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Field Trip 8
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Paleobotany and Sedimentology of Central Otago and Southland

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Photo: Chatton Formation, Cosy Dell lime pit, near Croydon, looking west towards the Hokonui Hills. Photograph: Daphne Lee.

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Introduction

The aims of this field excursion are to examine a variety of fossiliferous, mostly non-marine, but including estuarine and rocky shore sedimentary sequences of Oligocene and Miocene age in Central Otago and Southland and to use the plant fossils and information from palynology to reconstruct the vegetation and paleoenvironments, including changing paleoclimates. Terrigenous and biogenic sediments include coal measures, silcrete, lake silts, estuarine sediments, shallow marine sandstone and carbonaceous mudstone. Otago and Southland have some of the best-preserved plant macrofossils of Oligocene and early Miocene age in Australasia. In addition to yielding information on floral richness and diversity, the associations of exceptionally well-preserved leaf compressions with cuticle, wood and amber, together with estuarine and shallow marine beds make it possible to glimpse and reconstruct past ecosystems at selected intervals during the past 27–14 million years.

ITINERARY

Day 1. Thursday 1st December: The trip will leave Wanaka at the end of the conference.

Overnight and dinner/breakfast at Bannockburn and/or Cromwell.

Day 2. Friday 2nd December: Visit Bannockburn Inlet, then drive to St Bathans where we will look at sediments of Dunstan Formation with leaf fossils. Lunch at St Bathans. We will examine early Miocene lake sediments and associated fauna and flora and collect wood and amber at the Idaburn lignite mine. We will then drive south to Roxburgh (Miocene coal measures with amber). Overnight and dinner/breakfast at Gore.

Day 3. Saturday 3rd December: We will investigate two sites at Cosy Dell near Waimumu: a rocky shore locality in the Late Oligocene Chatton Formation and the late Oligocene–early Miocene Gore Lignite Measures. We will then visit the early Miocene Landslip Hill silcrete and the late Oligocene Pomahaka Estuarine Beds (both near Waikoikoi). If time permits, we will collect plant fossils from an Early Miocene carbonaceous mudstone deposit at Hindon.

Participants will arrive back at Dunedin airport in time for late flights north, or they can stay overnight in Dunedin.

Day 1. Thursday 1st December: Wanaka to Bannockburn

If weather and time permit, we will briefly examine the sediments resting unconformably on the schist basement in the road cutting between the bridge over the Kawerau River and the Bannockburn Hotel. The unconformity is not well-exposed at present, but moderately dipping quartz gravels and sands at the base grade up into brownish grey siltstone beds which have a variety of poorly preserved angiosperm leaf fossils and occasional Casuarinaceae 'cones'.

Day 2. Friday 2nd December: Bannockburn to Gore

We will be crossing two major river catchments of southern New Zealand – from the Clutha, with its tributaries of the Manuherikia and Pomahaka – to the Mataura River (Fig. 8.2). The trip takes us from Bannockburn through to another historic gold mining township, St Bathans, the upper Manuherikia River and the disused Idaburn lignite mine. We will then head south to Alexandra criss-crossing the Middlemarch-Clyde Rail Trail, stop at Harliwich's Pit and travel south to Gore.

Stop 1 Bannockburn Formation, Bannockburn

Stop 2 Alluvial beds, St Bathans, Manuherikia Group

Stop 3 Alluvial and lacustrine beds, Manuherikia River, Manuherikia Group

Stop 4 Idaburn lignite mine, Manuherikia Group

Stop 5 Harliwich's Pit, Manuherikia Group

Day 3. Saturday 3rd December: Gore to Dunedin

In marked contrast to Central Otago area where swamp and lake sediments rest unconformably on schist basement the landscape in the area around Gore is dominated by the east-west trending strike ridges of the Hokonui Hills in the Murihiku Terrane. At Cosy Dell farm, shallow marine sediments of Chatton Formation rest unconformably on Murihiku basement of Jurassic age. These marine sediments are overlain by Gore Lignite Measures which comprise lignite seams, mudstone units and quartz sands and conglomerates. Near Waikoikoi, we will examine estuarine sediments of the Pomahaka Formation which underlies the Chatton Formation. If time permits, we will make a brief visit to a maar lake deposit near Hindon, part of the Waipiata Volcanic Group, that was formed by a small volcano which erupted through schist basement.

Stop 6 Cosy Dell lime pit, Chatton Formation

Stop 7 Cosy Dell lignite mine, Gore Lignite Measures

Stop 8 Landslip Hill silcrete, Gore Lignite Measures

Stop 9 Waikoikoi Creek, Pomahaka FormationStop 10 Hindon Maar

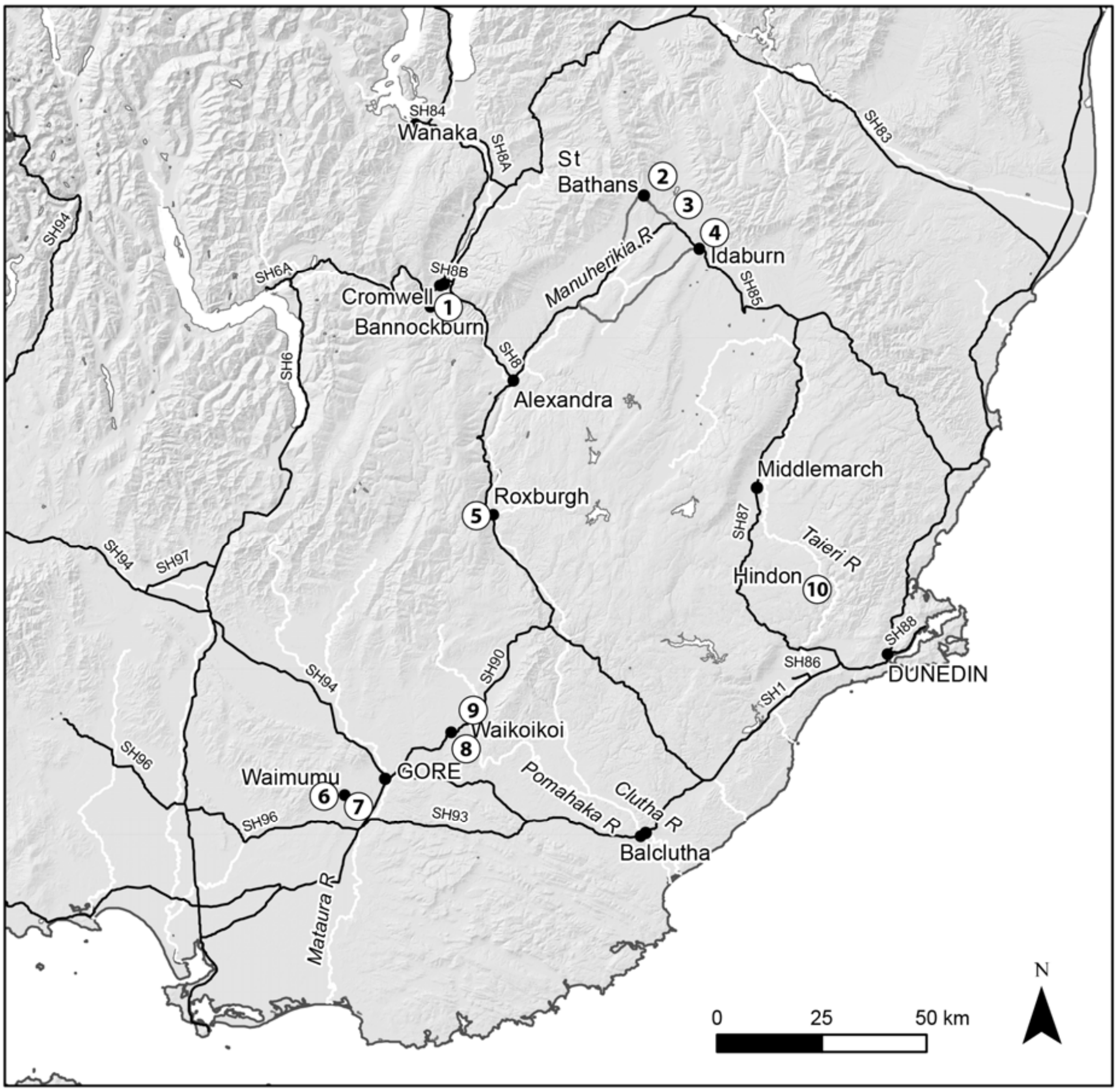

Fig. 1 Route map.

INTRODUCTION

Central Otago is dominated by tor-studded landscapes formed in schist basement. Originally greywackes and argillites deposited in Permian–Triassic times in ocean basins and trenches off Gondwana, these rocks were metamorphosed into Otago Schist during the Jurassic. By the early Cretaceous, about 110 million years ago, the once deeply buried schist had been uplifted and eroded down to a low relief erosion surface (‘peneplain’) over most of Otago. The Otago Peneplain represents a gap of >60 million years in the rock record and the more-or-less flat topped, tor-studded mountains such as the Rock and Pillar Range, Dunstan and Old Man Range are remnants of this widespread erosion surface.

By the Early Miocene (23–20 million years ago), a plate boundary had developed through New Zealand. This led to uplift and a gradual increase in the New Zealand land area. Large braided rivers and eventually a vast inland lake system covered most of the Central Otago region (Fig. 2). The sediments deposited by these rivers and lakes are collectively termed the Manuherikia Group (Douglas 1986). Now preserved in several Central Otago NNE-trending thrust-fault controlled half graben and as erosional remnants on schist horsts (Fig. 3), Manuherikia Group typically comprises a basal succession of alluvial conglomerate, sandstone, mudstone and lignite (Dunstan Formation) overlain by palustrine and lacustrine sediments (Bannockburn Formation) comprising mudstone and shale, along with thin sand and biogenic carbonate beds. Although Dunstan Formation lignites are widespread in Central Otago, they are surprisingly hard to find. Often the best indications of the dozens of former coal workings are signposts for ‘Coalpit Road’ or ‘Coal Creek’. Currently, the only active lignite mine is Harliwich’s Pit, near Roxburgh (Stop 5) where opencast lignite is mined largely for local use.

The younger Bannockburn Formation sediments were deposited in the vast paleolake Manuherikia which at its maximum covered an area of about 5600 km^2 (Douglas 1986) (more than the combined area of all modern New Zealand lakes). Up to 700 m of sediments accumulated in and around this lake basin, which, although fairly shallow, must have been slowly subsiding in order to hold the fine sands and muds carried in by meandering rivers. Fine-grained, white or pale brown lake sediments are well exposed in gold diggings and in road cuts near St Bathans, in and around the rail trail in the Manuherikia Valley and elsewhere. Sometimes, as in road cuttings near the Roxburgh Hydro Dam, they are brick-coloured from ‘baking’ by burning lignite.

At the time of Lake Manuherikia, the Central Otago landscape was subdued with low hills. But about 15 million years ago, after the Australian-Pacific plate boundary had developed through New Zealand, the landscape began to change. New Zealand’s land area began to increase, the sea retreated and eventually tectonic uplift resulted in vast quantities of greywacke-derived gravels from the north and schist-derived gravels from the south and west filling in the lake. Often the Miocene lake sediments are tilted and deformed, with younger undeformed, flat-lying gravels lying unconformably above them, as seen at Bannockburn and near St Bathans.

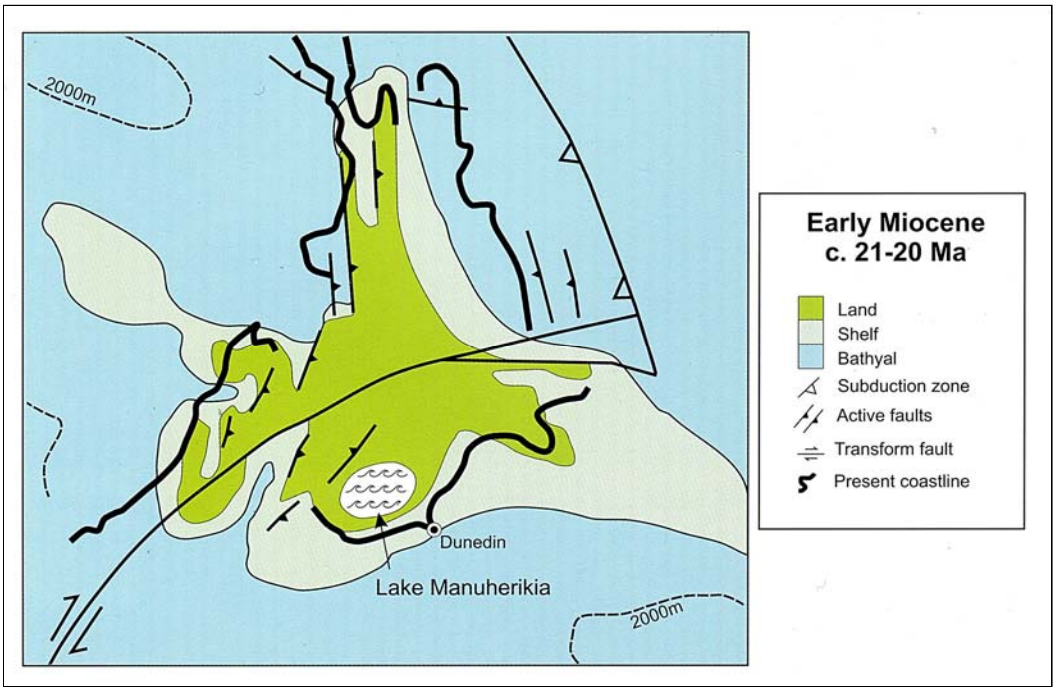

Fig. 2 Paleogeographic map of New Zealand in the early Miocene, showing the position of Lake Manuherikia (Lee & Forsyth 2009).

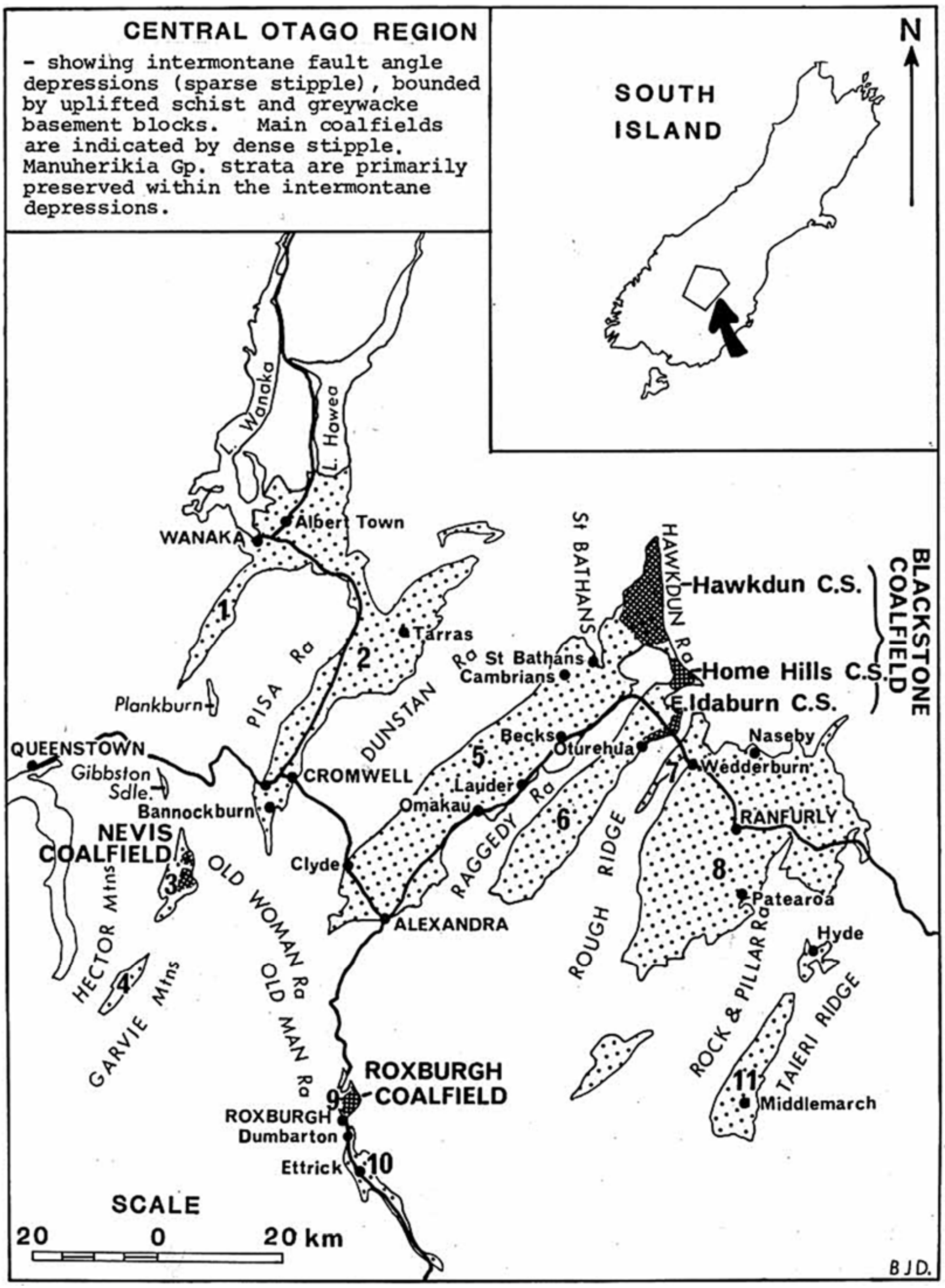

Fig. 3 Map of Central Otago structural basins: 1, Cardrona Valley; 2, Upper Clutha Valley; 3, Lower Nevis Valley; 4, Upper Nevis Valley; 5, Manuherikia Valley; 6, Ida Valley; 7, White Sow Valley; 8, Maniototo Valley; 9, Roxburgh Basin; 10 Ettrick Basin; 11 Middlemarch Basin (Douglas 1986).

Manuherikia Group

Manuherikia Group consists of fluvial lignite-bearing Dunstan Formation and an overlying Bannockburn Formation that consists mainly of lacustrine sediments. A detailed stratigraphy subdividing Dunstan Formation into units of regional extent is presented in Fig. 4 (Douglas 1986).

Much of the information on the Dunstan and Bannockburn Formations is modified from earlier field guides produced for Geological Society of NZ Conference (Lee et al. 2003; 2009).

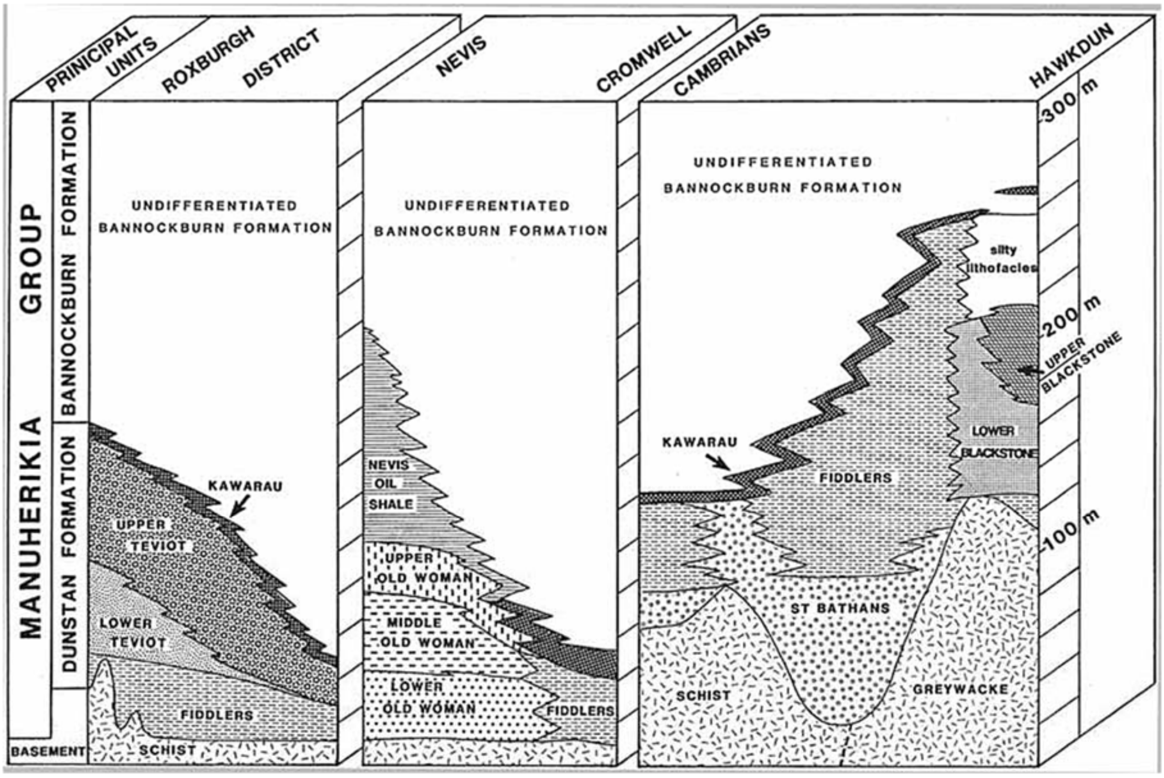

Fig. 4 Stratigraphic relationships of major Manuherikia Group units (Douglas 1986).

The earliest Dunstan Formation sediments in Central Otago were deposited by braided river systems that occupied the valley floors of an irregular, schist and greywacke landscape. The East Otago lower to mid Cenozoic marine transgression reached the Naseby and Middlemarch districts during the Late Oligocene and is not known to have extended further west.

Roughly coinciding with the dissipation of the braided channel system (during the early Miocene), a network of sandy, low-gradient meandering channels and muddy flood-basins extended over most of the Central Otago area. Fine-grained sediment appears to have been transported towards a depocentre formed from coalescing flood-basins that eventually became Lake Manuherikia. The low channel gradients across the alluvial plain and the large volume of fine to medium sands and mud imply a continual sediment source from a land area of low to moderate relief.

Manuherikia Group sediments that originally covered Central Otago were highly deformed by Kaikoura orogenic events and are now predominantly preserved in north to north-east trending Central Otago basins, bounded by uplifted schist and greywacke basement ranges (Fig. 3). Evidence for the former regional continuity of Manuherikia Group is provided by the similarity of local depositional patterns of strata in adjacent basins and by remnant fault-bounded outliers on the range tops.

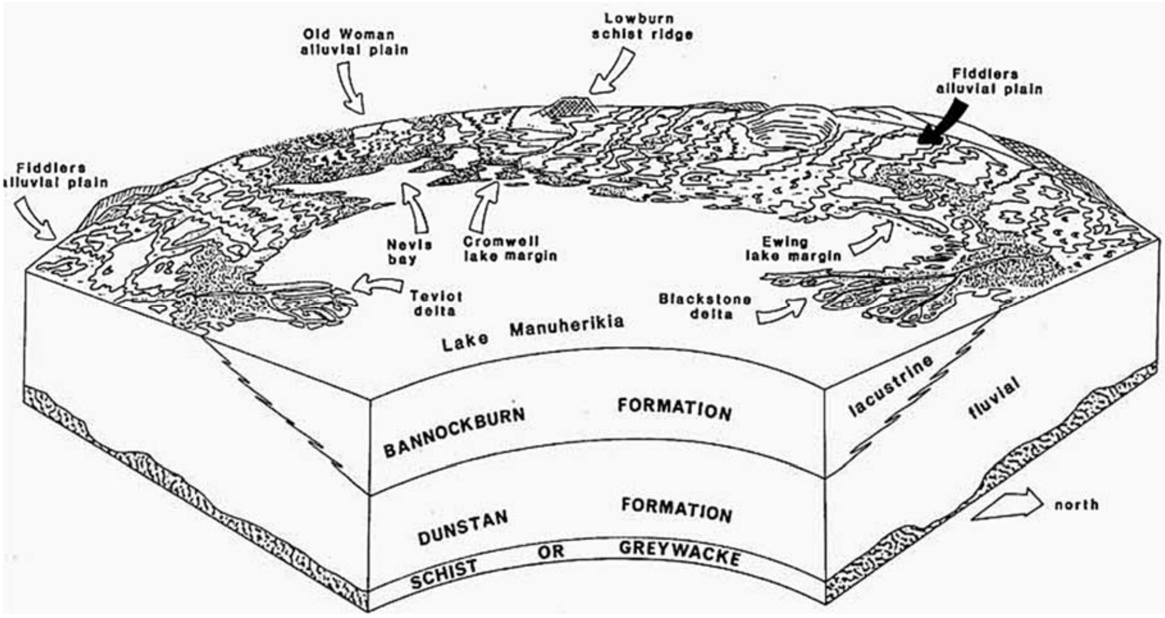

Fig. 5 Schematic reconstruction of Early to Middle Miocene depositional environments in Central Otago (Douglas 1986).

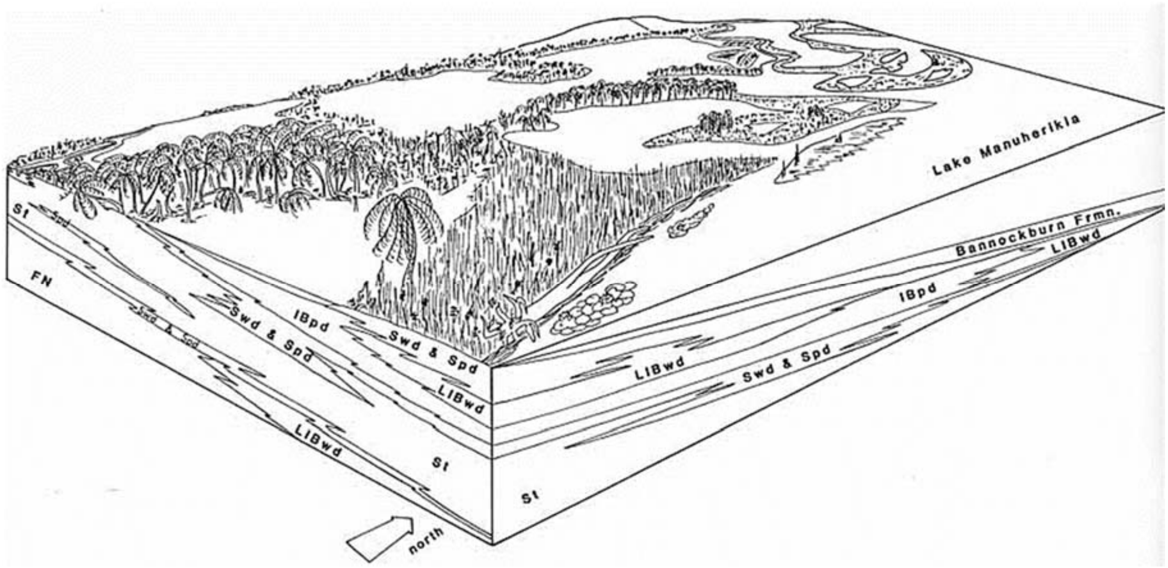

Fig. 6 Reconstruction of the fluvial-lake margin environment as interpreted from Cromwell Submember lithofacies exposed in the Cromwell-Bannockburn district (Douglas 1986).

Stop 1 Bannockburn Inlet

At Bannockburn Inlet, steeply dipping beds consist predominantly of richly carbonaceous lithologies of lignite, carbonaceous mud, organic shale and less commonly of non-carbonaceous mud and sand. These lithologies occur as thin beds arranged into cyclic sequences. One sequence consists of lignite (peat-forming herbaceous swamp to forest swamp material) and richly carbonaceous mud (poorly drained muddy swamp deposits). The other consists of moderately carbonaceous rooted mud (well-drained swamp), thinly bedded or interlaminated silts and muds (well-drained interdistributary bay) and richly organic clayshales and mudshale (poorly drained interdistributary bay).

The setting of poorly drained muddy swamps, peat-forming herbaceous and forest swamps that encroached over well-drained swamps, enveloping infilled or “starved” interdistributary flood-basins and interdistributary bays is illustrated in the paleogeographic models (Figs 5, 6) of the fluvial lake margin.

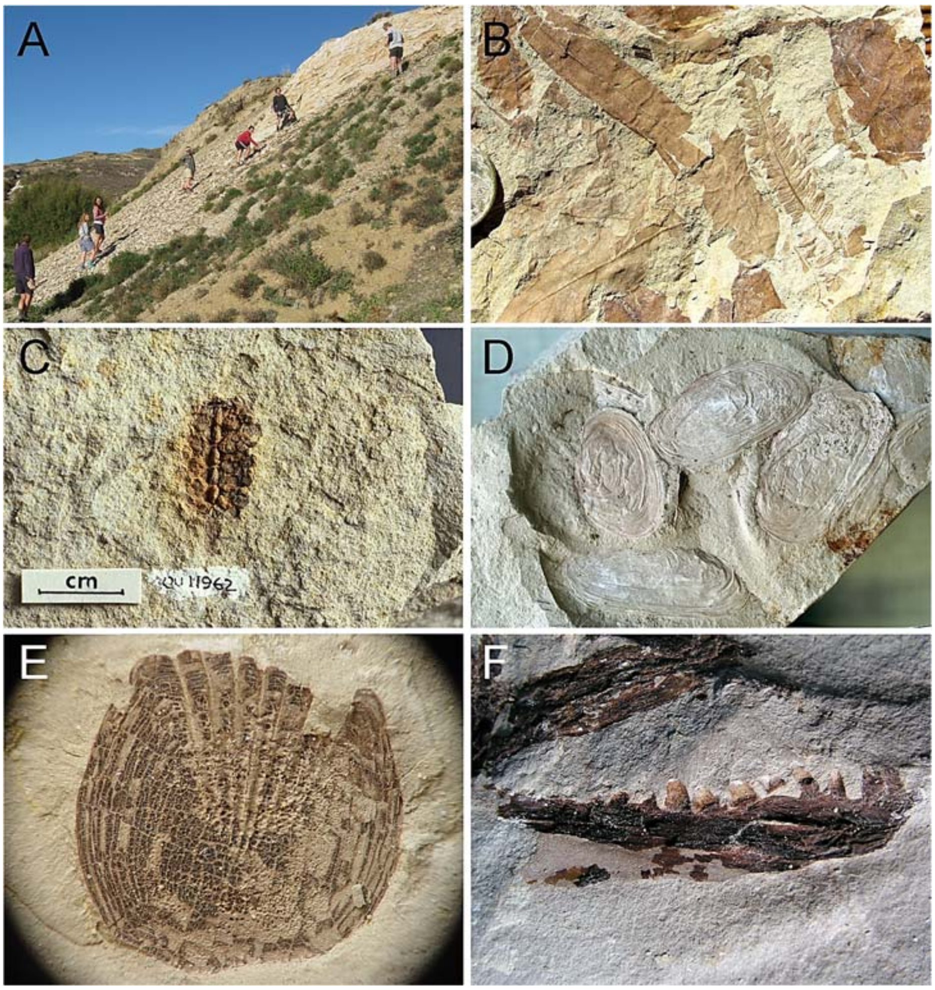

Fig. 7 Bannockburn fossil locality and representative fossils**. A.** Steeply dipping mudstones with plants and fish remains at Bannockburn Inlet. **B.** Bedding plane with fern, palm and dicot leaves. **C***.* Casuarinaceae 'cone'. **D.** Freshwater mussels. **E.** Perciform fish scale. **F.** Jaw of fossil *Galaxias*.

Plant and invertebrate fossils

A variety of plant, invertebrate and a few vertebrate fossils are known from the Bannockburn area, including Bannockburn Inlet (Fig. 7). Angiosperm leaves are the most common fossils although they are not particularly well-preserved. In Central Otago in the early-middle Miocene, pollen and macrofossils indicate a diverse flora that included a number of sclerophyll taxa such as *Beauprea*, *Diplopeltis*, *Gyrostemon* and *Micrantheum* as well as rainforest taxa such *Ilex* (Mildenhall 1989). Co-existing with these now locally extinct angiosperms were *Ripogonum*, *Phormium*, palms, araliads, *Fuchsia*, *Gunnera*, *Metrosideros*, *Nothofagus fusca* and *menziesii* types and *Weinmannia* as well as many, as yet, unassigned taxa (see Pole 1992, 1993). Pole et al. (2003) noted that more than ten conifer taxa are now known from Central Otago, as well as at least three ferns and a cycad (Fig. 7B). Mildenhall & Pocknall (1989) listed nearly 200 pollen and spore types from the Central Otago area.

Campbell & Holden (1984) described a new species of *Casuarina*, *C. avenacea* from Bannockburn and Casuarinaceae 'cones' and a variety of leaves are moderately common in a siltstone unit in the roadcut below the Bannockburn Hotel (Fig. 7C) and near the Inlet. Campbell et al. (2000) described the first fossil divaricate from equivalent beds in the Nevis Oil Shale and suggested that the influence of moa browsing on the New Zealand vegetation was at least this old. Discovery of probable moa egg shell elsewhere in Lake Manuherikia sediments suggests a long history of ratites in New Zealand (Tennyson et al. 2010).

Compressed double-valved freshwater mussels (*Echyridella*) are quite abundant in some beds (Fig. 7D). An almost entire freshwater crayfish (koura) was described from Bannockburn by Feldman & Pole (1994). McDowall & Lee (2005) described two large fish scales (Fig. 7E) collected from a temporary spoil heap from a drainage ditch opposite the Bannockburn store as representing a basal perciform fish widely present in southern cool-temperate lands but no longer living in New Zealand. New Zealand today has a freshwater fish fauna of about 35 described species belonging to 8 families. Further fish remains including fish jaws and skull fragments collected from a locality adjacent to Bannockburn Inlet were referred to a large species of *Galaxias* (Fig. 7F) (Lee et al. 2007).

Stop 2. Alluvial beds, St Bathans

Blue Lake, at the foot of Mt St Bathans, is an important historical gold mining area (Fig. 8) and unusual in that gold was mined here in an area of greywacke, rather than schist basement. Early Miocene erosion of schist hills further to the south produced quartz-rich river sediments that were transported northeast with their associated gold and deposited on greywacke bedrock in the St Bathans area.

Stratigraphically, the quartz gravel conglomerates at Blue Lake represent the St. Bathans member of the lower Dunstan Formation. Carbonaceous mudstone horizons and lenses interbedded with the quartz gravels can be disaggregated to reveal ferns, small conifer shoots, conifer leaves, numerous seeds and angiosperm leaf fragments. Some blocks have produced well-preserved angiosperm leaves including Lauraceae, Myrtaceae, Nothofagaceae and Elaeocarpaceae. Steeply dipping sandstones, siltstones and carbonaceous mudstones exposed at the southern end of the picnic area contain coalified plant detritus and occasionally rounded (transported) lumps of red and orange amber.

Fig. 8 Blue Lake at St Bathans infills a 70-m-deep hole left by removal of the 120 m high Kildare Hill by gold mining operations. Photo: Daphne Lee.

Stop 3. Manuherikia Group upstream of Manuherikia River bridge, Loop Road

Immediately north of Manuherikia River Bridge, a 300 m south-dipping succession of alluvial plain and lacustrine sediments of the Dunstan and Bannockburn Formations is exposed (Figs 9–11). The lower alluvial succession consists of quartz pebble and granule conglomerate, quartzose sandstone and silty mudstone beds from 1–6 m thick. The white to pale greenish grey silty mudstone paleosol beds are markedly homogeneous, containing abundant 2–4 mm diameter and 5–15 cm deep mud-filled rootlet casts. At the top of the coarse grained alluvial succession is a fine-grained association of woody lignite, root-mottled carbonacous mudstone, silty fine sand (commonly rootlet penetrated), micaceous lignitic shale and greenish grey claystone. The claystone facies contains fish vertebra, spines and teeth. This assemblage forms a transition with overlying palustrine and lacustrine beds and its component facies represent forested peat swamp (woody lignite), floodplain lake–open bay (laminated shale, fish bone-bearing claystone) and probable distributary splay (laminated silty sand) deposition.

Overlying the topmost lignite-bearing part of Dunstan Formation, the lower 8.8 m of Bannockburn Formation consists of fine silty sandstone, green claystone, calcareous mudstone and marl (Fig. 11). Fine-grained sandstones locally include quartz granules (<15 mm) and granules, marl pebbles and fish vertebra and spines. Unionid bivalves (*Echyridella*), ostracods, tubular microbial carbonate and stromatolitic carbonate grains are locally present. Rare 8–10 mm diameter trace fossils of possible crustacean origin display inverted-Y junctions. Distinctive fine-grained cream–pale greenish grey marls and calcareous mudstones up to 40 cm thick contain 1–3 mm diameter branching rootlet casts, infilled with green clay. Marl beds intensely disrupted by plant root, animal burrowing, or desiccation brecciation are preserved as weakly-cemented nodules enclosed by mottled greenish grey clay. The micritic carbonate is thought to have been precipitated during the photosynthetic activities of cyanobacteria, charophytes and other aquatic plants in a lake margin (carbonate marsh) setting prone to seasonal flooding and desiccation. Interbedded green claystones containing abundant root traces probably represent shallow lake deposition within the zone of nearshore plant growth. The interbedded nature of these two facies indicates a rapidly oscillating shoreline. Associated sandstones and intraformational rounded marl pebble and shelly bases to some sands, are interpreted as storm wave-sorted deposits.

The upper part of the lacustrine association is dominated by greyish green mudstone and laminated shale (Fig. 11) with subordinate silty mudstone and shelly and microbial carbonate beds. Blocky weathering green mudstones contain abundant 1–2 mm wide vertical rootlet-like structures. Hyriid bivalve moulds and occasional shelly, locally paired, inflated valves are present. The green mudstone supported abundant aquatic plants and is interpreted as a nearshore facies, as in the palustrine association. Thin sharp-based shelly sand lags contain fish and bird bones (Douglas et al. 1981), together with mollusc shell and algal carbonate fragments. Local concentrations of carbonate sand are composed of ostracods or gastropods, including sinistrally coiled (opening on the left) *Physa* sp. (Fig. 12A). Thin developments of stromatolites associated with carbonate sands (Fig. 12B) and composed of laminated microcrystalline calcite, are comparable with various forms described from other Manuherikia Valley localities (Lindqvist 1994).

Laminated shales, very dark grey–greenish grey when freshly exposed, contain fine organic matter and abundant mica flakes. Scattered fish vertebra, spines and scales are commonly preserved, as are compressed hyriid bivalve moulds. Some incomplete articulated fish specimens have been collected (McDowall et al 2006) and Schwarzhans et al. (2012) described 14 species of freshwater fish from several thousand otoliths, including new species of Galaxiidae, Retropinnidae and Eleotridae. The shale beds, typically grading upward into green mudstone, are interpreted to have been deposited in the deeper lacustrine profundal zone, perhaps during times of higher lake levels and increased input of mica-rich sediment from tributary rivers.

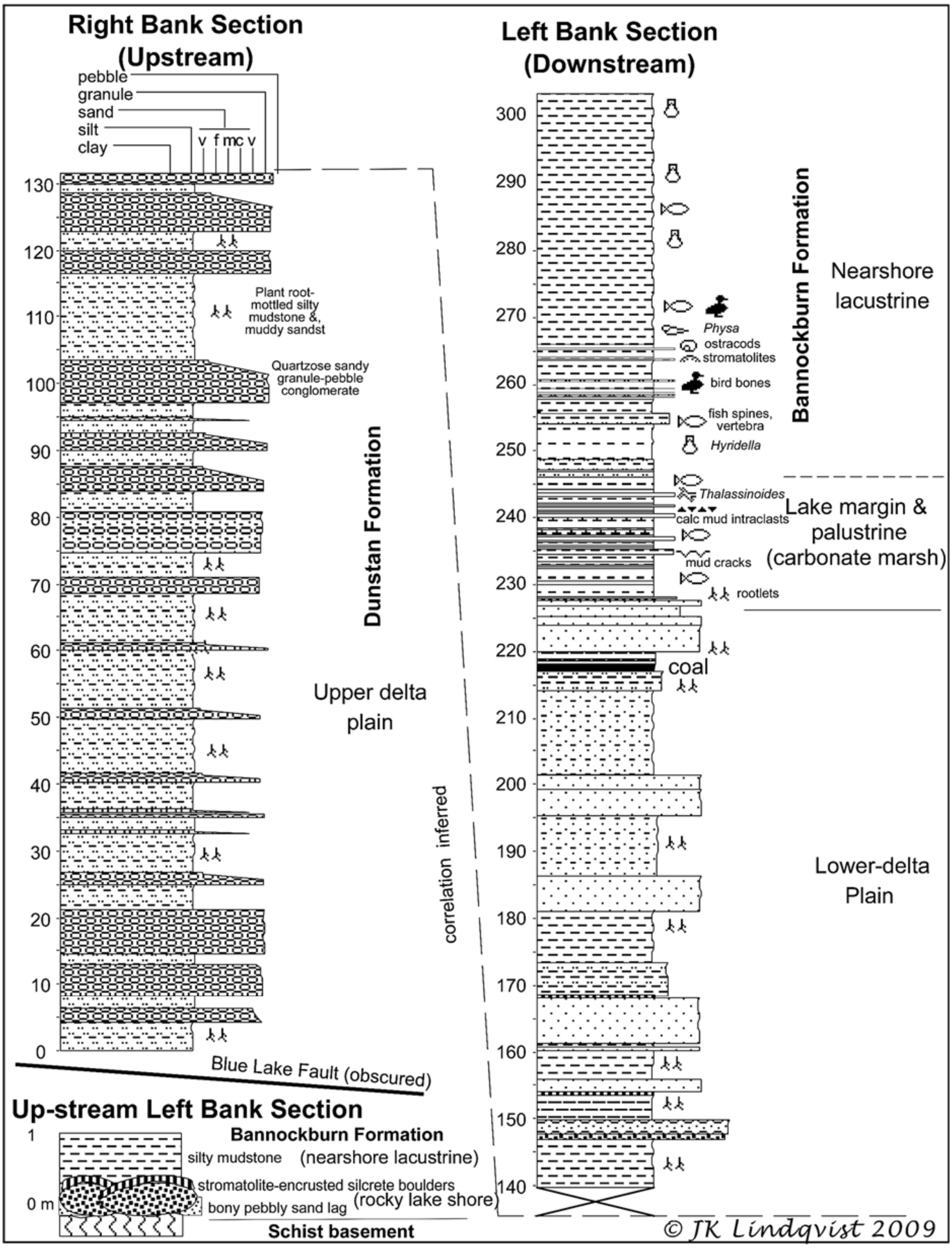

Fig. 9 Stratigraphic sections recorded upstream of Manuherikia River Bridge, St. Bathans Road. Figure: Jon Lindqvist.

Fig. 10 Paleobotanists Ian Raine and Liz Kennedy examining the lacustrine section above the Manuherikia Bridge. Photo: Daphne Lee.

Fig. 11 Interbedded brownish grey shale and green mudstone in the Bannockburn Formation lacustrine section near Manuherikia River bridge. Rock hammer for scale, lower left. Photo: Jon Lindqvist.

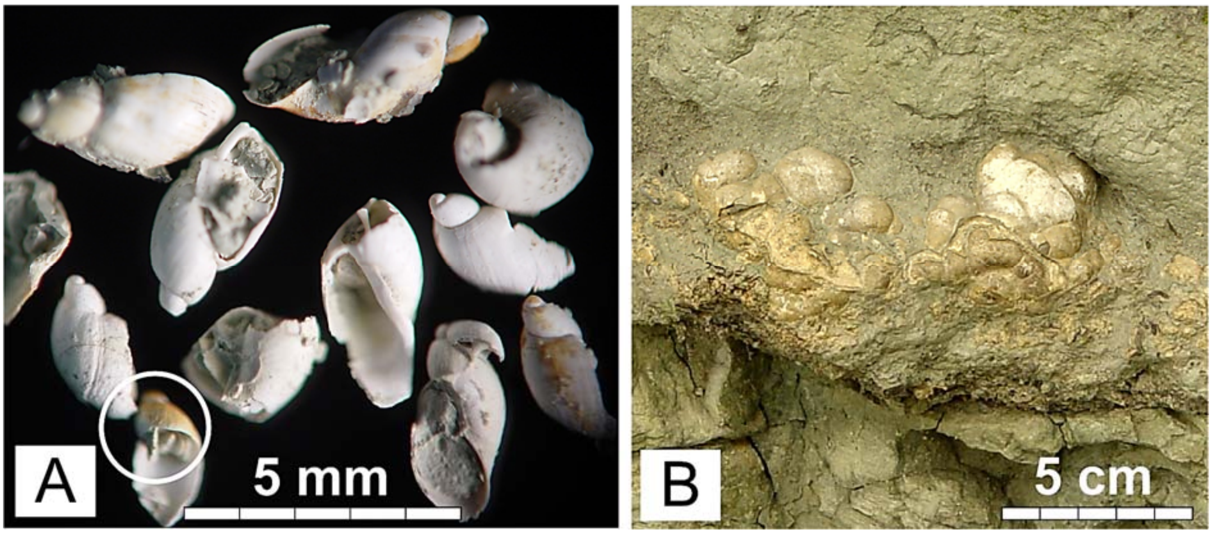

Fig. 12 A. Small sinistrally coiled freshwater gastropods (*Physa* sp.) from a 2–3 cm thick muddy shellbed. **B.** Stromatolite bioherm associated with laminated ostracod-rich carbonate sand. Photos: Jon Lindqvist.

Several outcrop samples examined for palynological age determination by Dallas Mildenhall in 2008 contain a number of taxa not known to be either older than Altonian or younger than Clifdenian (e.g. *Haloragacidites amolosus* Partridge, *Latrobosporites marginis* Mildenhall & Pocknall, *Lymingtonia cenozoica* Pocknall & Mildenhall, *Rhoipites hekelii* Mildenhall & Pocknall). They indicate that these beds are in the *Spinitricolpites latispinosus* Zone (Crundwell et al. in Cooper 2004) and are of Altonian-Clifdenian age. All fossiliferous samples include an abundance of Casuarinaceae pollen, with a variety of *Nothofagus* pollen types (mainly *Fuscospora* and *Brassospora*) increasing in abundance up sequence (cooler and wetter?). Podocarpaceae including *Dacrydium cupressinum, Dacrycarpus dacrydioides, Microcachrys, Phyllocladus* and *Lagarostrobos franklinii*, Araucariaceae, Asteraceae, Myrtaceae, Polypodiaceae, *Milfordia homeopunctata* (McIntyre) (Restionaceae) and various unidentified tricolporate pollen types are also common. The lake sediments are dominated by the freshwater colonial algae *Botryococcus* and *Pediastrum.* The pollen assemblage appears to be derived from a mixed beech/podocarp forest with she-oaks possibly flanking the depositional site. A site such as this fringing a large lake would result in much regional pollen being captured and so beech and probably other pollen may be derived from some distance.

The first fossil crocodile from New Zealand is a fragment of jaw collected by Mike Pole from near here (Molnar & Pole 1997). The bone is probably from an extinct group of mekosuchine crocodiles first recognised in Australia and now known from other SW Pacific localities as well as New Zealand.

A team led by Trevor Worthy has been excavating near St Bathans since 2001. Their research is providing new insights into the terrestrial vertebrate fauna of New Zealand, especially birds and reptiles (Worthy et al. 2007, 2008a,b, 2009, 2011). To date, they have reported some 30 species of birds, including 5 genera of anatids, making it the most diverse Neogene ‘duck’ fauna known worldwide globally. Other birds include a diving petrel, a gull, small waders, a possible flamingo, a pelican, several rails, an eagle, a pigeon and several parrots (Worthy et al. 2007; 2008). Thick eggshell is most likely that of moa, although no moa bones have yet been discovered (Tennyson et al. 2010). Other bones indicate the presence of frogs and diverse skinks and geckos (Worthy et al. 2013; Lee et al. 2009), as well as the first pre-Quaternary record of tuatara (Jones et al. 2009). The fauna also includes several species of bats. One of these, recently described as *Mystacina miocenalis* confirms that the endemic bat family Mystacinidae which today consists of two omnivorous and semi-terrestrial bats has a long history in New Zealand (Hand et al. 2015).

Stop 4. Idaburn coal mine, Idaburn

This open cast mine was formerly operated by the Idaburn Coal Mining Company Limited and exposes palustrine to fluvial sediments of the Fiddlers Member, Dunstan Formation, Manuherikia Group (Douglas 1986). The up to 8 m thick Oturehua Seam (of which only the uppermost part is now exposed) contains well-preserved conifer wood including branches, tree trunks and occasional *in situ* stumps and beds composed almost entirely of fern-like rachis (Fig. 13). In combination with fine-grained lighter (dark brown) facies devoid of xylitic detritus and laminae of fine quartz sand intercalated with the lignite, this indicates accumulation of richly organic sediment in environments fluctuating between herbaceous swamps, forest swamps and poorly drained muddy swamps (Douglas 1986). Blocks and lumps of amber are abundant in the lignite and amber blocks of 2.5 kg have been found at this site. Laminated, carbonaceous and leaf-bearing mudstone that accumulated in a poorly drained muddy swamp directly above the lignite is overlain by fluvial quartz sand and conglomerate facies (Fig 14).

Fig. 13 ***Upper row:*** The opencast pit at Idaburn, with well-preserved branches, occasional *in situ* rooted stumps and fern-like rachis. Photos: Beth Fox. ***Lower row:*** **A**. Transverse section of *Podocarpus* wood from Idaburn showing somewhat compressed growth rings (early wood and late wood) and ray cells (dark vertical lines). **B.** Tangential section showing tracheids (lighter colour) and ray cells (dark colour, oval shape). **C.** Radial section showing vertical tracheid cells and horizontal ray cells and intertracheid pitting. Photos: Mathew Vanner.

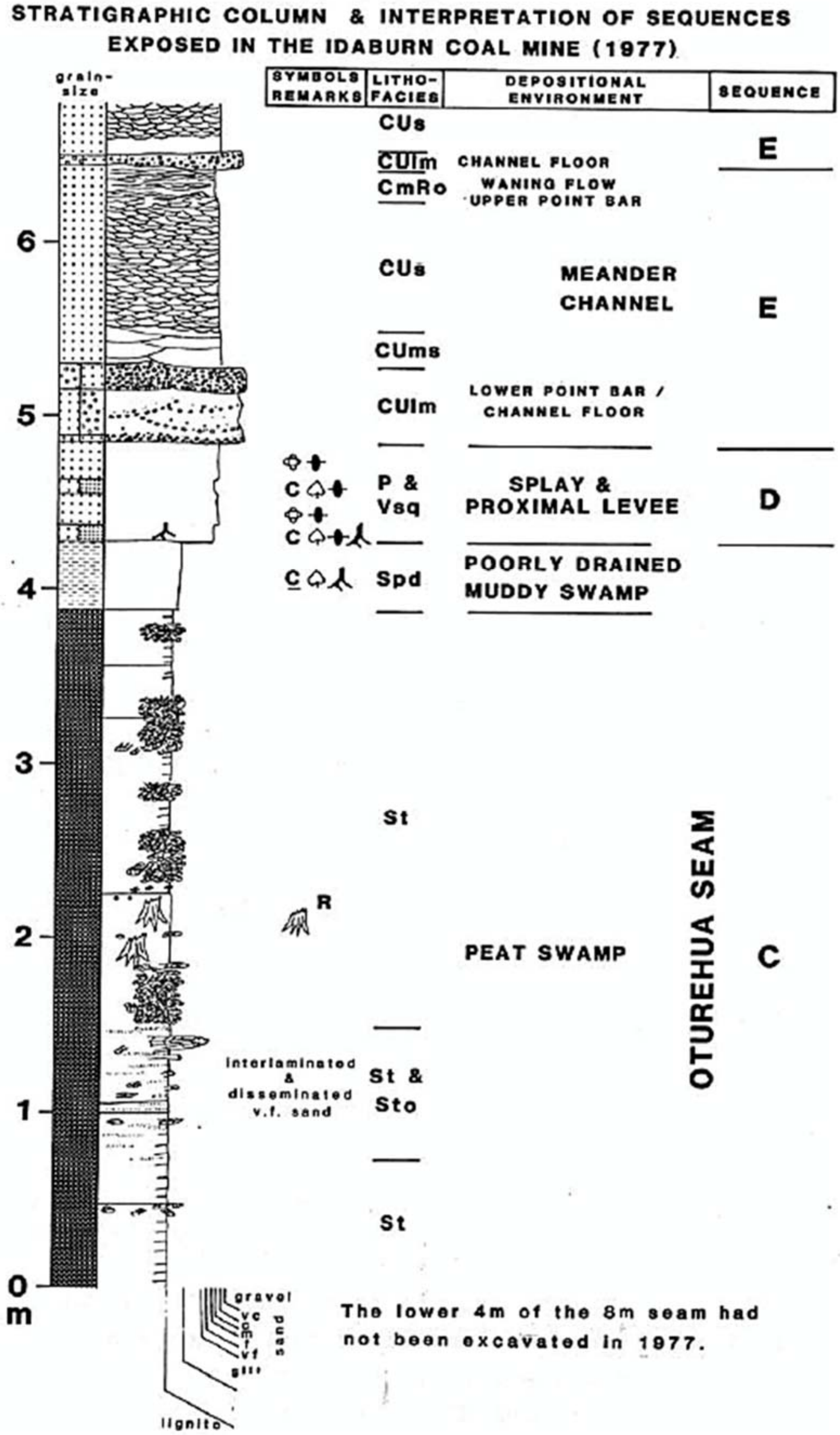

Fig. 14 Stratigraphic column and interpretations of the Idaburn sequence as exposed in 1977 (Douglas 1986).

Stop 5 Harliwich's Opencast Mine, Coal Creek, Roxburgh

The thickest lignite seam in the Central Otago region occurs in the East Roxburgh coalfield and varies from 33–85 m thick (Douglas 1986). It is currently mined at the open cast Harliwich's Pit (Fig. 15) where the seam reaches 45 m. Resin and woody stems and logs up to 6 m long, some in growth position, are locally abundant. According to Douglas (1986: 255), the McPherson Seam "represents deposits of a long-lived, peat-forming swamp that accumulated on the upper part of the Teviot delta plain."

Fig. 15 At Harliwich's Pit, a thick, gently dipping seam of lignite is exposed beneath white quartz sands. Photo: Daphne Lee.

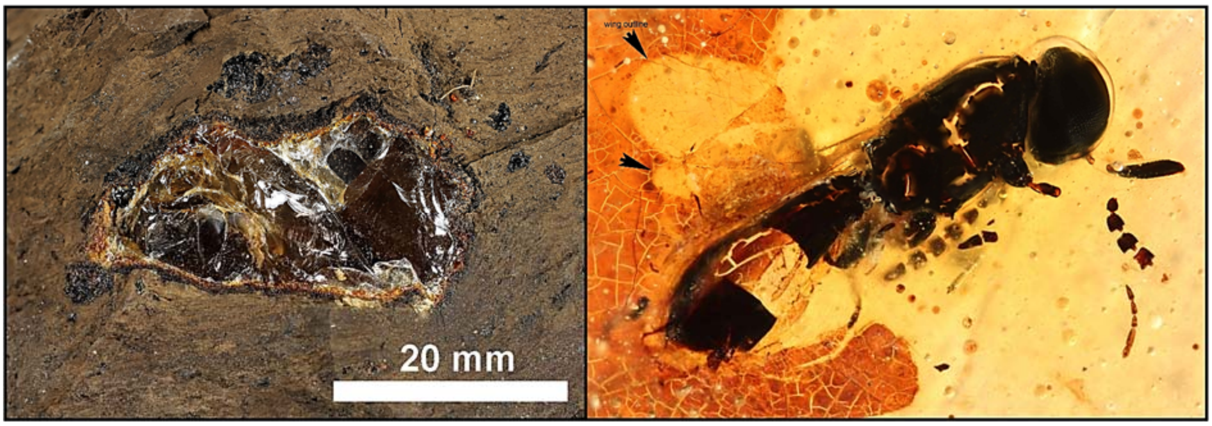

Fig. 16 Amber piece in carbonaceous mudstone and three-dimensionally preserved parasitic wasp in amber from Harliwich's Pit. Photos: Uwe Kaulfuss and Alexander Schmidt.

Fossil tree resin (amber) occurs in thin layers within the McPherson Seam, the overlying 'Rosin Seam' and in carbonaceous mudstones associated with the lignite, in a variety of sizes and shapes, from mm-sized droplets to lumps and blocks up to 10 cm in diameter (Fig. 16). Most of the Roxburgh amber is light to dark brown and opaque; translucent amber with yellow or orange colours is rare, as is 'layered' amber formed by successive resin flows. Preliminary chemotaxonomic analyses by gas chromatography suggest an araucarian origin, at least for some of the amber from the Roxburgh coalfield (Powell et al. 2013).

The discovery of three-dimensionally preserved fossil inclusions in some Oligocene and Miocene ambers in recent years has created novel avenues for exploring New Zealand's past biodiversity and biogeography (Kaulfuss et al. 2016). Amber inclusions from Harliwich's Pit include plant debris and ascomycete fungi and a diverse fauna including springtails (Collembola), four suborders of mites, spiders, diverse insects (Hymenoptera, Lepidoptera, Diptera, Coleoptera, Psocoptera), the second Southern Hemisphere record of a fossil pseudoscorpion (Philomaoriinae) and soft-bodied nematode worms; many of these taxa are the first fossil records globally. Finding these minute inclusions requires time-consuming microscopic screening of amber pieces; they are not likely to be detected with the unaided eye in the field.

Palynological samples from the East Roxburgh coalfield are dominated by Podocarpaceae, Myrtaceae or *Nothofagus* pollen. The Nothofagaceae include representatives of the *Fuscospora* group (*Nothofagidites lachlaniae*), *Lophozonia* group (*N. asperus*) and *Brassospora* group (*N. cranwelliae*). The Myrtaceae include forms resembling *Acmena*, *Metrosideros, Leptospermum* and *Eucalyptus*. Other common taxa include A*recipites otagoensis* (Couper), *Haloragacidites harrisii* (Couper), *Podocarpidites*, Palmae and Loranthaceae (Mildenhall & Pocknall 1989). In contrast, Pteridophyte spores are rare.

The spore-pollen assemblages were derived from a forest growing under humid, warm temperate conditions. However, occasional periods of drought and fire are suggested by the presence of charcoal, Gyrostemonaceae (*Gyropollis psilatus* Mildenhall & Pocknall) and *Mallotus-Macaranga* (*Nyssapollenites endobalteus* (McIntyre)) pollen and periods of cooler climate when *Fuscospora* dominate and Podocarpaceae. The age is likely to be Altonian (Early Miocene), based on the occurrence of *Anisotricolporites truncatus* Pocknall & Mildenhall and *Acaciapollenites miocenicus* Mildenhall & Pocknall (Mildenhall & Pocknall 1989) and all samples fall into the *Spinitricolpites latispinosus* Zone.

The only leaf macrofossils recognised from the locality are large palm fronds that resemble nīkau (*Rhopalostylis*) from baked mudstones associated with the lignite and *Eucalyptus*-like leaves (Holden 1983). Rare *Agathis* leaves with cuticle preserved have been found recently on bedding planes in the lignite. They resemble those described from Newvale Mine by Lee et al. (2007).

This is the only currently working coal mine remaining out of dozens that once operated in Central Otago.

Day 3. Gore to Dunedin

Stop 6. Chatton Formation, Cosy Dell Farm

At Cosy Dell farm, a new exposure of highly fossiliferous Chatton Formation is located close to the core of an eroded anticlinal structure that separates Waimumu and Croydon coalfields. Waimumu and Croydon coalfields are the smallest of six major lignite deposits in Eastern Southland (Isaac & Lindqvist 1990). They occupy a gently warped northeast-trending structural block, overthrust from the west along Bushy Park Fault by Murihiku Terrane basement rocks and bordered to the east by Hedgehope Fault which also has reverse throw, up on the west. Several en echelon splinter faults cause local structural disturbance within the block.

In the recently excavated Cosy Dell lime pit (Fig. 17) two shellbeds containing high diversity faunas dominated by robust thick-shelled molluscs are interbedded with shelly sands that contain scattered smaller thin-shelled bivalves and thin current-sorted concentrations (Fig. 18). The lower of the two main shellbeds includes abundant well-rounded Murihiku basement-derived andesites and granitoids, greywacke sandstone and mudstone conglomerate pebbles, cobbles and boulders. *Teredo*-bored logs are also present, together with well-rounded shaley coal clasts of uncertain origin. In the base of the lime pit, the Jurassic Murihiku basement has well-preserved *Cladophlebi*s seed fern foliage (Fig. 17). Although a straightforward storm-event depositional model appears applicable to the thin shell concentrations, the two main shell beds containing diverse faunas likely mark small but abrupt sea-level fluctuations, comparable to transgressive onlap shellbeds described from Wanganui Basin.

Chatton Formation was named from shallow marine sandy shell beds exposed in the Chatton district some 12 km north of Gore (Marwick 1928). Drilling data and surface exposures in the Waimumu–Mataura region indicate that it was deposited as a transgressive system, onlapping and infilling a moderate-relief basement topography that locally included thin valley-floor coaly sediments. In the Mataura coalfield, recent drilling indicates that Chatton Formation, where present, is up to 8 m thick (Stein 2009), whereas it exceeds 50 m in thickness in the Waimumu-Croydon area (Isaac & Lindqvist 1990).

The Chatton Formation has long been known to have a highly diverse assemblage of molluscs (e.g. Marwick 1929; Beu & Maxwell 1990) and recent research by Henry Gard as part of his MSc thesis on paleoecology of the Chatton Formation has increased this number to about 560 species, 360 of which occur at Cosy Dell. The fauna at Cosy Dell is remarkable for its taxonomic richness and diversity, particularly of molluscs; it includes robust, thick-shelled bivalves and large gastropods (up to 15 cm in length), an abundance of juveniles and micromolluscs and aragonitic molluscs with nacreous shell and colour patterns preserved (Fig. 19). Of note are 10 species of chitons, the nautiloid *Aturia*, 90 bivalves, 250 gastropods and 4 scaphopods. Basement-derived boulders carry oysters in life position and others were bored by still *in situ* pholadid bivalves. Other notable components of the biota include 127 ostracod species, 7 genera of barnacles (Buckeridge et al. 2014), foraminifera, brachiopods, bryozoans, echinoderms (including the small, subtropical *Fibularia*), solitary and hermatypic corals, numerous otoliths and penguin bones (Lee et al. 2014).

Nannofossil evidence confirms the age derived from molluscs and foraminifera and palynology as Late Oligocene (25.4–24.4 Ma), close to the Duntroonian/Waitakian boundary. The palynoflora comprises more than 100 taxa including at least 16 ferns, 10 conifers, 8 monocots and numerous dicots, including Casuarinaceae, Cunoniaceae, Euphorbiaceae, Loranthaceae, Malvaceae, Myrtaceae, 6 species of Nothofagaceae, Proteaceae and Strasburgeriaceae. The macrofossil drift flora includes abundant teredinid-bored wood (Fig. 17) and seeds including the tropical vine legume *Entada* (sea bean) (Conran et al. 2014). Elongate limpets and 'mangrove whelks' (*Terebralia*) provide indirect evidence for seagrasses and mangroves. The abundance of large, warm-water species confirms a subtropical climate in southern New Zealand in the late Oligocene. The boulder lags, abundance of wood, palynomorphs and seeds, numerous intertidal and estuarine species indicate proximity to forested land adjacent to a rocky coastline and nearby estuary.

In the vicinity of Cosy Dell Farm, Chatton Formation is known from exposures in Hedgehope Steam and in drillhole d1148 which intersected shallow Murihiku greywacke basement. Immediately downstream of Cosy Dell Farm a series of thin (2-10 cm) shellbeds interbedded with shelly quartzose sandstone, laminated glauconitic sandstone and thin mudstone beds is patchily exposed in Hedgehope Stream. The mudstone beds are riddled with *Thalassinoides* while *Ophiomorpha* burrows are locally abundant in sandstone beds. Interpreted as a storm-influenced nearshore succession by Isaac & Lindqvist (1990), it has facies analogies with Wangaloa Formation exposed at Mitchells Rocks in Kaitangata Coalfield (Lindqvist 1986).

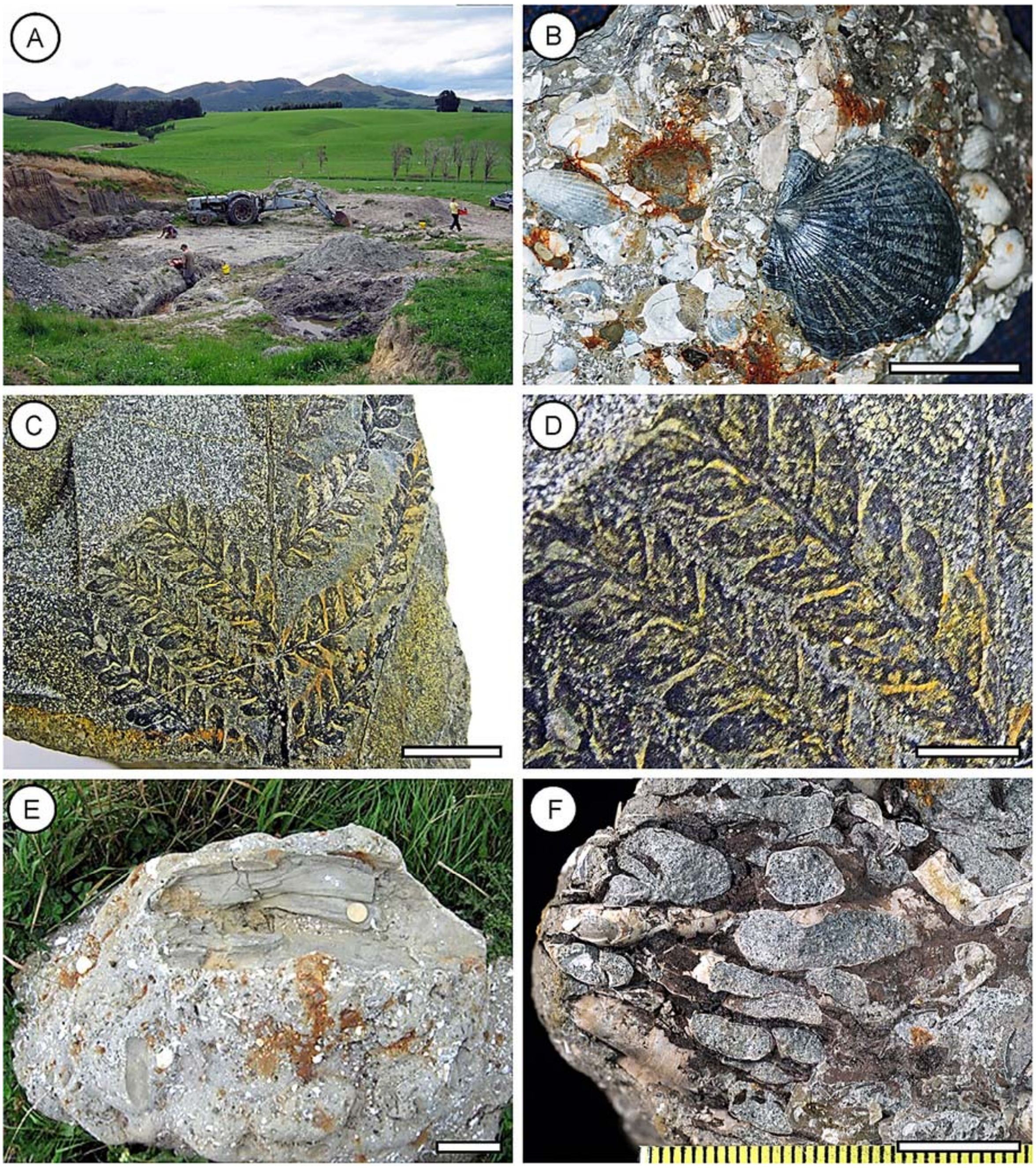

Fig. 17. A. View of Cosy Dell farm quarry with Murihiku Terrane basement exposed in trench in left foreground and in the Hokonui Hills in the distance. **B.** Calcite-cemented shelly concretion from Cosy Dell with the large Duntroonian–Waitakian index scallop *Athlopecten athleta*. **C.** *Cladophlebis* seed fern from exposed Murihiku Terrane basement. **D.** Detail of same. **E.** Block of driftwood in a concretion. **F.** Detail of block of driftwood showing numerous teredinid borings (from Conran et al. 2014).

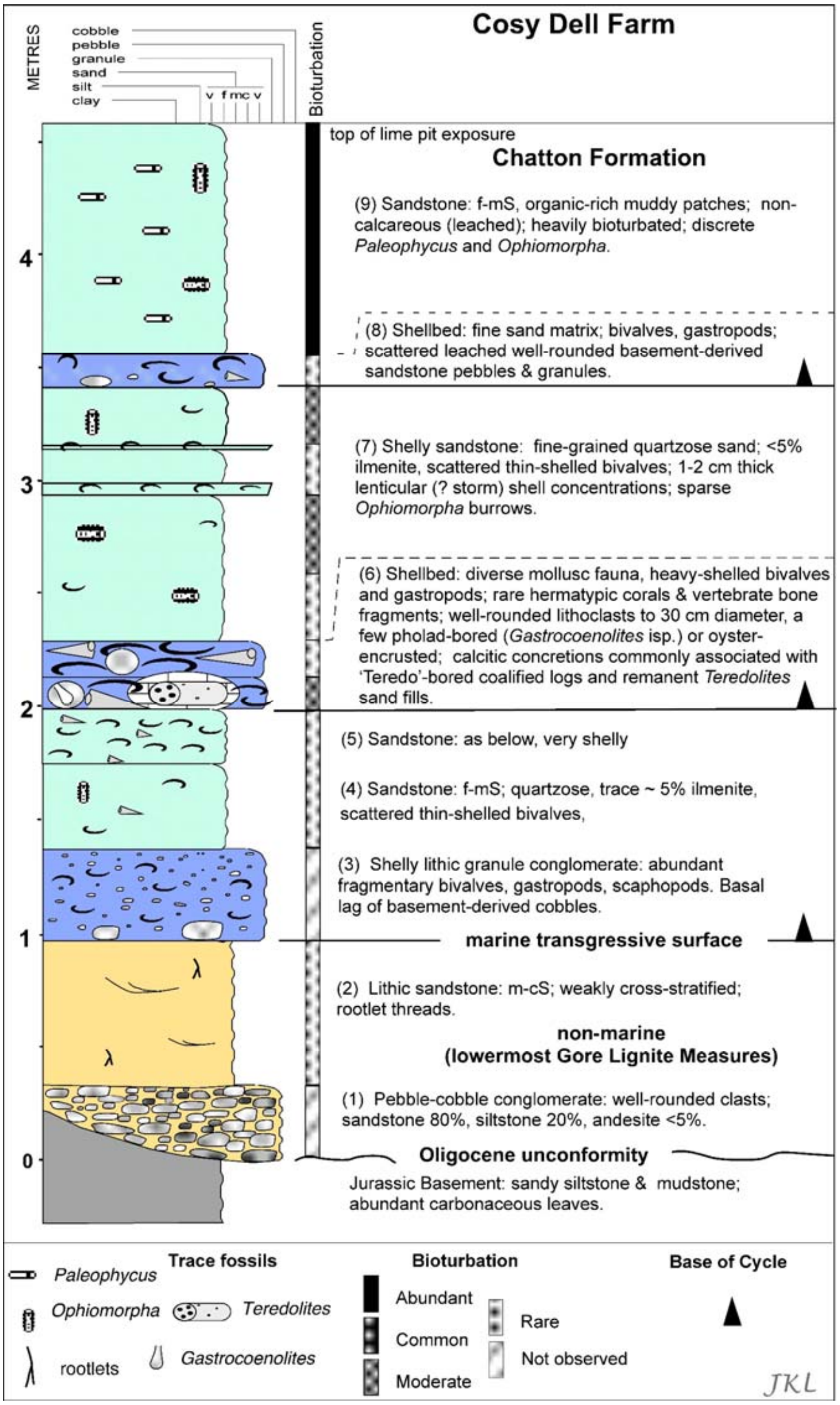

Fig. 18 Stratigraphic column showing Murihiku Supergroup basement of Jurassic age overlain by Chatton Formation, Cosy Dell farm quarry (Lee et al. 2014)

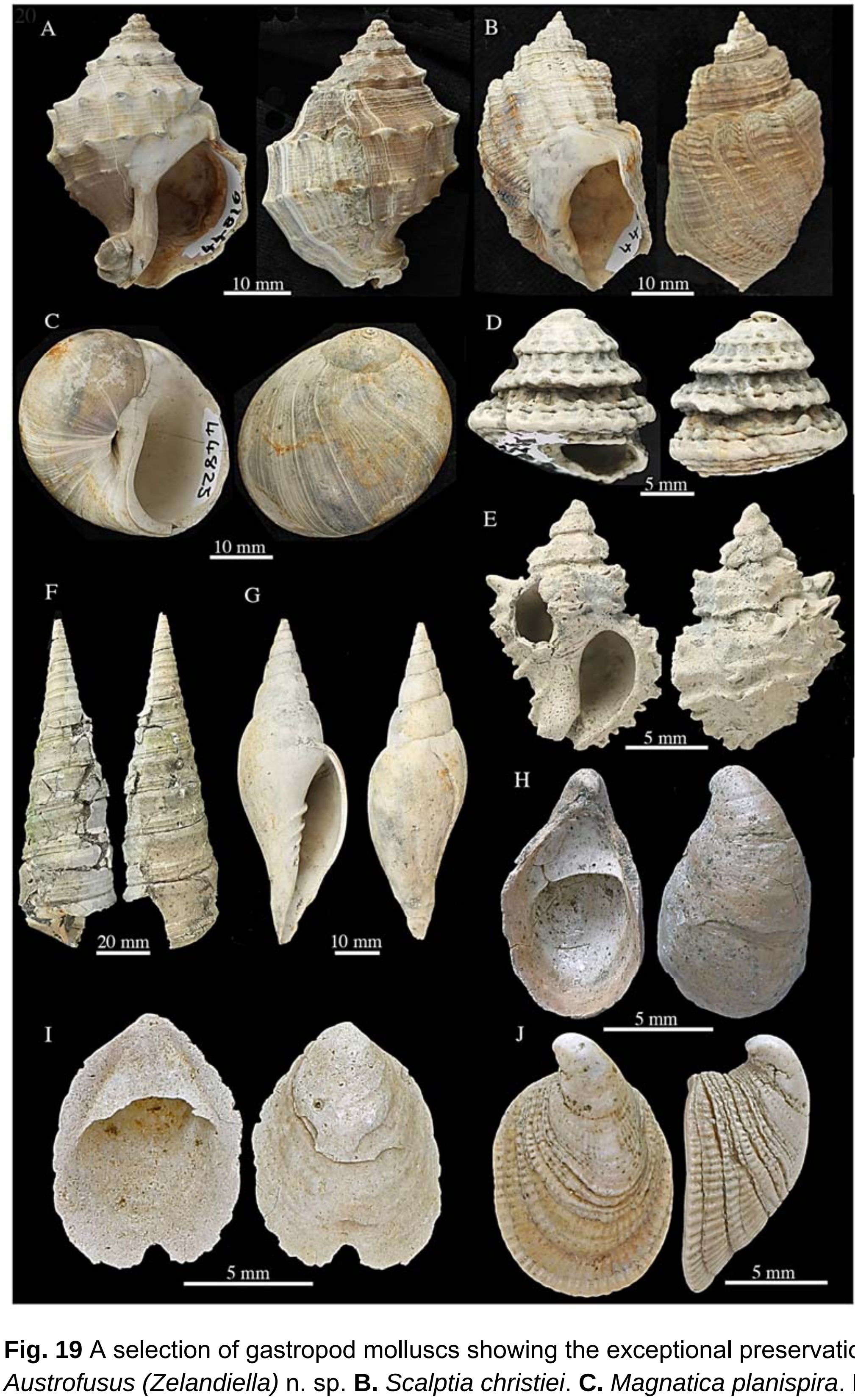

Fig. 19 A selection of gastropod molluscs showing the exceptional preservation. **A.** *Austrofusus (Zelandiella)* n. sp. **B.** *Scalptia christiei*. **C.** *Magnatica planispira*. **D.** *Bembicium* n. sp. **E.** *Murexsul* n. sp. **F.** *Tropicolpus (Amplicolpus) healyi*. **G.** *Clifdenia* n. sp. **H.** *Maoricrypta* n. sp. **I.** *Grandicrepdula* n. sp. **J.** *Hipponyx* n. sp. Photos: Jeffrey Robinson in Lee et al. (2014).

Stop. 7 Gore Lignite Measures, Cosy Dell Farm

Elsewhere on Cosy Dell farm, several small lignite pits of the Gore Lignite Measures are worked for local use. The Gore Lignite Measures accumulated on a low-lying coastal plain, at a latitude similar to that of present day southern New Zealand. There is no evidence for high relief, although there may have been low ridges in the hinterland, but the thickness of the Gore Lignite Measures hints at a large inland catchment and a slowly sinking depocentre. According to Isaac & Lindqvist (1990: 165), the Gore Lignite Measures were mainly deposited “in a range of fluvial channel, overbank splay, floodplain and swamp environments, as indicated by the presence of *in situ* terrestrial plant remains, lateral persistence of the multiple coal seams, common root-penetrated seat earths, large scale upward-fining clastic sequences typical of cyclothems and the paucity of marine fauna. The depositional setting was a prograding deltaic plain, which advanced across a shallow marine shelf during Late Oligocene-Early Miocene time.”

Elsewhere in the Waimumu Coalfield the Gore Lignite Measures consist of 10 major seams or seam groups separated by sandstone and mudstone which are overlain by 60 m or more of quartzose sandy conglomerate (Isaac & Lindqvist, 1990).

The age of the Gore Lignite Measures is Late Oligocene or Early Miocene (Waitakian to Altonian Stage) based on studies of palynofloras of Oligocene and Miocene strata of Otago and Southland by Pocknall & Mildenhall (1984) and Mildenhall & Pocknall (1989).

Stop 8 Landslip Hill silcrete, Smale's Farm, Gore Lignite Measures

Silica-cemented quartzose sandstone and conglomerate forming resistant hilltop exposures and boulder accumulations at Landslip Hill (Fig. 20) are part of the Gore Lignite Measures. Holden (1984) suggested, on the basis of scanning electron microscope examinations of plant fossils and enclosing sandstones, that the Landslip Hill Beds were cemented soon after burial and therefore classifiable as silcrete deposits. Silcrete has been defined as ‘a silica-indurated product of surface and near-surface diagenesis.’

The silcrete is sub-horizontally bedded, persists along strike for 2-3 km in the Charters Road scarp and at Landslip Hill to the south and may form part of a single alluvial channel belt (Lindqvist 1990). It is underlain by uncemented sandstone, mudstone and thin lignite. Exposures of leached sandy shellbeds belonging to Chatton Formation have been recorded in slump blocks on the lower slopes south of Waikoikoi Stream. Pomahaka Formation at the base of the exposed succession consists of thinly interbedded lignite, mudstone, sandstone and shellbeds (see Stop 9).

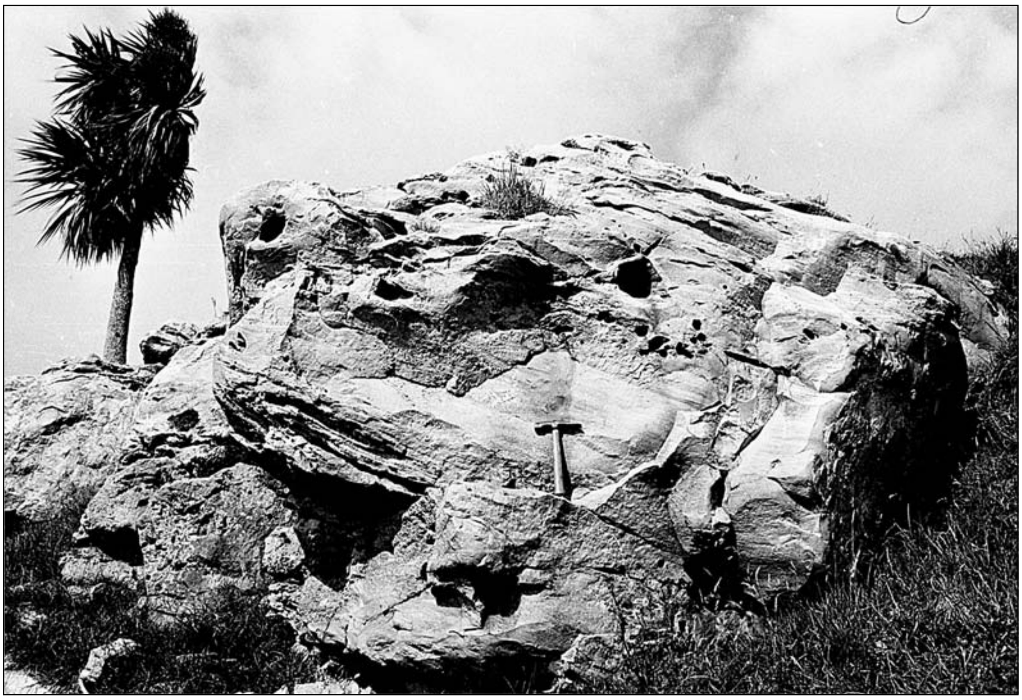

Fig. 20 Well cemented sandstone and conglomerate exposed on the west margin of Charters Road scarp. Large holes are moulds of transported tree trunks (from Lindqvist 1990).

Lindqvist (1990) described five sedimentary facies: pebble conglomerate; trough cross-stratified coarse grained sandstone, planar and ripple laminated fine-medium grained sandstone, mottled sandstone pervaded by root structures and silicified mudstone intraclast conglomerate from the Charters Road and Landslip Hill exposures.

Conglomerates consist of small pebbles and granules of mostly polycrystalline schistose quartz set in a matrix of fine-medium grained monocrystalline quartz sand. Breakage commonly occurs through, rather than around, individual quartz pebbles. Sand matrix is commonly cemented by aggregates of 1-15 µm wide quartz crystals oriented subnormal to the grain surfaces. In places the matrix is almost completely cemented by clear euhedral overgrowths that contrast with the 'dusty' appearance of detrital grains. Sandstones show various degrees of 'apparent' intergranular pressure solution at grain contacts which is difficult to reconcile with the moderate depth of burial (less than about 600 m) indicated by the lignite coal rank.

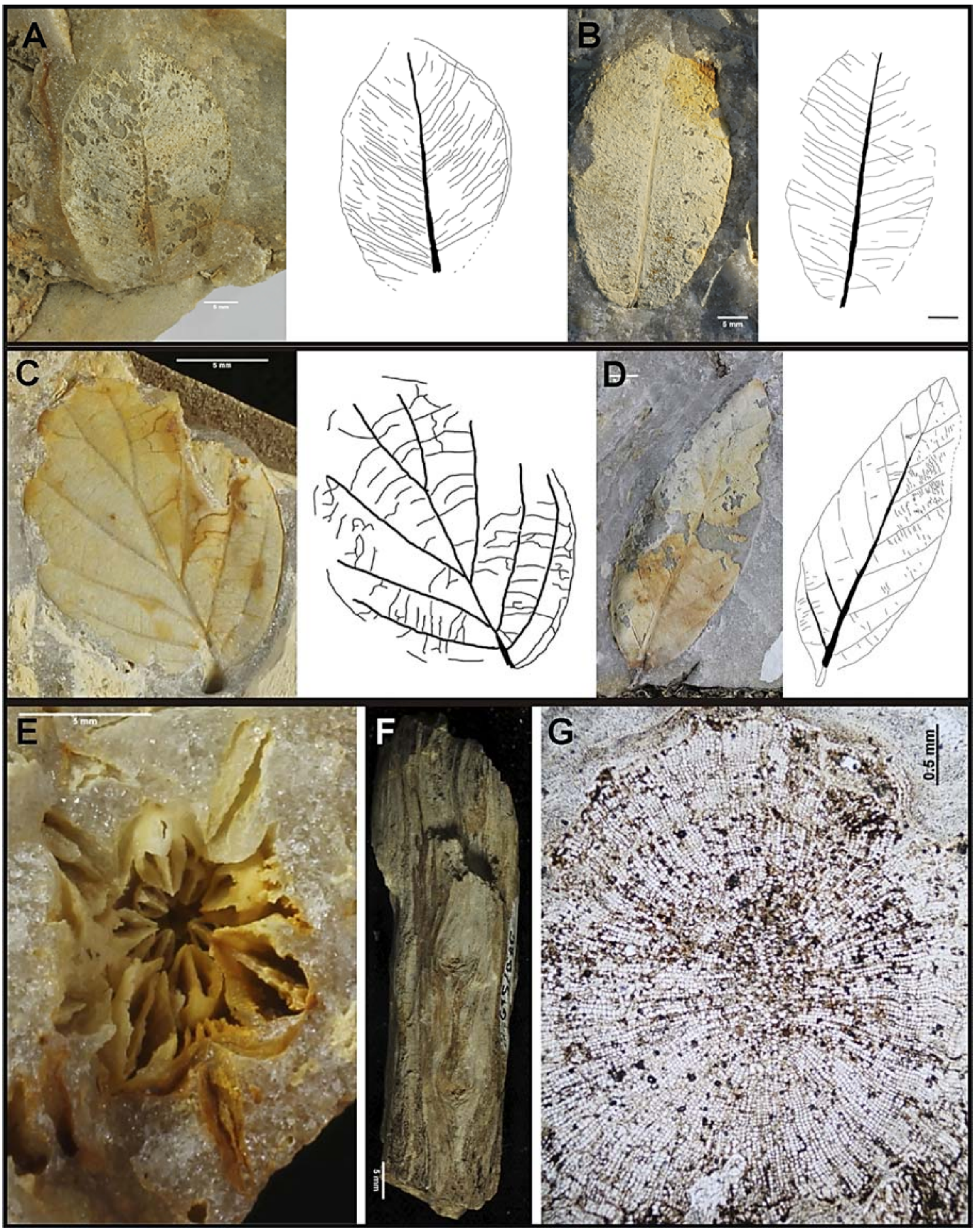

Fig. 21 Leaves, wood and a 'cone' from Landslip Hill silcrete. **A-D.** Representative dicot angiosperm leaves. **E.** Casuarinaceae 'cone' showing 3-dimensional preservation. **F-G**. Uncompressed podocarp wood and transverse section. Photos: Joe Jackson.

Plant fossils have been collected from the outcrops and loose blocks of Landslip Hill silcrete since at least 1862, when James Hector was appointed director of the Geological Survey of Otago and visited Landslip Hill on one of his first field trips beyond Dunedin. Hector collected further material in 1869 and commissioned James Park to acquire more specimens in 1886 (Campbell & Holden 1984). Many further collections have been made, several by amateur collectors and material is housed in the Geology Department, University of Otago, at the Otago Museum and elsewhere in New Zealand.

The plant remains include uncompressed three dimensional logs, leaves (Fig. 21), stems, roots and rootlets and a variety of fruits, some of which can be assigned to modern New Zealand taxa and others which are no longer present in the local flora (Jackson 2015). In his final published paper (Campbell 2002), Doug Campbell described and illustrated several examples of fruit and 2-dimensional leaves from Landslip Hill. These include fruit closely resembling dried drupes of *Corynocarpus* (karaka) and the modern New Zealand mangrove, *Avicennia*. In the same paper, leaves attributed to *Pomaderris*, *Nothofagus* and *Pouteria* were figured.

Campbell and Holden (1984) described 'cones' of *Casuarina* (she-oak) from Landslip Hill and named a new species, *C. stellata*, noting that its affinities were closest to *Gymnostoma*, living species of which are known from New Caledonia, NE Australia, Malesia and Fiji. Overall the pollen flora of the Gore Lignite Measures is generally dominated by *Nothofagus* (especially *N. cranwelliae*) and Casuarinaceae (*Haloragacidites harrisii*). According to Pocknall (1983) other families represented include podocarps and araucarians, palms, Chloranthaceae, Liliaceae, Loranthaceae, Myrtaceae, Proteaceae, Epacridaceae and Gunneraceae.

Stop 9 Pomahaka Formation, Waikoikoi Creek

Many New Zealand Cretaceous and Tertiary coal-bearing formations accumulated in coastal plain settings but few examples of significant peat development closely associated with shelly marine or brackish-marine facies have been documented. Remnants of fine-grained embayment facies containing inferred shallow-marine trace fossil associations occur in Brunner Formation, north Westland, the Waikato Coal Measures and the transition zone between Taratu and Wangaloa formations, Kaitangata Coalfield.

Pomahaka Formation, a ~30 m thick assemblage of shallow marine and freshwater swamp deposits, is the basal unit of the Late Oligocene-Miocene East Southland Group (Isaac & Lindqvist 1990). The Late Oligocene (Duntroonian) Pomahaka Formation, one of the few shelly paleo-estuarine deposits known from New Zealand, crops out along the Pomahaka River and Waikoikoi Stream near Tapanui, West Otago. It is inferred to have accumulated in a tidal interdistributary bay setting. Sediments include lignite seams interbedded with fossiliferous clays, muds, silts and occasionally sands. A drill core indicates that the entire sequence may be up to 90 m thick. The Pomahaka Formation rests unconformably on Caples Terrane basement of low metamorphic grade and is overlain by the glaucony-rich Chatton Formation.

As well as providing an example of coal accumulation in a coastal marsh environment, Pomahaka Formation contains an important record of New Zealand's brackish water mollusc fauna (e.g. Beu & Maxwell 1990).

Formerly well exposed following Waikoikoi Stream realignment in the late 1970's, Pomahaka Formation is overlain by a channelised coarse grained sand silty clay succession that marks the onset of Gore Lignite Measures deposition and southward progradation of the East Southland coastal delta system. Small isolated flat-lying exposures of Pomahaka Formation have been mapped in the banks and bed of Pomahaka River to the north and east (Isaac & Lindqvist 1990, Wood 1956). At Waikoikoi Creek bridge, Pomahaka Formation is exposed in the steeply dipping limbs of an antiformal decollement in the toe of Charters Road slump (Fig. 22). The beds strike consistently WNW–ESE and dips on each limb range from 35° to slightly overturned.

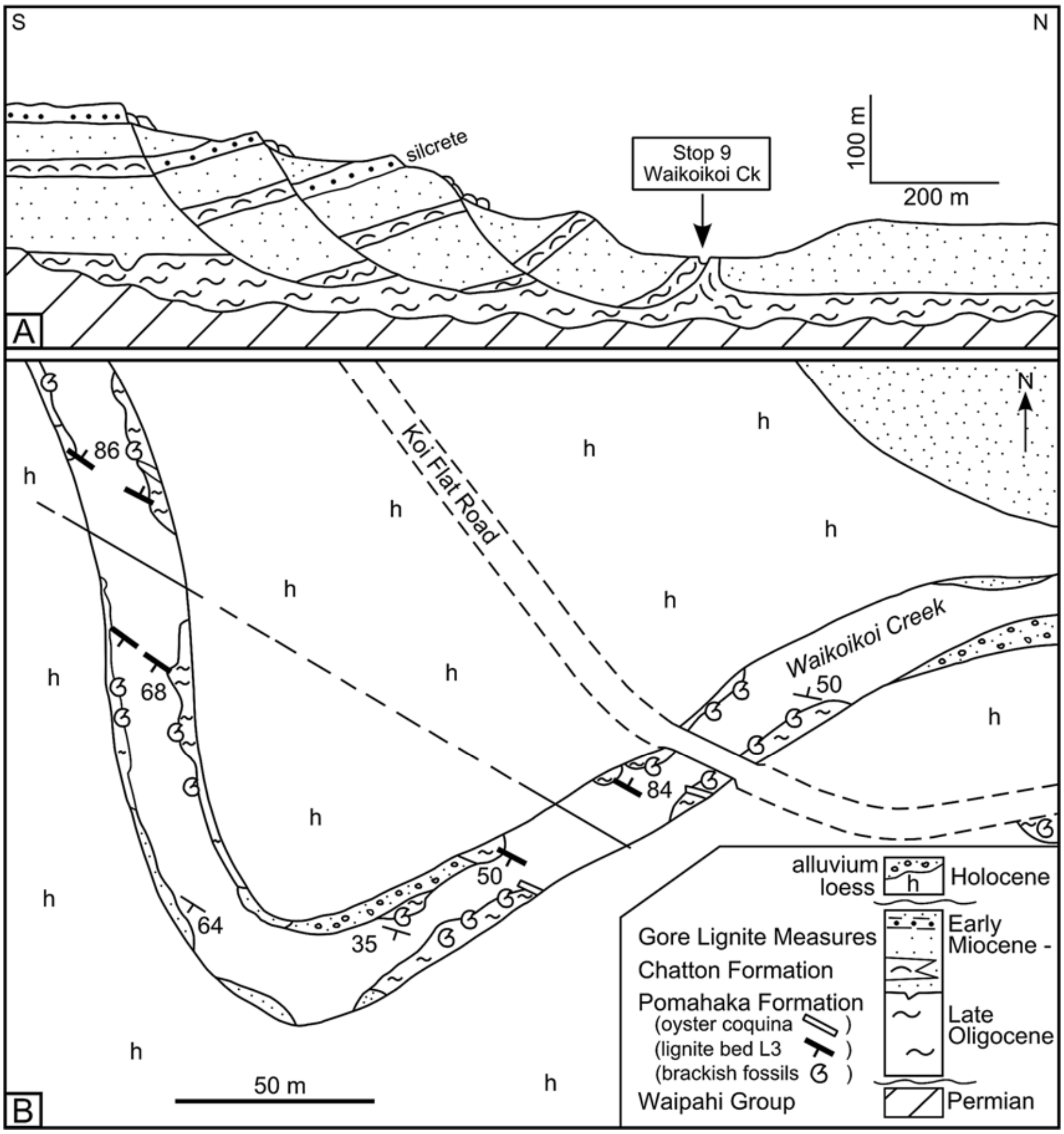

Fig. 22 Waikoikoi Valley exposures of Pomahaka Formation. **A,** Schematic southwest-northeast cross section. Pomahaka Formation is exposed in the steeply dipping limbs of an anticlinal fold in the toe zone of a rotational slump packet. **B,** Map of Waikoikoi Creek showing locations of measured sections. Riverbank exposures formerly accessible during low river flow are now overgrown (from Lindqvist, Gard & Lee 2016).

The estuarine beds near Pomahaka were originally collected in 1862 by James Hector. Wood (1956) probably collected a fauna from Hector's original Pomahaka River locality near the junction with Oyster Creek and used the term *Pomahaka Estuarine Bed* for 60 cm of shelly clay that he regarded as a lateral (east) equivalent of Chatton Formation. More recently Isaac & Lindqvist (1990) summarised the stratigraphic setting and sedimentology of Pomahaka Formation. Beu & Maxwell (1990) reaffirmed its Late Oligocene age (late Whaingaroan or Duntroonian Stage).

In exposures in the Pomahaka River, the Pomakaka Formation contains *in situ* tree stumps, resin, leaves with cuticle, concretions with crustaceans and estuarine shellbeds (Gard 2014; Lindqvist et al. 2016). One large block of well-preserved silicified wood is araucarian, although wood anatomy alone cannot distinguish between *Agathis* and *Araucaria*.

Pocknall (1982) noted that the dominant *brassi* beech pollen component in the Pomahaka Formation is *Nothofagidites matauraensis*, whereas *N. cranwelliae* is generally the more abundant in Chatton Formation and Gore Lignite Measures. The pollen and spores from Pomahaka include a number of unusual species, and/or the first record of important elements in the modern New Zealand flora. One group of assemblages is dominated by *brassi* beech pollen, with common gymnosperms (Araucariaceae and Podocarpaceae), *Casuarinaceae* and *Gunnera*. Pomahaka has the earliest record of the warmth-loving *Caesalpinia* and *Scaevola*, the latter now found only on the Kermadecs in the New Zealand region. According to Pocknall (1982), warmth-demanding taxa grew in specialised coastal habitats, while other species, adapted to damp conditions, grew on marshes away from tidal influence.

Unusual and well-preserved fossils representing taxa found nowhere else in New Zealand are present in the clay-rich, muddy and silty sediments. Shellbeds are up to 1 m thick and different molluscan-dominated assemblages occur at different horizons. Bivalves include ?*Hormomya, ?Barbatia,* an oyster *(Saccostrea* n.sp.), *Hinemoana acuminata, Potamocorbula,* a new species of the venerid *Tellinota* n.sp. as well as a new venerid genus. Gastropods include the small neretid *Clithon(?) pomahakaensis* with extraordinary colour markings, *Batillaria pomahakaensis, Melanopsis pomahaka, Batillona amara, Grandicrepidula, Pomahakia aberrans*, together with new species of *Potamopyrgus* and the freshwater genus *Melonoides.* Small drillholes, possibly made by the predatory gastropod *?Xymene*, are present in many molluscs. A species of a lobster-like decapod and trace fossils were found in concretions. Vertebrate fossils include a turtle xiphiplastron (Gard & Fordyce 2016), shark teeth of the family Odontaspididae (sand tigers) and bony fish remains. Plant fossils include numerous seeds, amber, leaves and *in situ* tree stumps up to 53 cm in diameter. Foraminifera include *Elphidium excavatum* and species of *Trochammina* and *Haplophragmoides*, unlike any modern New Zealand species: they suggest that most of the molluscs lived in a sheltered, brackish intertidal estuarine paleoenvironment. The neretid *Clithon(?) pomahakaensis* and the turtle plastron plate suggest that sea temperatures were at least marginally subtropical.

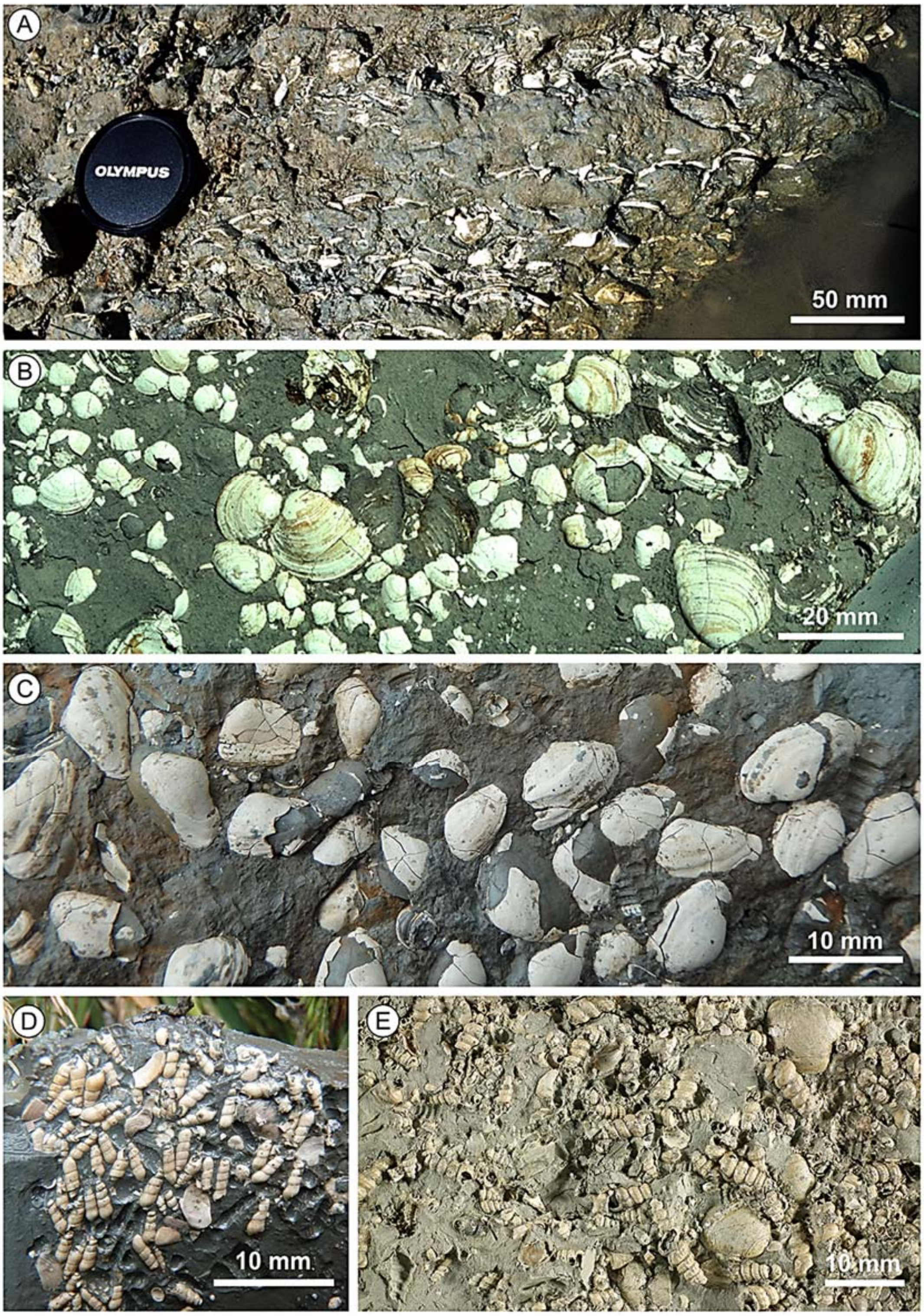

Fig. 23 Shell laminae in Pomahaka Formation. **A.** Concave-down *Hinemoana acuminata* valves in vertical section. **B,** Shell layer dominated by *H. acuminata.* **C,** *Potamocorbula* sp. bed. **D,** Bedding plane dominated by the small gastropod *Melanoides*. **E,** Bedding plane dominated by the gastropod *Battilona amara* (from Lindqvist et al. 2016).

Stop 10. Hindon Maar, Waipiata Volcanic Field

Geological mapping of four subcircular basins associated with high magnetic intensity near Hindon, east Otago combined with further geophysical and sedimentological investigation confirms that all four are partly eroded maar-diatreme volcanoes associated with the Waipiata Volcanic Field (Fig. 24). Palynostratigraphy suggests an early to middle Miocene age and this is now confirmed by newly obtained radiometric dating ($^{40}Ar/^{39}Ar$) of associated basalts.

Preliminary excavations in two craters have exposed finely-laminated diatomite (Fig. 25) and/or extremely fossiliferous laminated freshwater sponge spicule-rich carbonaceous mudstone and yielded a wealth of animal and plant fossils. The most common macrofossils are leaves (mainly *Nothofagus*), but the flora also includes cycads, palms, conifers including small cones, Lauraceae, Myrtaceae and leaves and flowers of several Araliaceae species. These indicate that the maar lakes were surrounded by *Nothofagus*/podocarp/mixed broadleaf forest growing under humid, warm temperate to subtropical conditions.

Fish fossils are abundant at Hindon and an eel resembling *Anguilla* is a key record for the Southern Hemisphere. Larval to adult stages of Galaxiidae are present, some with skin and mouthparts preserved. Also abundant in terms of numbers and diversity are insects, which currently comprise ~140 specimens belonging to the orders Hemiptera, Hymenoptera, Trichoptera, Thysanoptera and Coleoptera, with weevils particularly diverse. Kaulfuss & Moulds ((2015) recently described the first cicada (Cicadoidea) fossil from New Zealand, a new genus and species of primitive cicada (Hemiptera: Tettigarctidae) *Paratettigarcta zealandica* from Hindon.

The first record of fossil feathers supports the idea that common, but allochthonous quartz-sand-rich coprolites were derived from volant birds, presumably waterfowl. The remarkable preservation of soft-bodied fossils makes this a *Konservat-Lagerstätte* of potentially global significance (Fig. 26).

Ground-based magnetic, microgravity and seismic surveys carried out to characterise the size, depth and sediment infill suggest that ~200 m of laminated sediment is present and preliminary coring has retrieved >10 m of laminated sediments. Further coring in all four maars could yield a high resolution (seasonal to decadal) record of changing climate and ecosystems for Southern Hemisphere mid-latitudes which would complement the Foulden Maar record to produce an unparalleled understanding of early Miocene climate and environment.

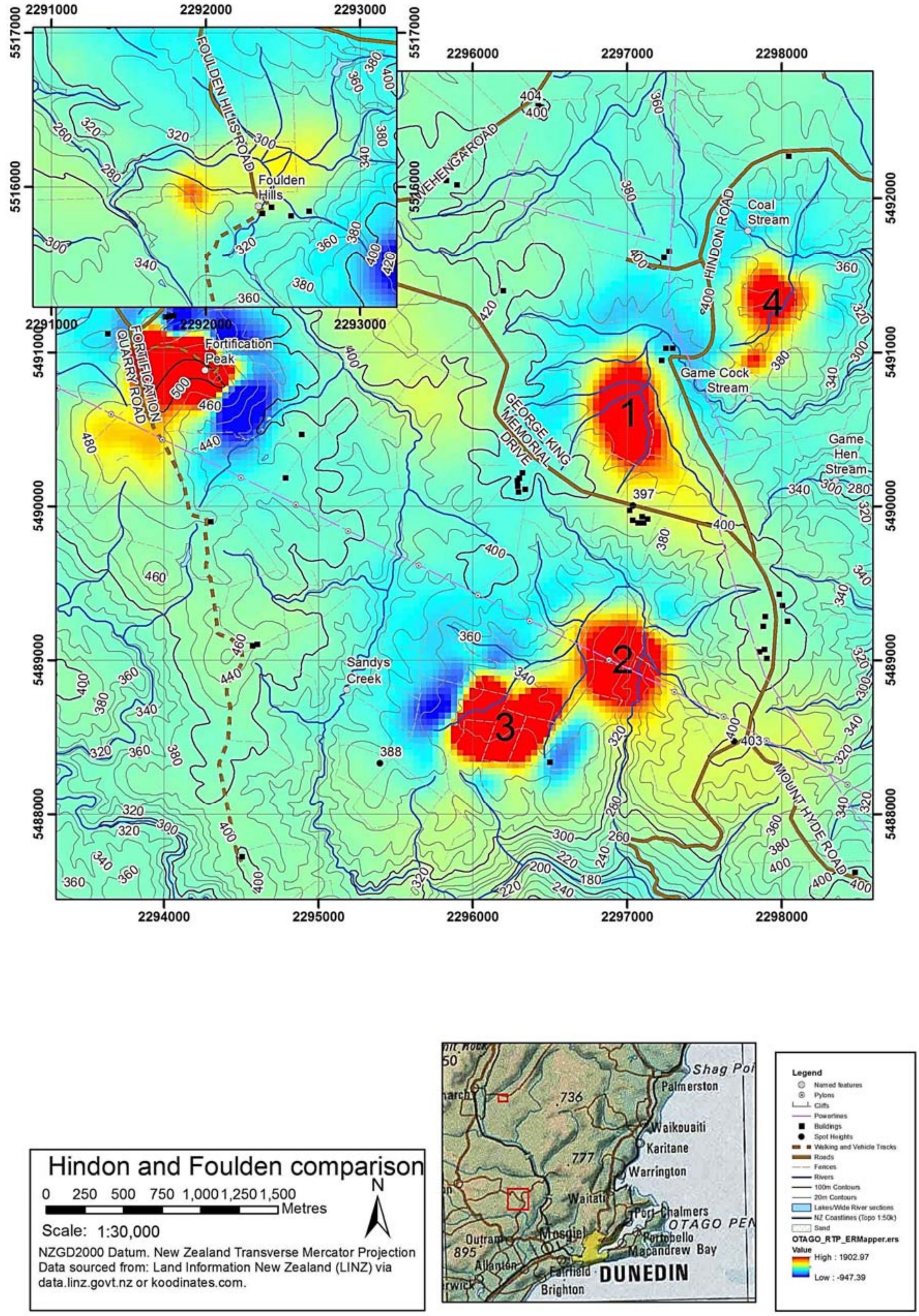

Fig. 24 Geophysical map of Hindon showing four subcircular basins defined by high magnetic intensity. Inset, top left shows Foulden Maar at the same scale.

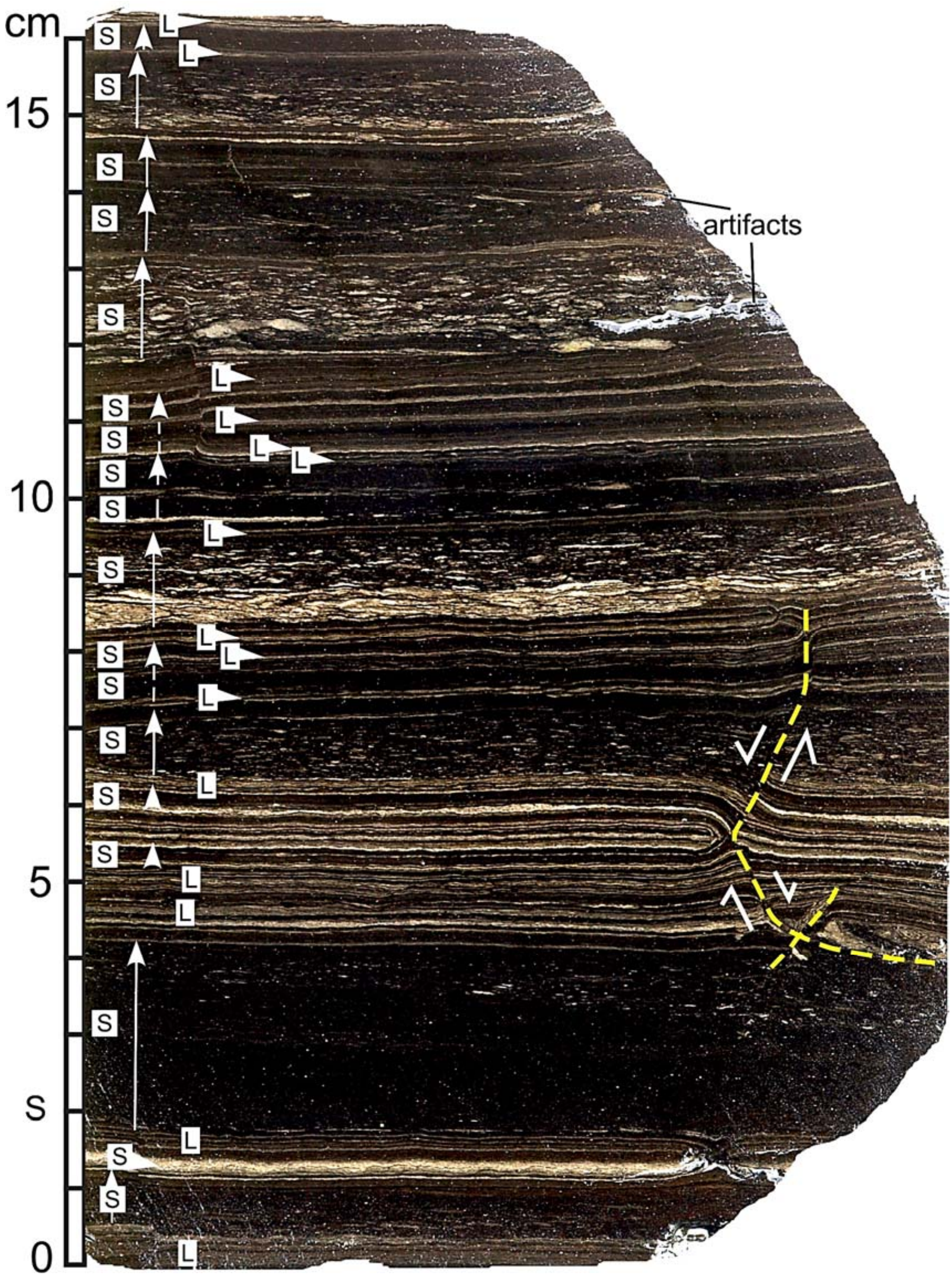

Fig. 25 Enhanced-contrast photograph of a water-flooded surface of a diatomite block from Area-1. The sample was recovered from a pit dug by members of the 2010 OU geophysics class. This 16.5 cm section is dominated by dark speckled beds (S; gravity flows) and subordinate dark and light laminated intervals (L; seasonal biogenic varves). The diatomite lithotypes resemble those from Foulden Maar (Lindqvist & Lee 2009) but are comparatively richer in organic matter. Small offsets associated with compressional faultlets are shown, right. Figure: Jon Lindqvist.

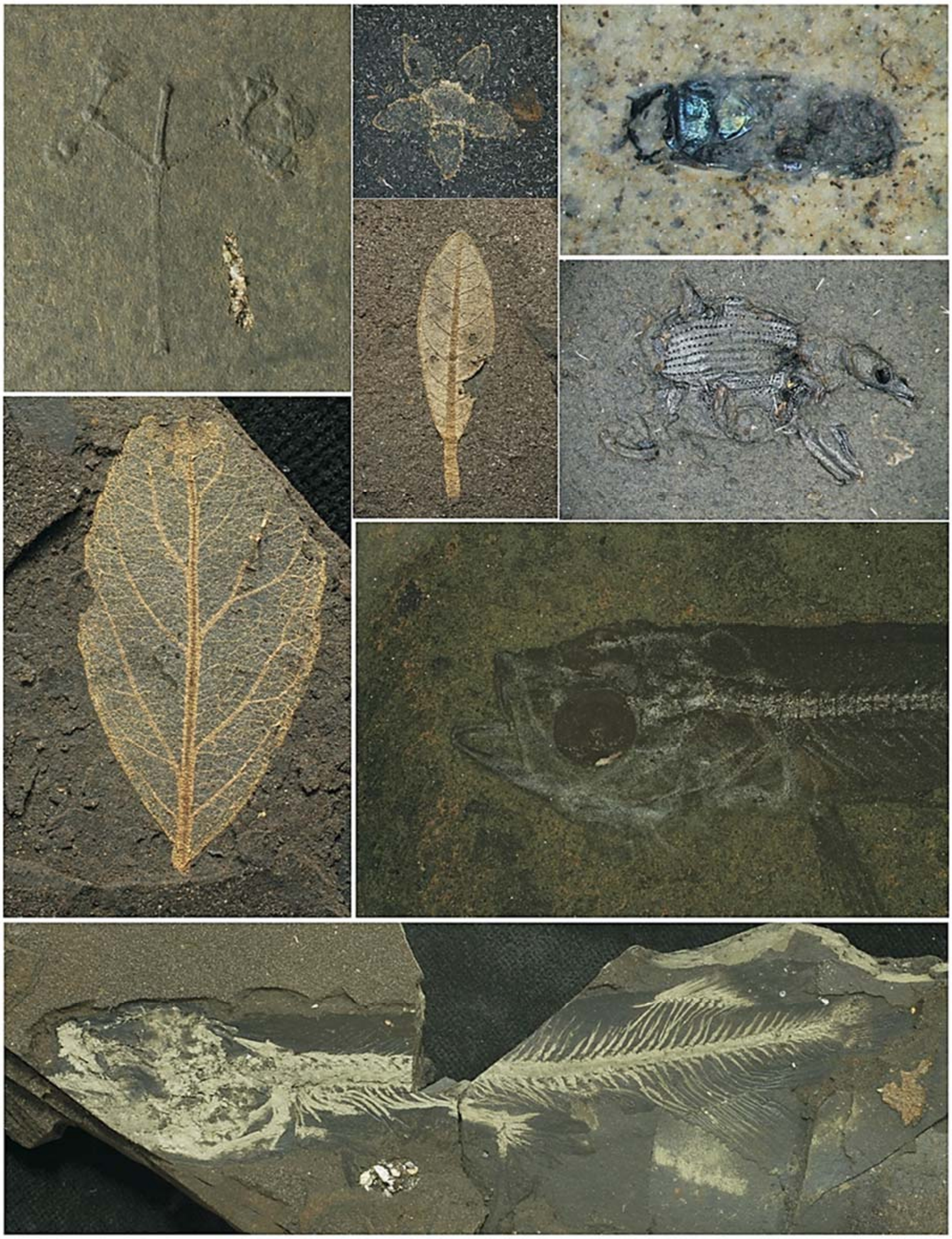

Fig. 26 Examples of well-preserved plant and animal fossils from Hindon Maar, including an araliad fruit and flower, two typical angiosperm leaves, a beetle with structural colour preserved and a spined weevil; and two examples of galaxiids, including one with preservation of soft tissue including skin and eyes. Photos: Uwe Kaulfuss.

References

Beu AG, Maxwell PA 1990. Cenozoic Mollusca of New Zealand. Drawings by RC Brazier. *New Zealand Geological Survey Paleontological Bulletin* 58: 1–518.

Buckeridge JS, Lee DE, Robinson JH 2014. A diverse shallow-water barnacle assemblage (Cirripedia: Sessilia) from the Oligocene of Southland, New Zealand. *New Zealand Journal of Geology and Geophysics* 57: 253–263.

Campbell JD 2002. Angiosperm fruit and leaf fossils from Miocene silcrete, Landslip Hill, Southland, New Zealand. *Journal of the Royal Society of New Zealand* 32:149–154.

Campbell JD, Holden AM. 1984. Miocene casuarinacean fossils from Southland and Central Otago, New Zealand. *New Zealand Journal of Geology and Geophysics* 22: 159–167.

Campbell JD, Lee DE, Lee WG. 2000. A woody shrub from the Miocene Nevis Oil Shale, Otago, New Zealand – a possible fossil divaricate? *Journal of the Royal Society of New Zealand* 30: 147–153.

Conran JG, Mildenhall DC, Lee DE, Lindqvist JK, Shepherd C, Beu AG, Bannister JM, Stein JK 2014. Subtropical rainforest vegetation from Cosy Dell, Southland: plant fossil evidence for Late Oligocene terrestrial ecosystems. *New Zealand Journal of Geology and Geophysics* 57: 236–252.

Crundwell MP, Beu AG, Cooper RA, Morgans HEG, Mildenhall DC, Wilson GJ. 2004. Chapter 12. Miocene (Pareora, Southland and Taranaki Series). Pp. 165–194 *in*: Cooper RA. (ed.). *The New Zealand geological timescale.* Institute of Geological and Nuclear Sciences monograph 22: 284 p.

Douglas BJ, Lindqvist JK, Fordyce RE, Campbell JD. 1981. Early Miocene terrestrial vertebrates from Central Otago. *Geological Society of New Zealand Newsletter* 53: 17.

Douglas BJ. 1986. Lignite Resources of Central Otago (Manuherikia Group of Central Otago, New Zealand: Stratigraphy, depositional environments, lignite resource assessment and exploration models. *New Zealand Energy Research and Development Committee publication* P104. 367 p.

Feldman RM, Pole M 1994. A new species of *Paranephrops* White, 1842: a fossil freshwater crayfish (Decapoda: Parastacidae) from the Manuherikia Group (Miocene), Central Otago, New Zealand. *New Zealand Journal of Geology and Geophysics* 37: 163–167.

Gard HJL 2014. *Paleoecology of the estuarine Pomahaka Formation, West Otago*. Unpublished B.Sc Honours Thesis, University of Otago. 97pp.

Gard HJL, RE Fordyce 2016. A fossil sea turtle (Testudines: Pan-Cheloniidae) from the upper Oligocene Pomahaka Formation, New Zealand. *Alcheringa: An Australasian Journal of Palaeontology* DOI: 10.1080/03115518.2016.1206319.

Hand SJ, Lee DE, Worthy TH, Archer M, Worthy JP, Tennyson AJD, Salisbury SW, Scofield RP, Mildenhall DC, Kennedy EM, Lindqvist JK 2015. Miocene fossils reveal ancient roots for New Zealand's endemic *Mystacina* (Chiroptera) and its rainforest habitat. *PLoS ONE*, *10*(6), e0128871. doi: 10.1371/ journal.pone.0128871

Hector J 1865. On the geology of Otago, New Zealand. *Proceedings of the Geological Society*, December 7, 1864: 124–128.

Hector J 1866. Report and awards of the jurors, New Zealand Exhibition 1865: 377.

Holden AM 1983. *Studies in New Zealand Oligocene and Miocene plant macrofossils.* Unpublished Ph.D thesis, Victoria University of Wellington. 369 p.

Holden AM. 1984. The flora and environment of the Gore Lignite Measures: evidence from plant macrofossils. *Geological Society of New Zealand* abstracts, p. 51.

Isaac MJ, Lindqvist JK 1990. Geology and lignite resources of the East Southland Group, New Zealand. *New Zealand Geological Survey Bulletin* 10: 1–202.

Jackson JA 2015. *A study of plant fossils from Landslip Hill silcrete*. MSc thesis, University of Otago.

Jones MEH, Tennyson AJD, Worthy JP, Evans SE, Worthy TH 2009. A sphenodontine (Rhynchocephalia) from the Miocene of New Zealand and palaeobiogeography of the tuatara (*Sphenodon*). *Proceedings of the Royal Society B* 276: 1385–1390.

Kaulfuss U, Moulds M 2015. A new genus and species of tettigarctid cicada from the early Miocene of New Zealand: *Paratettigarcta zealandica* (Hemiptera, Auchenorrhyncha, Tettigarctidae). *ZooKeys* 484: 83–94. doi: 10.3897/ zookeys.484.8883

Kaulfuss U, Lee DE, Schmidt A 2016. New discoveries of Miocene arthropods from amber and diatomite deposits in New Zealand. In: Penney, D. & Ross, A. (eds.) 7th International Conference on Fossil Insects, Arthropods and amber. Abstracts, p. 26.

Lee DE, Lindqvist JK, Douglas BJ, Bannister JM, Cieraad E 2003. Paleobotany and sedimentology of Late Cretaceous–Miocene nonmarine sequences in Otago and Southland. *Geological Society of New Zealand Miscellaneous Publication* 116B. 48pp.

Lee DE, Bannister JM, Lindqvist JK 2007. Late Oligocene–Early Miocene leaf macrofossils confirm a long history of *Agathis* in New Zealand. *New Zealand Journal of Botany* 45: 565–578.

Lee DE, McDowall RM, Lindqvist JK 2007. *Galaxias* fossils from Miocene lake deposits, Otago, New Zealand: the earliest records of the Southern Hemisphere family Galaxiidae (Teleostei). *Journal of the Royal Society of New Zealand* 37: 109–130.

Lee DE, Forsyth PJ 2008 (reprinted 2009). *Central Rocks: A guide to the geology and landscapes of Central Otago.* Geological Society of New Zealand Guidebook 14. 84pp.

Lee DE, Lindqvist JK, Mildenhall DC, Bannister JM, Kaulfuss U 2009. Field trip 12. Paleobotany, palynology and sedimentology of Late Cretaceous – Miocene sequences in Otago and Southland. *Geological Society of New Zealand Miscellaneous Publication* 128B. 38pp.

Lee DE, Lindqvist JK, Beu AG, Robinson JH, Ayress MA, Morgans HEG, Stein JK 2014. Geological setting and diverse fauna of a Late Oligocene rocky shore ecosystem, Cosy Dell, Southland. *New Zealand Journal of Geology and Geophysics* 57: 195–208.

Lee MSY, Hutchinson MN, Worthy TH, Archer M, Tennyson AJD, Worthy JP, Scofield RP 2009. Miocene skinks and geckos reveal long-term conservatism of New Zealand's lizard fauna. *Biology Letters*, doi: 10.1098/rsbl.2009.0440.

Lindqvist JK 1986. Teredinid-bored Araucariaceae logs preserved in shoreface sediments, Wangaloa Formation (Paleocene), Otago, New Zealand. *New Zealand Journal of Geology and Geophysics* 29: 253–261.

Lindqvist JK 1990. Deposition and diagenesis of Landslip Hill silcrete, Gore Lignite Measures (Miocene), New Zealand. *New Zealand Journal of Geology and Geophysics* 33: 137–150.

Lindqvist JK 1994. Stromatolites in a Miocene lake sequence: Manuherikia Group, South Island, New Zealand. Phanerozoic Stromatolites II, (Ed. by J. Bertrand-Sarfati & C. Monty), 227–254. Kluwer Academic Publishers, Dordrechte.

Lindqvist JK, Gard HJL, DE Lee 2016. Geological setting, sedimentology and biota of the estuarine late Oligocene Pomahaka Formation, New Zealand. *New Zealand Journal of Geology and Geophysics* 59: 352–365, DOI: 10.1080/00288306.2016.1150862.

Marwick J 1928. Tertiary molluscan fauna of Chatton, Southland. *Transactions of the New Zealand Institute* 59: 903–934.

Mildenhall DC 1989. Summary of the age and paleoecology of the Miocene Manuherikia Group, Central Otago, New Zealand. *Journal of the Royal Society of New Zealand* 19, 19–29.

Mildenhall DC, Pocknall DT 1989. Miocene–Pleistocene spores and pollen from Central Otago, South Island, New Zealand. *New Zealand Geological Survey Paleontological Bulletin* 59: 128 p.

McDowall RM, Kennedy EM, Lindqvist JK, Lee DE, Alloway MR, Gregory MR 2006. Probable *Gobiomorphus* fossils from the Miocene and Pleistocene of New Zealand. *Journal of the Royal Society of New Zealand* 36: 97–109.

McDowall RM, Lee DE 2005. Probable perciform fish scales from a Miocene freshwater lake deposit, Central Otago, New Zealand. *Journal of the Royal Society of New Zealand* 35: 339–344.

Molnar RE, Pole M 1997. A Miocene crocodilian from New Zealand. *Alcheringa: An Australasian Journal of Palaeontology* 21: 65–70.

Pocknall DT 1982. Palynology of late Oligocene Pomahaka Estuarine Bed sediments, Waikoikoi, Southland, New Zealand. *New Zealand Journal of Botany* 20: 263–287.

Pocknall DT, Mildenhall DC 1984. Late Oligocene–Early Miocene spores and pollen from Southland, New Zealand. *New Zealand Geological Survey Paleontological Bulletin* 51.

Pocknall DT 1982. Palynology of late Oligocene Pomahaka Estuarine Bed sediments, Waikoikoi, Southland, New Zealand. *New Zealand Journal of Botany* 20: 263–287.

Pocknall DT, Mildenhall DC 1984. Late Oligocene–Early Miocene spores and pollen from Southland, New Zealand. *New Zealand Geological Survey Paleontological Bulletin* 51.

Pole M 1992. Early Miocene flora of the Manuherikia Group, New Zealand. 1. Ferns.

Journal of the Royal Society of New Zealand 22, 279–286; 2. Conifers. *Journal of the Royal Society of New Zealand* 22, 287–302; 3. Possible Cycad. *Journal of the Royal Society of New Zealand* 22, 303–306.

Pole M 1993. Early Miocene flora of the Manuherikia Group, New Zealand. 4. Palm remains. *Journal of the Royal Society of New Zealand*, 23, 283–288; 7. Myrtaceae, including *Eucalyptus*. *Journal of the Royal Society of New Zealand* 23, 313–328; 8. *Nothofagus*. *Journal of the Royal Society of New Zealand* 23: 329–344.

Pole MS, Douglas B, Mason G 2003. The terrestrial Miocene biota of southern New Zealand. *Journal of the Royal Society of New Zealand* 33: 415–426.

Powell NG, Lee DE, Kaulfus U 2013. Paleochemotaxonomic investigation of Tertiary resins from southern New Zealand by gas chromatography–mass spectrometry: preliminary results. *VII Southern Connections Congress, Dunedin, New Zealand*, abstract book, 1 p.

Schwarzhans W, Scofield RP, Tennyson AJD, Worthy JP, Worthy TH 2012. Fish remains, mostly otoliths, from the non-marine Early Miocene of Otago, New Zealand. *Acta Palaeontologica Polonica* 57: 319–350.

Stein JK 2009. *The evolution of the Eastern Southland Lignite Basin*. BSc Hons thesis, University of Otago. 196pp.

Tennyson AJD, Worthy TH, Jones CM, Scofield RP, Hand SJ 2010. Moa's Ark: Miocene fossils reveal the great antiquity of moa (Aves: Dinornithiformes) in Zealandia. *Records of the Australian Museum* 62: 105–114.

Wood BL 1956. The Geology of the Gore Subdivision. New Zealand Geological Survey Bulletin 53.

Worthy TH, Tennyson AJD, Jones C, McNamara JA, Douglas BJ 2007. Miocene waterfowl and other birds from Central Otago, New Zealand. *Journal of Systematic Palaeontology* 5: 1–39.

Worthy TH, Lee MSY 2008a. Affinities of Miocene (19–16 Ma) waterfowl (Anatidae: *Manuherikia*, *Dunstanetta* and *Miotadorna*) from the St Bathans Fauna, New Zealand. *Palaeontology* 51: 677–708.

Worthy TH, Tennyson AJD, Hand SJ, Scofield RP 2008b. A new species of the diving duck *Manuherikia* and evidence for geese (Aves: Anatidae: Anserinae) in the St Bathans Fauna (Early Miocene), New Zealand. *Journal of the Royal Society of New Zealand* 38: 97–114.

Worthy TH, Hand, S. J.; Worthy, J. P.; Tennyson AJD, Scofield RP 2009. A large fruit pigeon (Columbidae) from the Early Miocene of New Zealand. *The Auk* 126: 649–656.

Worthy TH, Tennyson AJD, Scofield RP 2011. An Early Miocene diversity of parrots (Aves, Strigopidae, Nestorinae) from New Zealand. *Journal of Vertebrate Paleontology* 31: 1102–1116.

Worthy TH, Tennyson AJD, Scofield RP, Hand SJ 2013. Early Miocene fossil frogs (Anura: Leiopelmatidae) from New Zealand. *Journal of the Royal Society of New Zealand* 4: 211–230.