Spilites, Serpentinites and Associated Rocks of the Mossburn District, Southland

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Contents

INTRODUCTION AND ACKNOWLEDGMENTS

THIS paper embodies the results of a field and laboratory investigation of approximately 80 square miles of the Eyre, Lincoln and Burwood Survey districts of Southland (Fig. 1). The field mapping was carried out during three months of 1944, and was hindered by the lack of a good base map and by the wooded and rugged nature of the country. The laboratory work involved the examination of 200 rock sections and 450 hand specimens. The paper was prepared originally at the University of Otago during the tenure of a Smeaton Research Scholarship and the manuscript subsequently revised at the New Zealand Geological Survey. The writer desires to express his gratitude for the assistance and guidance given at all times by Professor W. N. Benson and Dr F. J. Turner. Mr R. W. Willett assisted in the field on several occasions. Acknowledgment is made of a monetary grant from the Scientific and Industrial Research Department to defray part of the field expenses. The assistance of the Cawthron Institute in undertaking cobalt analyses of serpentinite rock and soils is also gratefully acknowledged. The author is particularly indebted for the hospitality extended by Mr and Mrs G. Hamilton, "Cloverdon," Lowther, and by Messrs Taylor, of the West Dome Station.

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SUMMARY OF GEOLOGICAL HISTORY

The geological history of the region is summarized as follows:—

1. Late Palaeozoic Sedimentation The oldest rocks in the Mossburn area are limestones, greywackes and argillites belonging to the late Palaeozoic (Permian?) Mossburn group*. Contemporaneous with the deposition of these geosynclinal sediments were extensive outpourings or intrusions of basic pillow lavas and ejection of basic ash.

2. Metamorphism (Late Palaeozoic, early Triassic, or early Cretaceous?). Regional metamorphism has effected the older rocks throughout the whole of the Otago Province, and probably has slightly effected the Mossburn area. The widespread presence of inclusions of epidote, pumpellyite, sericite and chlorite in the feldspars of many rocks suggests that the Mossburn group has undergone regional metamorphism equivalent to the lowest subzone (Chl. I.) of the chlorite zone of metamorphism as defined by C. O. Hutton and F. J. Turner (1936).

3 Ultrabasic and Basic Instrusions Ultrabasic and basic intrusions now represented in the Mossburn region by serpentinites† and altered dolerites and gabbros have been injected into the Mossburn group. Two alternative ages are possible: (a) Injection in Permian or early Triassic time; or (b) injection during the early Cretaceous (?) Hokonui orogeny.

4. Hokonui Orogeny (Early Cretaceous?). The older rocks of New Zealand, including some of later Jurassic age, were almost everywhere involved, presumably in Early Cretaceous times, in the powerful Hokonui orogeny To this orogeny is attributed the general north-west trend of the rocks in the Mossburn group.

5. Peneplanation (Cretaceous). Widespread peneplanation followed the Hokonui orogeny throughout New Zealand and had reached an advanced stage by middle Cretaceous times.

6. Marine Transgression and Sedimentation (Mid-Tertiary). In parts of Otago, e.g., Bob's Cove (Hutton, 1939), marine sediments lie unconformably upon the Cretaceous peneplane, but rocks belonging to this group are not present in the Mossburn area.

7 Uplift, over-folding and thrust-faulting (Mid-Pliocene?). The Bob's Cove beds have been folded deeply into the underlying schist (and thus preserved from subsequent erosion) by a tectonic movement which affected the greater part of the South Island in Mid-Pliocene (?) time. (Benson and Holloway, 1940, p. 3; Wellman and Willett, 1942, p. 305.)

8. Late Tertiary Peneplanation (Benson, 1935)

9. Late Pliocene block-faulting. The elevation of the mountain ranges of the South Island is largely due to block-faulting subsequent to cutting of the Late Tertiary peneplane. A local effect in the Mossburn area was the elevation of the Eyre mountains.

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* Throughout the paper the term "group" is used as a rock unit; "Series" is better regarded as a time-rock unit (see Schenck and Muller, 1941; Moore, 1947).

† Serpentinites are rocks consisting almost exclusively of serpentine minerals (Lodochnickow, 1933, p. 145).

10. Pleistocene Glaciation. In the Mossburn district, streams flowing from Pleistocene glaciers, whose southern limit may be indicated by the presence of a moraine between the Oreti and Mararoa rivers south of Bald Hill (Hutton, 1940, map 1), have deposited the gravels and silts forming the terraced Burwood plateau and the sloping terraces south of the West Dome.

11. Post-glacial normal erosion.

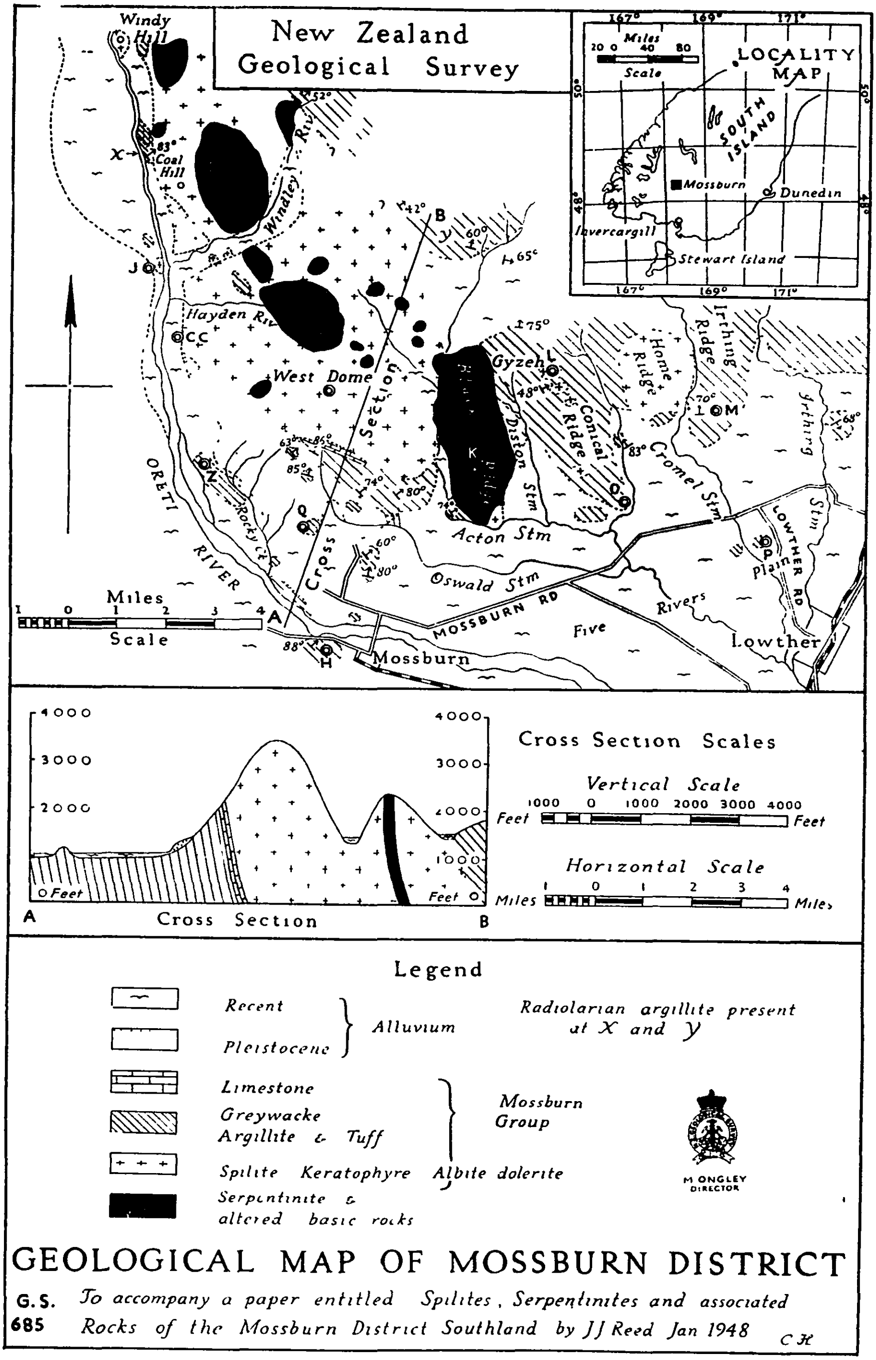
PREVIOUS WORK

In 1872, F. W. Hutton included the rocks of the Mossburn area in his upper Palaeozoic formation equivalent to the Te Anau group of J. Hector (1865, p. 128), but later (1875, p. 37) he recognised a younger Maitai formation running in a south-easterly direction from north of Burwood through Coal Hill. This distinction was supported by S. H. Cox (1879, p. 54), who placed in the Maitai group the dark-coloured jointed slates with bands of serpentinite occurring in the Mararoa River and passing through Coal Hill and Windley Creek towards the Dome. Cox noted, however (*loc. cit*, p. 55), that true Maitai slates are lacking.

Serpentinite was discovered in a creek south of Coal Hill by F. W. Hutton (1872, p. 102), who later (1875, p. 125) placed a specimen from Windley Creek in the Otago Museum. S. H. Cox (1878, p. 114; 1879, pp. 54–55) noted bands of serpentinite in the rocks comprising Coal Hill, while A. M. Finlayson (1909, p. 361) wrote of the pyritous nature of serpentinite from Windley Creek. In the summer of 1935–36, C. O. Hutton verified the existence of an ultra-basic intrusion extending from the West Dome to a point 52 miles further north, a preliminary report of the occurrence appearing in 1937. He considered that in the southern part of the intrusion (the area described in this paper) serpentinites were less abundant than rather feldspathic altered basic rocks (gabbros, dolerites), and associated with these rocks were a group with basaltic or doleritic affinities.

TOPOGRAPHY

Although a complete discussion is beyond the scope of this paper, some physiographical features may be briefly described. The topography is dominated by the Eyre mountains which rise above the alluvial plains formed by the Oreti and Mararoa rivers to heights over 5,000ft. above sea level. East of the West Dome, the highest peak, are four northward-trending ridges, designated Black, Conical, Home, and Irthing respectively, with three main dividing streams—Acton, Cromel and Irthing. North of Black ridge the Acton stream flows across a small alluvial plain on the eastern side of which high alluvial terraces are preserved. Large alluvial terraces constitute the broad Burwood plateau (2,000ft. above sea level) and its continuation southward through the Aparima Valley. Sloping alluvial terraces, comparable in height with those of the Burwood plateau, occur on the south side of the West Dome. The gravels and silts forming the terraces were apparently deposited from streams flowing from Pleistocene glaciers whose southern limit may be indicated by the presence of a moraine between the Oreti and Mararoa rivers south of Bald Hill (Hutton, 1940, map 1).



FIG, 1—Geological map and locality map of Mossburn District.

MOSSBURN GROUP

Geological Occurrence

The rock formations in the Mossburn district, apart from basic and ultra-basic intrusions and Recent and Pleistocene alluvial deposits, are grouped together in this paper as the Mossburn group. The rocks in this group include interbedded argillite, greywacke, limestone, and volcanic tuffs with intercalated spilitic basic lavas (spilites),* keratophyres, and albite dolerites, and their sequence is shown in the section from north-west of Black Ridge south to Mossburn (Section B–A, Fig. 1). The sequence briefly appears to be interbedded greywacke and argillite, spilitic igneous rocks, limestone, greywacke and argillite, and finally volcanic tuffs. The strike and dip are clearly shown by the greywackes and argillites, which strike 45–60 degrees west of north and dip in a north-easterly direction at high angles (60–88°) south of the West Dome and at lower angles (40–60°) north of the West Dome. A shale bed in the tuffaceous rocks outcropping at the sharp bend in the road one mile west of Mossburn also has the same strike and steep north-westerly dip. The north-west trend of the group thus corresponds to that of the Mesozoic Hokonui rocks to the south-east and south of the area here considered.

Near Coal Hill the bedding planes of the limestone are contorted, and this is in marked contrast to the adjacent argillites and greywackes. This unconformable relationship is due either to local faulting or folding (a likely possibility), or else it means that the limestone differs in age from the argillites and greywackes and should be separated from them. While this latter hypothesis receives some support from the local occurrence of limestone fragments in a tuff near Trig. P. on the Five Rivers plain, it seems advisable at this stage to include all the formations in the Mossburn group.

Spilites and associated keratophyres and albite dolerites are widely exposed in the Mossburn area (Fig. I.), and in several instances pillow structure has developed, e.g., pavements with individual pillows up to 2 ft. in diameter (cf. Benson, 1915, text-fig. 3) can be seen by the peaks on Conical ridge and on the ridge east of Coal Hill More detailed mapping is required, however, to determine the extent to which the spilites have originated as lava flows on the sea floor and how much intrusive into loosely compacted muds (see Benson, 1915, pp. 123–131). The latter mode of occurrence appears probable in the case of the spilites on Conical ridge It is appropriate to recall here that pillow lavas have been recognised along the shore between Orepuki and Riverton (*vide* Benson and Holloway, 1940, p. 11), and the Mossburn lavas are possibly coeval with them.

Grey, pink or green volcanic tuffs (lapilli tuffs in the nomenclature of Wentworth and Williams, 1932) outcrop principally in small rounded mounds and ridges near Mossburn. The tuffs are dominantly spilitic or keratophyric in character so that comparison may be made with spilitic and keratophyric tuffs from the Te Anau area (Turner, 1935, p. 332), from Jurassic conglomerates at Nugget Point (Mackie, 1935, p. 294) and Kawhia (Bartrum, 1935, pp. 95–107), and with

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* The term spilite is used in a descriptive sense, to denote a basic lava in which the feldspars have been albitized (Dewey and Flett, 1911),

metamorphosed spilitic tuffs from the Greenhills district of Bluff (Service, 1937, p. 191) and from Bryneira range (Benson and Holloway, 1940, pp. 9–10).

F. W. Hutton (1875, pp 37, 38) has recorded* the finding of species of *Perna* or *Inoceramus* at Coal Hill, and although the writer failed to recognise macrofossils in the hard grey limestone at Coal Hill, microscopical examination has revealed that the limestone possesses a distinctive internal structure of prismatic shell fragments which permits a definite determination as a *Maitaia* limestone (*vide* p. 113) Presumably it was this species which was collected by F. W. Hutton. Other localities in Otago and Southland where *Maitaia* has been recognised may be noted here. It was discovered by M. Ongley (1925, 1939, pp. 32–34) along with other Palaeozoic fossils in medium grained greywacke at Clinton, approximately 67 miles east of Mossburn, and in similar rocks unassociated with other fossils 33 miles to the north-west at Pyramid Hill (Macpherson, 1935, p. 7). *Maitaia* fragments have also been described from hard tuffaceous beds on the west coast of Howell Point, near Colac Bay, in limestone pebbles from the Takitimu region, and in shoad material on the eastern shore of Lake Te Anau (Wellman and Willett, 1944). Besides these occurrences limestone believed to contain *Maitaia* has been reported from the Harris Saddle (McKay, 1881, p. 142; Hutton, 1891, p. 45), from the Bryneira range (Park, 1887, p. 132) and from the north end of the Livingstone range (Park, 1921, p 40).

The other formations in the Mossburn district appear to be nonfossiliferous except that radiolarian casts are present in argillites from two localities—near Coal Hill and one mile north of the West Dome (positions X and Y, Fig. I). The preservation of radiolaria in these argillites may be compared with the occurrence of radiolaria in a small metamorphosed layer of limestone in the older rocks of southeastern Otago (Benson and Chapman, 1938).

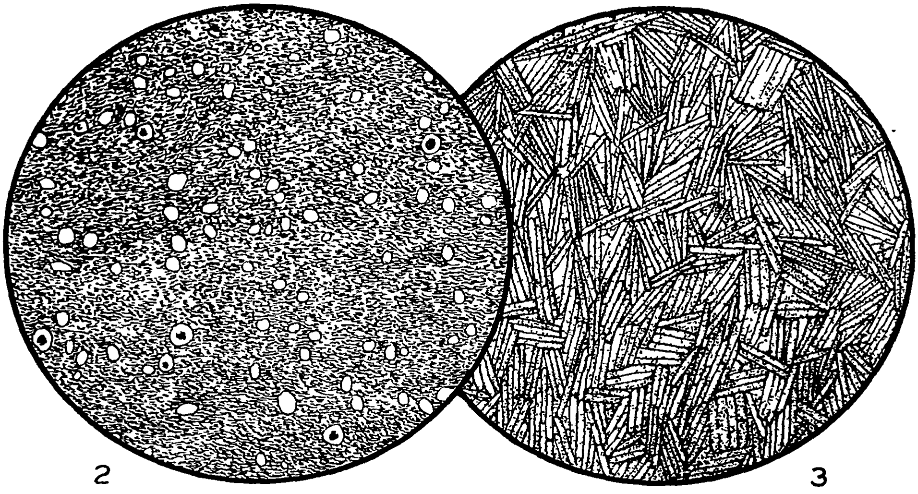

FIG. 2—No 7758 Radiolarian argillite showing radiolarian casts. × 28.
FIG. 3—No. 7752. Limestone containing prismatic *Maitaia* fragments. × 28.

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* Professor W. N. Benson drew the writer's attention to this reference,

The thickness of the Mossburn group is difficult to estimate in view of probable overturning and repetition of formations (cf. Macpherson, 1946, p 11). The writer believes, however, that the thickness is not less than 15,000 ft (cf. Hutton, 1875, p. 38).

Petrography of Argillites, Greywackes and Volcanic Tuffs

The argillites (Nos 7758–59, 75–94)* are indurated grey or black rocks with grain-size ranging from 0 1 to 0 01 mm. in diameter. Quartz, feldspar (albite in 7782) and plentiful flakes of biotite and muscovite (7782, 83) are the commonest minerals that can be identified under the microscope. Radiolarian casts were detected in two argillites (7758, 59) collected respectively from positions X and Y (Fig. I.). The casts are oval or circular in shape, 0 1 to 0 3 mm. in diameter, and with the internal structure replaced mainly by chalcedony, although in some there is an inner filling of carbonate and/or granular epidote (?) (Fig. 2). The main constituents of the massive greywackes (7795–7816) interbedded with the argillite are sub-angular to angular grains of feldspar and quartz (grain size 0 1 to 0 6 mm.). The feldspar may be orthoclase (7805), albite (7808) or more calcic in character and generally the grains contain inclusions of epidote, pumpellyite (7810) and sericite. Composite fragments present are argillaceous or igneous, and the occurrence of the latter marks the transition to tuffs.

The pyroclastic rocks (7817–7842) are mainly lapilli tuffs according to the nomenclature of Wentworth and Williams (1932). The rounded and sub-angular igneous fragments are either spilitic or keratophyric in character or else display trachytic structure in which slender feldspar laths are drawn out into parallel position (Fig. 4). Argillite and greywacke fragments are usually present and rarely *Maitaia* limestone (7819). The feldspar grains include albite, orthoclase and oligoclase and generally contain inclusions of epidote, pumpellyite (7841) and sericite Occasionally the feldspar has been zeolitized (7831). Fragments of colourless augite occur in most rocks and in one (7842) are accompanied by plentiful coarse brownish yellow hornblende; so far as is known it cannot be ascribed to any of the rock types occurring in the Mossburn area, and the coarseness of grains ($>$ 3 mm) suggests derivation from plutonic rocks. Quartz and biotite (7832) are rarer accessory clastic minerals. Veining by epidote and chlorite is common, and in one specimen (7818) pools of penninitic chlorite with anomalous blue interference colours are present. Dark brown isotropic material, comparable with the gel-palagonite of M. A. Peacock and R. E. Fuller (1928) occurs in one rock (7819), and in it structures simulating micro-organisms can be seen (cf. Campbell and Lunn, 1925, p. 436).

Although megascopically there is little sign of metamorphism, the obscuring of the feldspar in the greywackes and tuffs by alteration products such as epidote, sericite, pumpellyite and chlorite suggests that the Mossburn group has undergone regional metamorphism equivalent to the lowest subzone (Chl. I.) of the chlorite zone of regional metamorphism as defined by C. O. Hutton and F. J. Turner (1936).

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* Numbers refer to rocks or thin sections in the collections of the Geology Department, University of Otago.

Petrography of Limestone

Although macrofossils were not detected, the hard grey limestone (7751, 7754–56) possesses an internal structure consisting of prismatic shell fragments surrounded by plentiful isolated prisms of the completely shattered shell (Fig. 3). This structure appears comparable with that described by J. M Bell, E. C. Clarke and P. Marshall (1911, p. 18) and C. T. Trechmann (1917) from thin sections of Maitai limestone. "It [thin section of Maitai limestone] contains many shell fragments with corroded edges and the surrounding matrix is also largely made up of isolated prisms of the decomposed shell" (Trechmann, *op. cit.*, p. 56). This similarity was confirmed when thin sections of Maitai limestone from Wairoa gorge were examined by the writer. The prismatic shell fragments are almost certainly derived from *Maitaia* (Marwick, 1935, p. 295) = *Aphanaia* of Trechmann (*loc. cit.*).

Petrography of Spilites, Albite Dolerites and Keratophyres

(i) ***Structure.***

Both porphyritic and non-porphyritic types occur in the dark green spilites (7920–7967, 7912). In the former, phenocrysts of augite and feldspar (1–2 mm.) are set in a pilotaxitic base of augite prisms (0 2 mm.), feldspar laths (0 6 mm.), iron ore and chloritic minerals (Fig 5). Larger plagioclase and augite phenocrysts (2–3 mm.) are present in rocks (7931, 7946) transitional to dolerites. The non-porphyritic types consist of a pilotaxitic mosaic only (7935, 7941, 7944). A glassy phase, developed as selvedges in the pillows, is shown in two cases (7910, 7913) where abundant phenocrysts of feldspar and augite are set in a black glassy groundmass, in which plentiful feldspar microlites and pyroxene crystallites can be distinguished, and from which plentiful iron ore granules have crystallised. Variolitic structure is occasionally developed in rocks (7922,

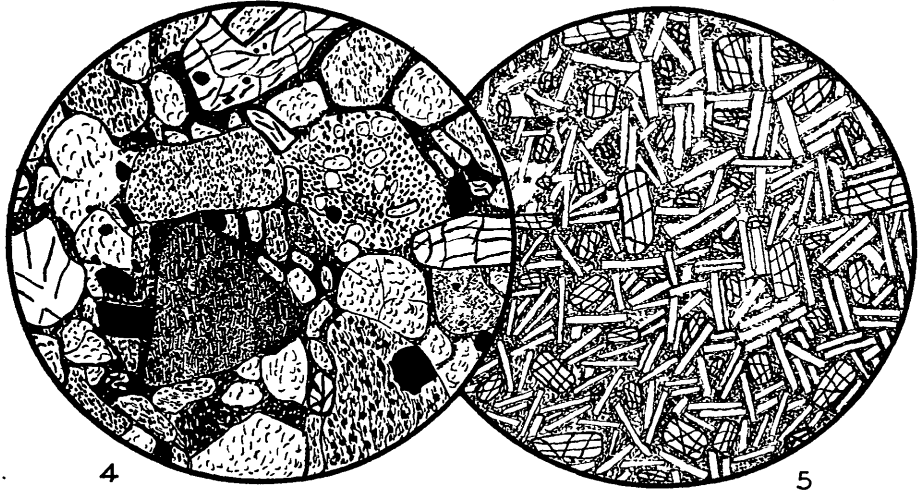

FIG. 4—No. 7842 Volcanic tuff composed mainly of igneous fragments, iron ore, pyroxene and hornblende × 17.

FIG. 5—No. 7912. Spilite showing augite and albite phenocrysts set in an altered pilotaxitic ground mass. × 28,

7923) possessing affinities with variolites. In the green albite dolerites (7892–7902), feldspar laths (2·5 mm.) enclose augite crystals (1 mm.) in ophitic texture (Fig. 7). Rarely the dolerites are coarser grained (7902, 7889), and in these cases the feldspar is 4 mm. in length and the augite 2–3 mm. The light green keratophyres (7903–7905) typically display a porphyritic structure in which feldspar phenocrysts (1–2 mm.) are set in a cryptocrystalline groundmass (Fig. 6). Shearing movements have affected several of the spilitic rocks (7928, 7896, 7901), and in some instances epidote has crystallized along the shear zones.

As will be shown in the mineralogy section of this paper, the spilitic rocks are characterised by fresh augite, albitic feldspar, and an abundant development of epidote and pumpellyite.

(ii) *Mineralogical Features.*

Plagioclase. Feldspar phenocrysts in the spilites and keratophyres, and laths in the albite dolerites do not normally exceed 3 mm. in length, but larger crystals are known from two dolerites (7889, 7902). In the pilotaxitic groundmass of the spilites, the laths are less than 0·6 mm. in length. The majority of the feldspar crystals contain plentiful fine inclusions of epidote and pumpellyite, and their presence may prevent accurate measurement of refractive index, although generally the twinning is not obscured. Much larger epidote grains (greater than 2 mm.) can be observed in the plagioclases of several dolerites (7907, 7985), spilites (7906, 7943), and keratophyres (7903–5). Feldspar free of inclusions is relatively rare (7912, 7922, 7892).

Three methods were used in determining the character of the feldspar: (1) The normal microscopical methods as described by A. W. Winchell (1933, pp. 337–352), particularly the measurement of extinction angles in sections normal to a bisectrix (p. 358); (2) measurement of the refractive indices α and γ with respect to Canada Balsam, usually with the aid of a universal stage, and (3) the standard four-axis universal stage procedure as described by W. Nikitin (1936, pp. 96–103), and F. J. Turner (1940, 1947). These methods indicated that the dominant plagioclase present is albite, typical determinations with the universal stage being:—

(a) spilites An_{0-10} three crystals (7935), An_5 (7912, 7943).
(b) albite dolerites An_{0-2} (7892), An_5 (7893).
(c) keratophyres An_{10} (7903).

More calcic feldspar has, however, been determined in several spilites—An_{18-20} (7936), An_{22-27} (7913), An_{33-36} (7942).

Pyroxene. Pyroxene is present as colourless prisms usually less than 2 mm. in length in the spilites and albite dolerites, and less than 0·2 mm. in the pilotaxitic groundmass of the former. A characteristic feature of the pyroxene is its fresh appearance, which is in marked contrast to the widespread chloritization of mafic minerals in many spilitic rocks (Dewey and Flett, 1911, p. 203; Gilluly, 1935, pp. 228–233), but on the other hand comparable with pyroxene in spilites described from New South Wales (Benson, 1915, p. 141), Eastern Fennoscandia (Eskola, 1925, p. 21) and the Great King Island (Bartrum, 1936, p. 420), Following the recommendations of F. J. Turner (1942) the composition of the pyroxene has been determined using Nemoto's method for twinned crystals on a universal stage (Nemoto, 1938). One determination (7932) gave $\gamma \wedge c = 40 \mp \frac{1}{2}$ and $2V = +50$; this suggests a composition of $Wo_{37}\ En_{9}\ Fs_{55}$ or that of a normal augite (Benson, 1944, p. 77). Measurement of optic axial angles of other pyroxenes agrees with this result. The pyroxenes of the albite dolerites also appear to be normal augite

Olivine. Olivine has not been observed but possible serpentinous pseudomorphs (bowlingite?) occur in three spilites (7913, 7932, 7946)

Iron Ores Iron ore is present as irregular or platy grains less than 0·1 mm. in diameter, and as densely crowded minute crystals, occasionally in two generations (7916). The ilmenitic character of part at least of the iron ore is shown by the formation of leucoxene (7901, 7894). Pyrite has been introduced in several instances where shearing has occurred (7947, 7952)

Amphibole. Fibrous green or bluish green amphibole is present in the mesostasis of several rocks (7923, 7922, 7943, 7912), and in vesicles where the main filling material is epidote and chlorite (7907).

Pumpellyite. Pumpellyite is widely developed in the spilitic rocks and generally forms in aggregates of prismatic crystals less than 0 04 mm. in length These aggregates have a distinctly granular appearance under low magnification. The mineral is readily recognised by its moderately high refractive index $\beta = 1{\cdot}70$), low birefringence and the distinctive blue green colour for the β vibration direction (7921, 7895, 7946, 7951) As a result of the combination of low birefringence and strong dispersion, brownish purple or blue anomalous interference tints are sometimes developed between crossed nicols (7951, 7946). The pumpellyite aggregates occur in the mesos-

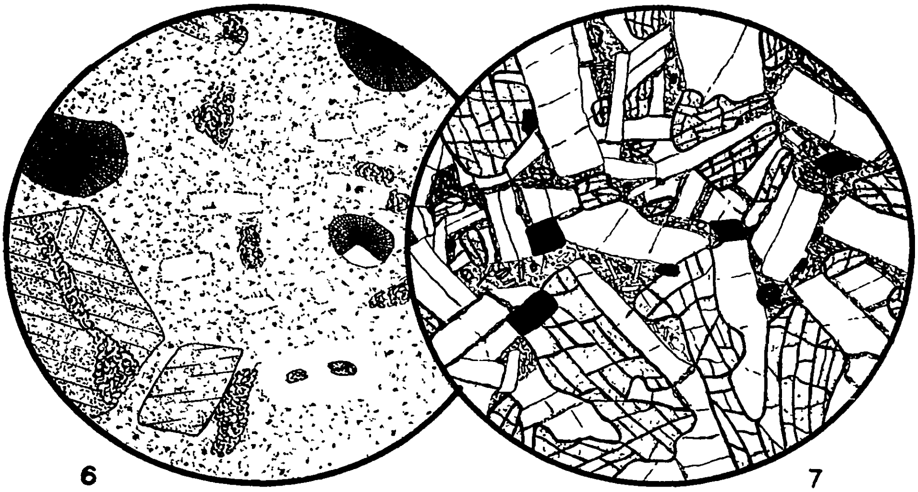

FIG. 6—No. 7903. Keratophyre composed of albitic feldspar set in a cryptocrystalline base Secondary chlorite, carbonate and epidote are abundant. × 28.

FIG. 7—No 7892. Albite dolerite showing ophitic texture of augite and albite. × 28.

tasis of many spilitic rocks, in vesicles (7951, 7929), veins (7895, 7930), and as inclusions in feldspar crystals (7918, 7949, 7934).

It is interesting to note here that pumpellyite has been observed in amygdaloidal lavas from Lake Superior (Palache and Vassar, 1925) and Haiti (Burbank, 1927), in spilitic dolerites from Nassau (Hutton, 1937, p. 530), in spilites and albite diabases from Eastern Borneo (Roever, 1947), and in albitophyres in the Urals (Zavaritsky, 1944). In New Zealand pumpellyite has been recorded in the reconstituted greywackes and low grade schists of Otago (Hutton, 1937b, 1940; Turner, 1939, pp. 37–39), and rarely in quartz-albite segregation veins in the schists (Hutton, *op.cit.)*.

Epidote Pale yellow epidote is widely developed in the spilitic rocks as plentiful small inclusions in the feldspar crystal and as aggregates of crystals in the mesostasis (7943, 7908, 7894). Veins of epidote have also been noted (7922) and in some cases the lime-rich solutions have crystallized along shear zones (7943, 7923). Vesicles filled with radially arranged epidote are present in several rocks (7903, 7931).

TABLE I—ANALYSES OF SPILITES AND DALY'S AVERAGE BASALT

	A.	B.	C.	D.	E.	F.	G.
SiO_2	53.86	52.59	51.31	52.94	53.15	51.22	49.06
Al_2O_3	14.75	15.93	12.67	12.81	14.39	13.66	15.70
Fe_2O_3	3.94	6.12	0.54	3.76	1.28	2.84	5.38
FeO	5.90	3.96	7.99	9.29	9.33	9.20	6.37
TiO_2	0.72	1.36	1.92	2.54	1.50	3.32	1.36
MgO	4.17	5.04	2.19	3.65	4.74	4.55	6.17
CaO	7.17	5.55	8.17	6.22	7.04	6.89	8.95
Na_2O	5.36	5.79	5.21	5.25	4.58	4.93	3.11
K_2O	0.46	0.67	0.54	0.18	1.01	0.75	1.52
H_2O+	2.53	2.16	2.31	2.33	2.02	1.88 }	1.62
H_2O-	0.92	0.16	0.04	0.21	0.19	— }	
CO_2	trace	—	6.15	none	0.10	0.94	—
P_2O_5	0.16	0.15	0.90	0.36	0.19	0.29	0.45
MnO	0.14	0.25	0.45	0.21	0.14	0.25	0.31
V_2O_5	0.043	nt.dt.	nt.dt.	nt.dt.	nt.dt.	—	—
S	0.03	,,	FeS_2 0.30 Fe_7S_8 0.17	0.12	FeS_2 trace?	— —	— —
BaO	none	,,	none	trace	none	—	—
SrO	,,	,,	nt.dt.	none	nt.dt.	—	—
NiO	,,	,,	,,	0.02	,,	—	—
ZrO_2	.	.	,	nt.dt	,,	—	—
Cl	trace	—	,,	0.02	,,	—	—
Cr_2O_3	none	nt.dt	,,	none	,,	—	—
	100.15	99.73	100.86	99.91	99.66	100.72	—

A. Spilite, 4 mls. N. West Dome, Mossburn. 7912 (this paper). Analyst: F. T. Seelye.

B. Metabasalt, Crystal Falls, Michigan. Analyst: H. M. Stokes (U.S. Geol. Surv., Mon XXXVI, p. 106, 1889, no. 2.)

C Spilite, Tayvallich Peninsula, Argyll. Analyst: E. G. Radley. (Dewey and Flett, 1911, p. 206, no. 1.)

D. Spilite, Great King Island, New Zealand Analyst· F. T. Seelye. (Bartrum, 1936, p. 417.)

E. Spilite, Oregon. Analyst: J. G Fairchild. (Gilluly, 1935, p. 235.)

F. Average Spilite. (Sundius, 1930, p. 9.)

G. Average basalt. (Daly, 1933, p 17, no 58.)

Zeolite and Carbonate. The centre of a large vesicle in one spilite (7948) is filled with a colourless mineral with the following properties: Refractive index about 1·48, double refraction 0 007, uniaxial and positive, non-fibrous; this mineral is believed to be chabazite. Carbonate has crystallized in one rock, a keratophyre (7903).

Chloritic Minerals. A very detailed investigation would be necessary to determine exactly the nature of the diverse number of chloritic minerals, but it is sufficient to record the main types as follows:—

(a) Interstitial cryptocrystalline or " celadonitic " green or yellow " chlorite " is invariably present in the mesostasis of the spilites and albite dolerites. In the writer's opinion, this material does not represent direct decomposition of ferro-magnesian minerals, but, following Fenner (1929, p. 245), it is believed that it results from the crystallization of residual magmatic ferruginous gels or solutions.

(b) Deep green fibrous chlorite with properties closely allied to penninite (Winchell, 1933, p. 281) is present in several rocks (7894, 7931).

(iii) *Petrogenesis*

(a) *Spilites.* The chemical analysis by F. T Seelye of a Mossburn spilite (7912) is compared with other spilitic rocks in Table I, and a close similarity is revealed. The relative deficiency of the Mossburn spilite in potash is clearly shown in the ternary diagram Or – Ab – An (Fig. 8), and this supports Sundius' conclusion (1930, p. 9) that extreme deficiency in potash is particularly characteristic of splilitic rocks. The calculated normative plagioclase is $Ab_{76}An_{24}$, whereas universal stage methods have indicated that many of the feldspars have the composition $Ab_{95}An_5$. The excess CaO must be present in the pyroxene and secondary pumpellyite and amphibole, for the Al_2O_3 and CaO required for these minerals in the mode would be calculated as anorthite in the norm. The Mossburn spilite is also noteworthy for the low titanium content, which contrasts sharply with the high TiO_2 value in the average spilite as computed by Sundius.

In the spilites, albite feldspar occurs with pyroxene only rarely altered to chlorite and amphibole. The question arises, therefore, whether the albite is a primary product of magmatic crystallization or whether it has originated from a more calcic plagioclase. The presence of plentiful inclusions of epidote and pumpellyite in most albite crystals, the occurrence of epidote and pumpellyite as filling in vesicles and veins, and the determination in some cases of plagioclase as basic as An_{33-36} would indicate that the albite formed from a more calcic plagioclase. Furthermore, considerations of physical chemistry show that it is most unlikely that albite could crystallise from a magma either earlier than or simultaneously with pyroxene (Gilluly, 1935, p. 338).

Although it seems reasonable to consider that the albite is secondary and formed from an originally more calcic plagioclase, it is not clear how this was effected. Two processes can be suggested: (a) A process of saussuritization whereby the albite formed is residual after the CaO and Al_2O_3, equivalent to the anorthite molecule had either migrated or appeared as epidote and pumpellyite (Sundius, 1915; 1930, p. 3; Gilluly, 1935, p. 342). (b) Metasomatic replacement of the

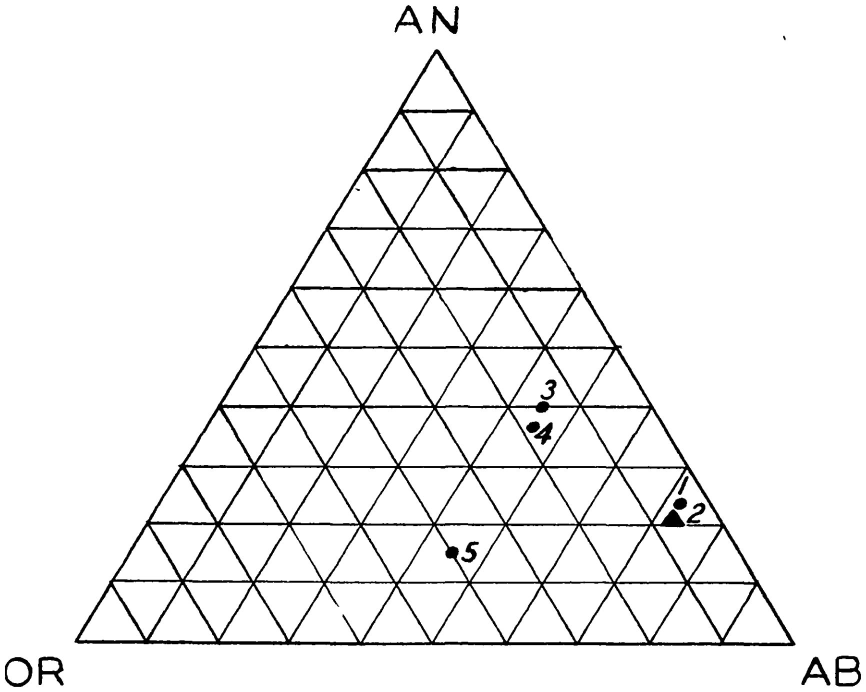

FIG. 8—Molecular percentage of normative feldspai of Mossburn spilite (1) compared with that of the average spilite as computed by Sundius (2), and the average basalt (3), andesite (4), and Trachyte (5) as computed by Daly.

original anorthite–rich feldspar involving essentially introduction of soda and migration of lime. If solutions are responsible these could possibly represent authigenic hydrothermal solutions formed during the consolidation of the basic magma (Bailey and Grabham, 1909, p. 253; Dewey and Flett, 1911, p. 246; Eskola, 1925, p. 91), or else resurgent water as postulated by Daly (1914, pp. 339-40) and Gilluly (1935, p. 346-7).

The formation of epidote and pumpellyite concomitant with albite in many crystals appears to favour the first process. This hypothesis can be criticised, however, on the grounds that the albite produced is insufficient and that some introduction of soda is required. Meagre chemical data are available in the Mossburn district to test this criticism, but if the original basic magma is assumed to have the composition of Daly's average basalt (Daly, 1933, p. 17, No. 58), and if the one chemical analysis is representative of the Mossburn lavas, then comparison of the two would indicate that introduction of soda is required with complementary removal of lime (Table I). Obviously, this comparison requires to be tested by additional chemical investigations. On the other hand, if metasomatism by solutions rich in soda is the dominant process, it would be expected (i) that the albite is present either in clear crystals or in crystals where albite surrounds remnants of calcic plagioclase (cf. Gilluly, 1935, pp. 232, 342); (ii) that the pyroxene is generally altered to chlorite (cf. Dewey and

Flett, 1911, p. 203; Gilluly, 1935, pp. 228–233) and (iii) that vesicles and veins filled with albite are plentiful. In the Mossburn spilites, clear albite, altered augite, and veins and vesicles of albite are relatively rare, and this suggests that soda metasomatism by solutions is only of minor importance. Another alternative which may be applicable is that the metasomatism is effected largely by migrations in the solid or semi-solid state. Definite conclusions, however, are not warranted on the evidence available.

To summarize, the albitic feldspar in the Mossburn spilites is considered to be secondary and formed from an originally more calcic plagioclase, but there are insufficient data to indicate how this was effected. Probably some process of soda metasomatism is involved.

(b) *Albite Dolerites.* The arguments put forward to explain the origin of the spilites apply also to the albite dolerites where fresh augite is present in ophitic texture with albite laths in which inclusions of epidote and pumpellyite are abundant. The writer believes that here, too, the feldspar is secondary after original calcic plagioclase, and that probably a process of soda metasomatism is important.

(c) *Keratophyres.* The volume of keratophyres in the Mossburn area is small compared with that of the spilites, a contrast with the keratophyres, quartz-keratophyres and spilites described by J. Gilluly (1935, p. 347) from eastern Oregon. It is possible, therefore, that the keratophyres originated by the differentiation along trondjheimitic lines, of the basic magma from which the spilites and albite dolerites were formed. The formation of oligoclase and albite in the keratophyres thus does not produce as difficult a problem as the albite in the spilites and albite dolerites. In many instances, the oligoclase and albite are free of inclusions, but the presence of abundant solutions rich in lime is indicated by the widespread occurrence of epidote, both as vesicle filling and as large crystals distributed throughout the rocks and in some feldspar phenocrysts. In the writer's opinion the lime-rich solutions are dominantly external in origin (cf. Benson, 1915, p. 160), but further study is necessary to determine the extent to which the albite and oligoclase are primary crystallizations.

TABLE II—COBALT CONTENT OF SERPENTINITE ROCK AND SOIL

Analyst: Miss J. Watson, Cawthron Institute

Locality	Cobalt in parts per million
Serpentinite, south end of Black Ridge	120.3
Serpentinite, west side of West Dome	107.1
Serpentinite soil, west side of West Dome	283.9
" " " " " "	311.5
" " " " " "	248.2
" " " " " "	385.0
" " Black Ridge	205.0
" " " "	277.3
" " " "	299.8
" " ridge east of Coal Hill	265.8
" " " " of Windy Hill	194.9

Age and Correlation of Mossburn Group

As the radiolarian casts in some of the argillites may be disregarded, the only fossiliferous formation in the Mossburn area is the limestone which contains abundant prismatic fragments of *Maitaia* and for which a late Palaeozoic (Permian) age may be ascribed (Trechmann, 1917; Marwick, 1925, 1935, p. 296). This limestone can be readily correlated with the Maitai limestone, but the Maitai group of formations typically includes red and green slates (McKay, 1879, p. 116), and since these have not been found in the Mossburn region (cf. Cox, 1819, p. 54), the writer has considered it advisable to group provisionally the limestone, argillite, greywacke, tuffs and intercalated spilites, keratophyres and albite dolerites, as the late Palaeozoic Mossburn group It is probable, however, that this group represents only a part of a larger Maitai group Discussion of the relationship of the Mossburn rocks to the Te Anau group must await clarification of the distinction (if any) between Te Anau and Maitai, for in recent years there has been a tendency to regard these two as synonymous (Park, 1921, p. 39; Turner, 1935, p. 331). Lithologically, the Mossburn rocks can be separated from the coarse red and green breccias characteristic of the Te Anau group.

SERPENTINITES AND ASSOCIATED ROCKS

1. *Geological Occurrence*

Serpentinite and altered basic rocks outcrop on Black Ridge, the western side of the West Dome, and on the ridges east of Coal and Windy hills (Fig. I). The outcrops are generally parallel to the bedding planes of the intruded sedimentary rocks, and therefore accord with E. Suess's dictum (1909, p. 564) " that the green rocks are sills in dislocated mountains sometimes following the bedding planes and at others the planes of movement " The altered basic rocks can be readily distinguished in the field from the serpentinites as mounds projecting above the latter. Quarrying operations have revealed also that the basic rocks occur as large " boulders " enclosed within serpentinite.

2. *Economic Use of Serpentinite.*

Serpentinite for the fertiliser industry has been quarried recently from the south end of Black Ridge, a site chosen in view of the road connection with the rail-head at Mossburn. Large quantities of serpentinite also outcrop on both sides of the Windley River, but their exploitation would necessitate the construction of a bridge across the Oreti River. The intimate association of serpentinite with other basic rocks is a disadvantage, especially from the quarryman's point of view, and if large quantities of serpentinite are to be required in the future, preliminary investigation by channelling or boring seems imperative to determine the relative proportions of these rock types at depth. The amount of cobalt present in the serpentinites and in soils derived therefrom is shown in Table II; this indicates that although a noteworthy concentration of cobalt is effected in the soils, the quantity in the serpentinites is insufficient for its use as a source of cobalt for pasture deficiency purposes.

3. *Petrology*

(a) *Petrography of Serpentinites.* The serpentine minerals used in this paper—chrysotile, antigorite, bastite and serpophite—follow the usage of earlier investigators in New Zealand as summarized by C. O. Hutton (1936, pp. 241–242). It should be noted that Lodochnickow (1933), however, citing evidence obtained by Russian workers of the very wide variation in optical properties of the serpentine group of minerals has proposed a purely textural classification of serpentine minerals.

The Mossburn serpentinites can be divided into mesh serpentinites with or without bastite, and sheared serpentinites. The mesh serpentinites are macroscopically dark green in colour, frequently slickensided and with a dull to enamel-like lustre. Bastite pseudomorphs are recognisable in several specimens (7729, 7722). In thin section, the serpentinites generally display a mesh or lattice structure of pale yellow chrysotile fibres less than 0 5 mm. in length, and this structure appears comparable with the mesh types described by C. O. Hutton from North-west Otago (1936, pp. 242–243). Occasionally yellowish green fibres with negative elongation radiate from cores of pale yellow serpophite (7724, 7728). Bastite pseudomorphs are present in many rocks (2719–22, 7729, 7730) as crystals generally less than 4 mm. in length and usually they display pleochroism ranging from yellowish green (X) to pale green (Z). Iron ore occurs as scattered irregular grains 0·2 mm. in diameter and as fine granules marking the mesh boundaries. In some instances, the coarse grains are chromite (7719). Vein serpentine in one specimen (7719) has a medium birefringence and a moderate pleochroism according to the scheme, X—light yellow, Z—dark golden yellow; this type would appear to be closely related to bowlingite (Winchell, 1933, p. 437).

Two sheared serpentinites were noted, one (7749) being a white variety from the south end of Black Ridge and the other (7733) a contorted dark green rock from the ridge east of Windy Hill. In thin section, both display a marked cataclastic structure, the main constituent of which is a low birefringent serpentine (serpophite?). Finely scattered iron ore is abundant in one specimen (7733).

(b) *Petrogenesis of Serpentinites.* Except where localised marginal shearing of the serpentinite has occurred, the Mossburn serpentinites are massive rocks in which mesh structure is dominant and chrysotile the most plentiful serpentine mineral. Relicts of peridotite have not been observed, but the presence of chrysotile serpentine with and without bastite suggests that the original peridotite had the composition of dunite and harzburgite. Asbestos veins have not been developed to any extent. The absence of other adjacent igneous intrusions from which solutions could emanate suggests that here, as in many other areas in New Zealand, serpentinisation probably results from autometasomatism of the original peridotite by concentration of magmatic waters during the consolidation of the magma after injection (Benson, 1918; Turner, 1933; Hess, 1933; Lodochnickow, 1933).

(c) *Petrography of altered dolerites and gabbros.* The altered basic intrusions associated with the serpentinites are massive, black, amphibole rocks veined with white prehnite. The amphibole is dominantly uralite occurring in fibres 1 mm. in length, and with a pleochroism ranging from colourless (X) to deep green (Z). Rarely a brown pleochroic amphibole has been observed, occasionally as separate crystals (7855), but more often as central cores to the green uralite (7861). A few relict prisms of augite remain (7859, 7876, 7875), and these are being replaced by uralite. Colourless prehnite is present both interstitially and in veins less than one inch in width. The prehnite sometimes displays a radiating spherulitic structure between crossed nicols (7889, 7857), and in this respect resembles the prehnite from the Baltic described by P. Eskola (1934, p. 134). Many rocks (7849, 7862, 7884) contain about equal amounts of uralite and prehnite; in others (7856, 7878, 7883) feldspar laths 3 mm. in length are essential constituents (5–30 per cent.). Although refractive index measurements were hindered by the presence of saussurite inclusions several determinations indicate that the feldspar is now albite (7856, 7883, 7878). Sphene is a common accessory mineral and its presence points to an original ilmenitic iron ore. Locally abundant are interstitial clear quartz (7877) and pale green chlorite (penninite) with anomalous blue interference tint (7876). Shearing of the basic rocks has occurred along the margins of the intrusions (8005).

(d) *Petrogenesis of altered dolerites and gabbros.* The occurrence of unfractured feldspar crystals and relicts of pyroxene indicate that basic intrusions were dolerites and gabbros which have now been converted into uralite-prehnite rocks. Earlier workers (Benson, 1918, 722–733, 1926, p. 43; Grange, 1927; Turner, 1930, p. 198, 1933, p. 271) have shown that this uralitization and prehnitization is probably brought about by the metasomatic effect of aqueous solutions emanating from the basic magma and as a result of the serpentinization of lime-bearing minerals in the original peridotite

(4) *Tectonic Significance and Date of Intrusion*

The serpentinites and altered dolerites and gabbros considered in the paper form the southern part of an arcuate line of ultrabasic and basic intrusions extending from D'Urville Island parallel to the main strike of the Southern Alps and then swinging in a westerly arc from the Olivine Range. Since it may reasonably be assumed that these ultrabasic intrusions belong to a single orogenic period (Finlayson, 1909, pp. 364, 365; Benson, 1926, p. 44; Turner, 1933, p. 276), " the structural significance of the magnesian belt is too evident to be overlooked in this connection " (Finlayson, 1909, p. 365). It is pertinent here to note the important conclusions of H H. Hess (1937, 1948) concerning peridotite injection. " Peridotite intrusions in mountain belts are an important tool because of certain peculiarities of their histories and loci of intrusion. Peridotites of the ultramafic magma suite occur in all alpine mountain systems and nowhere else. They occur in two belts about 50 miles on either side of the original location of the tectogene axis and less commonly in the area between the two belts. They are intruded during the first great deformation of the belt presumably during buckling of the crust, and later deformations of the same belt are not accompanied by intrusion of peridotites. Thus location of the peridotite belt and dating of its intrusion locate the old tectogene axis and date the initiation of the deformation of that zone " (Hess, 1948, p. 432). It will be seen from this statement how important is the dating of the South Island peridotite intrusions. and the evidence bearing on their age will now be considered.

In the Hokitika district, serpentinite pebbles have been found in the upper part of the " Miocene " Blue Bottom beds (Bell and Fraser, 1906, p. 87; Morgan, 1908, p 121), and since the Blue Bottom beds are now considered to be early Pliocene in age (Finlay and Marwick, 1940, p. 124; Gage, 1945, p. 182) this would place the upper age limit of peridotite injection as pre-Pliocene. Three alternative hypotheses are therefore possible for the date of peridotite intrusion—Tertiary, Mesozoic, and Palaeozoic.

Tertiary tectonic movements with which peridotite injection could possibly be correlated are believed to have taken place in Mid-Pliocene and Pliocene–Pleistocene times (Wellman and Willett, 1942, p. 305), i.e., after the deposition of the beds in which serpentinite pebbles have been found The Tertiary hypothesis is therefore untenable.

There remain two alternative hypotheses (a) injection during the early Cretaceous Hokonui orogeny, which is known to have involved the older rocks of New Zealand and which may be responsible also for the formation of the schists of Otago (Ongley, 1939, p. 32) and (b) injection in late Palaeozoic or early Triassic time, e.g. before, co-eval with or immediately following a late Palaeozoic or early Triassic regional metamorphism (Turner, 1938, p. 161). In the Mossburn area the serpentinite occurs with pillow lavas (spilites) and radiolarian rocks. This association is known from deformed geosynclines in many parts of the world (Bailey, 1936, 1943; Benson, 1926; Taliaferro, 1943) and as stated by E. B. Bailey (1936, p. 1719), " it is far too widespread in time and place to be accidental." In the California area, Taliaferro (*op. cit.*) has shown that the Franciscan-Knoxville group, comprising shales, arkosic sandstones, radiolarian cherts, pillow lavas, basic and ultrabasic intrusives and pneumatolytic metamorphic rocks, is limited to a comparatively short space of geological time, the Upper Jurassic. It is probable, therefore, that in the Mossburn area the serpentinites and altered basic rocks are closely connected in time with the late Palaeozoic (Permian?) Mossburn geosynclinal group of radiolarian rocks, argillites, greywackes, tuffs and pillow lavas (spilites). Further, in the Hokitika and Mikonui areas, peridotites and serpentinites have been metamorphosed to talc, actinolite–talc, and serpentine schists (Bell and Fraser, 1906, p. 70; Morgan, 1908, p. 84), and this suggests that injection took place in these districts prior to regional metamorphism. On the other hand, if the conclusion that the peridotites were injected in Permian or early Triassic time is correct, it is difficult to explain the absence of serpentinite pebbles from Mesozoic formations and their presence only in Pliocene beds.

To summarize, the evidence is inconclusive as to whether the peridotite belt was injected during the early Cretaceous Hokonui orogeny or whether it was earlier, possibly in late Palaeozoic or early Triassic time. The association of serpentinites with spilites and radiolarian rocks in the Mossburn region favours the second alternative.

CONCLUSIONS

The main conclusions of this paper may be summarized as follows.

1. In the Mossburn area, interbedded argillites, greywackes, radiolarian argillites, volcanic tuffs, *Maitaia* limestone and intercalated spilitic pillow lavas, albite dolerites and keratophyres, are provisionally grouped together as the Mossburn group for which a late Palaeozoic (Permian) age is most probable.

2. Ultrabasic and basic intrusions, now represented by serpentinites and altered dolerites and gabbros have been injected into the Mossburn group, but the evidence is inconclusive as to whether this took place during the early Cretaceous (?) Hokonui orogeny or whether it was older, possibly in late Palaeozoic or early Triassic time. The association of the serpentinites with spilites and radiolarian rocks favours the latter alternative.

3. The albitic feldspar in the spilites and albite dolerites is considered to be secondary after an originally more calcic plagioclase, and probably this was effected by some process of soda metasomatism.

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