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Field Trip Guides

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FIELD TRIP 7

IGNEOUS ROCKS OF THE SOUTHLAND COAST AND EASTERN FIORDLAND

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INTRODUCTION

The geology of the south island of New Zealand can be divided into Eastern and Western provinces based on contrasting ages and metamorphic histories (Landis and Coombs, 1967). The Western Province is composed of Lower Paleozoic metasedimentary rocks cut by Devonian to Carboniferous granitoids (Muir et al., 1998; Ireland and Gibson, 1998). It represents a fragment of the Paleozoic continental margin of Gondwana (Fig. 1a). The Eastern Province formed as the result of convergent margin processes and contains arc-volcanic rocks, arc-derived sedimentary sequences, and accretionary complexes of Permian-Cretaceous age. The two provinces are separated by a belt of variably deformed plutonic rocks that has been progressively referred to as the Median Tectonic Line (Landis and Coombs, 1967), the Median Tectonic Zone (Frost and Coombs, 1989; Kimbrough et al., 1993) and, most recently, the Median Batholith (Mortimer et al., 1999b)(Fig. 1b).

The field excursion will visit a number of localities in and adjacent to the Median Batholith along the Southland coast from Bluff Peninsula to Pahia Point as well as in eastern Fiordland. The eastern coastal section exposes a suite of plutonic rocks intruded in places into volcanogenic metasediments with the oldest intrusion dated at 265 Ma (Early Permian). These Permian rocks have been termed the Brook Street Terrane (Coombs et al., 1976) and in the past have been interpreted as the shallow crustal roots of an inter-oceanic island arc. The western part of the coastal section from Colac Bay to Pahia Point contains several rock suites which range in age from 247 Ma (Early Triassic) to 142 Ma (Early Cretaceous). Their relation to the older rocks of the Brook Street Terrane and to younger plutonic suites in eastern Fiordland has been the subject of much debate. The field excursion will visit the Bluff Peninsula on day 1, Riverton to Pahia Point on day 2, and the Borland area in eastern Fiordland on day 3.

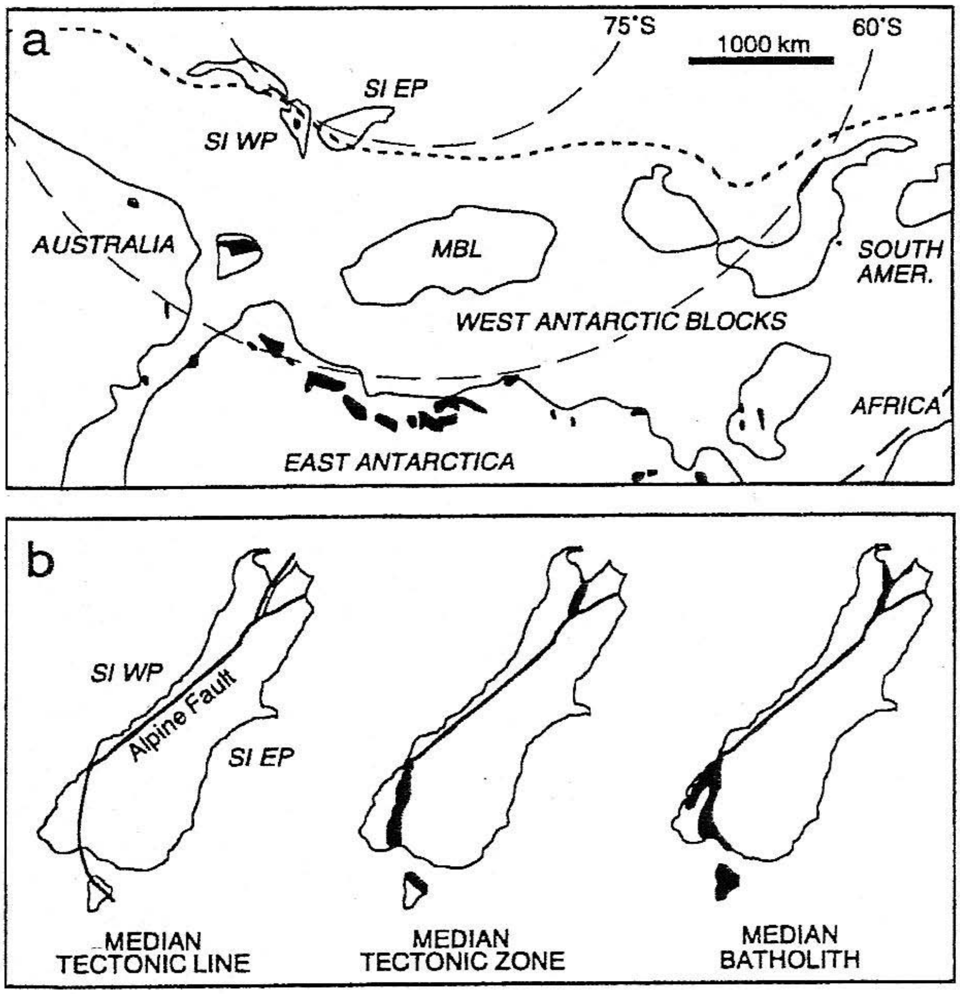


Figure 1: From Mortimer et al. (1999b). (a) Middle Jurassic paleogeographic reconstruction showing location of Eastern (SI EP) and Western Provinces (SI WP) along the Gondwana continental margin. (b) Development of nomenclature of the Median Tectonic Line, Median Tectonic Zone, and Median Batholith

THE BLIND MEN AND THE MEDIAN BATHOLITH

with apologies to John Godfrey Saxe (1816-1887)

It was six men of Godzone land to learning much inclined,
Who went to see the batholith (though all of them were blind),
That each by observation, might satisfy his mind.

The first approached the batholith, and moving to align
Against its broad and sturdy side, then started to opine:
“God bless me but this thing must be Median Tectonic Line!”

The second used his eager hand, and felt from foot to head:
“Ah, what this wondrous beast is like, is mighty plain” he said:
“Tis clear enough the behemoth, it is the MTZ.”

The third man turning to the east, cried “Ho! This is quite stark.
Yes, so much gabbro, layered too! There is no question mark,
This wonderful phenomenon, it is the Brook Street arc!”

The fourth who chanced to touch the ground, said “Now this is quite plain,
I know what it resembles most, let’s date this zircon grain.
The black box doesn’t lie, we’ve got the Median Terrane!”

The fifth no sooner had begun to fill out his timesheet
Than seizing on some traces left of radioactive heat,
Declared that he’d identified the igneous Median Suite!

The sixth approached the beast as well, and happening to halt,
With hammer hit no tholeiite not alkali basalt.
“This long thin thing it has to be a major strike slip fault!”

And so these men of Godzone land, disputed loud and long,
Each in his own opinion, exceeding stiff and strong,
Though each was partly in the right, and all were in the wrong!

So, oft in geologic wars, the disputants, I ween,
Tread on in utter ignorance, of what each other mean,
And prate about the batholith, not one of them has seen!

Nick Mortimer
Geological Society of NZ Newsletter 120: 4-5. 1999.

DAY 1: BLUFF PENINSULA

Depart from St Margaret's College 0800hrs Friday morning and head south on State Hwy 1. Make a quick rest stop in Gore before continuing on through Invercargill to Bluff. Bluff tide is high at 1150hrs. low at 1800hrs.

Dunedin to Bluff

The drive south to Bluff takes us through metasedimentary and minor metavolcanic rocks of five tectonostratigraphic terranes of the Eastern Province: Rakaia (Older Torlesse), Caples, Maitai, Murihiku and Brook Street (Fig. 2). As we leave Dunedin, we will be traveling away from the structural and metamorphic core of the Otago Schist, interpreted as the zone of maximum exhumation of the Mesozoic accretionary prism (Mortimer et al., 2002). We almost immediately cross into the Caples Terrane which has an oceanic arc provenance as compared to the active continental margin source of the Rakaia Terrane. Rocks of the Caples and Rakaia Terranes can be discriminated on the basis of geochemistry in the Otago Schist where primary sedimentary features have been destroyed.

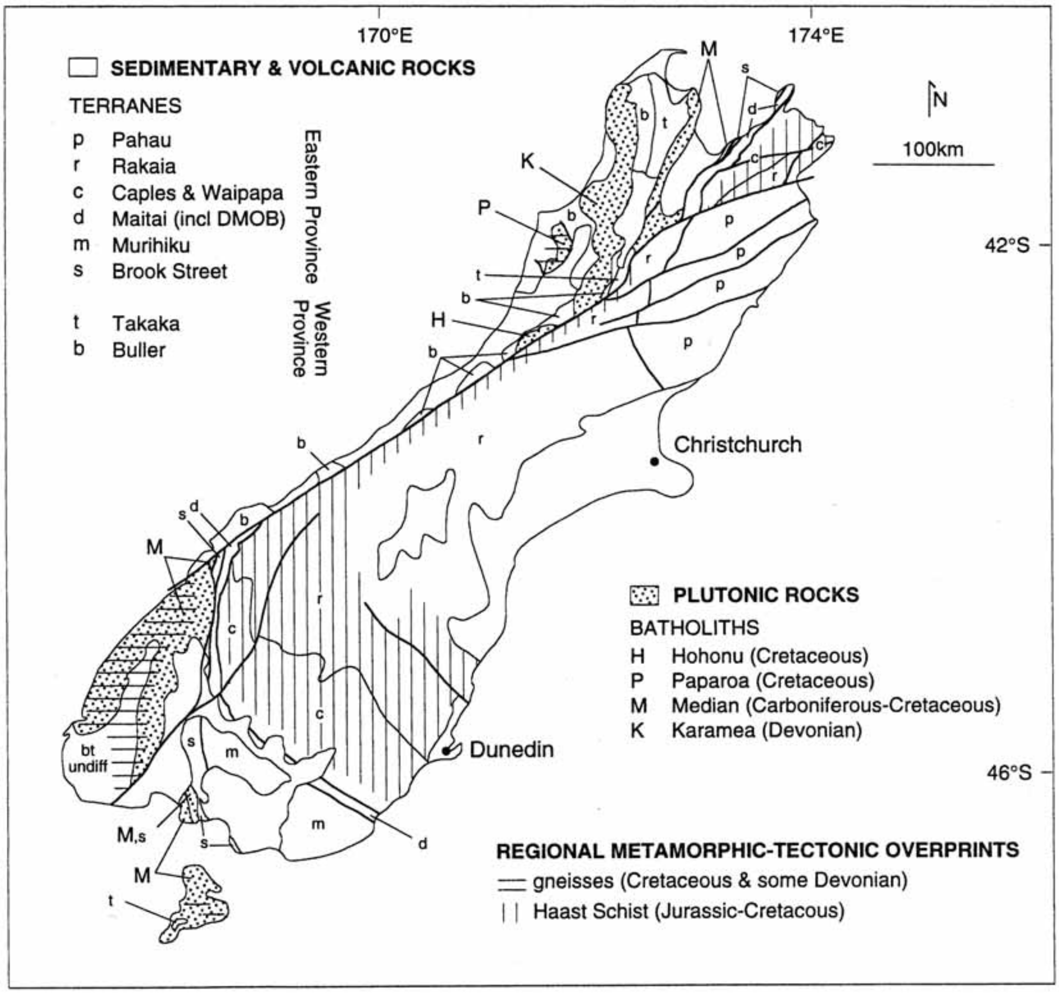


Figure 2: Simplified map of South Island basement, from Mortimer et al. (1999b).

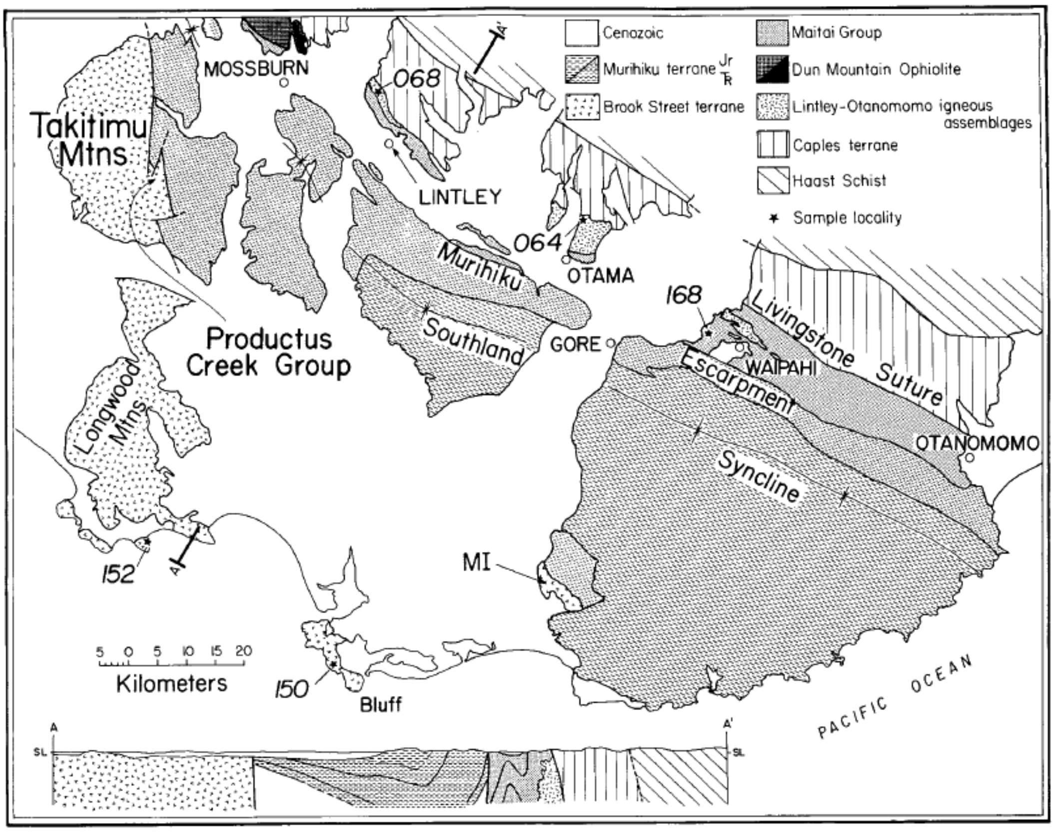


Figure 3: Simplified geologic map and cross section of Southland from Kimbrough et al. (1992). Zircon U-Pb ages reported by these authors from numbered localities are as follows: 064 Otama albite granite, 280 Ma; 068 Lintley granodiorite, 280 Ma; 150 Greenhills gabbronorite, 265 Ma; 152 Oraka Point granite, 260 Ma (revised to 247 Ma in Kimbrough et al., 1994); and 168 granite clast in Maitai Group conglomerate, 265 Ma.

After crossing the Clutha River at Balclutha, we will pass over the Livingstone Fault and into the Maitai Terrane (Fig. 3). The Lintley-Otama-Otanomomo complex is a distinctive, albeit poorly exposed basal component of the Maitai Terrane in Southland. It comprises 280 Ma (Early Permian) Na-metasomatised mafic to felsic igneous rocks which are coeval with plagiogranites in the correlative Dun Mountain Ophiolite Belt (Kimbrough et al., 1992). The upper portions of the Maitai contains clasts of ankaramite, a distinctive mafic volcanic rock of the Brook Street Terrane, and granite of similar age to the Median Batholith.

The escarpment forming the steep north limb of the asymmetric Southland Syncline is clearly visible on the left side of the road from Clinton to Gore (the somewhat prematurely designated “presidential highway”). This marks the northern edge of the Murihiku Terrane which contains Late Permian to Late Jurassic marine and non-marine volcaniclastic sandstones and mudstones metamorphosed to zeolite facies. Rocks of the Murihiku Terrane have well preserved bedding and relatively abundant fossils in strong contrast to the Rakaia and Caples Terranes. They are generally considered to represent deposition in a long-lived fore-arc basin and may have included detritus from volcanic equivalents of the Median Batholith.

The Murihiku-Brook Street Terrane boundary is covered by Cenozoic deposits in the vicinity of Invercargill. The Brook Street Terrane comprises submarine and subaerial basaltic lavas and volcaniclastic rocks of Permian age, although recently reported detrital zircon dates may extend this age range to Middle Jurassic (Adams et al, 2002). In the Takitimu Mountains (Fig. 3), 14 km of strata are exposed, but only 6-7 km are present along the Southland coast where it is intruded by younger plutonic rocks (Mortimer et al., 2002).

BLUFF PENINSULA

The earliest significant research on rocks of the Bluff Peninsula was that of Service (1937). The topographic highs on the Bluff Peninsula represent a series of resistant plutonic bodies intruded into Early Permian volcanogenic sediments of the Brook Street Terrane (Fig. 4). The sediments are particularly well exposed on the foreshore between Bluff Harbour and Stirling Point and along Mokomoko Inlet. They consist of well bedded volcanogenic sediments ranging from conglomerate/breccia to very fine sandstone/mudstone which have been regionally metamorphosed to greenschist facies. The original rock type was primarily andesitic in composition as judged from the larger clasts with affinities to intra-ocean island arc volcanics. Calcareous horizons form a minor component, occurring as both thin beds and concretions. Fossils are very rare but include gastropods and corals of Late Permian age (Mossman and Force (1969).

Greenschist facies regional metamorphism was locally overprinted by hornblende to pyroxene hornfels facies contact metamorphism during intrusion. Shelley (1979) records a reorientation of feldspars in the metasediments due to recrystallisation during contact metamorphism. Metasomatic interchange along the contacts between calcareous and andesitic sediments has resulted in the development of a variety of calcsilicate minerals including garnet, diopside, epidote, titanite and wollastonite.

The igneous intrusions range from gabbro to diorite with some late felsic pegmatites. They extend on a NW-SE axis, approximately parallel to the margins of the Brook Street Terrane (Fig 4). The largest is the Greenhills Complex, a 14km^2 layered dunite-wehrlite (olivine clinopyroxeneite)-gabbro intrusion with low-K island arc tholeiite or ankaramitic affinities.

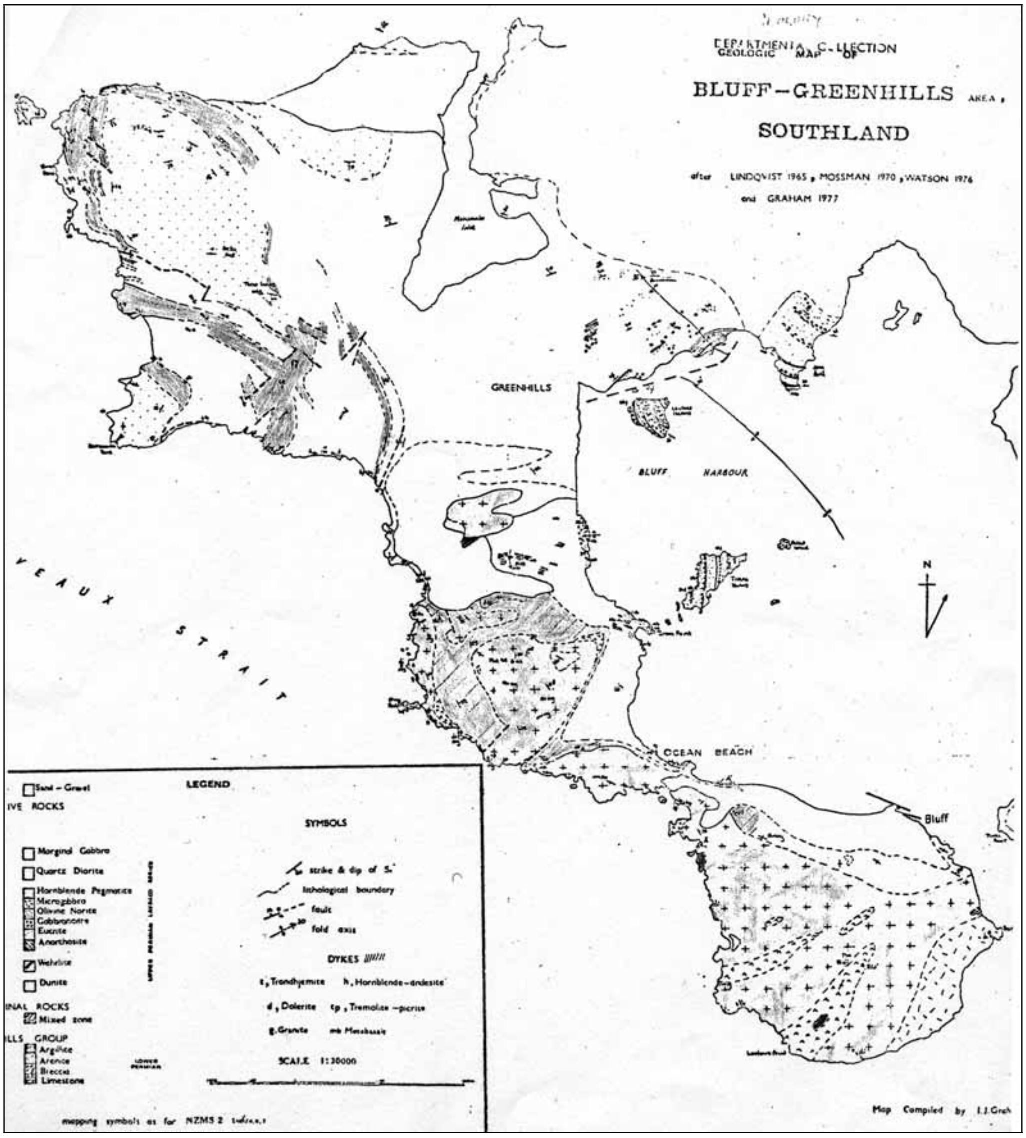


Figure 4: Geological map of the Bluff Peninsula from Graham (1977).

Mossman (1973) quotes hornblende K-Ar ages of 246 ± 10 Ma for gabbroic rock at Barracouta Point and 247 ± 10 Ma for a hornblende gabbro dike at S181/282836 as well as a biotite Rb-Sr age of 245 ± 7 Ma for pegmatitic granite intruding norite at Bluff (all uncorrected for modern decay constants). Kimbrough et al. (1992) obtained a conventional zircon U-Pb age of 265 Ma for a hornblende gabbronorite "closely associated with the Greenhills Complex" at S182/301805. Price et al. (2002) obtained a SHRIMP zircon U-Pb age of 259 ± 4 Ma for quartz diorite from the Flat Hill complex which lies halfway between the Bluff and Greenhills intrusive centers.

Field stops will be selected from the following list on the basis of time, tide and weather conditions.

Stop 1-1: Bluff Hill Lookout **E47/533896**

If the weather is favourable, this is a good vantage point to view the overall geological setting. Rock exposed at the lookout is Bluff gabbro. The northern coast of Stewart Island is to the southwest with its highest point Mt. Anglem, Ruapuke Island is to the southeast, and the long beach to the northwest is Oreti Beach, once the site of motorcycle speed record attempts. To the northeast is the Bluff aluminium smelter, refining Gladstone alumina derived from Weipa bauxite, and the low area further inland is the site of the Kapuka (Ashers-Waituna) coalfield with 1180 million tones reserves indicated. The mine envisaged would produce 12.1 million tones per annum for 30 years. Alluvial gold and platinum has been won from the beaches due east of the smelter and probably were sourced from the Waiau river area.

Stop 1-2: Stirling Point **E47/544895**

Stirling Point is the southern terminus of State Hwy 1 and location of the famous signpost.

Good exposure of the Bluff gabbro in the tidal zone. The rock is a medium grained noritic gabbro cut by irregular dikes of coarse grained leucogabbro which are in turn cut by fine grained basaltic dikes.

The best exposure of this rock was in Bluff itself where it was worked both as a building stone and for use in monumental masonry. The site is now the local (almost completely filled) rubbish tip. The gabbro is present as far east as the bridge connecting the peninsula to the harbour (manmade) island. A massive gabbro core, drilled during the preparation of the foundations for the bridge, is preserved on the harbour side of the bridge but is deteriorating rapidly as its pyrite content oxidizes. A small outcrop of Oligocene beach deposit (not visited) is preserved along the coastal track west from Stirling Point.

Stop 1-3: Foreshore in vicinity of War Memorial **E47/537905**

The rocks in the contact aureole, the Foreshore Group, are Early Permian volcanogenic sediments ranging from original fine grained tuffs to breccias and conglomerates with occasional calcareous horizons and concretions. Dips are steep compared with those at some distance from the intrusion (compare Omaui Road quarry at Stop 1-4) reflecting the forceful nature of the intrusive process.

Calcareous concretions are well exposed and contain a wide variety of calc-silicates (Service 1937). The adjacent Bluff gabbro has raised the metamorphic grade to hornblende hornfels facies (rarely pyroxene hornfels facies). Fig. 5 from Mossman (1973) illustrates the mineral assemblages. The metasediments are intruded by a variety of mafic dikes, both concordant and cross cutting.

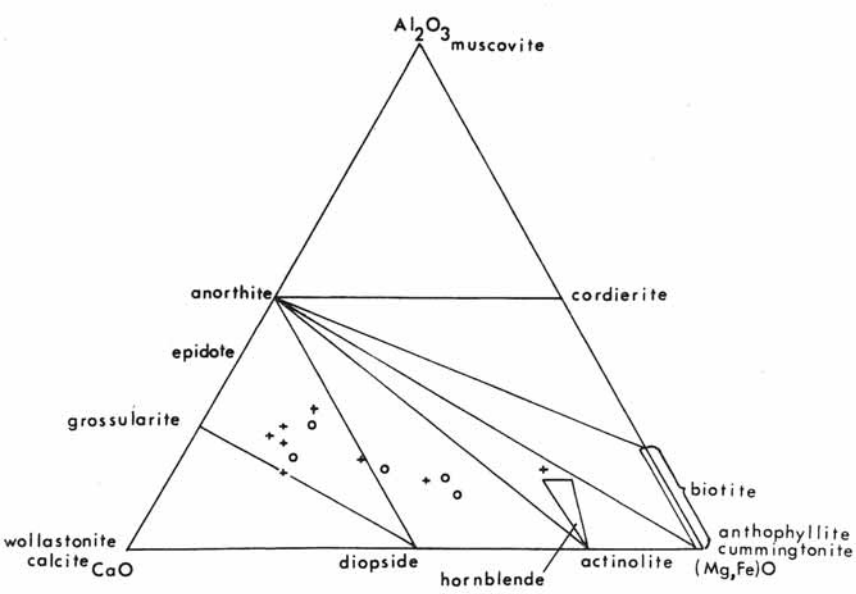


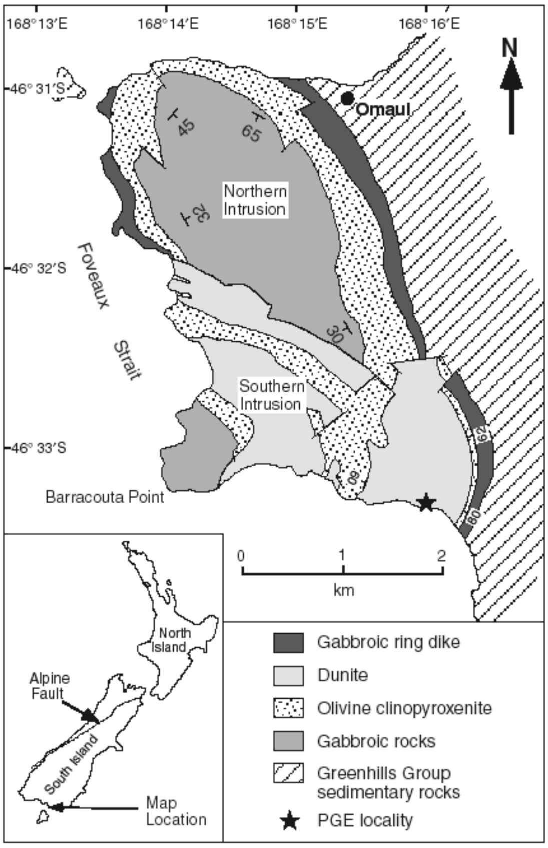
Figure 5: ACF diagram for hornblende-hornfels facies for rocks with excess SiO_2 and K_2O showing mineral assemblages and modes in samples of metasediments of the Greenhills (+) and Foreshore (o) Groups, from Mossman (1973).

Stop 1-4 Omaui Road quarry E47/489964

Fresh exposure of massive volcanogenic sandstones and siltstones of the Greenhills Group. Many of the blocks scattered about the entrance to the quarry show evidence of deposition from turbidity currents. Samples from this quarry have an epsilon Nd initial value of +7.5 (Frost and Coombs, 1989) indicating a depleted mantle source with no evidence of continental input. Quarrying ceased when it became too difficult to break up the large blocks. Similar lithologies just to the east on the coast of Collyers Island have been used by Maori as a source of artefact material.

GREENHILLS LAYERED MAFIC-ULTRAMAFIC COMPLEX

The layered ultramafic-mafic intrusion 14 km^2 is the largest and best exposed of all the plutonic bodies in the southern section of the Brook Street Terrane. It consists of two basin shaped bodies dominated by similar suites of cumulate rocks. Mapped by Mossman (1973) as a single intrusion, Spandler et al. (2003) believe there may be two separate lobes with caparable histories (Fig. 6). The base of the intrusion is not exposed and the sequence is dunite, olivine clinopyroxenite, and gabbro (Fig. 7), reflecting the sequential crystallisation and settling of olivine, olivine plus clinopyroxene, then olivine plus clinopyroxene plus plagioclase. Textures are predominantly adcumulate. Meter long disrupted mineral layering and graded bedding are seen only in the gabbro unit. An enigmatic gabbroic ringdyke forms the outer margin of the complex. Numerous dykes cut the complex, including a suite of ankaramites investigated by Mossman et al. (2000) and Spandler et al. (2000, 2003) (Fig. 8).



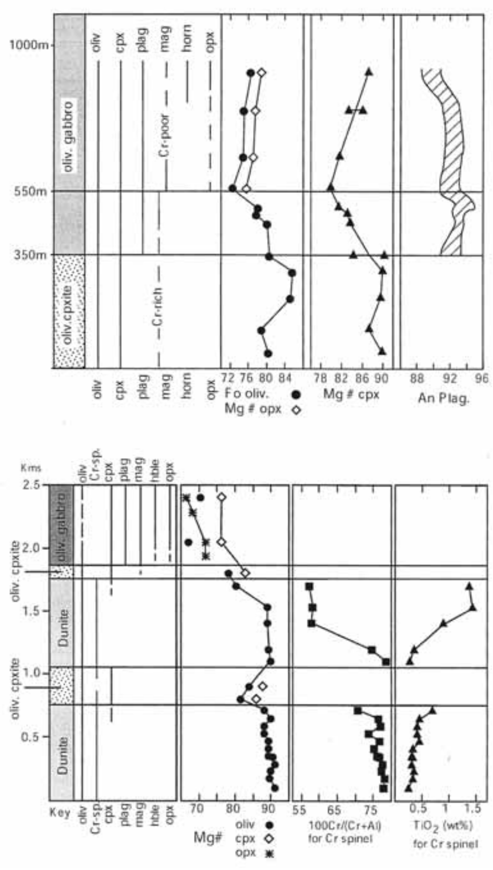


Figure 6: Geologic map of Greenhills Complex, from Spandler et al. (2000).

Figure 7: Cumulate mineral chemistry for the northern (top) and southern (bottom) lobes of the Greenhill Complex, from Spandler et al. (2003).

There are good coastal exposures although much is tide dependant. The dunite has been extensively quarried initially for addition to superphosphate fertilizer to prevent caking and provide Mg as a nutrient suppliment. This was abandoned with the discovery of asbestiform fibres in some quarries. One of the primary uses of the dunite at the present time is for road metal, since the traditional material, fluvial quartz gravels, has lost favour with the local governing bodies. Two localities will be visited, one on the south and one on the north coast, both illustrating sections through the margins of the intrusion.

Stop 1-5: South coast section of southern lobe of Greenhills Complex

There are excellent exposures of dunite on the southern shore with no obvious macroscopic variation (Fig. 6). No base to the dunite has been seen. Minor stringers of chromite, some platinum bearing, are very rare. Towards the eastern contact, the dunite is succeeded by coarse olivine clinopyroxenite which is in turn in contact with the marginal gabbro and the metasediments.

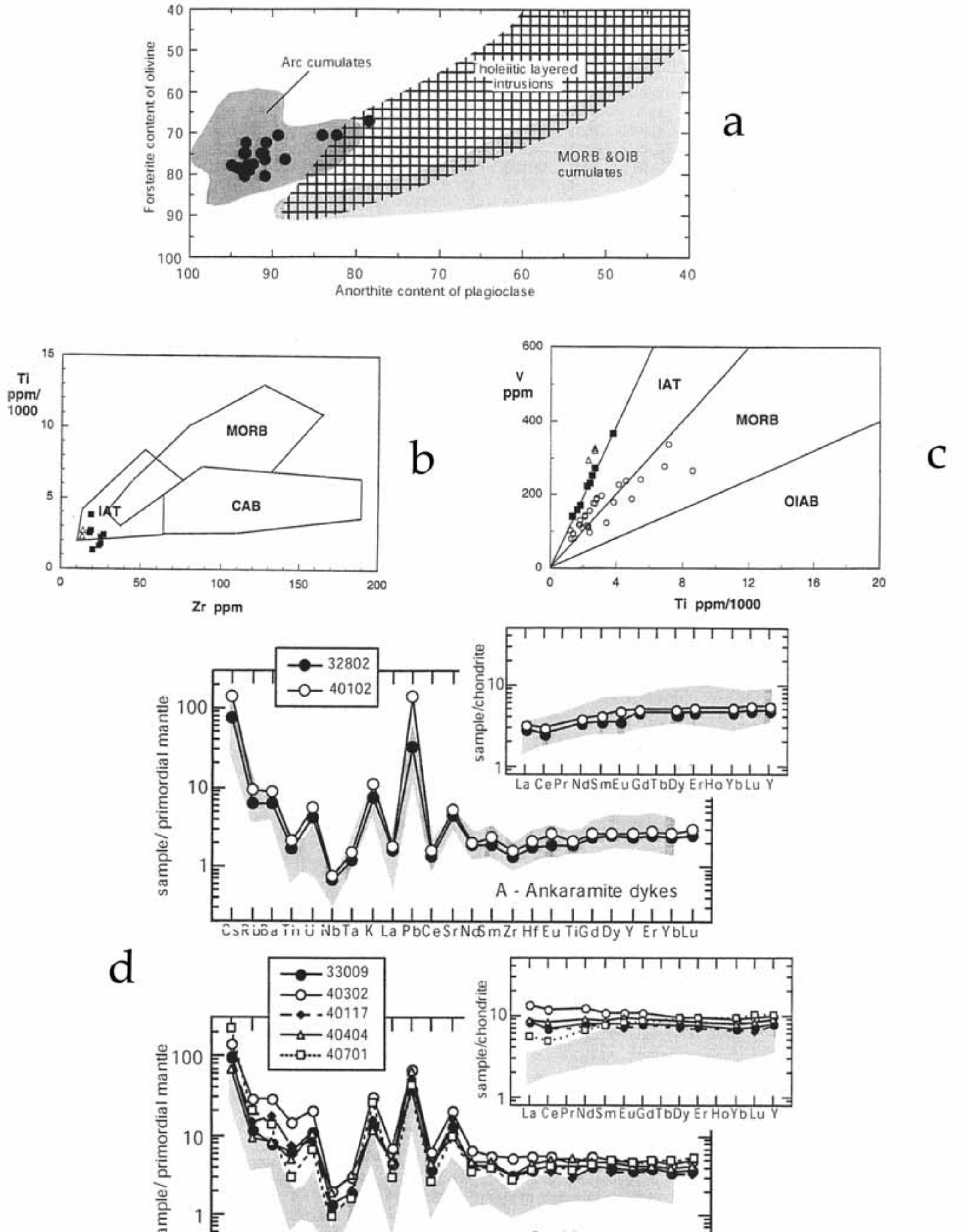


Figure 8. Mineral chemistry and whole rock trace element variation diagrams for Greenhills Complex showing island arc tholeiite and ankaramitic affinites, (a) and (d) from Spandler et al. (2003), (b) and (c) from Mossman et al. (2000). Shaded fields in (d) indicate values for low-K island arc tholeiites.

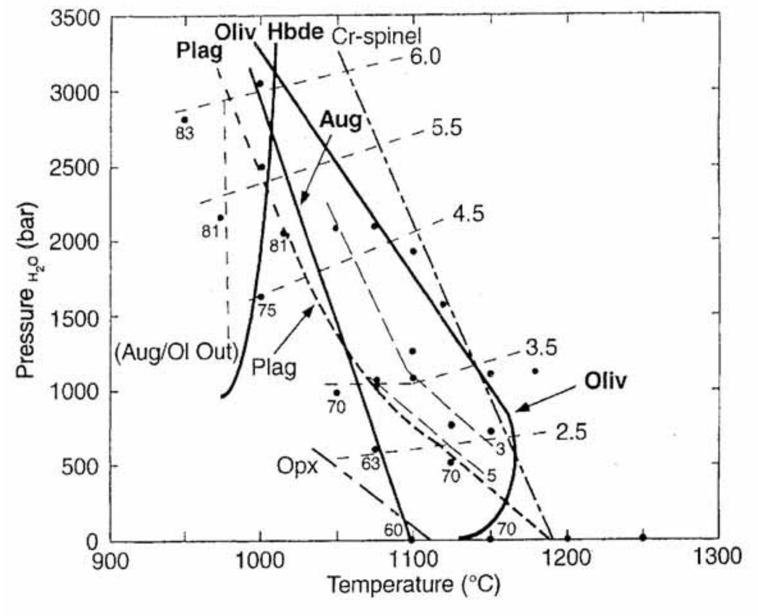


Figure 9: Results of water-saturated melting experiments on basaltic andesite illustrating the strong effect that high water content has on suppressing plagioclase crystallisation and extending the crystallisation of olivine and, to a lesser extent, clinopyroxene, from Moore and Carmichael (1998). Values next to positively sloped dashed lines are % H_2O in melt.

Stop 1-6: North coast section of northern lobe of Greenhills Complex

We will make a traverse from the Greenhills Group metasediments through the marginal gabbro and into the olivine clinopyroxenite (Fig. 6). The country rock metasediments are finegrained volcaniclastic sediments of andesitic composition with occasional thin calcareous and quartzitic horizons. Metamorphic grade increase markedly westward as the contact is approached and brown hornblende, diopside and garnet become increasingly common. The contact is difficult to locate due to the increasing metamorphism, and the development of partial fusion veins. It has been suggested that the noritic marginal gabbro may be partially remobilized pyroxene hornfels (Thayer in Mossman 1973). The succeeding olivine clinopyroxenite (wehrlite of Mossman) in this section is often very coarse grained, and contains a marker horizon mapped by Mossman as “poikilitic wehrlite”. It occurs in several localities near the base of the olivine clinopyroxenite and has a distinctive texture consisting of large oikocrysts of diopside containing numerous (≤2000) tiny olivine crystals.

If time and tide permit we may walk further westward to view fallen blocks of the gabbro containing modal layering and graded bedding.

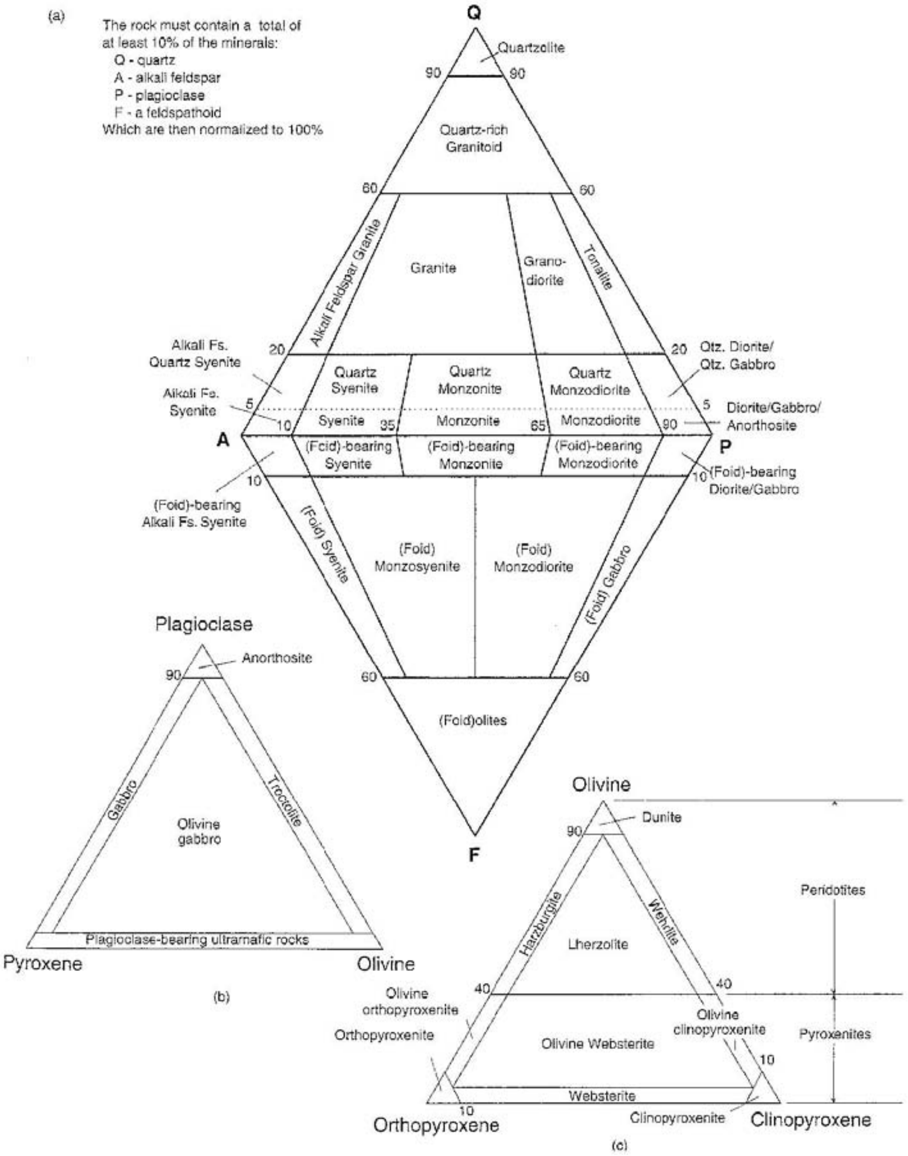
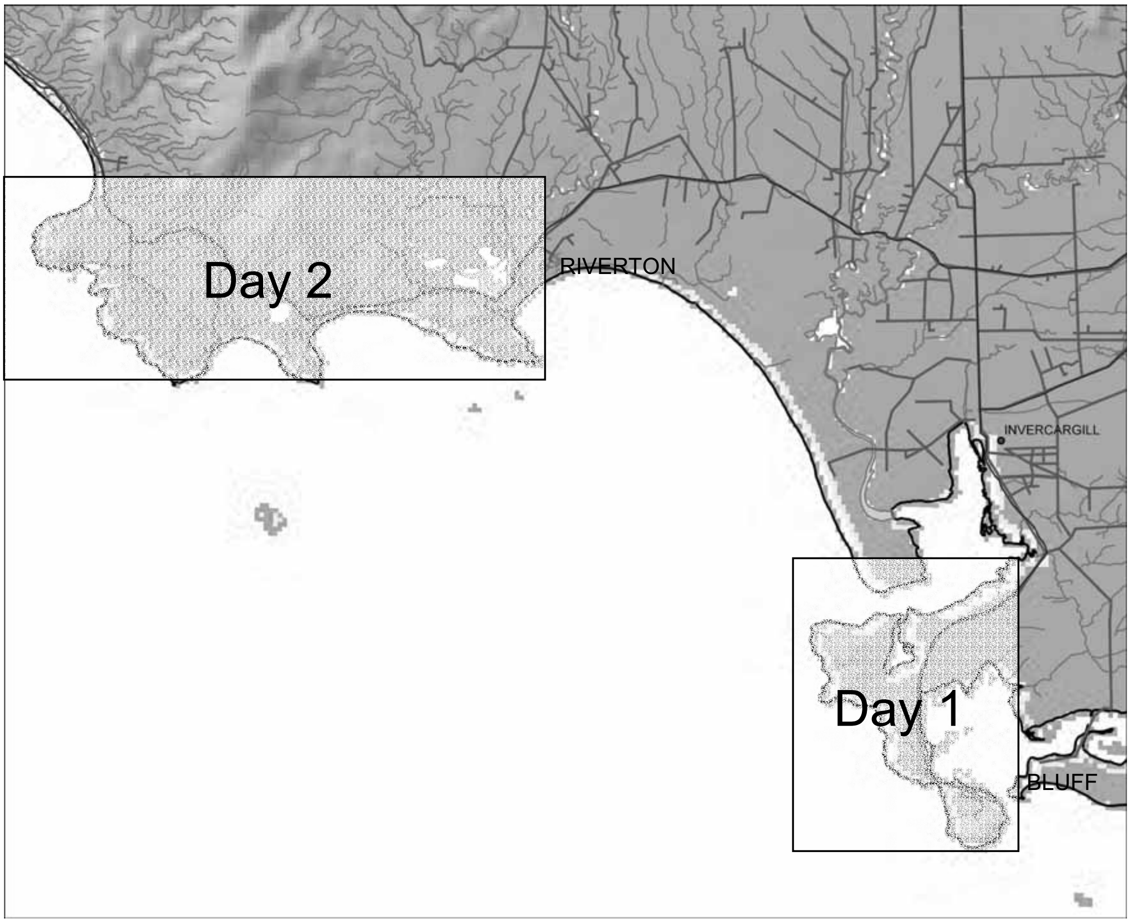


Figure 10: IUGS modal classification scheme for phaneritic (a) granitoid, (b) gabbroic, and (c) ultramafic igneous rocks.



DAY 2: HOWELLS POINT TO PAHIA POINT

Drive north to Invercargill then take State Hwy 99 to Riverton. Cross Riverton bridge, turn left at west end and follow signs to Riverton Rocks/Howells Point. Colac Bay tide is high at 1150hrs, low at 1800hrs; Kawakaputa Bay tide is high at 1110hrs, low at 1720hrs.

Background

The Longwoods Range comprises intrusive igneous rocks ranging in composition from ultramafic cumulates to granites (Price and Sinton, 1978). The inland ranges are heavily forested and rocks are poorly exposed, but exposures are excellent along the coastal section between Oraka Point and Pahia Point and it is on these exposures that the excursion is focused (Fig. 11).

Challis and Lauder (1977) included these rocks within the larger Longwoods Complex and, together with Coombs et al. (1976) and Price and Sinton (1978), considered them part of the Brook Street Terrane. Kimbrough et al. (1993) interpreted the southwestern part of the Longwood Complex as belonging to the redefined Median Tectonic Zone at least in part on the basis of zircon U-Pb ages. To the east, the Complex is in contact with rocks correlated with the Takitimu Group of the Brook Street Terrane and earlier work suggested that this was tectonic in character. Mortimer et al. (1999a) considered the rocks to represent the eastern side of the Median Batholith and described intrusive contacts with rocks of the adjacent Takitimu Group.

Geochronological information for the southern coastal Longwoods is summarised in Figure 12. Mortimer et al. (1999a) compiled geochronological data for Longwoods rocks and used this information to distinguish two distinct suites of differing age; an eastern Permian aged and dominantly gabbroic suite interpreted to be part of the Brook Street intraoceanic arc and a western Middle Triassic to Early Jurassic suite containing rocks ranging from ultramafic compositions through gabbros and diorites to tonalites. These age distinctions have been confirmed by new SHRIMP zircon data (Price et al., 2002) and by Rb/Sr geochronology (Fig. 12). Zircons from a gabbro from Oraka Point on the eastern end of the coastal section give an age of 245.0±4.3 Ma and show virtually no evidence of inheritance. Zircons from rocks to the west show more variability with some indications of inheritance and emplacement ages ranging from 203 to 227 Ma. A leucograbbro from Pahia Point yields a zircon population indicating an emplacement age of 142.4±2.3 Ma, similar to ages obtained from the Anglem complex on Stewart Island (Kimborough et al., 1994).

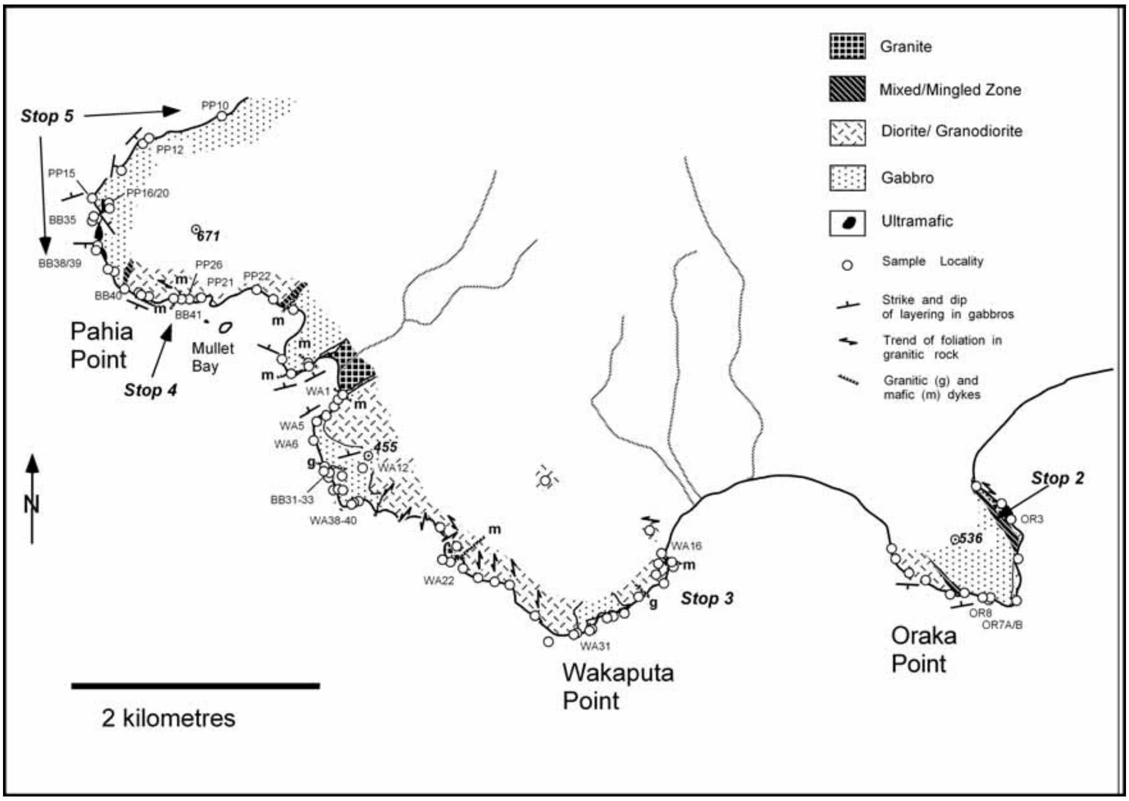


Figure 11: Geological map of southern Longwoods between Oraka and Pahia Points.

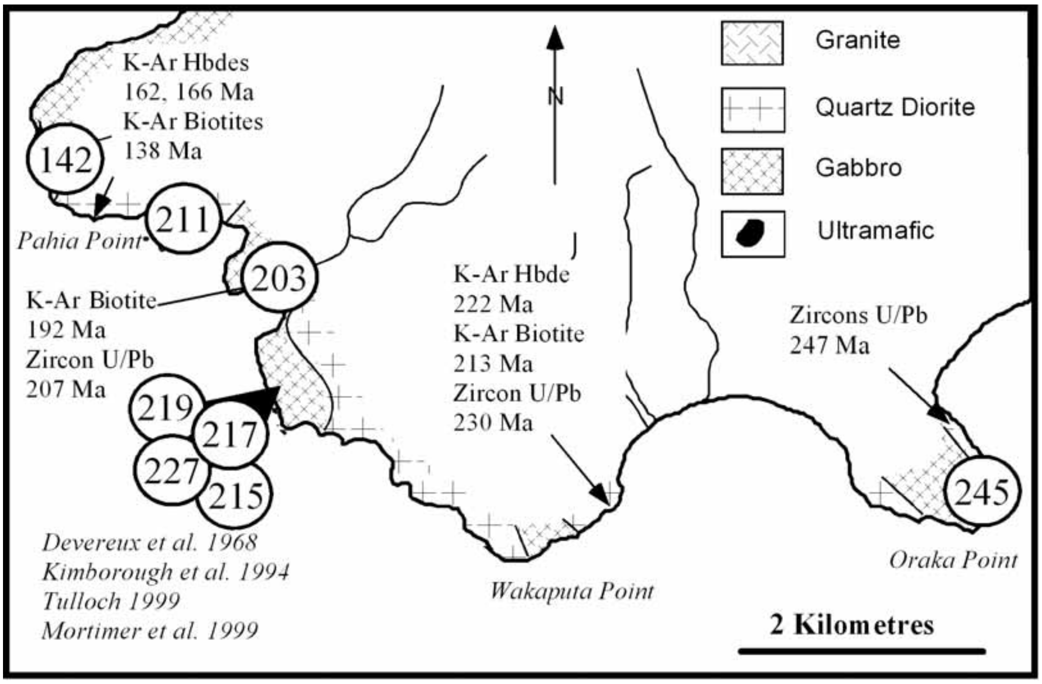


Figure 12: Geochronology for the Oraka-Pahia coastal section.

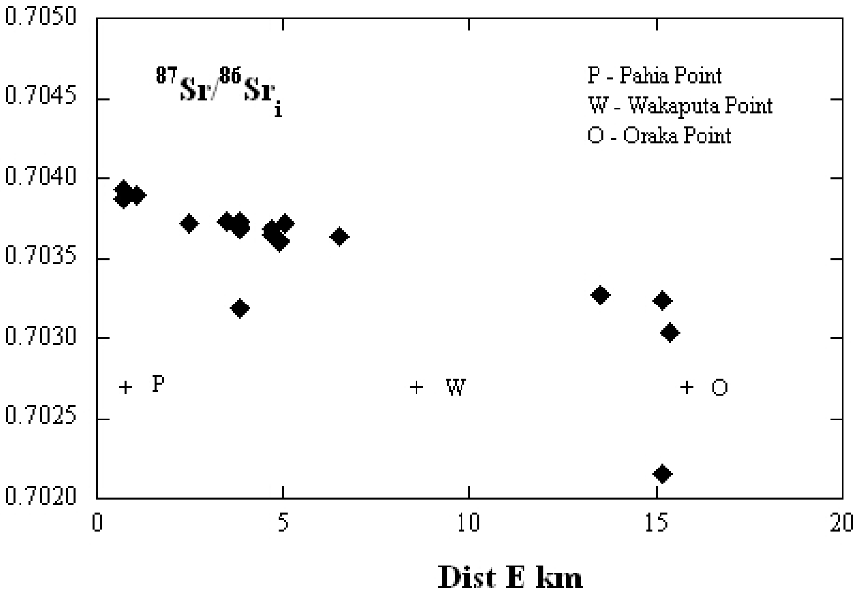


Figure 13: Strontium isotopic traverse across the southern Longwoods showing calculated $^{87}Sr/^{86}Sr$ initial ratios for intrusive rocks.

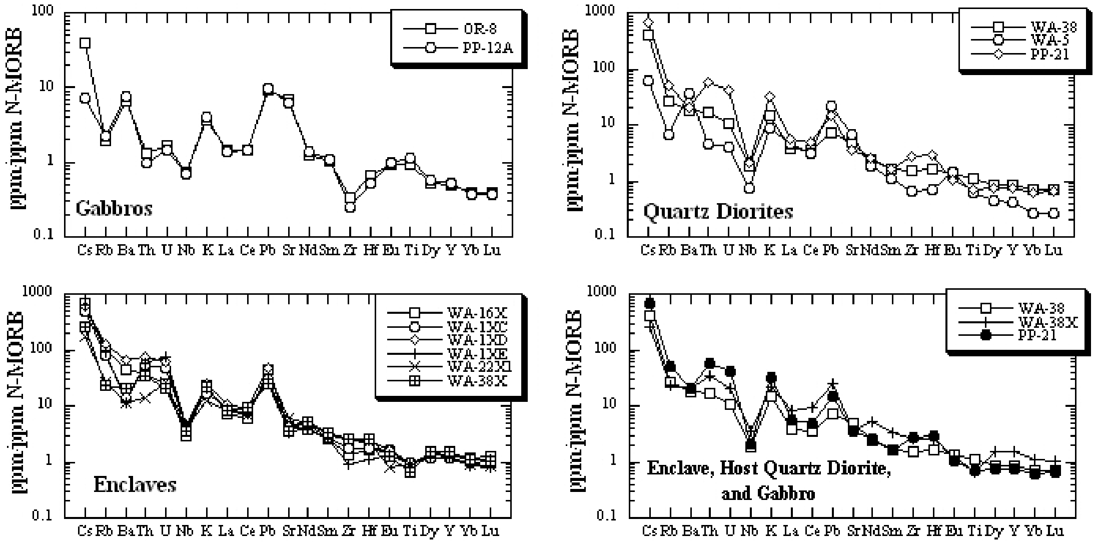


Figure 14: Normalised abundance diagrams for southern Longwoods rocks. Normalising values are from Sun and McDonough (1989).

Rb/Sr isotopic ratios for Longwoods intrusives vary systematically from east to west across the Longwood coast (Fig. 13). Initial $^{87}Sr/^{86}Sr$ isotopic ratios (Sr_i) are significantly lower for Oraka Point intrusives of the Brook Street Terrane than is the case for the Median Batholith intrusives to the west. From Wakaputa Point to Pahia Point the Sr_i values become progressively higher. These data, along with zircon inheritance patterns could be used to argue that the geochemical patterns are related to the progressive development of the Mesozoic crust and increasing involvement of crustal recycling in the younger suites.

Longwoods rocks of both the Brook Street Terrane and the Median Batholith show trace element characteristics typical of subduction-related magmas (Fig. 14). These include: relative enrichment in large ion lithophile elements such as Rb, Ba, and K; depletion of Nb relative to K and La; and enrichment of Pb relative to Ce.

Compositionally, rocks range from gabbros and ultramafic cumulates through diorites and tonalities to granites (Table 1). Dykes are abundant within both the Brook Street and Median Batholith parts of the southern Longwoods and many of these are composite with compositions ranging from dolerite through andesite to dacite. Within some dykes, pillow- like mafic material is contained within an envelope of more felsic rock and the margins of the blobs commonly show what appear to be chilled margins. Intermediate compositions within these dykes have compositions consistent with a derivation by mixing between mafic and felsic components. Dykes of this type could represent the feeder conduits for andesitic volcanoes that once overlay the intrusive complex. The felsic component in the dykes could be either a residual evolved magma left from an earlier recharge event or it may represent melt derived by anatexis of the host quartz diorite.

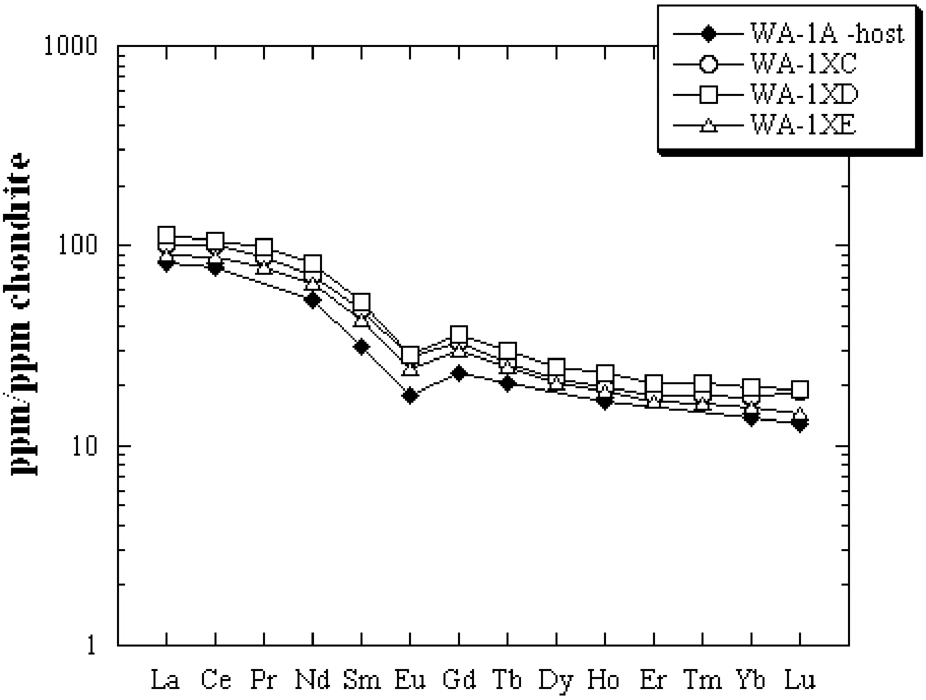


Figure 15: Chondrite normalised rare earth element plot for host diorite and mafic enclaves from coastal Longwoods north of Ruahine Hill. Normalising values are from Sun and McDonough (1989).

Dioritic rocks in the Median Batholith segment of the Longwoods contain abundant mafic enclaves and these are most common in complex zones marking the boundaries with gabbroic rocks. Enclaves of this type are commonly argued to represent mafic magma blobs that have mingled or mixed with the host (eg. Didier, 1973; Vernon et al., 1988). Enclaves from the Longwoods quartz diorites have very distinctive and uniform compositions (Fig. 14). They are enriched in rare earth elements (REE) relative to their hosts and the chondrite normalised REE patterns are characterised by depletion of the light relative to intermediate REE (Fig. 15). They all show distinctive Eu depletions and they are all relatively depleted in Ni compared to other rocks with similar SiO_2 contents (Table 1). They appear to be derived by crystal fractionation from magmas represented by the gabbroic rocks of the complex (Price and Sinton, 1978) and they were probably incorporated when quartz diorite magmas were intruded into and disrupted evolving basaltic magma chambers. If the quartz diorites are mixed magmas, then the enclaves cannot represent the mafic component of this mixing trajectory.

Table 1. Representative whole rock analyses - southern Longwoods Complex.

	1	2	3	4	5	6	7	8	9	10	11
	BB42A Basalt	OR7A Gabbro	OR3 Diorite	OR7B Granite	WA1A Granod.	WA1Xc Enclave	BB41A Dyke Felsic	BB41B Dyke Mafic	BB41E Host Diorite	PP5A Gabbro	BB34A U/mafic
SiO2	49.06	47.99	58.39	76.02	64.93	53.65	64.66	55.34	60.62	53.28	42.41
TiO2	0.95	1.15	1.25	0.21	0.62	1.27	0.48	0.88	0.87	1.37	0.29
Al2O3	17.10	18.86	15.48	12.41	16.90	18.20	17.58	17.72	17.11	18.62	8.03
Fe2O3	4.21	3.75	2.24	0.57	1.80	3.56	1.97	2.60	2.50	2.15	4.05
FeO	4.74	6.21	5.27	0.81	2.22	4.62	1.99	4.41	3.21	5.64	10.68
MnO	0.15	0.20	0.15	0.03	0.09	0.23	0.06	0.12	0.09	0.12	0.20
MgO	5.59	7.26	3.14	0.42	1.43	3.56	1.75	4.81	3.03	4.48	23.59
CaO	10.97	10.59	5.75	1.01	3.74	6.81	4.04	6.77	5.38	8.12	7.88
Na2O	2.68	3.08	4.13	2.92	4.87	5.31	2.94	2.72	2.92	4.35	0.57
K2O	0.27	0.18	2.24	5.11	2.55	1.24	2.33	1.72	1.86	0.75	0.10
P2O5	0.15	0.22	0.34	0.01	0.18	0.22	0.26	0.27	0.27	0.35	0.04
H2O+	2.98	1.18	1.33	0.53	0.58	0.86	0.82	1.57	0.90	0.56	1.12
H2O-	0.28						0.10	0.14	0.13		0.13
CO2	0.09	0.27	0.04	0.06	0.07	0.14	0.06	0.07	0.06	0.15	0.50
S	0.03						0.02	0.02	0.02		0.02
	99.25	100.94	99.75	100.11	99.98	99.67	99.06	99.16	98.97	99.94	99.61
O=S	0.02						0.01	0.01	0.01		0.01
Total	99.23	100.94	99.75	100.11	99.98	99.67	99.05	99.15	98.96	99.94	99.60
Ba	23	63	240	561	591	157	686	428	382	300	53
Rb	6	1	72	162	97	62	61	61	57	12	3
Sr	525	693	310	109	451	501	837	833	649	947	402
Pb	-	7	29	25	19	18	18	12	13	15	3
Th	-	0.6	6	22.8	7.6	8.3	4.6	2.2	5.7	0.8	2.4
U	-	0	1.2	3.2	1.6	1.3	1.3	0	0.5	0.3	-
Zr	86	32	343	149	229	121	176	110	175	74	34
Nb	2	1.4	6.8	1.6	6.3	8.7	2.9	3	5	3.6	1.7
Y	20	14	32	12	21	32	5	9	16	13	1
La	3	2	18	14	19	26	5	9	15	11	6
Ce	9	11	45	33	45	65	19	26	27	24	7
Sc	30	-	-	-	-	-	7	21	14	-	26
V	260	263	160	15	63	187	60	181	123	190	138
Cr	58	153	19	9	13	9	6	42	17	38	1601
Ni	45	63	14	5	5	9	14	46	21	-	583
Cu	85	70	180	9	13	64	9	71	15	-	17
Zn	75	96	109	24	66	133	63	88	82	-	122
Ga	58	20	19	13	21	24	6	42	17	-	10

Explanation: 1 = Howells Point; 2-4 = Oraka Point; 5-6 = N of Ruahine Hill; 7-8 = composite dyke W of Cosy Nook; 9 = host to composite dyke; 10-11 = Pahia Point.

Stop 2-1: Howells Point lookout

This stop provides an overview of the coastal section to the west. Pillow lavas of the Brook Street Terrane are exposed on the beach. These are low-K tholeiitic compositions typical of the Brook Street Terrane (Table 1, no. 1).

Stop 2-2: East side of Oraka Point

Exposures of the contact between gabbros and contemporaneously emplaced granite of the Brook Street Terrane. A sample of the granite yielded a conventional zircon U-Pb age of 247 ± 3 Ma (Kimbrough et al., 1994) and initial epsilon Nd of +6.8 (Mortimer et al., 1999a). Price et al. (2002) obtained a SHRIMP zircon U-Pb age of 245.0 ± 4.3 Ma for a sample of the gabbro and found no inheritance. The gabbros are similar compositionally to Howells Point dyke rocks and are low-K tholeiites (Table 1, no. 2). Mingling of magmas along the contact has produced hybrid lithologies with andesitic (dioritic) compositions (Table 1, no. 3).

Stop 2-3: Southwest end of Kawakaputa Bay

Take left turnoff from State Hwy 99 onto Wakaputa Rd and follow toward coast. Turn left onto Austin Rd and park near cabbage trees at the beach end, before the road turns up to a farm driveway.

The first exposures are of distinctive orange-weathering unit of quartz monzodiorite composition. As we walk south, mafic enclaves of various shapes become more abundant. By the point we reach a small slipway, the rock contains nearly 50% enclaves. They are hosted in quartz diorite which has a conventional zircon U-Pb age of 230 ± 2 Ma (Kimbrough et al. 1994) and an initial epsilon Nd of +4.8 (Mortimer et al. 1999a). Contacts between the enclave-free quartz monzodiorite and the enclave-bearing quartz diroite are not exposed.

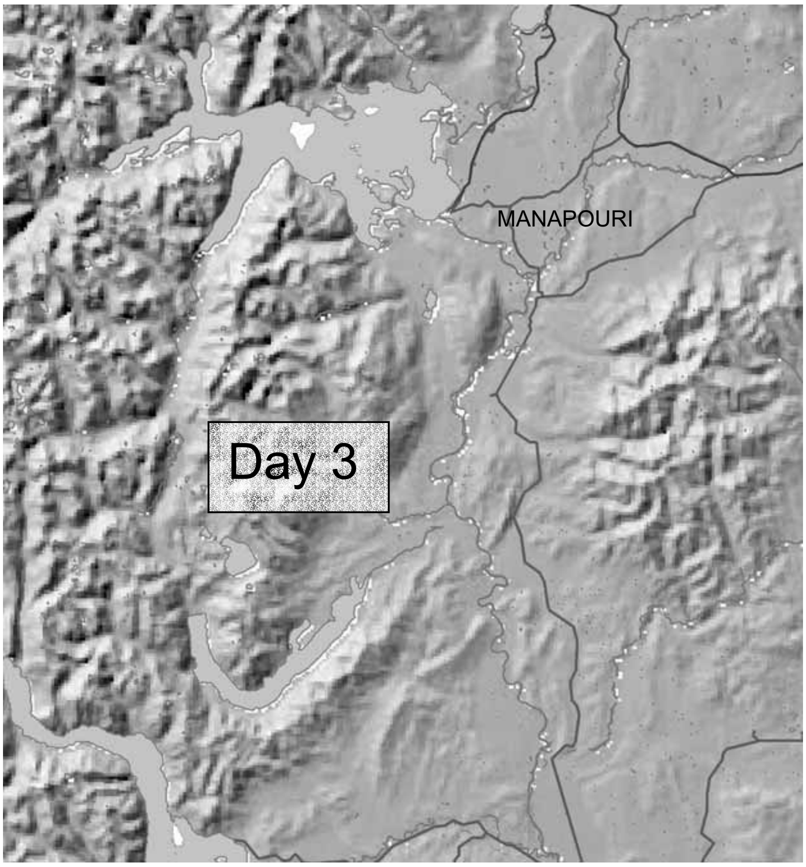
Many of the enclaves have “blobby” outlines, but others are quite angular. All exhibit a narrow range of major and trace element compositions. One interpretation is that the enclaves represent a dioritic (or more mafic) magma which intruded into a felsic and partially consolidated magma chamber. The diorite solidified to form dikes and plutonic “pillows”. Heating of the felsic magma during this process would have led to convective motion which disrupted the dikes and resulted in flow alignment of the enclaves. Trace element data preclude a simple mixing relation between the enclaves and the quartz monzodiorite to produce the host quartz diorite.

Stop 2-4: Cosy Nook

Composite dyke in quartz diorite. Diorites to the west of Cosy Nook are cut by several generations of more mafic dykes. Some of these dykes are composite with several different types being complexly mingled in single intrusions. Mafic material is disaggregated into pillow like bodies that have chilled margins and these pillows are surrounded by felsic material (Table 1, nos. 7-8). The components of composite dykes do not have a simple relationship to the rocks of the major intrusive units of the complex and they may represent the feeder conduits for andesitic volcanoes that once overlay the intrusive complex. The felsic material in some dykes could be either a residual evolved magma left from earlier recharge events or melt derived by anatexis of the host quartz diorite.

Stop 2-5: Pahia Point

A traverse along the coast through Pahia Point gabbros and diorites to exposures of cumulate gabbros.



DAY 3: EASTERN FIORDLAND

Drive west, then north on State Hwy 99 from Riverton through Tuatapere and Clifden. Take left turnoff to Lake Monowai about halfway to Manapouri. Follow the dirt road past turnoff to the Monowai power station and Borland Youth Lodge up to the Borland Saddle.

Background

The Western Province is composed of Lower Paleozoic paragneiss cut by Devonian and Carboniferous granitoids (Muir et al., 1998; Ireland and Gibson, 1998)(Fig. 16). Rocks within this province preserve a polyphase mid-Paleozoic history that includes low-P/high-T metamorphism followed by medium-P/high-T metamorphism. The main part of the Median Tectonic Zone or Median Batholith is a comparatively narrow belt of tectonically disrupted arc-related rocks with U-Pb zircon ages that mostly fall into two age groups: 247-195 Ma and 157-131 Ma (Kimbrough et al., 1994)(Fig. 17). This belt and the Western Province are intruded by stitching plutons of the Early Cretaceous (126-105 Ma) Western Fiordland Orthogneiss/Separation Point Suite (Kimbrough et al., 1994). Mafic dikes that intrude Lower Paleozoic host gneiss in the Western Province near Milford Sound suggest that the amalgamation of the Median Tectonic Zone with Gondwana may have occurred as early as ~136 Ma and probably by ~129 Ma (Hollis et al., 2003).

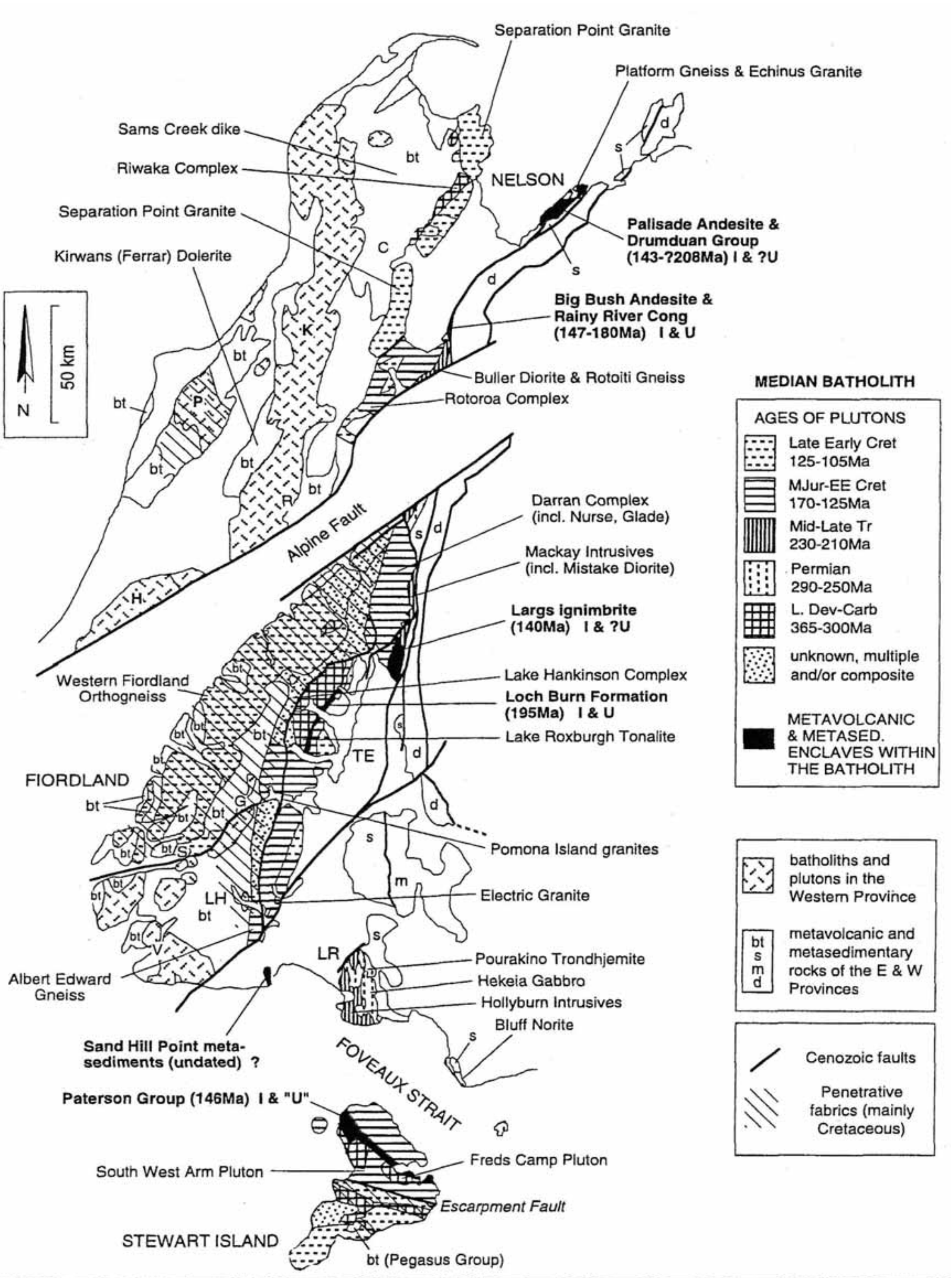


Figure 16. Simplified geologic map of the Median Batholith and adjacent rocks, South Island, from Mortimer et al. (1999b). Kimbrough et al. (1994) report conventional zircon U-Pb ages of 145 ± 12 Ma for a undeformed granite in Albert Edward Gneiss, 134 ± 2 Ma for the alkaline Electric Granite, and 155 ± 2 Ma for the Pomona Island Granite from the region north and south the Borland Road.

The Separation Point Suite is characterised by high Na, Al, Sr and low K and Y compositions that have been termed “adiakitic” (Muir et al., 1995). In easternmost Fiordland, the suite is dominated by tonalite, granodiorite, and granite (Tulloch and Rabone, 1993). In western Fiordland the suite includes gabbro, diorite and monzodiorite of the Western Fiordland Orthogneiss. Tulloch and Kimbrough (2003) have recently suggested that the high Na, Al, Sr and low Y (their HiSY type) characteristics of the Separation Point Suite represent partial melting of the base of older portions of the Median Batholith arc which were underthrust from the west during shallowing subduction.

By 108-105 Ma, extension affected parts of the Fiordland belt and other areas (Tulloch and Kimbrough, 1989). K-Ar ages of hornblende (Nathan et al., 2000) and U-Pb dates of apatite (Mattinson et al., 1986) suggest that granulites had cooled to 300-400°C by ~90 Ma. This last phase preceded inception of seafloor spreading in the Tasman Sea (~84 Ma) by ~15 Ma and was accompanied by the formation of extensional metamorphic core complexes elsewhere in New Zealand (Tulloch and Kimbrough, 1989).

Late Cretaceous extension and rifting associated with the breakup of Gondwana led to the opening of the Tasman Sea basin between Australia and New Zealand by ~84 Ma. By approximately 52 Ma, sea floor spreading along the central Tasman ridge system had ended and a new period of rifting initiated in the southwest Tasman Sea region south of New Zealand. Here, the Pacific-Australia plate boundary developed as a spreading center by at least 47-45 Ma (Sutherland et al., 2000). From 30 to 11 Ma, the spreading direction became progressively more oblique, and the boundary eventually evolved into a transform. Spreading ceased and oblique subduction initiated beneath the continent between 12 and 10 Ma. Later, clockwise rotation of the Euler pole resulted in strike-slip motion along most of the plate boundary, followed by transpression. Near the end of the Miocene (~6.4 Ma), a decrease in the obliquity of plate convergence resulted in an increase in the rate of convergence and the uplift of the Southern Alps (Walcott, 1998).

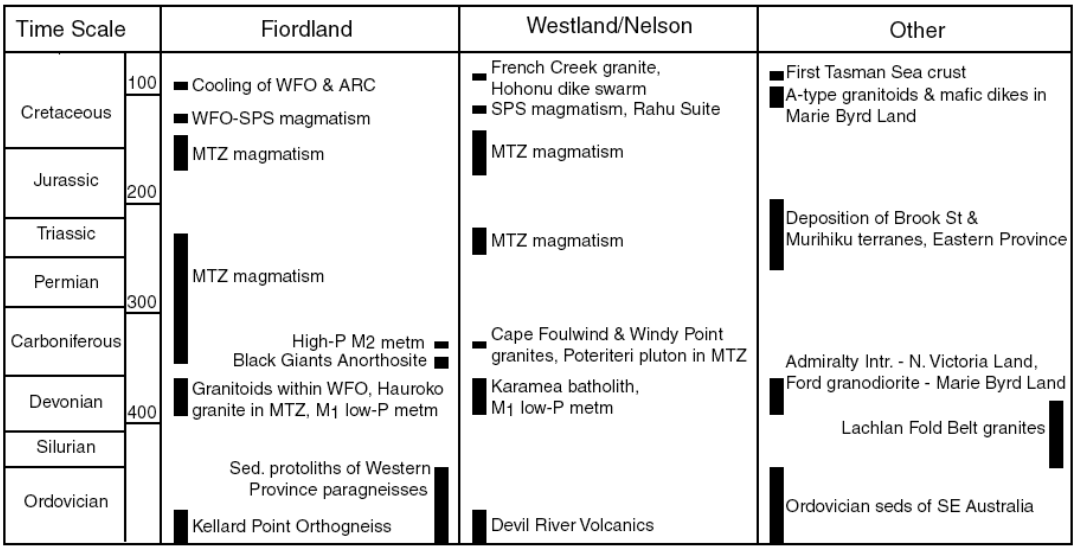


Figure 17. Geochronologic summary of Western Province of South Island, from Hollis et al. (2003).

Stop 3-1: Borland Saddle (for a short break from basement geology)

The view west from the Borland Saddle is of the headwaters of the Grebe Valley, which drains north to Lake Manapouri (Fig. 18). Out of sight to the south is Lake Monowai, a deep glacially scoured lake with, at present, no obvious major catchment source, although glacial features suggest ice movement from north to south (Fig 19). Between the Grebe River and Lake Monowai is a 45km^2 area (approximately 10km long by 5km wide), composed of bush-covered, hummocky mounds which rise over 500m above the valley floor, and in which are set many ponds, swampy areas and small lakes (the largest being Green Lake), several with no apparent outlet. Contrasting sharply with the glacially smoothed slopes of the ‘U’ shaped valley in which it occurs, the unmodified nature of the hummocky topography suggest formation occurred after the peak of the last glaciation.

The area of anomalous topography is part of the Green Lake Landslide (Hancox and Perrin 1994), a 27 km^3 volume of slide debris derived by collapse of a 10 km long segment of the alpine ridge of the Hunter Mountains by failure on a gently west-dipping shear zone. The present dip of the valley sides beneath Borland Saddle is thought to reflect the attitude of this failure plane. By comparing present-day features with estimated pre-slide topography, the slide debris is inferred to have travelled between 1.8 and 2.5 km laterally and 500-700 m vertically.

Figure 18: View west from ridge above Borland Saddle across north end of the Green Lake landslide toward central Fiordland, home of the Western Fiordland Orthogeniss.

When the Green Lake Landslide occurred, probably 12-13 ka, the glacier in the Monowai Valley must have retreated northwards towards present day Lake Manapouri, to a point about 4km north of Borland Saddle. The landslide is inferred to have truncated the proto-Lake Monowai, trapping the northern part of it behind an 800m high landslide dam, forming Lake Grebe. Eventually meltwater from the glacier filled Lake Grebe to a point where it overflowed south into Lake Monowai, cutting an overflow channel through blocks of slide debris. Radiocarbon dating of silts show the final infilling of the lake occurred 11000 to 11500 years ago. When the Monowai Glacier finally melted and retreated up tributary valleys to the west (Florence and Jaquiery Streams), Lake Grebe emptied by reversal of drainage into Lake Manapouri. Dating of peat deposits suggest the lake drained between 8.6 and 9 ka.

The Green Lake Landslide is the largest sub-aerial rock slide of its type on earth. Failure is believed to have been caused by a combination of factors:

- glacial oversteepening of the east side of the former Monowai Valley
- existence on the east valley wall of weak, sheared, hydrothermally altered gneiss, formed as part of the Mt Cuthbert Fault Zone
- reduction of slope stability within the shear zone through flooding of its toe by waters of proto-Lake Monowai
- final triggering of the landslide by strong ground motion associated with a large ($M \geq 7.5$) earthquake on the nearby plate boundary zone in western Fiordland.

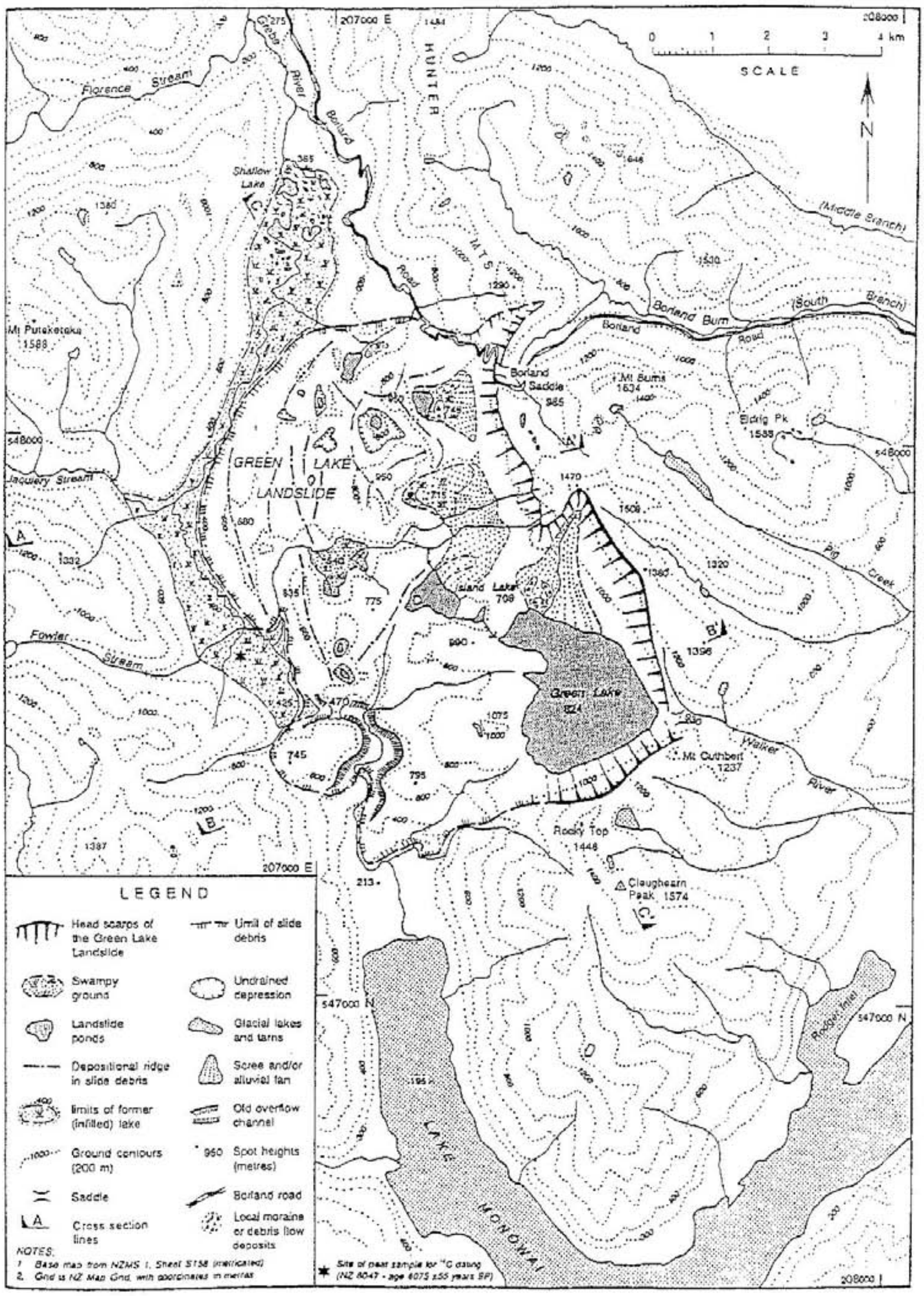


Figure 19. Geomorphological map of the Green Lake landslide and surrounding area, from Hancon and Perrin (1994).

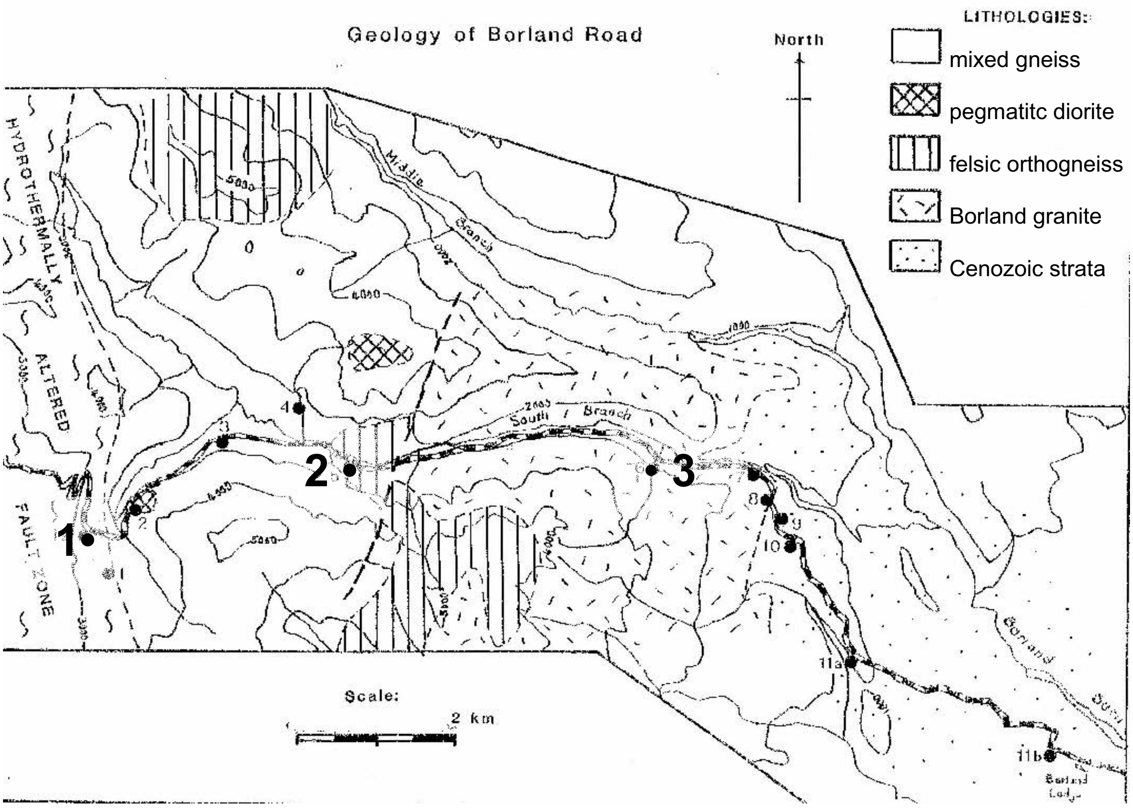


Figure 20. Preliminary geologic map of the Borland Road between lodge and saddle.

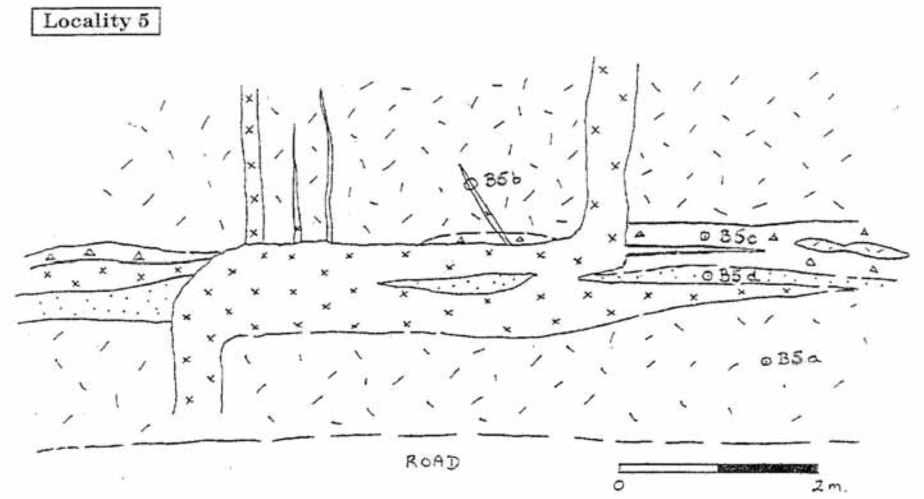


Figure 21. Geologic sketch of rock cut at stop 3-2. x = pegmatite, dashes = felsic orthogneiss, dots and open triangles = mixed gneiss.

Stop 3-2: Borland Road – felsic orthogneiss

Several generations of unfoliated granitic pegmatite intrude orthogneiss of granodiorite composition which in turn includes a possible "raft" of mixed gneiss (Fig. 21). The felsic orthogneiss contains abundant magmatic titanite as well as magnetite indicating it was quite oxidised. The abundance of pegmatite dikes increase to the east toward the inferred fault contact with the Borland Granite (Fig. 20). Some of the pegmatites contain garnet and magnetite.

Stop 3-3: Borland Road – Borland Granite

The age of the Borland Granite is unknown. However, Muir et al. (1998) have obtained SHRIMP zircon U-Pb ages for similar granitoids from Mt. Titiroa, 20 km to the north, and Cleughearn Peak, 20 km to the south. Comparison of major and trace element data from the three granites permit a "cheap and dirty" correlation of the Borland and Titiroa Granites. This would suggest the Borland Granite belongs to the Separation Point Suite.

Locality	Cleugheran Granite* South of Borland Rd	Borland Granite Locality 6	Titiroa Granite* North of Borland Rd
Age (Ma)	153.8 ± 2.3	?	120.9 ± 1.8
SiO2	74.19	72.31	72.96
TiO2	0.22	0.13	0.12
Al2O3	13.66	15.79	16.06
Fe2O3	1.85	1.15	1.08
MnO	0.06	0.03	0.05
MgO	0.45	0.30	0.27
CaO	1.60	1.98	1.92
Na2O	3.92	5.35	5.16
K2O	3.81	2.34	2.89
P2O5	0.06	0.06	0.06
LOI	0.40	0.33	-0.13
Total	100.21	99.76	100.44
Ga	13	16	16
Pb	26	28	26
Rb	115	48	71
Sr	202	716	630
Th	15	4	6
Y	9	2	5
V	21	17	19
Cr	<3	4	<3
Ni	4	3	3
Zn	29	34	35
Zr	82	76	53
Nb	7	6	5
Ba	800	1106	891

* data from Muir et al. (1998)

Borland to Dunedin

As we drive down the Borland Road, we hopefully will have spectacular views of steeply dipping Permian volcaniclastic strata of the Brook Street Terrane in the Takitimu Mountains to the east. On the return to Dunedin, we will drive around the north end of the Takatimus and into the Murihiku Terrane. From here to Lumsden, West Dome, the southern limit of the Dun Mountain Ophiolite Belt in the Maitai Terrane, is visible. Once in Gore, we will retrace our route back to Dunedin, stopping at the airport as needed.

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