collection we had made. Then there it was, an unusual-looking but well-preserved lined whelk. I tossed it in the bag. Only when we got home and tipped the shells out on the table did I realise why it was odd-looking. It was coiled the wrong way, sinistral rather than dextral. I knew that sinistral gastropods existed and had seen sinistral freshwater snails from the Rotorua lakes, but had never before seen a sinistral marine snail.

I initially identified the shell as the common lined whelk, *B. linea*, but subsequently mollusc expert Peter Poortman corrected me and it is a specimen of the much rarer lined whelk, *Buccinulum pallidum powelli*. This endemic species is only known from the northeast coast of the North Island from Three Kings to East Cape (Powell 1979) with its type locality at nearby Rangitoto Island. It has seldom been recorded from a wash-up on a beach, with most records being of live specimens seen when diving off more exposed coasts. This could be the first record of a specimen from an Auckland city beach. The other nearest records are from Rangitoto (type) and Oneroa Beach, Waiheke (M. Morley collection, unpubl.).

I decided to google search for records of sinistral marine shells from New Zealand and found a compilation by the Auckland Shell Club of known specimens in museum and private collections (https://www.aucklandshellclub.net.nz/). My specimen is the 20th sinistral shell on the list and the first for *B. pallidum powelli*. There is one sinistral *B. linea* collected from Stewart Island in the 1930s.

The above refers to 20 sinistral specimens of marine gastropods that are normally dextrally coiled. There are, however, two families of marine microgastropods (smaller than 1 cm), the Triphoridae and planktic Limacinidae (sea butterflies), which have dominantly sinistral species with a number of only occasionally collected living and fossil



Fig. 1. Extremely rare specimen of sinistrally-coiled *Buccinulum pallidum powelli* from wash-up at Takapuna Beach boat ramp carpark, April 2026. Background of newspaper to show that the photo has not just been reversed in photoshop.

species recorded from New Zealand. There is also a record of a sinistral gastropod from the New Zealand Triassic – an unidentifiable, high-spired specimen from the Torlesse Terrane on the Wellington City coast (Campbell 1982). Two sinistral specimens of the dominantly dextral early Miocene fossil gastropod *Alaginella fraudulenta* are held in National Museum Te Papa (https://www.aucklandshellclub.net.nz/).

It has been estimated that only about 1 in 100,000 individuals is sinistral in a usually dextral-coiling species of marine gastropod. Specimens with left-handed coiling shells are believed to be the result of a freak genetic mutation and generally this cannot be passed on to offspring. This is because a snail's reproductive organs occur only in one side of the body (right side in dextral snails) and are matched to its shell coiling direction making it virtually impossible for a sinistral individual to mate with normal dextral individuals.

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STEWART'S LAVA CAVES – FORMATION SEQUENCE?

Hugh Grenfell

Introduction

Stewart's Cave in Landscape Road, Auckland, is one of seventeen known lava flows from Three Kings Volcano (Kermode 1994). It is a complex system of overlying and interconnected lava tube segments that total about 180 m in length (**Fig.1**).The entrance is about 80 m above sea level, and about 200 m from the volcanic vent source of an extensive lava flow field that advanced northwestwards from Three Kings Volcano as far as Western Springs (see note in **Fig.1**). The main passage of the cave (up to 14 m wide) ends at a roof-sag ring passage. The arched ceilings (up to 8 m high) vary in shape, and cooling fractures are visible in the rock. Natural roof collapses have formed the entrances, and there are many rock falls from the ceilings. The solidified floor surface is mainly rough *aa* lava with some very rare *pahoehoe*.

The geologically interesting features of the cave system are many, with three interconnected lava tubes, multiple levels, some large passage cross-sections, some unusual irregular ceilings, a cave-in-cave, lateral flow-kerbs, flow-level benches, floor-to-wall clefts, curved flow-wrinkles, and lavatites (lava driblet stalactites).

In the Auckland Volcanic Field, Stewart's Lava Cave(s) ranks second only in its features and preservation, to Wiri Lava Cave. After a GeoClub field trip in May 2025, questions were asked regarding the sequence of their formation. Such as which cave / lava flow came first or last, were they contemporaneous, how did they interact? Here are some thoughts.

First some anecdotes and background

The late, great GeoClubber and NZ Geological Survey geologist "Sir" Les Kermode (1932–2002) for many years led trips to Stewart's (Hayward 2021). I took over from Sir Les and for a number of years also ran dozens of trips for the public to Stewart's including at least two for GeoClub and an unusual one for the City of Auckland Pipe Band, which included Geocene editor Jill Kenny. The acoustics were amazing because of the ceiling and wall texture and you can still watch Jill and others in action on YouTube (see City of Auckland Pipe Band 2010, in **References** for the link). Although low resolution, you can also see some of the cave's features, such as people posting themselves through the "Letterbox" (see below, and the sound can always be muted if necessary!). GeoClub also had a big cave clean up at one time to remove decades of all kinds of rubbish. During my time access to the cave was made possible through the generosity of the then landowners Tibby and Dave Chamley. Tibby (Elizabeth) was the daughter of New Zealand geologist Larry Harrington (Hodgson 2015). Larry was the brother-in-law of Sir Ed. Hillary. The owner before the Chamleys' was NZGS geologist Dave Skinner (1938–2019) (Graham & Hayward 2019) who bought it c.1977, and who as an operatic bass baritone also appreciated it's fantastic acoustics (Blom pers. comm.).

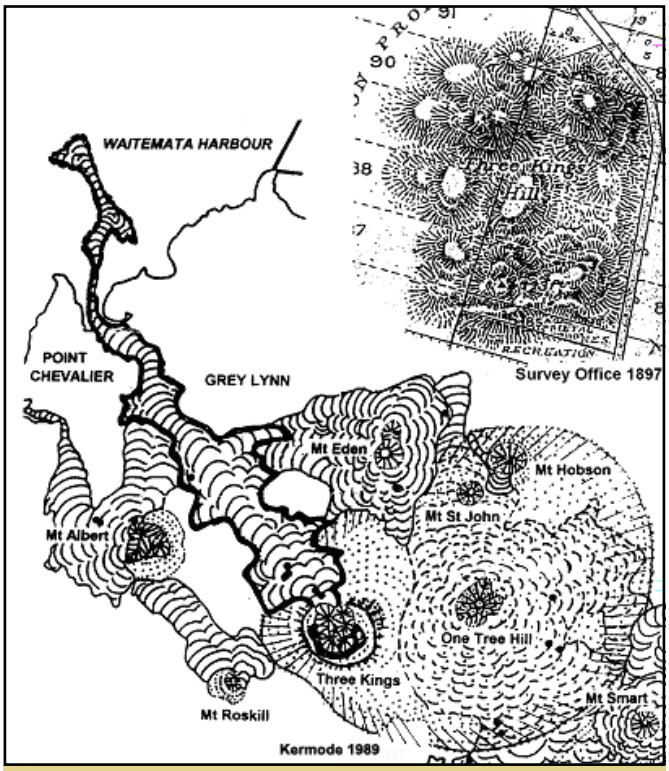


Fig. 1. Top right: Three Kings Volcano as it was in 1897. Road indicated is Mt Eden Road. Lower: location of Three Kings Volcano and flows (outlined) relative to other centres. Black dots are lava caves (Kermode 1989). NB: the outcrop of flows in the Waitematā Harbour at Te Tokaroa (Meola Reef) are now not thought to be lava from Three Kings Volcano, but are more likely to be from Mt St Johns Volcano (see Hayward *et al*. 2011, p.135).

The Chamleys' took their responsibilities as custodians seriously and protected the cave as best they could from vandals and other low-life, eventually having to put a gate on the entrance. But they made the mistake on one occasion of allowing a children's TV series crew to use the cave for filming. Without permission, the crew thought it would be fantastic if they threw thousands of sparkly plastic sequins everywhere in the entrance cave to "enhance" the scene. And of course they picked them all up – yeah right! Despite later efforts at cleaning up, to this day you can still find sequins the length of the cave system (at least 100 m) carried in on the soles of muddy footwear.

Jill Kenny was in touch with an early childhood friend, Mark Dashpar, whose father designed and helped build the house presently sitting over the cave in the late 1950's. Mark had some interesting recollections growing up there. He went into the cave hundreds of times over the years and related that his father made him learn how to find his way out in the dark in case his light source failed. The caves were sometimes called Mortimer's Cave after Mark's grandfather who lived next door. Grandad Mortimer was also responsible for the concrete strips at the cave

entrance (directly below the original hole in the cave roof now covered by the concrete floor of the house) when he had a mushroom growing venture there. He also spoke of "Fatman's Entrance" which is a tricky, tight connection (a squeeze) between the "North West Branch" (at the upper end of it) and the "South Branch" (or "South Cave") shown on Stewart's 1869 map (see caption for Fig.2 also). The squeeze was also known as "The Toilet Bowl" because it had an S-bend in it. Easy for people of Sir Les' stature but not for most of us. I never told trip participants about it, or let them go into it, in case they got stuck. I didn't feel like having to pull their arms or legs off to get them out.

Hochstetter visited Three Kings Volcano with the Rev. AG Purchas on the 17th of February 1859. While he mentions the lava caves in his diaries, there is no evidence that he saw them for himself (e.g. Nolden & Hayward 2023). In January 1869, members of the Auckland Institute (which a couple of years later became the Auckland Institute & Museum then later Auckland Museum Institute) had a field trip to what is now known as Stewart's Lava Cave. They had a good outing and soon after the Institute Secretary, botanist Thomas Kirk (1828–1898), and civil engineer and surveyor James Stewart (1832–1914) went back to seriously survey the cave system. This resulted in a paper that described and mapped the cave system after about ten hours work over two days (Stewart 1869).

Stewart had a very interesting career involving many projects (Stewart Ball 2007). In my opinion Stewart's excellent description, map and diagrams, with plan and cross sectional views, are still the best available of the caves. In recent years there has been LiDAR mapping of the caves but I don't think they have been published to date. Although they are a little confusing, to avoid even further confusion, I will use the names Stewart gave to various parts of the system (Fig.2). To get a better view of Stewart's figure by zooming in, download the pdf version of his paper from the link below (Stewart 1869). You will see some interesting detail. For instance, the arrows on the diagram indicate air flow in the caves and that there were originally two entrances to the caves. The "South Cave" entrance, which was next to the track to the Three Kings Farm, is no more.

The "Principle of Superposition" is used for relative age dating and in undisturbed sedimentary or volcanic rock sequences, the oldest strata are at the bottom and younger strata are deposited on top. Taking into account that the lava flows and caves formed on a slope, we can see at "D" on Stewart's sketch plan cross section that the "South Cave" (which extends down slope, northwards, away from Three Kings) is at the bottom (oldest) and the "Main Cave" or "North West Cave", extending northwest, is at the top (youngest).

Stewart (1869) does discuss the origin of the caves and thought the whole group was formed by a single "molten stream" and "not at different times from different levels". He initially talks about the upper caves forming first but later discusses the "probability of lava having found its way into the hollows of some older lava streams". But you are best to read his descriptions for yourself rather than my interpretation.

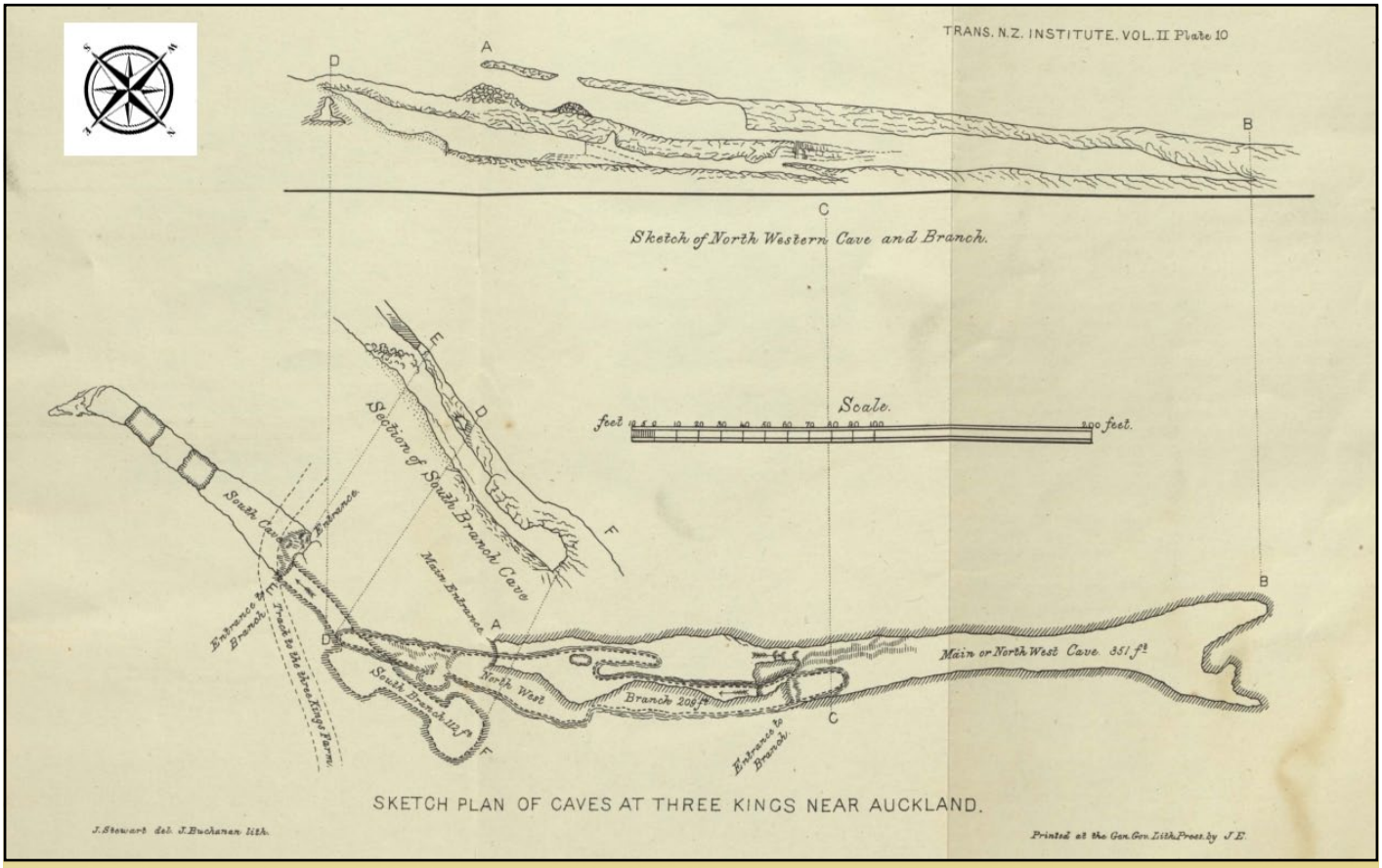


Fig. 2. Plan and sectional views of the Stewart's Lava Cave system (Stewart 1869). The "South Cave" is orientated N–S and the "Main or North West Cave" NW–SE. "Fatman's Entrance" is just above the letter "B" in the label for the "South Branch".

So here are some of thoughts on the questions of which lava tube / cave formed first, were they contemporaneous (i.e. formed by the same event / pulse of lava) and how did they interact? Unless you think molten lava could have melted its way through previous solid rock and formed a new cave under an older cave or flow, then the "Principle of Superposition" should hold here. From Stewart's cross section (and later observations), the "South Cave / Branch" is the oldest, the "North West Branch Cave" next and the "Main or North West Cave" youngest. The almost north–south orientation of the "South Cave" suggests, for whatever reason, that these lava flows followed a different path northwards away from Three Kings compared to later flows. You can see such sinuous, ever changing flow paths of lava flows in recent footage of Icelandic lava flows for example. This makes them an unpredictable, tricky hazard to manage when close to urban areas.

A suggested sequence of cave formation:

1) The "South Cave", formed by lava flowing north, is the oldest. Some later lava flows must have also entered it and then drained into the younger "North West Branch Cave" because there is a connection through the "Toilet Bowl" / "Fat Man's Entrance / Squeeze" S-bend mentioned above.
2) Later pulses of lava, now flowing northwest, formed the "North West Branch Cave". You can stand in the upper part of the "North West Branch", but the lower half requires you to waddle like a duck to get through. About halfway along this section, there appears to be a vertical "chimney" or hornito, which was covered by later lava flows. This suggests that prior to the later flows that formed the youngest "Main or North West Cave", gas and lava were vented through the hornito to the surface when the tube was at maximum capacity or just gas at other lower flow levels. At the lower end of the "North West Branch" tube, the roof has collapsed, providing easy entrance to it. But if you go left instead of right, teeny, tiny people can go out the end of the tube and back into the "Main or North West Cave". You can see this indicated at C on Stewart's sketch (**Fig.2**). The fact that there is still an open exit for the "North West Branch" tube suggests that flows through it were at least in part contemporaneous with lava flowing through the "Main or North West Cave". When the last flows of the "Main or North West Cave" drained away, whatever lava was in the "North West Branch" also drained away leaving it open.
3) The youngest tube, the "Main or North West Cave", is complex with many of the features mentioned above (e.g. benches and lateral flow kerbs). The size of the tube indicates that the greatest volumes of lava were flowing at this time. The large entrance cave, with its lower end oddly domed and shaped like the head of a sperm whale, has two constricted exit points (shown on **Fig.2**). The domed shape and the extensive presence of lavatites on the roof and walls suggest remelting and "thermal erosion" of this area as lava was dammed here. A similar bulbous feature can be seen in the lower end of the "South Cave". From the narrow exit on the left, lava would have cascaded over a shelf with a steep drop (c.8 m) to the next level. The one to the right exits through a slot which, because you can "post" yourself through it, is known as "The Letterbox". High flow / pressure through here would have created a jet of lava into the lower level at times. Benches on the sides of the tube indicate lava was dammed here from time to time by further constrictions down slope, draining away as supply decreased. After the last pulse of lava, the "Main or North West" and the "North West Branch" tubes emptied as much as possible. Later fractures, roof collapses, sediment being washed in and a bit of human modification leave us with what we see today.

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COMPARING CAMBODIA'S REVERSING RIVER WITH OTHER REVERSING RIVERS

Egon Eberle

Reversing rivers

All rivers flow backwards at their mouths, to some degree, when high tides force water upstream. In cases where there is a large tidal variance, this flow can become quite spectacular. One example of this is the phenomenon of tidal bores, which occur in a few locations all over the world during high tides. A tidal bore is a powerful, natural, tidal phenomenon in places where there is a large tidal range and a shallow, narrowing broad bay, in which the leading edge of the strong, exceptionally high, incoming tide forms a wave (or waves) of water that travels up a river against the river current. The funnel shape increases tidal range and decreases the duration of the incoming tide to such an extent that the tide appears as a sudden increase in water level. It can appear as a single, breaking wavefront, characterised by a turbulent roller of churning, aerated water (**Fig. 1**), or a smooth, non-breaking lead wave followed by a series of smaller, secondary waves (**Fig. 2**). They are preceded by a loud roar or rumble that can be heard several kilometres away, caused by turbulent air bubbles trapped in the breaking wave and water striking obstacles along the riverbed and bank (Biology Insights 2025, Wikipedia 2026).

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See References, Wikipedia 2026. Figure accompanying section on Tidal regime and estuarine processes.

Fig. 1. Front of a tidal bore on the River Ribble in Lancashire, England (Photo credit: Wikipedia 2026).

Fig. 2. Tidal bore in the Petitcodiac River, Bay of Fundy, Canada (Photo credit: Coastal Wiki 2026)

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See References, Coastal Wiki 2026. Figure 10.

With the Bay of Fundy in eastern Canada having the highest tidal range in the world, most rivers draining into the upper bay between Nova Scotia and New Brunswick have significant tidal bores (Wikipedia 2026). The world's largest tidal bore is found on the Qiantang River in China, where it is known as the Silver Dragon. The bore can reach heights of up to 9 m and travel at speeds of up to 40 km/hr. The Severn Bore, on the Severn Estuary between England and Wales, is another well-known example. The estuary has one of the world's largest tidal ranges, sometimes exceeding 15 m and can form a tidal bore up to 2 m high (Biology Insights 2025).

Other examples include up river from the mouth of the Ganges River in India, Ireland's River Shannon, many rivers in England and France, the Colorado River in the United States, the Amazon in Brazil, and the Daly River in the Northern Territory of Austalia.

New Zealand even has its own tidal bore, on the Wairoa River near Dargaville, flowing into the Kaipara Harbour in Northland. I will digress a little here, because one of the few descriptions of the Wairoa Tidal Bore, from the New Zealand Herald (1914), is delightfully descriptive. Some excerpts include –

"*The presence of a tidal bore in the Northern Wairoa is not generally known to the bulk of residents on its banks below Dargaville ... , but to those living in the upper reaches of the great waterway, the tide inrush is watched for daily during the summer months. ... at this period of the year, when the down-flow is comparatively feeble, it is at times observable near the borough, which is situated close on 40 miles from the harbour entrance.*"

"*At the head of the Maunganui Reach* [more than nine miles upstream from Tangowahine] *it attains its maximum height and force ... oar-propelled boats find it necessary to take to mid-river in order to escape being swamped, and stationary log-rafts become quickly dismembered. On many occasions the heavy rafting-chains are snapped, and rafters are always on the qui vive for the bore approach at this season of the year.*"

"*Its speed of travel is assessed at 12 miles an hour.*"

"*The height of the bore in mid-stream appears to be only about 12in, but the wash on the river banks is surprisingly heavy, and as the swell passes, the level of the tideway is raised often as high as 3ft.*"

"*On a still evening, the approach of the bore can be heard two miles away, its noise rivalling that of a large vessel travelling under a full head of steam, and the sight in the Maunganui Reach is, at times, somewhat awe-inspiring.*"

"*No damage other than to rafts is occasioned by this summer tidal wave, but inexperienced boatmen have had momentary hair-raisings, especially at abnormal spring tides, when making their first acquaintance with the Wairoa bore.*"

Another example of spectacular river flow with high tidal variance is the rare phenomenon of reversing rapids. The best example is the 'Reversing Falls' in the city of St John on the southern coast of New Brunswick, eastern Canada. It is about half way along the northern coast of the Bay of Fundy, where the height difference from low to high tide averages 8.5 m. Further northeast, as the funnel becomes narrower, is where the Bay of Fundy experiences the highest tidal range in the world, averaging about 16 m.

In central St John, the St John River runs through a narrow gorge several hundred metres wide in the centre

of the city before emptying into the Bay of Fundy. The twice-daily tides force the flow of water to reverse against the prevailing current when the tide is high. The rapids, or 'falls', have a difference in elevation from top to bottom of 4.25 m and are created by a series of underwater ledges at the narrowest point (**Fig. 3**). The powerful rapids flow in both directions depending on the sea level height in the Bay of Fundy (Dalton 1960).

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Photo found in Google images.

Fig. 3. The Reversing Rapids, formerly referred to as the Reversing Falls, in St John, New Brunswick, eastern Canada. (Photo credit: Google images)

While every stream or river that flows into the Bay of Fundy will also have reversing water flow to a greater or lesser extent, the St John River is the most spectacular because of the strong head of water in its catchment. At 720 km in length, it is the longest river on the North Atlantic seaboard apart from the St Lawrence River. There is an enormous amount of water involved and great strength is required by the rising tides to overcome the flow (Dalton 1960).

But these above examples are rapidly-changing, twice-daily phenomena. There is one place in the world where reversing river flow happens inland and has nothing to do with coastal tides. It is an annual occurrence, not a daily event, and is not tidal.

Cambodia's unique version of a reversing river

The annual occurrence still involves a river – the mighty Mekong – which flows southeast from its source on the Tibetan Plateau in China, turns briefly towards the southwest where it doubles as the short border between Myanmar and Laos, returns towards the southeast again as it forms most of the border between Thailand and Laos, cuts through Cambodia then southernmost Vietnam, and finally reaches the South China Sea at the vast Mekong Delta (**Fig. 4**). I will discuss this reversing river phenomenon, which is confined to the Cambodian section.

I was recently visiting Angkor Wat, the ancient temple complex in the Siem Reap region in the northwest of the lower Mekong plain, northwestern Cambodia. During that time, my tour party also visited a large lake, just to the south of Angkor Wat. The lake is called Tonlé Sap and is the largest lake in Southeast Asia, even in the dry season (**Fig. 5**). It was touted by our tour guide to be the ONLY

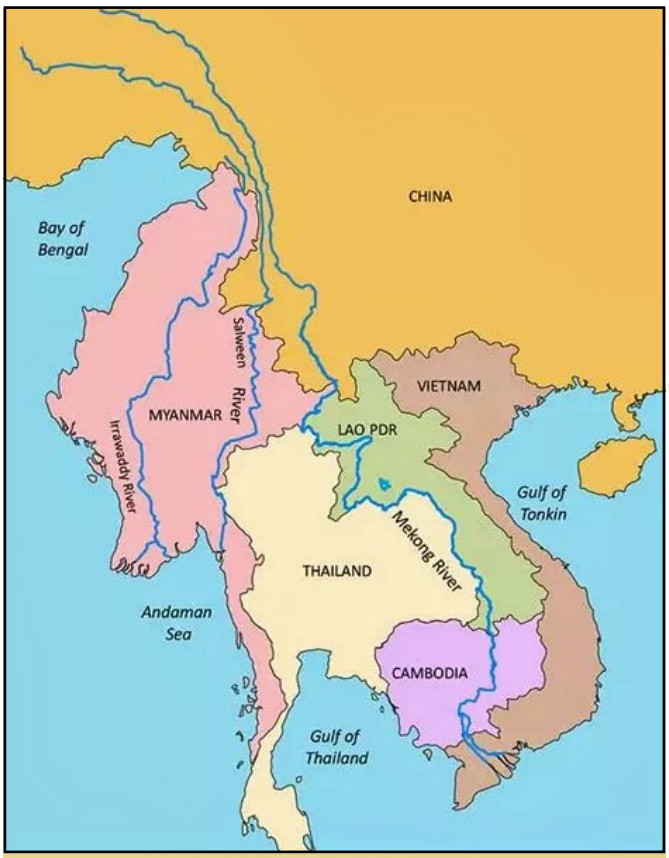


Fig. 4. Course of the Mekong River in Southeast Asia (Mekong map 2023).



Fig. 5. Tonlé Sap Lake (coloured blue) and Tonlé Sap River within Cambodia, draining into the Mekong River, still within Cambodia, then through Vietnam to its delta and into the South China Sea (figure 2 of Morton & Olsen 2018b). Tonlé Sap is the largest lake in Southeast Asia.

reversing river in the world. It could be the only inland example but I suspect there are probably more and, as I have listed earlier, there are many reversing rivers in coastal regions worldwide. Our tour guide told us that there is a huge water level and volume difference between the wet and dry seasons, but the high level is not the only result of high monsoon rainfall in the immediate area.

My mind wandered back to my visit to Lake Disappear in New Zealand, between Raglan and Kawhia in the western Waikato, where the lake disappears into the limestone, leaving the valley dry (**Fig. 6**). With prolonged rain, the valley fills up with water to become a lake (Hayward *et al.* 2025). But Tonlé Sap in Cambodia is orders of magnitude larger – enormous – and although it involves rainfall, it is not in the style of Lake Disappear.



Fig. 6. Water draining from Lake Disappear blind valley, western Waikato. A high water mark is visible as a change in grass colour. In dry conditions, the valley floor is covered by flat green meadows crossed by a small meandering stream. The only outlet to the valley is a stream-sink at the foot of the slope across the fence. (Photo from figure 16 in Kenny & Hayward 2010)

Tonlé Sap geology

Our tour guide said that Tonlé Sap Lake is in a geological down-warp between the mountains – a basin – and the only outlet is the Tonlé Sap River.

I have found that the 'basin' was formed by the sustained collision of the Indian Plate against the Eurasian Plate and subsequent collapse of the Southeast Asian Subplate. Indosinia forms the northern part of this Subplate (**Fig. 7**). Three regional strike-slip faults, all striking northwest, cut Indosinia into large elongated crustal slabs. Tectonic extrusion is throught to have occurred, in which the three strike-slip faults facilitated extrusion of the intervening elongated crustal slabs towards the southeast from Oligocene to Quaternary times (Tija 2014). The tectonic history is complex, involving reversal of strike-slip movement and rotation of the stress field. It is sensibly avoided here and not relevant to my story anyway.

Mekong and monsoons

Our tour guide told us that people have been living around the Tonlé Sap Lake for a very long time. Their houses are built on long stilts to accommodate the 8–10 m fluctuation of the water level between the dry and wet seasons. The

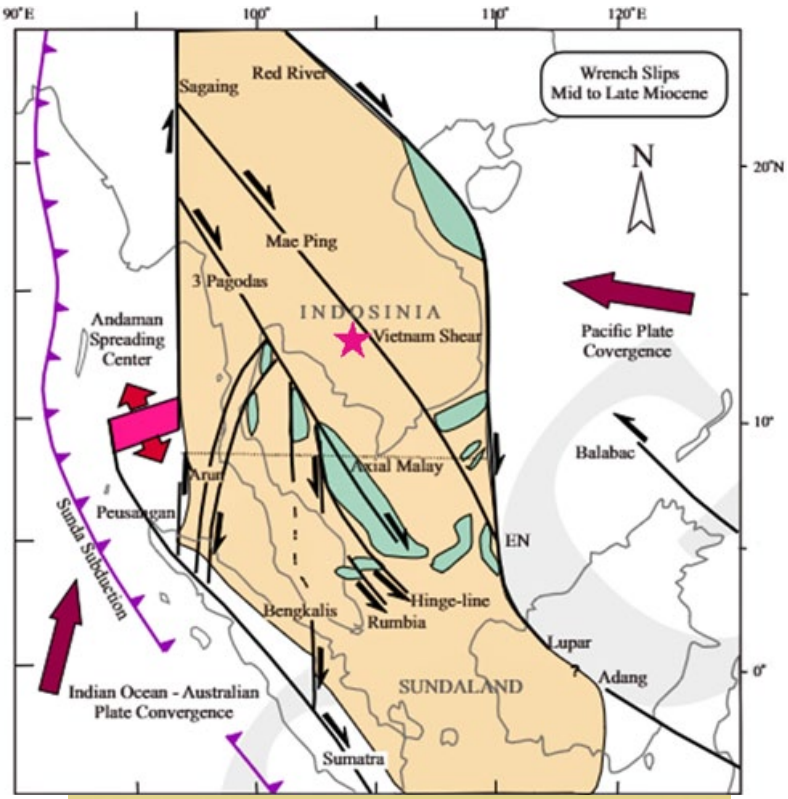


Fig. 7. Map of the Southeast Asian Subplate, showing the Indosinia portion in the north. Three left-lateral strike-slip ('wrench-slip') faults cut it into three elongated slabs. The pink star is the location of Tonlé Sap Lake. The current Southeast Asian coastline is shown as a pale grey outline. Modified from Tija (2014), figure 1.



Fig. 8. Tonlé Sap Lake at reduced dry season area, with a surounding area of dark green indicating highest wet season lake levels. The lake empties and fills from Tonlé Sap River at the southeastern corner of map. Angkor Wat historic site is labelled in the north in yellow. Modified from Google Maps, accessed 20 May 2026.

*surface area varies accordingly, from between 3000 km² in the dry season to around 16,000 km² during the wet season (**Fig. 8**). Settlements not only exist at the shore area (**Fig. 9**), but also several floating villages where residents trade*



Fig. 9. We walked from the tour bus past stilt houses on the shore of Tonlé Sap Lake, left high and dry at the end of the dry season.



Fig. 10. Our boat sped past clusters of houses latched on to barges. The residents would either fish from the barges or use their decrepit boats instead.

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See References, Olsen & Morton 2018b,
[https://www.tandfonline.com/doi/abs/10.2489/jswc.73.3.60A]
figure 1.

Fig. 11. Floating villages on Tonlé Sap Lake are home to fisheries: men, women, and children who make their livings catching, processing, and marketing fish, reptiles, frogs and other amphibians, insects, and aquatic vegetation. Photo and caption from Olsen & Morton (2018b, figure 1).

*goods (**Figs 10–11**). Their main income is from fishing, and a little from farming using water buffalos instead of tractors. During the dry season, space underneath the houses can be used for schooling the children.*

Tonlé Sap Lake and Tonlé Sap River form a complex hydrological system found nowhere else in the world and is strongly influenced by the Asian monsoon (Olsen & Morton 2018b). During the dry season (November to April) Tonlé Sap River, a tributary of the Mekong River, is 120 km long and connects Tonlé Sap Lake to the Mekong near Phnom Penh, the capital of Cambodia. During these months, Tonlé Sap Lake is a shallow, flat bottomed, freshwater lake, 120 km long and 35 km wide, that seldom exceeds 3.5 m depth. It is prevented from fully draining into the Tonlé Sap River by a bedrock ridge near Kampong Cham (Olsen & Morton 2018b). The dry season Tonlé Sap River and Lake surface areas cover 3,100 km^2 to 7,800 km^2 respectively.

With the onset of the Asian monsoon in mid-May, the Mekong River begins to flood. The increased volume forces the water to back up into the Tonlé Sap River, reversing its direction so that it flows into Tonlé Sap Lake (**Fig. 12**). The flow is fastest from August to October with peak flow rates of about 10,000 m^3 sec^{-1}. Flooding and reverse flows extend the dry season lake (120 km long by 35 km wide) into its floodplain and create a wet season lake 250 km long, 100 km wide and 8–10 m deep. That is an expansion that covers more than 24,600 km^2 and the volume of the Tonlé Sap Lake expands from 10 km^3 to 80 km^3. This equates to a 200% to 300% increase in Tonlé Sap Lake's size and an 800% increase in water volume, which covers the western section of Tonlé Sap River and shortens the river length by about 65 km during the monsoon season (Olsen & Morton 2018b).

During the monsoon season, the Mekong River supplies the lake with water, fish, and sediments via the Tonlé Sap River. But unlike the Mississippi River in the US, where navigation dominates management decisions, and keeping the channel deep is a priority, the Mekong River sediment is highly valued, and its annual sediment transport has made Tonlé Sap Lake one of the most highly productive fisheries in the world (Carling 2009; Olsen & Morton 2018b).

In November, the monsoon rains abate and the Mekong River levels begin to fall. Eventually, the Mekong River depth falls below the flooded Tonlé Sap River, so that the river flow reverses and begins draining into the Mekong River again.This begins to empty Tonlé Sap Lake until the bedrock ridge prevents any further drainage. Thousands of floating houses (**Figs 10–11**) come closer to dry land again, as they were when I saw them in late April.

Therefore, the Tonlé Sap River flows northwest into Tonlé Sap Lake for six months (**Fig. 12**) and then for six months it flows in the opposite direction (southeast) into the Mekong River and finally into the Mekong Delta (**Fig. 5**).

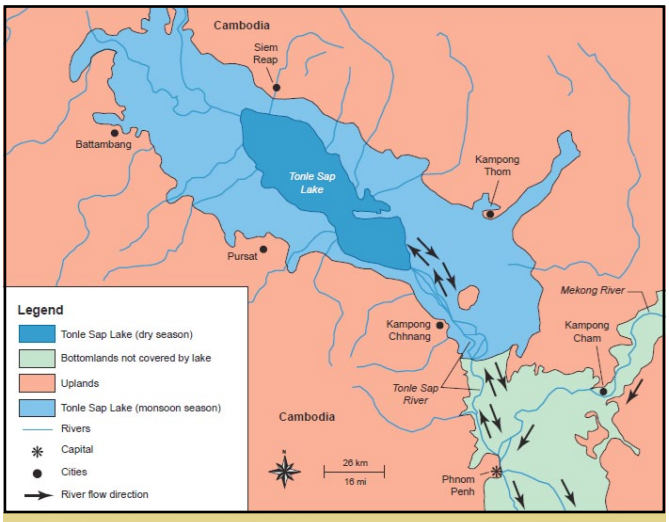


Fig. 12. Tonlé Sap Lake and River of northwestern Cambodia (figure 3 of Morton & Olsen 2018b). In the monsoon season when the Mekong River floods, water backs up into the Tonlé Sap Lake and River system, becoming a reversing river. With the onset of the dry season, the floodwates recede and the Tonlé Sap flow changes direction and flows into the Mekong River and thence southeastward to the South China Sea.

Damn the dams

Our tour guide mentioned that the building of dams in the upper Mekong River has reduced the water inflow into the river, adding to its shrinkage, on top of the climate change effects and dwindling fish supply.

The Mekong River is a major water resource in Southeast Asia, and all countries that the Mekong flows through have plans to utilise the river's hydroelectric potential. China and Laos have already built dams and hydroelectric plants on the main river and its tributaries and are actively planning new dams to produce power in the future (**Fig. 13**). These plans are viewed by environmentalists and riparian communities as threats to fisheries, lake and riverbank farming, and local cultures (Campbell *et al*. 2009; Hortle 2009; Olsen & Morton 2018a).

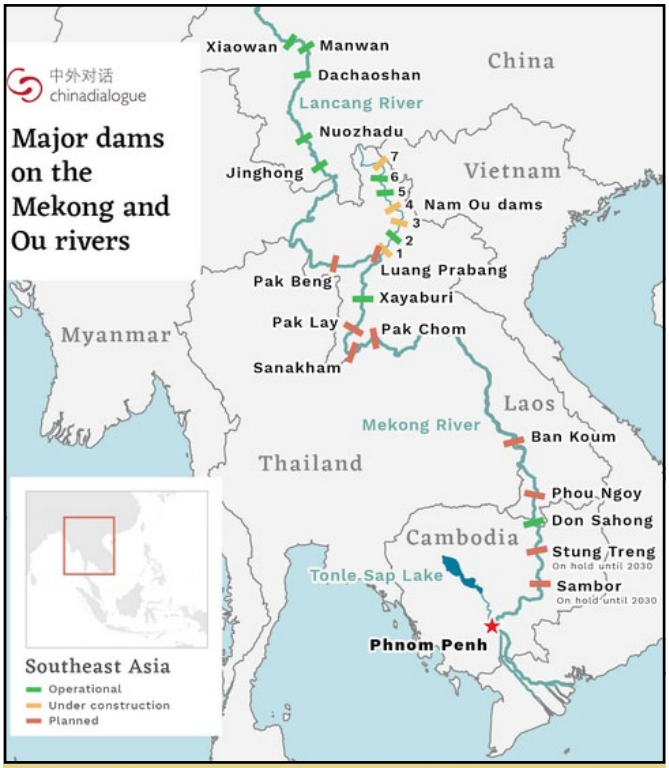


Fig. 13. Major dams, operational, under construction or planned as of 2020, along the Mekong and Ou rivers as they flow from China to Cambodia (from Roney 2020).

My final thoughts, based on the tour guide's message

Of course, the locals don't know their lake is special. This is how it has always been. But now they are becoming aware that all is not well. Dams up the Mekong are holding back monsoon floodwaters and releasing it in the dry season. That means downstream flow is highly regulated and doesn't necessarily backlog up the Tonlé Sap River into Tonlé Sap Lake. Fish do not make it up to the lake as before, fields are not fertilised with annual sediment, and the system is not flushed out at the end of the cycle.

Acknowledgements

I'd like to that the Editor (my wife) for searching for suitable internet articles and keeping me on track while writing this paper, and to Bruce Hayward for editing it.

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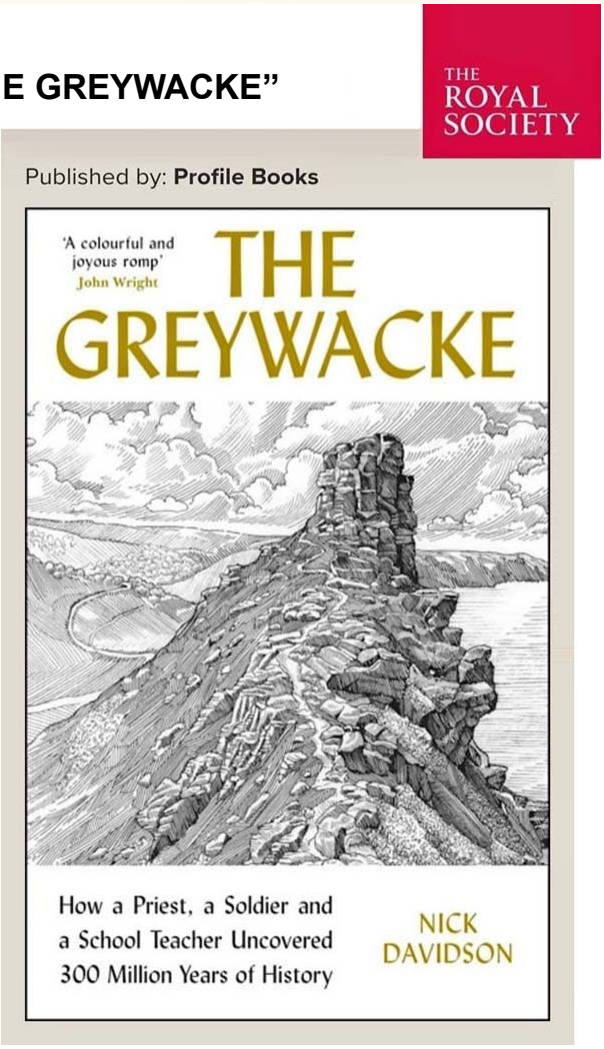
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Book Review:
THE BEDROCK OF HISTORY: A REVIEW OF "THE GREYWACKE"

Wendy Goad *



For us in New Zealand, greywacke is far more than just a common rock; it is the enduring backbone of our landscape. Whether we are traversing the rugged Torlesse Terrane or mapping the foundations of the Southern Alps, this ubiquitous sandstone is the very fabric of our geological identity. Yet, in Nick Davidson's '*The Greywacke: How a Priest, a Soldier and a Schoolteacher Uncovered 300 Million Years of History*', a similar, but far older, stone becomes the centre of one of the most vitriolic and fascinating chapters in scientific history.

When William Smith produced the first stratigraphical map of England and Wales in 1815, he was not able to further classify the rocks of Wales. A chaotic and incomprehensible jumble of hard-to-trace strata, they were collectively referred to as the titular Greywacke. Given that these rocks might contain the first evidence of like on Earth, they were of great interest to geologists. From 1831 to 1920, three scholars would spend their lifetimes deciphering them. The narrative follows three titans of 19thC geology: Adam Sedgwick (the priest). Roderick Murchison (the soldier) and Charles Lapworth (the schoolteacher). Davidson masterfully recounts the 'Great Devonian Controversy' and the subsequent "Silurian-Cambrian War". What began as a collaborative effort to decipher fossil-bearing rocks in Britian devolved into a bitter dispute over rock strata that permanently severed the friendship between Sedgwick and Murchison.

It was their personal and intellectual rivalry, pursued on treks through Wales, Scotland, Cornwall, Devon and parts of western Russia, that revealed the narrative structure of the Palaeozoic Era, the 300-million-year period during which life on Earth became recognisably itself. From the Permian that ended ~252 mya, through the Carboniferous, Devonian, Silurian, Ordovician, to the Cambrian that started ~539 mya, '*The Greywacke'* tells the story of how those geological periods got their names and transports the reader back to the heydays of Victorian geology.

While accessible to any reader, this book holds a special resonance for geologists. It is a compelling testament to the fact that geology is as much about human persistence as it is about the rocks themselves. Davidson captures the raw reality of early fieldwork - the gruelling treks through the wilderness and the intellectual leap required to visualise deep time. The resolution of the conflict, provided by the observant Lapworth through his meticulous study of graptolites, serves as a brilliant reminder of how careful biostratigraphy can settle even the most entrenched ego-driven debates.



Stackpole Rock (not greywacke, but a Carboniferous limestone on the Pembrokeshire coast, SW Wales) drawn by Mrs Murchison

But this is more than a history of geology. As we travel through some of the most spectacular scenery in Britain, it's a celebration of the sheer visceral pleasure generations of geologists have found, and continue to find, in noticing the earth beneath our feet.

For the record, Mt Murchison in the South Island was named in 1860 by geologist Julius van Haast in honour of Sir Roderick Murchison (1792–1871), the Scottish geologist featured in this book. Other items named for him in New Zealand include Murchison Glacier in Mt Cook National Park and the Murchison Mountains in Fiordland National Park. Murchison was President of the Geological Society of London and a founder of the Royal Geographical Society. Murchison became a celebrity; his Silurian system adopted worldwide. He basked in the fame and glory he never achieved in his time as a soldier. The work undertaken by Lapworth, after Murchison's death, showed that some of that fame and glory was misplaced.

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* Wendy has compiled this review from a number of sources including AI (Gemini), other online reviews, and her own thoughts.

HYPERLINK INSTRUCTIONS

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