The oldest rocks in New Zealand occur in the northwestern tip of South Island in the Nelson district, and in the southern-most extremity of this island, Southland. These oldest rocks, ranging from Cambrian (500 million years) to Jurassic (145 million years) in age, form the foundation of the South Island, and are overlain by younger rocks with a much less complex geological history (Table 1). These foundation rocks are known as basement rocks. In Southland they extend in a broad arc from the east coast northwards toward Milford Sound, and include the rugged Fiordland region.

The basement rocks occur as a series of subparallel, fault-bounded groupings of rocks which were formed in different times and places relative to one another. Each group of rocks is internally continuous and is representative of a particular depositional environment. Such fault-bounded groupings of rocks are known as terranes. These terranes have been juxtaposed (i.e. accreted) with one another by plate tectonic forces more than 110 million years ago. The oldest of the terranes was part of the old supercontinent Gondwanaland, upon which the younger terranes were accreted. The younger terranes represent fragments of the leading edges of tectonic plates which were deposited over a period of about 180 million years.

The terranes are composed of a wide range of rock types, including volcanic rocks, sedimentary rocks, limestones, granites and unusual intrusive rocks originating from deep in the crust. They have been folded, faulted, metamorphosed and carved into a range of landforms, with glacial features dominating the relatively young landscape.

This guide uses a series of sites to demonstrate the diverse geology and landforms of this region. The sites are easily accessed and pass through scenic and in many cases visually dramatic countryside. The route linking the sites passes along the coastline from Dunedin to Invercargill, eventually heading inland and northwards to Milford Sound via Te Anau (Map 1). Features examined on the route include:

- The characteristics of a major, regional fold, the Southland Syncline
- The characteristics of the individual terranes
- The Permian and Triassic marine sedimentary rocks, including limestone
- Cathedral Caves, a large sea cave in limestone
- The fossilised forest at Curio Bay
- The distinctive layered mafic and ultramafic intrusions at Bluff
- Permian submarine lavas
- Intermixed magmas at Wakapatu Point
- Relatively young Miocene limestone and other sedimentary rocks at Clifden and the Waiau River
- Glacial landforms, multiple alluvial terraces, broad glacial outwash areas
- Granite, gneiss and glacial landforms of the Fiordland area
- Diverse rock types of several terranes in the Eglinton River
- Exotic, coarse mafic pegmatite near Homer Tunnel
- Glacial landforms at Milford Sound
<table>
<thead>
<tr>
<th>PERIOD</th>
<th>YEARS AGO</th>
<th>LIFE FORMS</th>
<th>GEOLOGICAL EVENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td>0 - 10,000</td>
<td>Human Beings</td>
<td>Earthquakes, landslides, northeast trending ridges continue to rise. Continued rising of land, down-cutting by rivers and sea, glaciation and loess deposition, continued formation of alluvial terraces.</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>10,000 - 1,800,000</td>
<td>Grazing and carnivorous Mammals</td>
<td>Widespread glaciation started about 2 million years ago, resulting in commencement of extensive loess and thick floodplain deposition. Southern Alps begin forming about 3 million years ago as a result of compression by convergent Australian and Pacific Plates. Gravels and sands deposited on land, whilst sands, gravels and limey sediments form in shallow ocean. Uplift of marine sediments along coast form sandstone, conglomerate and limestone.</td>
</tr>
<tr>
<td>Pliocene</td>
<td>1,800,000 - 5,300,000</td>
<td>Modern mammals</td>
<td>Crustal uplift followed by deposition of sandstone, conglomerate and coal swamps.</td>
</tr>
<tr>
<td>Miocene</td>
<td>5,300,000 - 23,000,000</td>
<td>Placental animals</td>
<td>New Zealand mostly under sea to 25 million years ago, resulting in widespread sandstone, limestone, siltstone, greensand and coal. Initial movement on Alpine Fault results in regional uplift and retreat of ocean.</td>
</tr>
<tr>
<td>Oligocene</td>
<td>23,000,000 - 33,900,000</td>
<td></td>
<td>Australia separated from Antarctica 55 million years ago. Boundary between Australian and Pacific Plates formed through New Zealand 45 million years ago. Deposition of marine sediments.</td>
</tr>
<tr>
<td>Eocene</td>
<td>33,900,000 - 55,800,000</td>
<td></td>
<td>Tasman Sea fully opened by 60 million years. Continued erosion of New Zealand land mass. Deposition of marine sediments.</td>
</tr>
<tr>
<td>Paleocene</td>
<td>55,800,000 - 66,500,000</td>
<td></td>
<td>Collision of Gondwana margin 130 million years ago uplifted New Zealand area. New Zealand separated from Gondwana 130-85 million years ago, resulting in formation of Tasman Sea. Final Median Batholith magmas intrude along Gondwana margin.</td>
</tr>
<tr>
<td>Cretaceous</td>
<td>66,500,000 - 145,500,000</td>
<td>Last dinosaurs. First flowering plants</td>
<td>Continued deposition of marine sediments. Crustal compression 160 million years ago resulted in metamorphism with formation of schists in Caples Terrane. Rocks of Murihiku Terrane deposited in a deep ocean adjacent to a plate boundary offshore of Gondwana.</td>
</tr>
<tr>
<td>Jurassic</td>
<td>145,500,000-200,000,000</td>
<td>First birds. Reptiles and ammonites abundant.</td>
<td></td>
</tr>
<tr>
<td>Triassic</td>
<td>200,000,000-250,000,000</td>
<td>First dinosaurs, ammonites and primitive mammals</td>
<td></td>
</tr>
<tr>
<td>Permian</td>
<td>250,000,000-299,000,000</td>
<td>Mammal-like reptiles. Last trilobites.</td>
<td>New Zealand area part of Gondwana. Erosion of continent formed marine muds, sands and, gravels and minor limestone. Some volcanic activity. Rocks of Caples, Maitai and Brook Street Terranes formed in deeper ocean waters adjacent to a plate margin which was associated with volcanic islands.</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>299,000,000-359,000,000</td>
<td>First reptiles, fern forests</td>
<td>Earliest intrusion of Median Batholith magmas along margin of south Gondwana.</td>
</tr>
<tr>
<td>Devonian</td>
<td>359,000,000-416,000,000</td>
<td>First amphibians and insects</td>
<td>Final deposition of Takaka Terrane rocks.</td>
</tr>
<tr>
<td>Silurian</td>
<td>416,000,000-443,000,000</td>
<td>Vascular land plants</td>
<td></td>
</tr>
<tr>
<td>Ordovician</td>
<td>444,000,000-488,000,000</td>
<td>First corals, fish with vertebrae</td>
<td>Rocks of Buller and Takaka Terranes deposited in a deep ocean adjacent to a continental margin.</td>
</tr>
<tr>
<td>Cambrian</td>
<td>488,000,000-542,000,000</td>
<td>Shellfish, trilobites</td>
<td>Rocks of Takaka Terrane deposited in ocean adjacent to plate margin.</td>
</tr>
</tbody>
</table>

Table 1. Simplified geological history of the Southland-Fiordland region.
DUNEDIN TO NUGGET POINT

The drive from Dunedin to Nugget Point (about 105 km) travels mainly along the coastal plain with few outcrops to be easily examined (Map 4). The route passes from high grade metamorphic rocks of the Haast (Otago) Schist textural zone 4 (refer to Otago tour guide) through decreasing metamorphic grades until virtually unmetamorphosed Carboniferous to Permian rocks are reached. The route passes close to the Titri Fault, a major northeast-trending reverse fault which has moved the rocks to the east of the route northwards relative to the rocks on the western side. The highway passes along a series of plains which have been formed by tilting and subsidence of the area along faults, creating a half graben in the south and a graben in the north. The Otago peneplain (see Otago tour guide) is visible to the west of the highway, sloping to the southeast.

Close to the town of Milton the route passes into layered sedimentary rocks which slope (i.e. dip) toward the southwest and progressively become younger in that direction. These rocks are on the northern flank of the Southland Syncline (Maps 2 and 4), a large fold which has warped the rocks of this region into a wide, asymmetrical U-shaped structure (see cross section, Map 3).

Once the route reaches the coastline near Port Molyneux sedimentary rocks become evident on the coastal plain and marine Triassic sediments are seen near Nugget Point (Map 4). These latter rocks are formed of marine sediments which have been deposited in a large embayment (Marl Island Channel) which is formed by the large faulted fault of the Titri Fault. These marine sediments are also formed of sediments which have been deposited in a large embayment (Marl Island Channel) which is formed by the large faulted fault of the Titri Fault. These marine sediments are also formed of sediments which have been deposited in a large embayment (Marl Island Channel) which is formed by the large faulted fault of the Titri Fault.

Photo 1. View east from Nugget Point showing steeply dipping Triassic marine rocks of the Murihiku terrane.

Map 1. Topographic map of the Southland-Fiordland area of South Island showing suggested route and geological observation sites.
beaches and headlands. These are Triassic (see Table 1) siltstones, sandstones and mudstones of the Murihiku Terrane which were (at this time) deposited in a deep ocean. Note how the layering (i.e. bedding) in the rocks dips very steeply, mostly to the south. On the northern side of the Southland Syncline the rocks dip steeply, whereas on the southern side they dip at low angles (see cross section, Map 3). This asymmetry in dips may be due to unequal forces directed on the rocks during folding, possibly during the collision of the Murihiku and Maitai Terranes.

Photo 2. Steeply dipping Triassic marine rocks on Nugget Point.
After arriving at Nugget Point, walk to the lighthouse and viewing platform. The view eastward from here shows the steeply dipping Triassic Murihiku Terrane rocks and the isolated, nuggety rocky islets which give the locality its name. A seal colony is generally evident amongst the rocks of the shoreline. Note how the bedding in the rocks is very regularly layered, and is very continuous (Photos 1 & 2). This is a common feature of sedimentary rocks deposited in a deep ocean, where there are no strong currents or wave action to erode and dismember the sedimentary layers. Bedding dips mainly to the southwest, but can also be seen dipping locally to the northeast. The northeast dipping beds are overturned: i.e. folding by...
Map 4. Simplified geological map (top) and terrane map (bottom) for the route between Dunedin and Nugget Point.
the Southland Syncline has locally tilted the rocks so that their original top surfaces now face downward.

Walk from Nugget Point to Roaring Bay. Proceed to the rocky outcrops on the southwest side of the bay. These are Triassic rocks of the Murihiku Terrane. The boundary between the Triassic and Jurassic rocks lies very close to this locality and to the south. The rocks here include fossiliferous and non-fossiliferous sandstone, pebbly sandstone, siltstone and conglomerate and some limestone. The rocks dip steeply to the southwest (Photo 3).

This is a very important fossil locality. Abundant shelly marine bivalve species (Photo 5), cephalopods, nautiloids and some isolated vertebrae from an *ichthyosaur* occur throughout the site. Plant fossils occur further south along the headland. The marine fossils demonstrate that the rocks here were deposited towards the end of the Triassic period in a relatively shallow ocean (marine shelf). They contrast with deeper water rocks (slope basin and upper continental slope) in the regions to the north, and indicate that uplift of the ocean
floor was rapidly taking place at this time. As will be demonstrated at Curio Bay, the uplift was accompanied in places by emergence and deposition on land.

Note that there is a wide range of pebble types in these rocks (Photo 4), including andesitic to dacitic volcanics ash and possible glassy lavas, and rare rhyolite and granite. These typify the composition of the Triassic and Jurassic rocks of the Murihiku Terrane. They indicate that the source area was a volcanic chain along a continental margin which produced large amounts of ash. The granite pebbles indicate that the older continental rocks of local Gondwana were undergoing erosion.

**NUGGET POINT TO CATHEDRAL CAVES**

The route from Nugget Point to Cathedral Caves (about 57 km) crosses the Southland Syncline and passes through Jurassic sedimentary rocks (Map 5) of the Murihiku Terrane. After crossing the syncline axis the layering of the sedimentary rocks changes from steeply dipping, as was seen at Roaring Bay, to low angle. These rocks were deposited in a shallow ocean, and include sandstones, siltstones and limestones.

Cathedral Caves are two large cave entrances which join within the headland (Photo 6). The caves are only accessible at low tide. A fee is charged for entrance to the site, which requires a 20 minute walk to the beach, followed by a 10 minute walk to the headland. Taking a torch is recommended.

The caves occur in layered Jurassic limestone. The cathedral-like cave ceiling is up to 30 m high in places. Note how the limestone layers are almost...
After departing cathedral caves it is a short drive to McLean Falls. This is a pleasant locality to stroll through native forest and admire a beautiful series of waterfalls cascading over Jurassic sedimentary rocks. The turn-off to McLean Falls is about 800 m west of the Cathedral Caves road intersection. It is about 3.2 km to the falls car park, with an easy walk of about 300 m to the falls. The falls occur as a series of tiered drops over well bedded sandstones and siltstones with shallow or horizontal dips (Photo 9). The attractive, tiered form of the falls has developed because of different rates of erosion of the horizontally layered rocks, resulting in a stepped appearance.

The drive to Curio Bay is about 30 km from the McLean Falls intersection. The road passes through low hills of Jurassic sedimentary rocks. Continue along the Chaslands Highway until the turnoff to Niagara and Waikawa is reached. Proceed to Waikawa and turn into the Waikawa-Curio Bay road in the approximate centre of Waikawa. Follow this road for about 6 km until the T-intersection with Mair Road. Turn right and proceed for 200m to the Curio Bay parking area (Map 6). Follow the walking track to the shoreline.

Curio Bay is a locality world renowned for its petrified forest of fallen Jurassic logs and stumps. This site is best examined at low tide, as the exposures occur on the coastal rock platform. The forest extends from here about 20 km southwest to Slope Point. It consists of numerous stumps and fallen trunks of silicified (quartz-impregnated) fossil wood in a sandstone bed (Photos 10-13).

The silicified wood shows very well preserved internal structure, including growth rings and bark. Some rare species are present. Please
don’t damage or remove the fossils. Excellent examples of the logs can be observed in the rock platform, and in the adjacent cliff faces multiple layers of tree trunks and stumps are evident. In other, nearby localities fern and leaf fossils are found in mudstone layers.

The petrified forest grew on a broad, well-timbered floodplain about 180 million years ago on the eastern margin of Gondwana. The floodplain was flanked by active volcanoes which were the major contributor to the sand and silt which was deposited on the plain. Vegetation comprised abundant trees (resembling New Zealand Kauri and Matai, and Norfolk Pine) and tree ferns with a fern-rich undergrowth, including cycads. At about this same time much of the area traveled over from Dunedin was beneath the ocean. Over a period of about 20,000 years at least four abrupt, violent sheet floods of gravel, sand and mud derived from the flanks of a distant volcano swept across the plain, flattening the forest which regrew, only to be destroyed again. Each sheet flood is preserved in local cliff faces as distinct layers of volcanic debris and tree remains.

As the sedimentary layers which encase the forest remains were buried over millions of years, the wood was slowly replaced by quartz (silica). This is the process of petrification.

BLUFF PENINSULA

To travel to Bluff Peninsula, travel towards Waikawa and turn into the Haldene-Curio Bay road (Map 6). Follow this road through Haldene to Tokanui, a total distance of about 20 km (Map 7). Turn left onto the highway and follow this to Invercargill. Navigate to the Bluff Highway and follow this to its very end at Lands End (Map 9), a distance of about 30 km from Invercargill.

The Bluff Peninsula comprises a number of complex igneous intrusions of Late Permian age which have intruded into Early Permian marine sedimentary rocks of the Brook Street Terrane (Figure 1). This terrane is a remnant of an island arc system which has segments exposed near Gympie in Queensland (Australia) and in New Caledonia. This very extensive arc system was associated with a long subduction zone near the margin of Gondwana during the Permian. The arc was disrupted into separate terranes during accretion to the Gondwana margin and in the subsequent breakup of Gondwana. The igneous rocks present in this terrane include lavas which erupted beneath the ocean (which will be examined at Howells Point), and the plutonic rocks which fed the volcanic eruptions (examined here).

Two intrusions will be examined on the Bluff Peninsula: the Bluff intrusion, and the Green Hills intrusion. Age dating has shown that the intrusions range from about 241 to 266 million years old.

These intrusions were emplaced at shallow levels in the Earth’s crust in a magma chamber associated with a subduction zone. As the magma sat in the chamber it began cooling, resulting in the crystallisation of some minerals which settled to the bottom of the chamber. Layers of different crystals and crystal mixes (which later solidified into rock) were built up, with the earliest formed occurring at the base of the chamber. This process is known as fractional crystallisation. The earliest crystallised mineral was olivine, which formed a body of dunite more than 600 m thick. As pyroxene began to crystallise it settled
Map 7. Route and terranes between Curio Bay and Invercargill.

Map 8. Simplified geological map of the area between Invercargill and Curio Bay.
with olivine to form a 150 m thick layer of *wehrlite*. Finally, plagioclase began to crystallise with pyroxene, the two minerals settling above the wehrlite layer to form a 640 m thick *gabbro*. Additional magma was introduced into the chamber, resulting in gabbroic dykes cutting the previously formed layers. Some movement of the crystal layers (which were still in a mush-like state) caused some degree of mixing of the rocks along their boundaries. Finally, the layers of unsolidified crystals were forced higher into the magma chamber and adjacent rocks, accompanied by folding, faulting and intrusion of dykes.

Some of the rocks characterising the Bluff intrusion can be examined on the rocky exposures at Lands End. The main rock here is a black *gabbro* (a rock composed of the minerals feldspar and pyroxene). This is cut by irregular dykes of paler gabbro which are in turn cut by fine-grained, black gabbro dykes (Photo 14).
To examine the other rock types which make up the suite of Late Permian intrusions it is necessary to return from Bluff to Omaui Road, just to the south of Greenhills township, a distance of 10 km. Turn into Omaui Road and proceed for 3 km to the first major bend (Map 10), passing two quarries on the south side of the road. At the bend, turn left into the lane and follow it for 300 m to the end. Continue on foot southward (see Map 10) toward the coastline. Thick gorse may be encountered near the start of the walk, but this gives way to grassland after about 100 m. The walk passes through prominent outcrops of dunite of the Greenhills Complex, a layered intrusion of gabbro, wehrlite and dunite. After reaching the rocky shoreline, examine the outcrops and waterworn pebbles, particularly to the west (see Map 10). These rocks include dark green dunite (composed of olivine), dark green to black wehrlite (composed of olivine and pyroxene), paler gabbro and a pyroxene-poor gabbro (troctolite).

HOWELLS POINT

Howells Point occurs to the south of Riverton, a distance of about 66 km from Greenhills (Maps 12 & 13). The route largely passes across plains of alluvial outwash from the glaciated ranges to the north. Howells Point is an excellent site to examine basaltic pillow lavas and dykes of the Permian Brook Street Terrane (Figure 1, page 16).
Map 12. Simplified geological map of the route between Bluff and Wakaputa Point.

Map 13. Terrane map of the route between Bluff and Wakaputa Point.
Turn off the highway at Riverton and follow Bay Road through The Rocks village to Howells Point, a distance of about 4.5 km. Stop off the roadside where shown on Map 11. Walk onto the beach and walk eastward to the prominent outcrops on the eastern edge of the headland. This is site 1 shown on the satellite image (Map 11).

The dominant rock types here are basaltic lavas of Permian age which were erupted beneath the ocean. These are well shown at sites 1 and 3 as pillow lavas.

When a lava enters a deep body of water fractures open in the rapidly chilling edges of the flow and molten rock pushes through. The lobe-like molten lava is known as a pillow. Successive pillows overlap each other, building up a thick accumulation of pillows (Photo 18). Newly formed pillows flow into the irregular surface below, forming a loose jigsaw texture.

The lavas have undergone alteration of some minerals during their immersion whilst hot in sea water. This process is called spilitisation, and produces minerals such as green chlorite and blue pumpellyite throughout the rock.

Some of the lava is very pale due to alteration, and contain amygdales. These are original gas bubbles in the lava which have subsequently been filled with minerals such as quartz or zeolite. This is particularly evident at site 2, where amygdales are sparsely scattered through the rock, or are concentrated in curved layers which represent zones within indistinct pillows.

Pillow lavas at site 3 are intruded by black dolerite dykes (Photo 20). Dolerite is chemical equivalent of basalt, but is intrusive, whereas basalt is extrusive. The dykes exhibit chilled margins, with increasing grain size toward the core of the dyke.

**WAKAPUTA POINT**

The next geological site is at Wakaputa Point. This site gives an introduction to one of the many plutonic igneous rocks of the Median Batholith. To travel to this site, return to Riverton and follow the Orepuki-Riverton Highway for 16 km to the intersection with the Round Hill-Wakaputu Road. Turn into this road and follow it for 6.5 km to the shoreline on Austin Road, (Map 14) stopping just before the road enters a farm.

The Median Batholith (also known as the Median Tectonic Zone) comprises an Early Permian to Middle Cretaceous (110 - 375 million year old) group of large intrusive igneous masses (which make up about 90%
The intrusions range in composition from granitic to gabbroic rocks. They have intruded the volcanic and sedimentary rocks of the Brook Street and Takaka Terranes (see Figure 1 and Map 3). Part of the plutonic portions of these terranes are included within the Median Batholith.

The rocks examined at Wakaputa Point are examples of one of the many igneous plutons of the Median Batholith.

Low tide allows easy access along the rocky shoreline to the south of the access point. The rocks here change compositionally along the shoreline. Closest to the starting point the rocks are granodiorite (a plutonic igneous rock composed of quartz, feldspar, biotite and hornblende; it is darker in colour than granite) with associated magmatic eruptions on the land surface, commonly as chains of volcanic islands - similar to the Pacific “Ring of Fire”) which had formed on the margin of Gondwana above an active subduction zone. The intrusions range in composition from granitic to gabbroic rocks. They have intruded the volcanic and sedimentary rocks of the Brook Street and Takaka Terranes (see Figure 1 and Map 3). Part of the plutonic portions of these terranes are included within the Median Batholith.

This package of rocks represent the deeply buried portions of an island arc system (i.e. a region of crustal melting of the Median Tectonic Zone) with associated sedimentary and volcanic rocks. 

Figure 1. Age and spatial relationships of the tectonic terranes in the southern end of New Zealand.

Photo 21. Dark enclaves of possible diorite within a granodiorite.

Photo 22. A large, dyke-like enclave.

From Bob and Nancy's Geological Tour Site: http://ozgeotours.110mb.com
with sparse, dark coloured enclaves (fragments of rock within another igneous rock which are genetically related) of another igneous rock (Photo 21). The enclaves become more abundant to the south, reaching about 50% of the rock near a small slipway. At this point the host rock is a quartz diorite (a grey igneous rock composed mainly of plagioclase and hornblende).

The enclaves show a range of sizes and shapes (Photo 22), and some are very angular. It is interpreted that the enclaves represent a magma similar to a diorite which intruded into a magma chamber containing a partly consolidated granitic to granodioritic magma. The diorite solidified, but was subsequently disrupted by convective motion within the still fluid host. Many enclaves show an alignment of their long axes which is consistent with flow within the magma chamber.

This is an example of a process known as magma mixing, whereby the mixing of two or more magmas or magma batches form a hybrid magma. The resulting magma commonly inherits intermediate properties of the two parent magmas. Therefore, it would be possible to create a granodiorite by introducing a diorite into the granitic magma chamber. This hybridisation has not happened at Wakaputa Point, as the diorite was able to cool and crystallise before mixing and assimilation could take place.

**CLIFDEN TERTIARY LIMESTONE**

The drive from Wakaputa Point to Clifden (Map 15) is a journey of 51 km. It passes through Quaternary alluvial material associated with the coastal margin, and the Orouea River floodplain. The adjacent rocks are marine and non-marine Tertiary sedimentary rocks which were deposited in a basin formed by the uplift of Fiordland to the west and the Takitimu Mountains to the east (Map 2). The basin occurs on rocks of the Median Batholith.

From about 55 to 35 million years ago (Table 1) the basin was above sea level, and commenced fill-
ing with river gravels, sands and silts, with minor swampy peat (which are now thin coal seams). By the Oligocene epoch (Table 1) the basin had been inundated by the ocean, and in places thick banks of shellfish resulted in the formation of limestone beds. Limestones were deposited into the Miocene epoch, and those exposed in the banks of the Waiau River at Clifden are an important locality for establishing the age and relationships of these limestones. Following their deposition the rocks were tilted into their present position by movement along major faults.

On reaching Clifden, navigate to the old Clifden suspension bridge (Map 16). The limestone outcrops on the south bank of the river (Photo 23).

The limestone beds at Clifden are locally sandy (Photo 24), and contain fine to coarse shelly material which includes pectens, gastropods, brachiopods and rare sharks’ teeth. These are of Middle Miocene age (about 12 to 17 million years old). They have been quarried about Clifden as a source of agricultural lime.

_Honeycomb weathering_ is visible in parts of the limestone on the cliff (Photo 26). This forms from the expansion of salts which have been introduced into solution into the porous or fractured rocks either from sea water flung against a rock face, or from saline accumulations in inland areas. Evaporation of the solution leaves the salts behind, which can expand up to 3 times their normal size when heated by the sun. The pressure of the expanding salt crystals weakens the rock, resulting in preferential erosion of the softer material, creating the honeycomb-like surface texture.

_Photo 26. Honeycomb weathering in sandy limestone._
Walking upstream for about 600 m shows the limestone grading upward into sandstone, with increasing siltstone and mudstone. Fossils are locally abundant.

**BORLAND SADDLE - FIORDLAND**

The route travels to Borland Saddle in Fiordland, a distance of about 45 km. The journey to this site passes through alluvial flats of the Waiau River, Tertiary sedimentary rocks, and Ordovician sedimentary and metamorphic rocks (Map 17). A granite of the Median Batholith (Map 18) is also examined along the route.

From Clifden the road passes through Blackmount to the intersection with the Lake Monowai Road on the left, a distance of 31 km. Follow this road for 3.5 km, pausing near the suspension bridge over the Waiau River to view some interesting outcrops of Tertiary limestone, and thinly layered siltstone and mudstone. Note the steepness of the bedding dips at this locality. The rocks are also dipping in the opposite direction to those at Clifden, suggesting that these rocks are on the opposite side of a large fold. The rocks can be examined on the eastern side of the river. Care is advised in descending the track to the river bank. The river is very deep and fast flowing.

Continue along Lake Monowai Road for 4.4 km to the intersection with Borland Road. Turn
right into Borland Road and proceed for 9.4 km until a tall road cutting in granite is reached (Photo 28). Park safely to examine this rock and the adjacent ridges. This granite is one of the many plutons of the Median Batholith. The host rocks, which aren’t accessible at this site, are Ordovician high grade metamorphic rocks which were very deeply buried but have been brought to the surface by rapid uplift and erosion of the Fiordland area. The Ordovician host rocks which have probably melted to form this granite will be examined at the next site.

Uplifted Tertiary sedimentary rocks overlying Median Batholith rocks occur on the ridge to the east (see Map 17). These rocks are part of the Tertiary rock package which we have examined at the last two sites. They have undergone significant uplift on the eastern edge of Fiordland since their deposition due to rapid vertical movement along major faults.

Continue along the road for a further 2.2 km, where a long and high road cutting is encountered. Park safely. This cutting has exposed the Ordovician metamorphic rocks which have melted locally to form igneous rocks of the Median Batholith. The metamorphic rocks are gneisses: layered, crystalline rocks composed of quartz, feldspar and biotite (Photo 30), and amphibolite: a black rock composed of amphibole and feldspar. The layering in the gneiss is produced by alignment of platy minerals by the high pressures which formed the gneiss. An increase in the pressures and accompanying high temperatures resulted in parts of the gneiss melting to form a range of partial melts or local pods of melt which migrated into larger masses to form plutons. The compositions of those partial melts depends upon the material being melted. At this locality a range of different igneous rock types reflect the various compositions of the original rocks. Pale granite and somewhat darker granodiorite (Photo 31) were formed from the melting of feldspathic sandstone or rhyolitic to rhyodacitic volcanic rocks (and their gneissic metamorphic derivatives). Amphibolite formed from the metamorphism of basaltic rocks, but has not melted. Dykes of coarse grained, quartz and feldspar-rich pegmatite and fine-grained aplite have intruded into the rocks, representing the migration of late stage crystallisation products.

Continue along the road for 4.1 km to Borland Saddle. This site offers some great views of Fiordland,
and views of the world’s largest land-based landslide, the Green Lake landslide. A walk along a spur to the north of this site presents an excellent view of paired glacial valleys, complete with cirques and hanging valleys and moraines, and the Green Lake landslide.

From the saddle parking area and plaque, walk or drive to the track which gives access to the power pylons on the spur to the north. It is possible to park beneath the pylons, shortening the walk to the crest of the spur (Photo 32). The walk to the crest is steep in places, with a sheer drop on the southeastern face.

Whilst ascending the spur it is possible to view the southern pair of the intersecting glacial valleys (Map 19). The head of the valley is marked by a cirque (Photo 33), a bowl-shaped landform which developed at the head of a glacier. A cirque forms by accumulations of snow in favourable site which is protected from sunlight and winds. The snow thickens and compresses into ice, and a process of freeze-thaw weathering takes place beneath the ice. As the mass of ice continues to build up it eventually begins moving down slope under
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gravity, eroding the base of the cirque and commencing the process of grinding a typical U-shaped glacial valley.

From the crest of the spur the main glacial valley (Map 19) can be examined (Photo 34). This valley, and others within Fiordland contained glaciers during the last glaciation which ended about 13,000 years ago. The abundance of glaciers during this period eroded deeply into the land surface, weakening the intervening ridges. Following the melting of the glaciers many ridges collapsed, forming large landslides throughout Fiordland. The largest of these, the Green Lake landslide is visible to the west of this site (Photo 35).

The landslide comprises an area of 45 square kilometres of disrupted rocks and semi-intact blocks of debris which occupy a broad area of hummocky, irregular topography surrounded on three sides by tall ridges (Figure 2). It is estimated to have a volume of about 27 cubic kilometres, is up to 1 km thick, and transported debris up to 2.5 km laterally.

The Green Lake landslide occurred about 12,000-13,000 years ago following glacial recession in a warming climate. The withdrawal of numerous glaciers from their deep valleys and the removal of support for the over-steep, glacially eroded mountain walls reduced the stability of the region. A low angle fault zone exists beneath the range and valley, acting as a failure surface. Research indicates that the landslide was triggered by an earthquake of magnitude 7.5 or greater on the Alpine Fault off the Fiordland coast. The resulting landslide collapsed about 700 m vertically into a deeply glaciated valley occupied by a glacial lake. The lake was cut in two by a landslide dam about 800 m high. The impounded lake was up to about 11 km long, and was gradually infilled with glacial sediment and subsequently peat and swamp deposits. The former lake is now the Grebe Valley which commences at the toe of the landslide and ends at Lake Monowai.

One phenomenon which is clearly shown from this locality is the alpine tree line (Photos 33-35, Map 19). This is the edge of the habitat at which trees are capable of growing. In this region the tree line is probably related to cold temperatures.

Return to the main road and turn left towards Manapouri. After a distance of about 8 km the route enters a broad river valley with prominent, elevated river terraces visible on the eastern side of the road (Photos 36 and 37). These are Pleistocene terraces resulting from the deposition of large volumes of glacial debris during and after the last period of glaciation, about 13,000 years ago. This material filled the river valley, but has been uplifted in at least two events to form the multiple levels of terraces visible here. The periods between
uplifts allowed the river to plane the sands and gravels which form the terraces into flat sheets. After each uplift the river began cutting downward into the older terrace, planing a new terrace top as it progressed. The satellite image (Photo 36) shows two terraces, with the present river flats potentially forming the top of a third terrace should there be further uplift.

The route continues to Te Anau and northward to Milford Sound. It passes initially through Pleistocene and younger alluvial sediments (Map 20), then follows the shoreline of Lake Te Anau before entering rocks of the Median Batholith. Glacial-carved vistas and landforms are common along the route, and some unique, coarse mafic pegmatite is examined near Homer Tunnel. High terraces border the Eglinton River. A geological site on a tributary of the Eglinton River reveals a range of pebbles and boulders brought down stream from otherwise inaccessible terranes further to the east.
The journey from Te Anau to Milford Sound is about 116 km. Passing northward from Te Anau the road cuts through unconsolidated pebbly and bouldery deposits of terrace material. Following the shoreline of Lake Te Anau the high ridges of the Median Batholith are evident to the west, with remnants of Tertiary sedimentary rocks overlying them above the shoreline (Maps 20 & 22). The Tertiary rocks can be seen dipping towards the lake, commonly high on the ridge in the foreground.

About 60 km from Te Anau a sign posted gravel track to the west leads to the Deer Flat campsite (Map 20). Follow the track for several hundred metres until it passes close to the gravel beds of the Eglinton River. This watercourse and its tributaries is sourced from the north, northeast and northwest, and through its gravel beds provides an example of the rocks to be found in that region (Map 21).

This area is significant as rocks of the Maitai and Brooks Street Terranes are sandwiched between those of the Median Batholith and Caples Terrane. The Brook Street and Maitai rocks are attenuated, providing an example of the rocks to be found in that region (Map 21).

Photo 38. Bare ridges of Maitai Terrane rocks east of Deer Flat. Note the layering on right of photo.
squashed and interleaved along faulted margins. Examples of these rocks can be found as pebbles and boulders in the creek. Boulders of volcanic breccia (a rock composed of angular fragments of other rocks) and black andesite (a lava commonly formed above subduction zones) which are representative of the Permian Brook Street Terrane are common. The site also provides views of the bare ridges of Maitai Terrane rocks to the east (Photo 38).

Continue along the river valley for about 3 km from the Deer Flat turnoff, passing the small settlement at Knobs Flat. Evidence of the presence of a glacier is supplied by sparse clusters of drumlins (Photo 39) on the western side of the road. These are elongated, whale-shaped hills formed by deposition beneath a glacier on the valley floor. The long axis of an intact drumlin is parallel with the movement of the glacial ice, and the blunt, higher end is the downstream portion. They commonly occur in clusters. The drumlins shown along this route have undergone modification by flood-related erosion and have lost some of their characteristic form. At least six drumlins, some of which are vegetated with trees, are evident over a distance of about 400 m.

Key Summit Walk. The staging area for the Routeburn Track and the Key Summit side track is sign posted on the eastern side of the road as The Divide. The Department of Conservation indicates a duration of 1 hour 20 minutes to reach the end of the Key Summit walk, although this is dependent upon many factors. The Key Summit track is suitable for any walker capable of managing steep gradients on a well formed and signed track. This walk passes through native forest, and exposures of the bedrock are visible in the drainage trenches along the track. On a day with no low cloud, this is an ideal site to view impressive post-glacial scenery. Be aware that weather conditions can deteriorate rapidly in this environment, so travel prepared!

Various facies of the Permian Maitai Terrane are apparent along the track. Lowermost outcrops are of bright green, metamorphosed andesitic to basaltic rocks of the Dun Mountain Ophiolite. The track subsequently passes into
dark grey siltstone and sandstone. Quartz veins are locally apparent.

A self-guided tour at the crest of the ridge uses fixed signs to describe the flora, fauna and landforms of the site. The landforms result from glacial sculpting which took place during the last ice age between 2 million and 13,000 years ago. Fiordland was carved into its present geometry by huge glaciers which cut deeply into the surface rocks, forming curved networks of U-shaped valleys. A huge glacier flowed down the main valley visible from the top of Key Summit (Photo 40) and overtopped the locality by 500 metres. The present valley shows glacial smoothing from the valley floor nearly to the height of the tree line (Photo 40). U-shaped glacial valleys, which are visible from the crest, bifurcated from the main glacial valley (Photos 41 and 42). The angularity of the ridges is indicative of their periodic uplift and resulting instability and rapid erosion.

Valley intersection. From the Routeburn Track staging site travel 10 km to the parking area constructed near the intersection of two large valleys. This site represents the confluence of two very large glaciers, which have carved out the present U-shaped valleys (Photo 43).

These landforms typify the deeply eroded character of Fiordland (Figure 3). Numerous glaciers during the previous ice age were developed in a closely packed, curved array, with many intersecting and bifurcating. The glaciers were many hundreds of metres thick, carving very deep, U-shaped valleys into the rocks. The resulting very steep, high valley walls are very unstable and prone to avalanches and rockfalls.

Homer Tunnel diorite and hornblende-plagioclase pegmatite. Park safely off the road on the eastern portal of Homer Tunnel. This site examines the diorites and associated pegmatites of the Median Batholith (Maps 20, 22) which typify the bedrock between Homer Tunnel and Milford Sound.

Fresh samples of the diorite (Photo 44), with some coarse pegmatite are present as boulders on the edges of the parking area. The diorite is a dark col-

Photo 40. The glacially-carved Hollyford valley below Key Summit.  
Photo 41. The high level Lake Marian glacial valley adjacent to Key Summit.  
Photo 42. High level glacial valley east of Key Summit.  
Photo 43. U-shaped valley profile with glacially-eroded range in background.
oured rock comprising crystals of white plagioclase feldspar and black hornblende, possibly with small amounts of white quartz, black biotite mica, or dark green pyroxene. Very coarse-grained equivalents of the diorite, known as pegmatite occur here. However, the best examples of pegmatite (Photo 45) occur toward the head of the valley, several hundred metres from the tunnel entrance. To reach these rocks, walk toward the head of the valley on the northern side of the road using one of the unformed walking tracks amongst the boulders. An icy snow drift may be present near the head of the gorge.

This site is within Devonian and younger intrusive rocks of the Median Batholith (Maps 21 and 22). A pegmatite is a very coarse-grained igneous rock formed by the slow cooling of minerals squeezed into veins from a crystallising igneous rock. Pegmatite composed of very large crystals of black hornblende and white plagioclase feldspar is examined here (Photo 45). The parent diorite which produced the pegmatite occurs in the adjacent ridge. This is a rare form of pegmatite, as the most common pegmatites throughout the world are associated with granites and are composed of quartz, feldspar and mica. It is advisable not to approach the valley walls, as ice-weakened rocks can plummet downward without warning!

It is worth considering that this site is at the head of a glacial valley (Figure 3). Consequently, this site must have been a cirque, the point of origin of the glacier which carved the valley.

Continue to Milford Sound through tall, glacial ridges and flat, moraine-filled valleys. The route passes...
through hard intrusive rocks of the Median Batholith which end at Milford Sound village. Most of Milford Sound occurs within Ordovician sedimentary and metamorphic rocks (Map 20).

**Milford Sound** is a 15 km long **fiord** (a long, narrow inlet with steep sides, created in a valley carved by glacial activity). It is surrounded by glacially-carved ridges up to 1700 m high and is up to 450 m deep.

Fiordland is a region of crustal elevation, yet many seaward glacial valleys are inundated by the sea. This phenomenon is due to sea level rise since glaciation ended, about 13,000 years ago. During the previous ice age the sea levels fell significantly as water was locked up in the extensive ice sheets which covered large parts of the Earth. As the ice melted the seas rose, flooding the previous glacier channels.

One of the prominent features of Milford Sound are the numerous **hanging valleys** (Photos 46 & 47). These are tributary valleys with their floor at a higher elevation than the floor of the main valley. They are most commonly associated with U-shaped valleys when a tributary glacier flows into a glacier of larger volume.

Most of Milford Sound occurs within Ordovician metamorphic and sedimentary rocks (Map 20). These were formed in deep oceans, and generally composed of volcanic debris and fine silt and clay. They have been folded and metamorphosed and are now exposed as tilted, very hard outcrops of **meta-sediment** which are cross cut by later veins which are also folded (Photo 48). Minor copper mineralisation occurs within the rocks, and is evident in places as green and brown staining resulting from the decomposition of copper- and iron-bearing sulphide minerals (Photo 49). In places the metasediments have partially melted, and include veins and masses of granitic material (Photo 50).

In the eastern parts of Milford Sound these rocks are interlayered with green to black **nephrite jade** and pale green **bowenite**, precious stones to the Maori who extracted them for the manufacture of jewellery, tools and weapons. Nephrite and bowenite are only found

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in the South Island. Nephrite is a calcium and magnesium rich amphibole which forms in narrow alteration zones at the contact of serpentine rocks (serpentinite) and metasedimentary rocks which have been metamorphosed and altered.
Nephrite has formed by the chemical interaction of metamorphic fluids from the serpentinite and metasediment.

Bowenite is the rare, gem form of the pyroxene mineral *antigorite*. This is one of the *serpentine group* of minerals, which indicates that they are the common components of serpentinite. Bowenite generally occurs pervasive throughout some serpentinite, and may also occur as veins within the serpentinite or adjacent metasedimentary rocks.

Further evidence for the glacial origin of Milford Sound can be seen in the many cliff exposures of striations (Photo 51) gouged into the hard rock by the movement of the glacier. Rocks carried by the glacial ice were forced against the sides and base of the valley, cutting grooves into the otherwise smoothed rock face. Surfaces such as this are common at present glaciers such as Fox and Franz Josef.

The waters filling Milford Sound comprise a surface layer of relatively dark coloured, tannin-rich fresh water overlying saline water of the Tasman Sea. The fresh water layer is from 1 to 10 m thick, but filters sunlight passing into the salt water. This has the impact of encouraging deep sea plant life which prefers dark conditions to grow in relatively shallow water. The head of the fiord, about the village, has more fresh water than salt.

Photo 51. Glacial striations on the Milford Sound valley walls.

This concludes the Dunedin to Milford Sound geological guide. The third guide of the South Island series continues northward from Te Anau to Picton. We would be pleased to receive any feedback or comments to aid in the improvement of this, and any of our guides.

**BIBLIOGRAPHY**


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