Hornblende-gneisses, Marbles and Associated Rocks from Doubtful Sound, Fiordland, New Zealand.

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[*Read before the Otago Branch, September 13, 1938; received by the Editor, September 16, 1938; issued separately, March, 1939.*]

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INTRODUCTION.

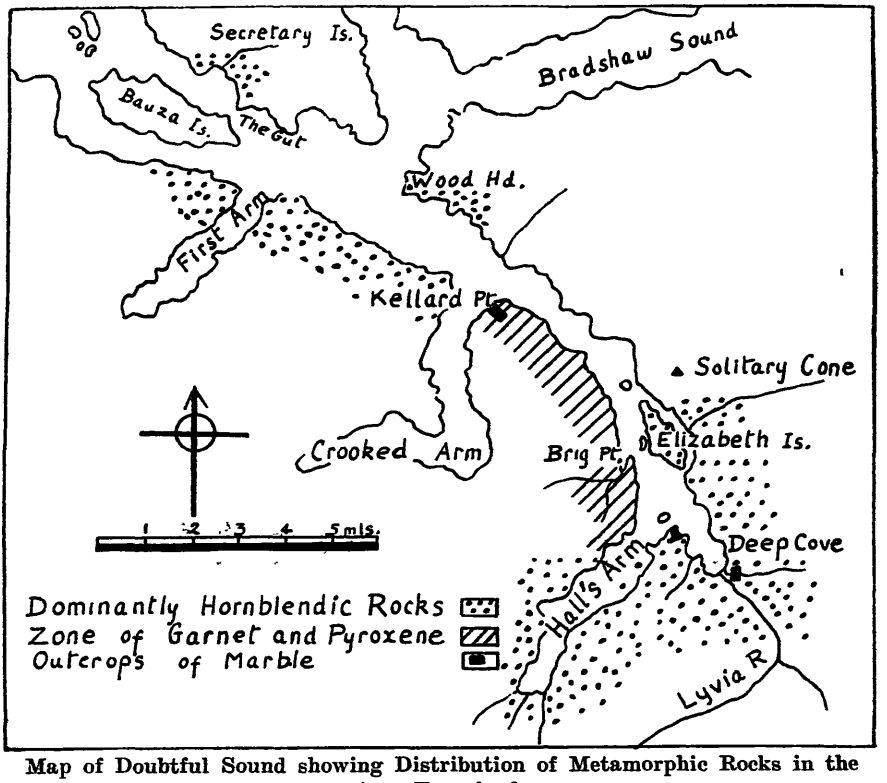
THE rocks which form the subject of this investigation were collected in December, 1937, during a visit to Doubtful Sound financed by a grant from the Australian and New Zealand Association for the Advancement of Science.

The Sound is one of the most extensive of the West Coast fiords and lies immediately west of Lake Manapouri, from the West and North Arms of which it is accessible via Wilmot and Fowler Passes respectively. Its maximum length, from the coast to the head of Hall's Arm, is about twenty-five miles, while the width varies from one to two miles. For the most part it is bordered by lofty precipices rising sheer from the water's edge and sloping steeply upward to the mountain summits, which in this district reach a height of between 4500 and 5000 feet. Dense forest fills the valleys and clothes all but the steepest slopes.

Geological work was practically confined to the shores, where continuous outcrops are beautifully exposed along the cliff bases. The portions examined in detail include the eastern shore from the north end of Elizabeth Island to the head of Deep Cove, the western shore from the head of Deep Cove to Kellard Point, and both shores of Hall's Arm. Rocks were also collected at intervals from the south-western shore between Crooked and First Arms, and from the southern side of Secretary Island. It is hoped to extend the work further on some future occasion.

The dominant rocks throughout the whole of this region are massive hornblendic, sometimes garnetiferous gneisses of " dioritic " aspect, locally merging into types rich in biotite, feldspar or pyroxene. At several points bands of marble and calc-gneiss are interstratified

with the hornblende rocks. Veins of granite-pegmatite occur here and there, but are never numerous. The whole association presents a marked contrast with that developed further east around Lake Manapouri, where granitic intrusions invade the hornblende-gneisses on a large scale (Turner, 1937a, 1937b, 1938).



Map of Doubtful Sound showing Distribution of Metamorphic Rocks in the Area Examined.

NOTE ON DETERMINATIVE METHODS.

In all 150 thin sections have been examined microscopically, following the normal procedure, without use of a universal stage. The composition of the plagioclase was determined in each case by a combination of methods described by Winchell (1933), use being made especially of extinction angles Z or X to (001) or (010), in sections perpendicular to X and Z respectively (Winchell, 1933, p. 318). Selected sections were also examined with a universal stage, with the purpose of measuring axial angles for pyroxenes, epidote minerals and amphiboles, and checking the composition of the plagioclase. In all cases the compositions of plagioclase as determined by the two methods agreed reasonably closely; further, the axial angles of plagioclase as given by universal stage measurement were found to correspond closely with the curve given by Winchell (1933, p. 318). Typical data are given below in illustration [determinations (a) based on extinction angles, (b) based on measurements with universal stage] :—

Section No. 4608.

(a) Section $\perp$ X; Z to 010 = 88°, Z to 001 = 4° } An_{18} or An_{22}.

(b) Twin axis lies in composition plane; co-ordinates of pole of twin axis with respect to indicatrix axes, 9° (Z), 81° (Y), 86° (X).

Three possible solutions:—

Twin axis = [100], An_{10} or An_{25}.

Twin axis = $\perp \frac{[100]}{(001)}$, An_{10}.

2V = 88° (+) and 86° (−); this favours composition An_{25}.

Section No 4595.

(a) Section $\perp$ X; Z to 010 = 65°, Z to 001 = 33° } An_{48}.

(b) Twin axis $\perp$ (010), composition plane (010); co-ordinates of twin axis with respect to indicatrix axes, 27° (Z), 67° (Y), 87° (X); 2V = 76° (+). } An_{45}.

Twin axis [010], composition plane (001); co-ordinates of twin axis 27° (Z), 63° (Y), 82° (X); 2V = 74° (+). } An_{44}.

Section No. 4598.

(a) Section $\perp$ X; Z to 010 = 56, Z to 001 = 50 } An_{70}.

Symmetrical extinction to (010) in twinned sections $\perp$ (010), 37°. } An_{68}.

(b) Twin axis $\perp \frac{[100]}{(010)}$, composition plane (010); co-ordinates of twin axis, 48° (Z), 54° (Y), 61° (X); 2V = 90°. } An_{70}.

Twin axis $\perp$ (001), composition plane (001); co-ordinates of twin axis 46° (Z), 63° (Y), 58° (X); 2V = 84° (−). } An_{78}.

Twin axis $\perp \frac{[100]}{(010)}$, composition plane (010); co-ordinates of twin axis 51° (Z), 63° (Y), 55° (X); 2V = 84° (−). } An_{79}.

THE HORNBLENDE-GNEISSES.

The most widely distributed rocks in Doubtful Sound are dark green coarse gneisses of "dioritic" appearance, which consist essentially of plagioclase and hornblende often accompanied by biotite and less commonly by epidote or quartz. Gneissic structure is usually distinct and may be very well defined (e.g., Nos. 4600 to 4603), but massive non-foliated rocks are occasionally met with (e.g., Nos. 4568, 4569, 4573). The structure results from a tendency for the dark minerals to be concentrated in streaks and bands, combined with parallel dimensional orientation of crystals of amphibole

and mica. Most rocks show marked cataclastic effects such as granulation and elongation of grains of quartz and plagioclase, with simultaneous bending of twin-lamellae and development of undulose extinction; these are most intense in rocks showing most strongly marked gneissic structure.

For convenience of description the hornblende-gneisses are divided into four groups, viz.:—

(1) Hornblende-plagioclase-gneisses with minor biotite.

(2) Hornblende-plagioclase-biotite-gneisses.

(3) Hornblende-plagioclase-epidote-gneisses, usually containing biotite in fair abundance.

(4) Non-feldspathic hornblende-biotite-gneisses.

Transition-types connect group (1) with the second and third groups.

(1) Hornblende-plagioclase-gneisses (Nos. 4557, 4558, 4566, 4568–4571, 4573–4576, 4580, 4594–4596, 4604, 4610, 4612, 4642–4645, 4648, 4649, 4654, 4658, 4681, 4682, 4688). These are dark-green rocks composed essentially of hornblende (30% to 60%) and plagioclase (30% to 60%) usually accompanied by biotite (10%) and small amounts of colourless rather poorly birefringent epidote.

The hornblende is a common green variety, usually with the pleochroism

$$X = \text{pale yellow}$$
$$Y = \text{deep olive-green}$$
$$Z = \text{deep blue-green}$$
$$Z > Y > X.$$

In some slides, however, the mineral is deep greenish-brown for vibrations parallel to Z (e.g., Nos. 4558, 4566, 4595). Schiller structure with grains of opaque iron-ore arranged along lines parallel to the *c* crystal axis is common; in one rock (No. 4688) the schiller inclusions are small prisms of yellow rutile, a feature typical of the non-feldspathic hornblende-gneisses. In the coarser rocks a stout prismatic habit is common and a tendency to develop sieve-structure may occasionally be shown (e.g., Nos. 4576, 4681), but in some of the finer-grained well-foliated rocks (e.g., No. 4594) the hornblende occurs as slender parallel prisms.

The plagioclase is typically basic oligoclase or acid andesine, ranging between Ab_{75} and Ab_{65} in composition, but a rather higher content of anorthite is usual in the feldspar of rocks from near the head of Deep Cove (No. 4557, Ab_{58}; No. 4669, Ab_{48-50}; No. 4576, $_{56}$; No. 4595, $AbAb_{55-55-60}$). It tends to occur in equant grains often deformed and partly granulated as a result of shearing. Multiple twinning on several laws with (010) or (001) as composition plane is fairly common in undeformed grains.

Biotite is usually present in quantities less than 10%, but may be absent in some rocks. It is usually yellowish-brown, or in a few slides reddish-brown. In addition to the epidote already mentioned, common accessories are sphene, apatite and pyrite, while in one section (No. 4568) needles of yellow rutile are plentiful at

plagioclase-hornblende junctions. In several slides the percentage of sphene lies between 1% and 5% (Nos. 4573–4575, 4610, 4648, 4649, 4658). In Nos. 4573 and 4574 it takes the form of coarse rounded drop-like grains enclosed in hornblende or plagioclase, while in No. 4658 it is coarse and idioblastic, being conspicuous even in the hand-specimen. In other rocks (e.g., No. 4575) it occurs as large granular clusters 2 mm. to 3 mm. in diameter, enclosing highly corroded central cores of a deep golden-brown non-pleochroic, highly refractive mineral provisionally identified as rutile. Quartz was recorded in a number of rocks, usually in quantities between 5% and 10% (Nos. 4558, 4576, 4604, 4610, 4648, 4649, 4652, 4658, 4682). Calcite and scapolite occur as accessories in Nos. 4580 and 4682 respectively.

Frequently observed retrogressive mineralogical changes connected with late shearing include chloritisation of biotite, and conversion of hornblende to pale-green actinolite or tremolite (Nos. 4557, 4558, 4644). In rare instances (e.g., No. 4569) sharply crystallised flakes of pale chlorite free from any trace of relict biotite may have originated in some other way, possibly from the hornblende. The epidote, though present in only small quantities, usually appears to be a member of the original hornblende-plagioclase-biotite assemblage, but in special cases may be a product of later reaction during shearing. For example, a coarse hornblende-plagioclase-gneiss, No. 4569, has locally been reduced by shearing to a fine-grained variant in which about 5% to 10% of yellowish epidote and small amounts of secondary calcite accompany the dominant plagioclase and hornblende; the compositions of the plagioclases of the coarse and sheared phases are Ab_{48-50} and Ab_{35-50} respectively.

Structurally the hornblende-plagioclase-gneisses vary from coarse non-foliated rocks indistinguishable from diorites (e.g., Nos. 4573, 4574, 4569) to strongly foliated gneisses (e.g., Nos. 4557, 4558, 4576) similar to those described from Manapouri in previous papers (Turner, 1937a, 1937b, 1938).

(2) *Hornblende-plagioclase-biotite-gneisses.* (Nos. 4556, 4559, 4561–4563, 4565, 4577, 4599, 4646, 4652.) Rocks of this class (Fig. 1) contain between 15% and 30% of deep golden-brown biotite in addition to the usual plagioclase and hornblende (each ranging between 30% and 50% of the total composition). On account of the relatively high content of mica and its tendency toward parallel orientation, these rocks tend to have a more pronounced gneissic structure than is usually shown by the biotite-free members of the previously described group. The hornblende is the normal blue-green type, often showing schiller structure and in several sections replaced partially or almost completely by actinolite (e.g., No. 4565). The plagioclase ranges between Ab_{50} and Ab_{70} and shows the same characters as in the hornblende-plagioclase-gneisses. In most slides iron-ore is present as granules enclosed in hornblende, but other accessories are rare; in No. 4577, however, epidote, rutile and zircon are all present. Essential features of several typical slides are recorded below:—

No. 4556 is a " dioritic " gneiss with average grain of 1 mm., consisting of plagioclase (An_{42-48}) 40%, brown biotite 30%, amphibole

30% and accessory magnetite in granular clusters associated with the amphibole or mica. The original hornblende or pyroxene is now entirely replaced by pseudomorphous masses of prismatic actinolite, edged with a deep blue border against the enclosing feldspar. These resemble but are not structurally identical with pseudomorphous masses of actinolite in epidiorites from Manapouri (Turner, 1937a, p. 87).

No. 4562 is a similar coarse-grained rock of dioritic aspect in which compact brownish-green hornblende occurs in large equant grains with marked schiller structure. Several clinopinacoidal sections show a well-defined basal parting sub-parallel to X and inclined at 72° to *c*; this, taken in conjunction with the schiller structure, strongly suggests derivation from augite [cf. the Manapouri epidiorite, No. 2794 (Turner, 1937a, p. 87)].

Nos. 4559 and 4563 are fine-grained strongly foliated varieties reminiscent of the amphibolites from the islands of Lake Manapouri. The composition of No. 4559 is estimated as plagioclase (Ab_{70}) 50%–60%, hornblende 30%, biotite 10%–20%, and about 1% of iron-ore in rather coarsely granular streaks. The hornblende is in parallel, often twinned, elongated prisms usually with complex schiller structure. In addition to the usual strings of iron-ore oriented parallel to the vertical cleavages, many clinopinacoidal sections show oblique strings of included material making angles of 36° to 42° with *c* and reversed across the trace of the (100) twinning plane; this would agree with orientation parallel to ($\bar{3}02$). In other cases the central portions of hornblende crystals are crowded with masses of irregularly oriented grains of iron-ore.

No. 4646 differs from the other hornblende-plagioclase-biotite-gneisses in that it contains about 15% of intensely sheared quartz. The composition is hornblende 40%, red-brown biotite 25%, basic oligoclase 20%, quartz 15% and accessory sphene, epidote and apatite.

(3) *Hornblende-plagioclase-epidote-biotite-gneisses.* (Nos. 4600–4603, 4657, 4691, 4692, 4695.) The hornblende-gneisses containing epidote as an essential constituent differ in several respects from the rocks described in the two previous classes; coarse idioblastic prisms of epidote make up between 10% and 30% of the composition; the plagioclase is more sodic than in other hornblende-gneisses (Ab_{75} to Ab_{80}); streaky foliation is invariably very pronounced and not only involves parallel orientation of mica and hornblende, but in many cases may also be correlated with definite elongation of feldspar grains. Biotite is usually sufficiently plentiful (10% to 25%) to rank as an essential constituent of the mineral assemblage.

Nos. 4600–4603 are representative of the strongly foliated epidote-bearing gneisses from Elizabeth Island and the adjacent eastern shore of the Sound. In these rocks (Fig. 3) blue-green hornblende in coarse sometimes schillered prisms which may show well-developed sieve structure (Nos. 4602, 4603) makes up between 15% and 30% of the composition and is associated with less plentiful intensely pleochroic, yellowish-brown biotite. The plagioclase (40% to 60%) approximates in composition to Ab_{80}. Colourless, moderately birefringent coarse prisms of epidote (0·8 mm. x 0·4 mm.) are abundant

in every section, while in some instances (Nos. 4600, 4601) the same mineral may also occur as smaller sharply idioblastic crystals enclosed in the larger grains of feldspar. Coarse sphene is always present, usually in the form of granular streaks associated with hornblendic foliae; in No. 4603 it encloses small nuclei of iron-ore or of the yellow highly refractive mineral identified elsewhere as (?) rutile. Quartz occurs in small amounts in the biotite-hornblende streaks of No. 4603, while apatite is a constant accessory in all four sections.

Other rocks of this group are somewhat coarser in grain than the rocks from Elizabeth Island, especially as regards the epidote which takes the form of stout idioblastic prisms 2 mm. to 3mm. in length, sometimes exhibiting good sieve-structure (Nos. 4691, 4692) and in one slide (No. 4657) enclosing vermicular inclusions of intergrown quartz. Though always colourless, the epidote varies considerably as regards birefringence and axial angle, even within the limits of a single section. Thus in No. 4692 the following values of 2V were recorded for separate crystals, the sign in every case being negative: 64°, 74°, 75°, 84°, 86°; this corresponds to variation from 55% to 86% of the clinozoisite molecule (i.e., from 22% to 7% Fe_2O_3).* The presence of small amounts of quartz in Nos. 4657 and 4692, and of plentiful acicular rutile in No. 4691 is also noted.

In conclusion attention is drawn to the general similarity between some of the rocks just described and certain of the epidote-bearing hornblende-plagioclase-gneisses of the North Arm of Lake Manapouri, e.g., No. 2382 (Turner, 1937b, p. 228).

(4) *Non-feldspathic hornblende-biotite-gneisses.* (Nos. 4597, 4606, 4614–4617, 4617a, 4654). No. 4614 may be taken as typical of the least altered of the non-feldspathic hornblende-gneisses. The main constituent (80% of the rock) is hornblende in coarse crystals (2 mm. to 4 mm.) with strong pleochroism from pale yellow (X) to deep blue-green (Z); Z to $c = 22°$. These are often riddled with small but well-formed prismatic crystals of pale yellow rutile showing parallel orientation. The remainder of the rock is composed of intensely pleochroic biotite (X = very pale yellow, Y = Z = deep greenish-brown), accompanied by accessory epidote, sphene and apatite.

No. 4617 is a somewhat sheared phase of the same rock, collected from the same locality. The coarse green hornblendes have been partially replaced by masses of twisted prisms of pale-green actinolite and are surrounded by a continuous matrix of actinolite and epidote; the latter is particularly plentiful along surfaces of shearing. Relatively coarse inclusions of rutile are enclosed abundantly in the hornblende relicts. Granular sphene is abundant as an accessory and often enclosed shapeless grains of deep yellowish-brown (?) rutile.

No. 4615, from the same locality, represents the end-product of shearing of a gneiss locally containing minor plagioclase. It is a completely schistose rock consisting of plagioclase (Ab_{75}) 10%,

* As determined from curves in Winchell (1933, p. 313).

epidote 50%, pale actinolite 20%, biotite 20%, and accessory apatite and coarse pyrite. Amphibole, fine-grained biotite and small epidote prisms make up a matrix enclosing the rounded feldspars which have apparently undergone rotation during the deformation. The hand-specimen shows a few relict aggregates of coarse hornblende scattered through a schistose matrix represented by the section.

No. 4654 is a variety in which dominant green hornblende with the usual enclosed prisms of rutile is accompanied by 10% of yellowish-brown biotite, 20% of plagioclase (Ab_{72}) and coarse sphene in accessory quantity. In No, 4656 pale bluish-green hornblende is the only constituent.

The frequent presence of rather coarse grains of yellow sulphide —probably pyrite—in most rocks of this group is noteworthy.

(5) *Origin of the Hornblende Gneisses.* One of the most difficult yet fundamental problems connected with the geology of Fiordland concerns the origin of the various hornblende-plagioclase-gneisses that occur so abundantly throughout this region. The rocks in question might conceivably belong to any of three categories:—

(a) Primary gneissic diorites in which hornblende and plagioclase are essentially direct products of crystallisation from dioritic magma.

(b) Basic and semibasic plutonic rocks that owe their present mineral composition and structure to deep-seated regional metamorphism (cf. Harker, 1932, pp. 282–286).

(c) A series of basic lavas, tuffs and interstratified calcareous sediments or greywackes that have undergone intense regional metamorphism at depth (cf. Harker, 1932, pp. 268–270; Vogt, 1927, pp. 485, 486).

It seems likely that the hornblende-gneisses of Fiordland are not all of one origin; for example, in the vicinity of Preservation Inlet rocks that are definitely gneissic diorites and granodiorites occur as marginal phases of the main granitic intrusions (Benson and Bartrum, 1935), while the hornblendic gneisses of Lake Manapouri are certainly metamorphic even though the probability of igneous origin be admitted in many cases.

At Doubtful Sound the gneisses consisting of the associations hornblende-plagioclase, hornblende-plagioclase-biotite and hornblende-plagioclase-epidote-biotite, though separated for descriptive purposes, show gradual transition between all three types and are therefore regarded as of common origin. While the hornblende-andesine association might have resulted from either magmatic crystallisation or metamorphic recrystallisation, assemblages such as hornblende-oligoclase-epidote-biotite-sphene and the garnet-bearing associations to be described later must be regarded as metamorphic. The writer therefore believes that the hornblendic gneisses of Doubtful Sound, like those of Manapouri further east, have acquired their present mineralogical and structural condition during deep-seated regional metamorphism of pre-existing solid rocks.

In Table I analyses (A to E) are given of five hornblendic gneisses from Lake Manapouri and Doubtful Sound, together with comparable analyses selected from Washington's tables (G and H) and the composition of Daly's average basalt (F). The rocks chosen for analysis are typical of the more basic hornblende-rich biotite-poor gneisses of both districts, and are representative of the group of rocks to which the term " diorite-gneiss " has been applied in earlier accounts of Fiordland geology.

	A	B	C	D	E	F	G	H
SiO_2	52.16	49.13	49.40	47.83	54.27	49.06	52.27	49.29
Al_2O_3	17.37	17.04	18.25	17.80	18.40	15.70	17.68	18.49
Fe_2O_3	1.73	3.83	2.85	2.58	1.02	5.38	2.51	2.38
FeO	5.25	7.32	6.55	7.99	7.32	6.37	5.00	6.77
MgO	5.07	4.90	4.87	6.87	3.35	6.17	6.05	6.09
CaO	7.80	7.79	8.69	9.51	7.27	8.95	8.39	8.14
Na_2O	4.56	3.90	3.94	3.10	4.14	3.11	4.19	3.93
K_2O	1.90	1.57	1.58	0.54	1.09	1.52	1.58	1.79
H_2O above 105° C.	1.72	1.36	1.82	1.93	0.62	1.62	0.82	0.88
H_2O below 105° C.	0.18	0.14	0.08	0.21	0.02			
CO_2	—	—	—	0.14	0.44		tr.	
TiO_2	1.29	1.84	1.36	1.22	1.00	1.36	1.49	2.22
P_2O_5	0.45	0.74	0.42	0.29	0.40	0.45		tr.
ZrO_2	—	—	—	—	tr.			
S	0.33	0.06	0.02	0.04	0.53			
MnO	0.11	0.26	0.13	0.17	0.15	0.31	0.23	0.22
NiO	tr.	tr. (?)	tr.	—	—			
Cr_2O_3	tr. (?)	tr. (?)	0.01	0.02	—			
BaO	0.07	0.07	0.08	0.02	0.04		0.06	
SrO	0.11	0.04	0.02	0.04	0.12			
Total ..	100.10	99.99	100.07	100.30	100.18		100.27	100.20

TABLE I.—ANALYSES OF HORNBLENDE-GNEISSES.

A—No. 2373, plagioclase-hornblende-epidote-biotite-gneiss, West Arm, Lake Manapouri. Anal., F. T. Seelye.

B—No. 2429, fine-grained amphibolite, Mahara Island, Lake Manapouri. Anal., F. T. Seelye.

C—No. 4514, fine-grained amphibolite, South Arm, Lake Manapouri. Anal., F. T. Seelye.

D—No. 4569, coarse hornblende-plagioclase-gneiss, Deep Cove, Doubtful Sound. Anal., F. T. Seelye.

E—No. 4594, hornblende-plagioclase-gneiss, Deep Cove, Doubtful Sound. Anal., F. T. Seelye.

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

G—Quartz-basalt, New Mexico (Washington, 1917, p. 486, no. 60).

H—Basalt, Japan (Washington, 1917, p. 512, no. 248).

The fine-grained amphibolites (B and C) from Manapouri (Turner, 1937a, p. 85; 1938, p. 126) and the typical coarse " dioritic " gneiss (D) from Doubtful Sound agree sufficiently closely to indicate origin from similar parent rocks. Their compositions are consistently basic and show close agreement with various basaltic and gabbroid rocks (e.g., H) listed in Washington's tables, and may be compared with Daly's average basalt (F). The coarse hornblende-gneiss No. 2373 (A), typical of the gneisses of West Arm, Lake Manapouri (Turner, 1937b. p. 228), is also probably of basaltic or gabbroid

origin (cf. quartz-basalt, G), while a fine-grained rock (E) from Doubtful Sound shows fair correspondence with a number of diorites and gabbros listed by Washington. The derivation of the hornblendic phases of the Manapouri and Doubtful Sound gneisses from basic igneous rocks is thus established with reasonable certainty. It should be noted, however, that rocks with plentiful biotite have not yet been analysed, and may well include tuffaceous and sedimentary as well as probably igneous rocks.

There still remains the vexed question as to whether the gneisses in their premetamorphic condition were in the main plutonic rocks (dominantly gabbro or diorite) or a mixed series of lavas, tuffs and sediments as suggested in earlier papers for the rocks of Manapouri. While the latter alternative seems more probable to the writer, it seems preferable at this stage not to present a final conclusion on a problem not yet fully investigated, but to summarise the available evidence bearing upon the question.

In favour of a plutonic origin the following points are put forward:—

(a) The typically dioritic structure and mineral composition of some of the less gneissic rocks, particularly specimens from the eastern shore of Deep Cove within a mile of the head of that Arm. This is offset, however, by the basic rather than semibasic composition of typical "diorite"-gneisses such at No. 4569.

(b) The occasional presence of hornblende that appears to be pseudomorphous after diallagic pyroxene, e.g., No. 4562 described above; the widespread development of schiller structures even suggest that replacement of augite may have been much more frequent than is otherwise indicated.

(c) The anorthite-content of the plagioclase in the least gneissic "dioritic" rocks is noticeably higher than in the strongly foliated rocks, and epidote is often abundant in the latter. While not conclusive, this suggests conversion of anorthite to epidote during metamorphic transition from diorite to gneiss.

(d) The composition of the non-feldspathic hornblende-biotite gneisses is strongly suggestive of origin by reconstitution of pyroxenites. Although it is impossible to be certain, the field relations of these rocks to the adjacent plagioclase-bearing gneisses (as shown about 1½ to 2 miles from the head of Deep Cove on the western shore) support an intrusive origin.

The contrasted view that the hornblende- and associated gneisses represent a mixed series of lavas, tuffs and sediments has already been put forward by the writer for the corresponding rocks of Lake Manapouri (Turner, 1937a, p. 86; 1937b, p. 237). At Doubtful Sound the banded structure noted at Manapouri is not so prominent nor so regular, but at many points bands of quartzo-feldspathic gneiss that appears more probably sedimentary than igneous are interstratified with gneisses of "dioritic" aspect and composition. More significant is the occurrence, at three widely separated localities, of lenses and beds of marble in intimate association with hornblendic gneisses. These could be interpreted only as members of a stratified

series, or as major roof-fragments engulfed in a plutonic intrusion. The low dip and great extent of the main exposed mass of marble (that of Kellard Point) are somewhat against the latter alternative.

Typical hornblendic gneisses occurring as small discontinuous parallel lenses and bands surrounded by marble include the following specimens:—

No. 4594. Fine-grained well-foliated hornblende-plagioclase-biotite-gneiss consisting of plagioclase (Ab_{70}) 50%–60%, blue-green hornblende 30%, red-brown biotite 10%, epidote 2%, pyrite* 2% and accessory sphene and apatite. Comparable with the amphibolites of Holmwood and adjacent islands, Manapouri, and with Nos. 4559 and 4563, Doubtful Sound. For analysis, see Table I.

No. 4595. Coarse hornblende-plagioclase-gneiss consisting of brownish-green hornblende 40%–50%, plagioclase (Ab_{52-57}) 40%–50%, colourless epidote 5%, red-brown biotite 5% and accessory apatite, sphene and iron-ore. Section No. 4591 from the same locality shows hornblende-plagioclase gneiss of this type apparently interbedded with diopside-gneiss (an impure phase of the marble).

No. 4596. Hornblende-plagioclase-biotite-gneiss with accessory epidote, pyrite, sphene and apatite.

No. 4642–4644. Coarse hornblende-plagioclase-gneiss in which the two principal minerals make up 95% of the composition. Minor biotite, epidote, sphene and often pyrite. Secondary actinolite developing from hornblende in No. 4644. Composition of plagioclase Ab_{70-75}.

No. 4655. A similar rock to the above, but containing 10% red-brown biotite.

No. 4646. Hornblende-plagioclase-biotite-quartz-gneiss (see earlier description).

No. 4649. Coarse hornblende-plagioclase gneiss with 5% colourless epidote and 5% sphene with lamellar structure.

No. 4669. Hornblende-plagioclase-epidote-gneiss containing small amounts of calcite, biotite, pyrite and apatite. Granulation is strongly marked and the hornblende shows a tendency to be replaced by pale actinolitic amphibole.

The Feldspathic Gneisses.

(1) *Oligoclase-quartz-gneisses.* (Nos. 4572, 4579, 4605, 4607–4609, 4613, 4641, 4650, 4653, 4659, 4660, 4661, 4663, 4665, 4666,* 4680, 4683). Quartz-bearing oligoclase-gneisses occur in association with the hornlendic gneisses throughout the whole of the region examined by the writer. Oligoclase of basic to medium composition (Ab_{68-80}) makes up between 40% and 80% of the composition of these rocks and is usually accompanied by between 10% and 25% of quartz.

* Mr F. T. Seelye, who analysed this rock, has noted that much of the "pyrite" is probably pyrrhotite, since H_2S is evolved rapidly when the rock is treated with dilute HCl.

Rarely the quartz content is as low as 5% (Nos. 4605, 4607) and in one section was estimated as 30% (No. 4641). Typically biotite is an essential constituent ((10%–20%) and may even reach 25% to 30% in some sections (Nos. 4665, 4666*). A few sections, however, are poor in dark minerals, and approach the trondhjemite-gneisses of Manapouri in appearance and composition (e.g., Nos. 4608, 4641). Epidote is constantly present in small amount, and in a number of rocks is almost or quite as plentiful as biotite (e.g., Nos. 4609, 4650, 4665, 4666*). It is the usual colourless moderately birefringent type, and in the single instance where the axial angle was measured (No. 4608) gave $2V = 76°$ (negative), corresponding to a clinozoisite content of about 75%. Blue-green hornblende accompanies the biotite as a minor constituent (10%) in several sections (e.g., Nos. 4579, 4609, 4613, 4659), and in others is present in accessory amounts.

Sphene and apatite are ubiquitous accessories, and in some rocks the former may make up two or three per cent. of the total composition (e.g., No. 4659). Small crystals of zircon were noted in three sections (Nos. 4572, 4579, 4607). Less frequent accessory minerals are rutile (Nos. 4607, 4608), muscovite (apparently primary in Nos. 4607 and 4608) and allanite (Nos. 4572, 4607, 4608). The latter mineral is strongly pleochroic with

$$X = \text{pale yellow}$$
$$Y = \text{deep plum-colour}$$
$$Z = \text{greenish yellow}$$
$$X < Y > Z.$$

Small amounts of potash-feldspar occur interstitially in the trondhjemite-like section No. 4608, but the hand-specimen shows more biotite than is typical in the Manapouri trondhjemites.

As seen microscopically most of the oligoclase-gneisses have a more or less granitoid structure, with coarse feldspars, parallel flakes of mica, and interstitial, granular, often sheared quartz. Cataclastic structure is very pronounced in some sections (e.g., Nos. 4660, 4661, 4663, 4683). Quartz is finely granulated and drawn out into elongated streaks between the larger feldspars, which themselves are considerably crushed in such rocks, while biotite and epidote are reduced to strings of small grains and flakes. The extreme end-products are rocks of almost myloritic texture (e.g., No. 4683).

As in the more feldspathic gneisses of Manapouri, the rocks just described are characterised by association of oligoclase, quartz and biotite with variable amounts of epidote, hornblende and sphene. The Doubtful Sound rocks are consistently poorer in dark minerals, however, and especially in hornblende. Nevertheless individual specimens from the Spey River, Wilmot Pass and the western side of South Arm, Manapouri, agree fairly closely with the oligoclase-quartz-gneisses of Doubtful Sound.

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* For analysis, see Table II.

	I	J	K
SiO_2	58.68	59.59	58.34
Al_2O_3	17.97	17.31	18.08
Fe_2O_3	2.16	3.33	3.23
FeO	3.30	3.13	3.87
MgO	2.69	2.75	2.07
CaO	5.16	5.80	5.76
Na_2O	5.04	3.58	5.65
K_2O	2.30	2.04	1.30
H_2O above 105° C.	1.04	1.26	0.55
H_2O below 105° C.	0.02		0.05
CO_2	—		0.12
TiO_2	0.88	0.77	1.07
P_2O_5	0.39	0.26	0.22
ZrO_2	—		
S	0.09		
MnO	0.09	0.18	
NiO	—		
Cr_2O_3	—		
BaO	0.07		
SrO	0.08		0.07
Total ..	99.96	100.00	

TABLE II.

I—No. 4666, oligoclase-quartz-biotite-epidote-gneiss, Kellard Point, Doubtful Sound. Anal., F. T. Seelye.

J—Average andesite (Daly, 1933, p. 16, no. 49).

K—Diorite, Hesse (Washington, 1917, p. 500, no. 157).

Their origin is doubtful. Neither sedimentary nor igneous rocks of corresponding composition are common. To the writer it seems perhaps most probable that feldspathic sands or tuffs were the parent rocks. No. 4666, which, however, is hardly typical of the group as a whole, is fairly close to certain andesites and diorites in composition. (See Table II.)

(2) *Plagioclase-gneisses without Quartz.* (Nos. 4598, 4651, 4655.) No. 4598 is a coarse white feldspathic rock with local patches of amphibole. In section the main constituent is bytownite (Ab_{17-30}) occurring in coarse equant twinned grains making up 80% of the rock. The amphibole (10%) is a colourless to pale-green member of the actinolite-tremolite series, in sheaves of prismatic crystals often showing multiple twinning; 2V was determined as 86° (negative). The remainder of the rock consists of colourless optically positive chlorite here and there enclosing biotite relicts, a little secondary sericite, and accessory coarse colourless epidote (2V = 83°, negative) and apatite. This rock, which is unlike any other recorded from Doubtful Sound, was collected from a small boulder at the waterfall near the head of Deep Cove. It is possibly gabbroid, but on the other hand is more probably a phase of the calc-gneisses that occur in association with marble at this locality. In any case development of actinolite and chlorite appear to be effects of a late (low-temperature) phase of metamorphism.

No. 4651 is a local quartz-free phase of the associated oligoclase-quartz-gneiss No. 4650. Its composition is oligoclase 90%, biotite 8%, epidote 2%, and accessory allanite, apatite, sphene and iron-ore.

No. 4655 consists of plagioclase 70%, epidote 15%, biotite 10%, hornblende 5%, and accessory epidote, sphene and apatite.

(3) *Plagioclase-quartz-microcline-gneisses.* (Nos. 4611, 4617b.) Potash-feldspar occurs in noteworthy amount in only two of the feldspathic gneisses. Though the composition of the section in each case approaches that of certain of the trondhjemites and oligoclase-granites of Manapouri, it is obvious from the hand-specimens that the rocks in question are merely microcline-bearing variants of the oligoclase-gneisses with which they are intimately associated.

The composition of No. 4611 is estimated as oligoclase-andesine 50%, quartz 20%, coarse perthitic microcline 10%, biotite 10%, epidote 5%, muscovite 3%, apatite 1%, garnet 1% and a few prisms of zircon. The macrostructure is highly gneissic. Beneath the microscope granulation of quartz and mica between the larger feldspar grains is perfectly shown. No. 4617(b) is a similar rock containing sphene, allanite, apatite and zircon as accessories.

It is not improbable that the microcline occurring in rocks of this type has been introduced from magmatic sources, as is probably the case with microcline-bearing phases of the plagioclase-hornblende-biotite-gneisses of Manapouri. The presence of allanite in some of the oligoclase-quartz-gneisses is also probably due to the influence of magmatic emanations derived from subjacent intrusive granite (cf. Turner, 1937b, p. 239).

THE GARNET-BEARING GNEISSES.

Along the northern shore of Hall's Arm and the western shores of the Sound between Hall's and Crooked Arms the grade of metamorphism rises, and garnet is conspicuous in many of the gneisses exposed in this neighbourhood. Typical specimens are Nos. 4679, 4684, 4685, 4686, streaky non-fissile rocks in which large shattered porphyroblasts of red garnet are enclosed in a dark matrix containing abundant hornblende, biotite or diopside. In many places the garnet porphyroblasts occurring in any individual specimen (e.g., No. 4685) are crossed by closely spaced parallel fractures (*ac* joints of Sander) constantly oriented perpendicularly to the linear foliation. Two contrasted types of garnet-gneiss rich in biotite and diopside respectively are described below:—

In section No. 4679 coarse augen of plagioclase 3 mm. or more in diameter are enwrapped by subparallel prisms of epidote and flakes of brown biotite; cataclastic structures are not developed, however. The composition was estimated as plagioclase (Ab_{70}) 30%–40%, quartz 15%–20%, biotite 25%, epidote 10%, hornblende 5%, garnet 3% and accessory apatite. Sieve structure is well exhibited by the large garnets and coarse prisms of colourless epidote, while the latter may sometimes enclose intergrown vermicular quartz. In the hand-specimen garnet is considerably more plentiful than in the section.

The rock is closely similar to coarse garnet-gneisses from Milford Sound (cf. G. 4 and G. 18 of Marshall, 1907, p. 500; An 1, An 9, An 11 of Speight, 1910, p. 265).

No. 4686 has an entirely different composition, viz., plagioclase 40%, pale green diopside 30%, garnet, 20%, hornblende 5%, biotite 5%, rutile 1% and accessory iron-ore and apatite. The plagioclase is basic oligoclase (Ab_{73}) in coarse equant grains 1 mm. to 2mm. in diameter often showing incipient peripheral granulation. The hornblende shows a rather unusual pleochroism.

X = pale yellow
Y = deep brownish yellow
Z = deep green with a yellowish tinge.
Z = Y > X.

The mineral identified as rutile is the same as that referred to in the description of the hornblende-plagioclase gneisses. No. 4684 is closely similar to the above, but the section contains less garnet and correspondingly greater amount of plagioclase (Ab_{75-80}).

Leucocratic garnet-feldspar granulites or gneisses of quite a different type (Nos. 4693, 4694) were collected from narrow sharply-defined bands cutting hornblende-plagioclase-epidote-gneiss (No. 4692) on the northern shore of Hall's Arm.

No. 4693 represents a vein four inches in thickness cutting almost perpendicularly across the foliation of the enclosing hornblendic gneiss. It is a white feldspathic rock studded with red grains of garnet (2 mm. to 5 mm.) that make up about 25% of the bulk composition. In the corresponding section garnet is a good deal more plentiful. The feldspar is entirely plagioclase (Ab_{68-74}) and is considerably sheared and granulated. A strongly pleochroic highly birefringent mineral optically indistinguishable from biotite (X = pale yellow, Z = deep green), is frequently associated with the garnet, both marginally and along cracks in the larger fractured grains; this is possibly a ferruginous "chlorite" allied to stilpnomelane or bowlingite. Colourless epidote is present in small amounts together with accessory apatite, hornblende and iron-ore. No. 4694* (stream boulder) is macroscopically similar to No. 4693 but differs entirely in structure and in the presence of diopside and orthoclase. About 50% of the section is made up of plagioclase (about oligoclase-andesine) and minor orthoclase, both in a partially granulated condition. Enclosed in the feldspathic matrix are ill-defined composite spots consisting of garnet, diopside and quartz (Fig. 5). The central portion of each spot consists of aggregated equant grains of pale-green diopside sometimes with one or two grains of pink hypersthene at the centre itself. The nucleus of pyroxene is surrounded by a border consisting of pink garnet and interstitial quartz, with quartz occurring also as small inclusions in some of the garnet grains. Coarse yellow rutile is often present in the outer zones, less commonly in the pyroxenic nuclei of these aggregates. The section also shows a string of larger slightly darker crystals

* For analysis, see Table III.

of garnet without sieve structure, and apparently unrelated to the composite pyroxene-garnet spots. A few prisms of apatite and flakes of biotite were also noted. The rock appears to be closely comparable both structurally and mineralogically with a gneiss from Duck Cove, Doubtful Sound, described by Marshall (1907, p. 501; G. 24) and Speight (1910, p. 260; D. 3).

An isolated occurrence of melanocratic garnet-gneisses in association with sheared hornblendic gneisses about half-a-mile from the head of Deep Cove on the south-western shore is represented by Nos. 4554, 4555,† 4560. The chief constituents of the sections are biotite 40%–50%, amphibole 25%–40%, oligoclase-andesine 15% and garnet 5%–10%. The coarse flakes of biotite appear quite unaltered and show an unusual pleochroism from very pale yellow (X) to deep brownish-yellow (Y and Z). The amphibole is pale bluish-green actinolite, in aggregates of slender prisms often more strongly coloured at the margins than centrally, just as has been recorded for the secondary amphibole in associated hornblende-gneisses. Coarse

	L	M
SiO_2	43.04	55.81
Al_2O_3	18.03	18.61
Fe_2O_3	1.20	0.42
FeO	11.55	7.06
MgO	11.12	4.02
CaO	3.38	7.20
Na_2O	1.52	3.13
K_2O	4.89	1.79
H_2O above 105° C.	3.54	0.18
H_2O below 105° C.	0.39	0.09
CO_2	—	—
TiO_2	0.88	1.07
P_2O_5	0.24	0.44
ZrO_2	—	tr.
S	0.14	0.02
MnO	0.18	0.12
NiO	0.02	—
Cr_2O_3	tr.(?)	0.01
BaO	0.05	0.08
SrO	0.01	0.10
Total ..	100.18	100.15*

TABLE III.

L—No. 4555, garnet-biotite-gneiss, Deep Cove, Doubtful Sound. Anal., F. T. Seelye.

M—No. 4694, garnet-plagioclase-diopside-gneiss, Hall's Arm, Doubtful Sound. Anal., F. T. Seelye.

* To this should be added Rare Earth Oxides, 0.06.

fractured grains of garnet in Nos. 4554 and 4560 have suffered partial replacement by sharply crystallised, colourless to green chlorite (sign positive, twinning frequent) (see Fig. 4). In the third section the garnets are shattered, but the fractures are filled with fine-grained plagioclase and biotite, chlorite being absent. The analysis

† For analysis, see Table III.

of No. 4555 is quite different from that of any igneous rock recorded in Washington's tables. The rock appears to be a derivative of an aluminous sediment rich in FeO and MgO.

The Hypersthene Gneisses.

Two rocks containing abundant hypersthene as well as diopside (Nos. 4687, 4689*) were collected from the stretch of coast between Hall's and Crooked Arms, where they occur associated with the garnet-gneisses described in the previous section. The estimated composition is plagioclase 50%–60%, hypersthene 25%, diopside 10%–20%, minor deep yellowish-green hornblende, and accessory quartz, apatite and iron-ore (Fig. 6). The plagioclase (Ab_{65-70}) is considerably granulated and shows only occasional twinning. The hypersthene is intensely pleochroic (X = bright salmon-pink, Z = sea-green) and shows notable dispersion of the optic axes ($r < v$). It is optically negative, with 2V = 62°–70°, corresponding to a composition between 32% and 42% Fe SiO_3—a surprisingly low iron-content in view of the intensity of the absorption tests. The analysis (Table IV) corresponds fairly closely with that of the oligoclase-biotite-epidote-quartz-gneiss, No. 4666.

	N	O
SiO_2	55.52	55.93
Al_2O_3	18.31	18.32
Fe_2O_3	2.14	2.39
FeO	4.74	4.91
MgO	3.51	3.97
CaO	6.52	6.17
Na_2O	4.79	4.29
K_2O	1.93	2.62
H_2O above 105° C.	0.49	0.22
H_2O below 105° C.	0.12	
CO_2	—	
TiO_2	1.14	0.81
P_2O_5	0.49	0.56
ZrO_2	—	
S	0.11	
MnO	0.11	0.14
NiO	—	
Cr_2O_3	—	
BaO	0.07	
SrO	0.09	
Total ..	100.08	100.33

Table IV.

N—No. 4689, hypersthene-diopside-plagioclase-gneiss, Doubtful Sound. Anal., F. T. Seelye.

O—Orthoclase gabbro-diorite, Yellowstone National Park, U.S.A. (Washington, 1917, p. 484, no. 38).

Perhaps originally of similar composition is No. 4690, in which the only recognisable pyroxene is diopside in a state of partial replacement by actinolite; it is possible that some of the actinolite

* For analysis, see Table IV.

aggregates represent hypersthene, though no trace of that mineral is still preserved. As in the hypersthene-bearing gneisses garnet is absent, but biotite is a minor constituent.

A hypersthene-gneiss without diopside (No. 4564) is associated with melanocratic garnet-gneisses and hornblendic gneisses on the western side of Deep Cove, half a mile from the head. In this rock plagioclase (Ab_{46-50}) is associated with abundant hypersthene and yellow-brown biotite, minor pale hornblende, a little secondary actinolite and accessory apatite. The hypersthene is almost colourless, but the axial angle has a much lower value ($2V = 46°–50°$, negative) than was determined for the strongly pleochroic hypersthene of the other gneisses, indicating a composition correspondingly richer in $Fe SiO_3$ (60%–65%). Most crystals are bordered by a narrow rim of secondary pale-green to colourless actinolite ($2V = 76°$, negative).

THE MARBLES AND CALC-GNEISSES.

Marbles and associated rocks composed of calc-silicates were observed at three localities, viz., at Kellard Point a short distance in from the entrance of Crooked Arm, at the southern headland of the entrance to Hall's Arm, and at the great waterfall on the eastern side of the head of Deep Cove. Calc-silicate gneisses not associated with marble were also recorded just south of the entrance to First Arm and on the eastern shore of the Sound half a mile from the head of Deep Cove.

The marbles (Nos. 4582, 4593, 4618, 4634, 3667, 3670, 4673, 3677) consist of a mosaic of coarse usually twinned grains of calcite* enclosing isolated rounded crystals or composite spots of silicate minerals (Fig. 8). At Kellard Point the dominant marble is copiously flecked with golden-brown phlogopite (almost colourless and uniaxial in section), which typically is accompanied by pale diopside (No. 4673) or occasionally by brilliant flakes of graphite (No. 4677). Less common at this locality are marbles containing isolated grains of scapolite, orthoclase, diopside and phlogopite (No. 4670), or scapolite, diopside and clinozoisite (No. 4667). The two sectioned specimens from near Hall's Arm are simpler types containing in one case diopside (No. 4618) and in the other phlogopite (No. 4634). More complex associations of silicates characterise the marbles from the Deep Cove waterfall (Nos. 4582, 4593). In the latter rounded isolated grains of quartz, diopside, epidote, scapolite and sphene and a composite cluster of diopside, epidote, microcline and apatite were recorded. In No. 4582 there are several patches (2 mm. to 5 mm. wide) consisting of microcline, quartz, labradorite, pale amphibole, diopside, biotite and zoisite (the latter intergrown with quartz), while the remainder of the rock is spotted with single grains of orthoclase, perthite, microcline, diopside and a colourless epidote mineral with very low birefringence and anomalous blue interference tints (zoisite or clinozoisite). Thus in the Doubtful Sound marbles the minerals commonly occurring singly in equilibrium with calcite are diopside, phlogopite, scapolite, potash feldspar, zoisite, clinozoisite, quartz, sphene.

* Staining tests with ferric chloride and ammonium sulphide show that dolomite is almost absent.

The calc-silicate rocks occur mainly as small nodules and discontinuous streaks up to four inches in thickness enclosed in or adjacent to marble. In addition to the hornblende and biotite-rich bands already referred to, the essential associations recorded are as follows:—

Epidote-diopside-sphene-quartz: with dominant epidote, Nos. 4619, 4622, 4627, 4628; with dominant diopside, Nos. 4626, 4639.

Epidote-diopside-quartz (with minor microcline, sphene and calcite): Nos. 4588, 4589.

Epidote-diopside-plagioclase: Nos. 4591, 4592, 4668 (with minor hornblende, scapolite and sphene).

Epidote-quartz: Nos. 4629, 4636, 4578 (with minor hornblende and apatite).

Zoisite-diopside-plagioclase (with minor biotite or hornblende, and sphene): Nos. 4674, 4678, 4672 (with epidote in addition).

Zoisite-scapolite-quartz (with epidote): Nos. 4583, 4647.

Diopside-hornblende-plagioclase-epidote: Nos. 4591, 4592.

Diopside-epidote-zoisite-scapolite-quartz: Nos. 4587 (with microcline), 4590 (with bytownite).

Plagioclase-quartz-epidote-sphene: Nos. 4633, 4635.

Plagioclase-actinolite-epidote-sphene: Nos. 4630 (with minor diopside and orthoclase), 4640 (with plentiful quartz), 4671.

Garnet-diopside-epidote-quartz: Nos. 4620, 4621, 4625.

Garnet-diopside-quartz-calcite: No. 4676.

Diopside-epidote-scapolite-garnet (with minor plagioclase and sphene): No. 4631.

Microcline-hornblende-epidote-zoisite-diopside-plagioclase-quartz-biotite-scapolite (with accessory sphene and apatite): No. 4586.

Microcline-scapolite-anorthite-zoisite-quartz: No. 4583.

Plagioclase-diopside-hornblende-epidote-calcite-microcline-quartz: Nos. 4662, 4664.

Minerals of the epidote group occur in almost every section, and include three varieties, viz., epidote, clinozoisite and zoisite, all of which may sometimes be associated in a coarsely crystalline condition within the limits of a single rock-section (e.g., Nos. 4583, 4587, 4590). The most widely distributed variety is a moderately to highly birefringent, colourless, optically negative epidote, that characteristically occurs as very coarse irregularly bounded crystals not infrequently enclosing numerous small granules of quartz, calcite or sometimes plagioclase (e.g., Nos. 4622, 4668, 4671). Usually less plentiful than epidote is colourless clinozoisite occurring either as separate prismatic crystals (e.g., No. 4590) or as narrow marginal zones bordering grains of epidote (e.g., No. 4583). Low birefringence and strong dispersion combine to give a characteristic anomalous blue interference tint which is intensified as extinction is approached and gives place to brownish yellow after extinction is passed. The positive sign and large axial angle are distinctive: $2V = 72°$ (No. 4678); $2V = 66°, 90°$ (both in No. 4590). As shown by the variable

axial angle the almost iron-free clinozoisite grades through types containing a small amount of iron into the colourless optically negative epidote just described. In the rocks of Doubtful Sound zoisite always takes the form of elongated, sharply bounded, rather coarse colourless prisms, typically grouped in subparallel position and separated by coarsely intergrown quartz (Fig. 7). It is distinguished from the clinozoisite which so often is also present by its normal grey-white interference tints and consistently small optic axial angle: $2V = 10°$, 30°–40°, 40° (No. 4678); 35°–40° (No. 4583a), 30°–35°, 40° (No. 4590). The sign of elongation is positive or negative, and the optical character is positive. Where zoisite and epidote are associated in the same rock there is nothing in their mode of occurrence to suggest other than an equilibrium relationship between the two minerals.

Diopside is also widely distributed in the calc-silicate rocks and is the main constituent of narrow dark-green bands and lenses that occur here and there among the marbles. In the rocks of Kellard Point it is almost colourless in thin section, but elsewhere is typically pale-green or occasionally deep-green (e.g., No. 4631). In most slides the crystal outline is not sharply defined, but salite structure is often prominently developed. Rarely (e.g., No. 4630) it appears to be undergoing replacement by pale actinolitic amphibole, but on the other hand in sections where diopside and strongly coloured hornblende are closely associated the two phases appear to coexist in equilibrium (e.g., Nos. 4592, 4639).

Equant rounded or irregularly bounded grains of scapolite are plentiful in many rocks, particularly those from the Deep Cove waterfall (Fig. 7). It approximates, in all cases where birefringence was measured,* to mizzonite, but appears to vary within wide limits within a given slide. Thus in No. 4583a ($\gamma-\alpha$) was estimated as 0·023, 0·029, 0·030, 0·038 in different grains, corresponding to variation between about 45% and 80% meionite. [Note that these percentages are only approximate, since the birefringence of scapolite is affected also by the amount of sulphur and (OH) present in the molecule (Winchell, 1933, pp. 295, 296)]. A single measurement in No. 4590 gave ($\gamma-\alpha$) = 0·030. There is a marked tendency for scapolite to occur plentifully in rocks containing zoisite. In sections where it is associated with basic plagioclase (e.g., Nos. 4583, 4590) the two minerals appear to be in equilibrium, but in one section of spotted marble (No. 4667) some of the larger spots of scapolite are in process of replacement by clinozoisite, slender prisms of which have grown radially inward from the margins.

Nodular masses of pink garnet-rock 2 mm. to 5 mm. in diameter are not uncommon in the marbles from near Hall's Arm, but are rare at Kellard Point and were not observed at the head of Deep Cove. Sections show coarse granular aggregates of pinkish-yellow or pale-pink garnet sometimes with abundant inclusions of calcite (No. 4620) associated with clinozoistic epidote, diopside, quartz and

* Birefringence was determined in all cases by the standard Universal-stage method described by Nikitin (1936) using adjacent grains of quartz for comparison.

accessory sphene. The epidote often contains plentiful vermicular grains of intergrown quartz (Nos. 4621, 4625) or calcite (No. 4620) and tends to build up marginal zones incompletely surrounding the aggregates of garnet grains. Garnet of similar appearance is a minor constituent of a large diopside-epidote-scapolite nodule (No. 4631) from the same locality and is concentrated conspicuously towards the outer portion of the specimen. No. 4676 (Kellard Point) shows a rather different assemblage, small granular patches of garnet (5 mm. in diameter) being scattered through a marble that contains abundant rounded crystals of diopside in addition.

Green or greenish-brown hornblende is for the most part confined to the hornblende-plagioclase bands already described. Where these adjoin diopside-bearing rocks, an assemblage consisting essentially of hornblende, andesine, diopside and epidote minerals is developed at the junctions (Nos. 4591, 4592). A similar but more complex association of minerals, including calcite, microcline and quartz in addition, characterises the calc-gneisses (Nos. 4662, 4664) locally interbedded with feldspathic gneisses south of the entrance to First Arm. A small streak consisting entirely of dark olive-green hornblende cuts sharply across a section of diopside-epidote rock (No. 4639) from the Hall's Arm locality. A pale-green actinolitic amphibole, occurring in rather stout prismatic crystals with a tendency to sieve structure, is associated with epidote and sphene in several specimens of highly sheared leucocratic rocks rich in plagioclase (Nos. 4630, 4640, 4671). It seems to have replaced a more strongly coloured amphibole, relicts of which are still preserved in No. 4630. Actinolite is certainly secondary after hornblende in No. 4662 and after diopside in No. 4630.

Plagioclase approximating to acid andesine (Ab_{60} to Ab_{70}), though sometimes rather more calcic or more sodic than this range, is a member of several assemblages. Highly calcic varieties were noted in two sections, viz., Nos. 4590 (bytownite) and 4583 (anorthite). In the latter section observations on lamellar twins having the twin axis perpendicular to the composition plane give the following co-ordinates for the pole of the twin axis with respect to the axes of the indicatrix: 46° (Z), 65° (Y), 57° (X). Two solutions are possible: if the twin axis is $\perp$ (010) the composition is Ab_5 An_{95}; if the twin axis is $\perp$ (001) the composition Ab_{20} An_{80}. The former alternative is confirmed by the axial angle as determined in adjacent twin lamellae [$2V = 74°$ (—) and 76° (—)], and the birefringence ($\gamma - \alpha = 0{\cdot}011$) as observed in comparison with adjacent grains of quartz.

Microcline is present in a number of rocks from Deep Cove and in the two complex diopside-bearing calc-gneisses (Nos. 4662, 4664) from the southern side of the entrance to First Arm. In No. 4583 (Deep Cove waterfall) it is intricately intergrown with either anorthite or epidote. Rounded grains of orthoclase, perthite or microcline are also present in several marbles. This frequent presence of potash-feldspar in the calcareous rocks of Doubtful Sound is contrasted with its rarity in associated hornblendic and feldspathic gneisses, suggests that it is derived from reaction between dolomite,

calcite, silica and detrital sericite (cf. Tilley, 1920, p. 497) or from recrystallisation of authigenic orthoclase originally present in the parent limestones (cf. Daly, 1917, pp. 661–662; Spencer, 1925) rather than from magmatically introduced material. The latter possibility cannot be excluded, however, in view of the abundance of scapolite in these rocks and the presence of occasional dykes of granite-pegmatite in adjacent gneisses.

Sphene, sometimes coarse and idioblastic but more often in rounded or spindle-shaped grains of rather small size, is a minor constituent of most rocks. In some slides it is plentiful (more than 5% of the total composition), especially as inclusions in diopside (Nos. 4622, 4626, 4639) or epidote. Apatite is a frequent and pyrite a rare accessory mineral of the calc-silicate rocks.

Distribution and Mutual Relations of Rock-types.

For a distance of about a mile from the head of Deep Cove, hornblende-plagioclase-gneisses and hornblende-plagioclase-biotite gneisses are the main rocks exposed along the eastern shore. The plagioclase of these rocks is often more calcic than in similar gneisses further north (e.g., Ab_{48-50} in No. 4569: Ab_{55-65} in No. 4576). Oligoclase-quartz-gneisses are relatively unimportant in this section of the coast. Beneath the great waterfall at the head of the cove, minor lenses and bands of marble and calc-gneisses are interstratified with various types of hornblende-gneiss,* while about half a mile north of this a small band of epidote-quartz rock (No. 4578) was recorded. From a point about 1 mile to 1½ miles from the head of the cove to the southern end of Elizabeth Island, oligoclase-quartz-gneisses, often containing allanite and locally notable amounts of microcline (No. 4611) predominate over hornblendic rocks. The rocks of Elizabeth Island and the adjacent eastern shore of the Sound, however, are strongly foliated hornblende-plagioclase-epidote-biotite-gneisses of a distinctive and uniform type (composition of plagioclase, Ab_{75-80}).

Hornblende-plagioclase-gneisses and hornblende-plagioclase-biotite-gneisses with subordinate oligoclase-quartz-gneisses are also the principal rocks exposed along the western shore of the Sound between the head of Deep Cove and the entrance to Hall's Arm. There are several noteworthy departures from this general association, however. At the small headland half a mile from the head, hornblende-plagioclase-biotite-gneisses containing abundant yellow-brown biotite are intimately associated with biotite-rich garnet-gneiss. The single specimen of hypersthene-bearing gneiss (No. 4564) from this locality is perhaps an incompletely metamorphosed norite, since the hypersthene has the lamellar structure peculiar to rhombic pyroxenes of the plutonic rocks (Hess and Phillips, 1938), and is a colourless variety differing greatly from the metamorphic pink hypersthene observed north of Hall's Arm. Retrogressive conversion of hornblende (or hypersthene) to actinolite and of garnet to chlorite is common in the rocks of this locality. A special phase of gneiss

* Strike 15° W. of N.; dip 30° to E.

occurring for some chains on either side of the first headland south of the entrance to Hall's Arm is a non-feldspathic hornblende-biotite rock (Nos. 4616-4617), often greatly sheared and apparently intrusive into the associated rocks. At the point marking the southern side of the entrance to Hall's Arm, and again on the small island nearby, marble and calc-gneiss are regularly interbedded with the normal hornblende-plagioclase-gneisses; the dip is regularly eastward at 40° to 45° (strike 10° W. of N.).

The rocks of Hall's Arm are mainly streaky well-foliated hornblende-plagioclase-epidote-biotite-gneisses (Nos. 4691, 4692, 4695) similar to those of Elizabeth Island. Along the north shore of the Arm for a distance of between one and two miles from the entrance, these rocks are associated with garnet-bearing gneisses, indicating a higher grade of metamorphism than was reached further south. This higher grade is maintained between Hall's Arm and Kellard Point, the typical associations being garnet-diopside-plagioclase, garnet-biotite-epidote-plagioclase-quartz, hypersthene-diopside-plagioclase; intimately associated with these are rocks consisting of the assemblages hornblende-plagioclase-quartz and plagioclase-quartz-biotite. The principal outcrop of calcareous rocks, phlogopite-marble accompanied by the usual calc-gneisses containing epidote, diopside, garnet, scapolite, etc., occurs at Kellard Point. The strike here is between 20° and 30° W. of N., with an easterly dip of about 25°.

Between Crooked and First Arms the coastal section was examined in less detail than elsewhere. Oligoclase-quartz-gneisses predominate and hornblendic rocks are less abundant than elsewhere. Garnet-bearing types were not observed. Immediately south of First Arm calc-gneisses containing oligoclase, quartz, microcline, diopside, calcite, epidote and minor hornblende (Nos. 4662, 4664) are interbedded with the normal feldspathic gneisses which locally are intensely sheared.

The dominant rock at the one point where a landing was effected on Secretary Island (W. shore, 1 ml. N. of The Gut) is a strongly foliated hornblende-plagioclase-gneiss (No. 4658) containing minor biotite, epidote and very coarse sphene. Beach boulders include garnet-bearing types, however, while a rock collected by Dr P. Marshall (1907, p. 502) from Blanket Bay is a hornblende-oligoclase-gneiss with minor biotite, garnet, quartz and rutile.

Two rocks described by Professor R. Speight (1910, p. 262) from Wood Head, opposite the south-eastern end of Secretary Island, are a strongly schistose quartz-biotite-muscovite-gneiss, and a hornblende-plagioclase-gneiss with minor biotite, epidote, quartz and rutile.

Conditions of Metamorphism.

The persistent development throughout the whole of the region under consideration, of mineral assemblages containing hornblende and plagioclase (oligoclase to labradorite) shows that metamorphism was of a regional nature and was effected at high temperatures. Though maintenance of temperature may have been assisted by the

influence of subjacent granitic intrusions, the existence of which is suggested by the presence of occasional pegmatitic dykes, metamorphism of the Doubtful Sound gneisses is not to be regarded as essentially a contact effect. Shearing stress of a high order operating simultaneously with high temperature in reconstitution is indicated by the presence of foliated structures in most rocks, and, judging from the consistently shattered state of garnet porphyroblasts and the granulated and milled condition of quartz and feldspar in many rocks, must have been maintained to a late stage. Shearing seems to have ceased before the temperature began to fall, however, for retrogressive transformations like chloritisation of garnet and biotite and conversion of hornblende to actinolite are usually inconspicuous.

The general association of hornblende with plagioclase, biotite and epidote in varying proportions corresponds to the amphibolite facies of Eskola, or to a metamorphic grade at least as advanced as in the high-grade portion of the garnet zone of the Scottish Highlands (cf. Wiseman, 1934, p. 385). Possibly the grade may even be equivalent to that of the kyanite zone (cf. Harker, 1932, pp. 281, 283, 284), for, though Wiseman finds that in the Scottish epidiorites biotite disappears at the kyanite isograd, the biotite-rich members of the Doubtful Sound rocks obviously are richer in potash than the rocks studied by Wiseman.

Along the western coast of the Sound between Hall's and Crooked Arms the prevalence of gneisses containing almandine garnet and pyroxenes, though associated always with hornblende rocks in which these minerals are absent, is an indication of an even more advanced grade of metamorphism. The principal associations here are:—

Garnet-diopside-plagioclase (basic oligoclase) with minor hornblende and biotite.

Hypersthene-diopside-plagioclase (acid andesine) with minor hornblende.

Garnet-biotite-epidote-plagioclase-quartz with minor hornblende.

Plagioclase-quartz-biotite.

Hornblende-plagioclase-quartz.

On the map this locality is marked as a zone of garnet- and pyroxene-bearing gneisses; rocks containing garnet and hypersthene also occur locally at a point about half a mile from the head of Deep Cove on the western side. Assemblages containing garnet and diopside on the one hand or diopside and hypersthene on the other are characteristic of the highest grade of regional metamorphism, and, together with the coarsely crystalline condition of the rocks in question, indicate that reconstitution probably took place at great depth (cf. Harker, 1932, p. 284).

In a series of recent studies on the depth conditions governing the crystallisation of various metamorphic assemblages, D. K. Korjinsky (1936, p. 48; 1936a, pp. 279, 280; 1937, p. 393) has proposed

the following high-temperature facies arranged in order of decreasing depth for rocks without an excess of CaO and Al_2O_3 but saturated in SiO_2:—

(1) Hornfels facies
(2) Almandine-hornfels facies
(3) Eclogite facies
(4) Garnet-amphibolite facies (almandine-hornblende-diopside)
(5) Hypersthene-gneiss facies (almandine-hypersthene-plagioclase, with or without biotite; hypersthene-diopside-plagioclase, with or without biotite or hornblende).

The garnet- and pyroxene-bearing gneisses of Doubtful Sound would appear to correspond to a transition facies between (4) and (5) in Korjinsky's scheme.

The same writer (Korjinsky, 1937) has paid particular attention to the relation of calc-silicate assemblages to depth, and proposes the following scheme for calcareous and dolomitic rocks (listed in order of decreasing depth):—

(1) Larnite-merwinite facies
(2) Gehlenite-monticellite facies (without larnite, merwinite, spurrite, etc.)
(3) Periclase facies (without gehlenite and monticellite)
(4) Wollastonite-grossularite facies (equivalent to garnet-amphibolite facies)
(5) Facies characterised by absence of grossularite and wollastonite (equivalent to the hypersthene-gneiss facies). Characteristic minerals, as developed in the Aldan massif of Eastern Siberia, are calcite, diopside phlogopite, pargasite, hornblende, scapolite, andesine, chondrodite, clinohumite, spinel, quartz, potash feldspar, dolomite, forsterite.

The minerals characteristic of the calcareous rocks of Doubtful Sound are calcite, epidote, diopside, clinozoisite, zoisite, scapolite, plagioclase (oligoclase, andesine or rarely bytownite or anorthite), hornblende, phlogopite, microcline (or orthoclase), garnet,* quartz, sphene and dolomite (rare). The presence of a grossularite garnet and the great abundance of epidote minerals distinguish this general assemblage from that of Korjinsky's deepest zone, though of the epidote mineral zoisite at least is stable in deep-seated facies (Korjinsky, 1937, pp. 390, 391). On the other hand complete absence of wollastonite and the presence of quartz and calcite in mutual association are significant grounds for distinction from rocks of the wollastonite-grossularite facies and would appear to indicate crystallisation at a greater depth than these. The mineralogy of the Doubtful Sound rocks is thus apparently consistent with their crystallisation under conditions intermediate between those governing the facies listed above under (4) and (5) in Korjinsky's grouping.

*A member of the grossularite-andradite series containing appreciable iron; $\mu > 1.79$.

Retrogressive mineralogical changes are, on the whole, unimportant. They include replacement of garnet and biotite by chlorite, and crystallisation of pale tremolite or actinolite at the expense of green hornblende, diopside or hypersthene. In a few instances granular epidote appears to have formed by the breaking down of plagioclase or of hornblende during especially intense shearing.

STRUCTURE.

Vertical or steeply dipping joints, which are often very regular and may simulate bedding when seen from a distance, constitute the most conspicuous structural element of the gneisses of Doubtful Sound. Foliation is usually obvious on close inspection, but definite bedding is usually difficult to distingush. Where both these structures are distinctly developed, as where marbles and hornblende-gneiss are interstratified, they appear to be parallel. Linear structures when present are usually difficult to record accurately unless the outcrops show well-defined foliation surfaces.

On both sides of Deep Cove and along the western shores of the Sound north of Hall's Arm, the dominant strike of the foliation is N.N.W. (330° to 360°). The dip is mainly eastward at angles of between 15° and 40°, but becomes relatively flat around the entrance to First Arm, and at the single point where landing was made on Secretary Island is definitely westward. Three sets of approximately vertical joints were observed, of which not more than two were recorded at any one locality: (a) striking between 235° and 275°, i.e., roughly perpendicular to the foliation; (b) parallel to strike of the foliation; (c) striking in a W.N.W. direction (295° to 300°).

Along both sides of Hall's Arm and the eastern shore of the Sound immediately opposite (in the vicinity of Elizabeth Island) the foliation strikes consistently in a N.E. direction (25° to 55°), and cross joints are prominently developed nearly perpendicularly to this (295° to 320°).

There is thus structural evidence of two deformations connected respectively with a N.N.W. and a N.E. tectonic axis. While the former axis is on the whole the more conspicuous of the two, the N.E. axis dominates the structure in the vicinity of Hall's Arm and Elizabeth Island; with it the W.N.W. cross jointing locally developed elsewhere should probably be correlated. The north-east trend of Hall's Arm itself is perhaps ultimately connected with the same tectonic direction. The dominant structures of the gneisses of Lake Manapouri have also been correlated with deformation across a tectonic axis having a prevalent N.N.W. trend but locally deviating to N.W. or N.E. (Turner, 1938, p. 132). The same tendency for local north-easterly deflection of a strike that generally trends slightly west of north has been recorded by Professor W. N. Benson for the slates, schists and gneisses of Preservation and Chalky Inlets (Benson, 1934, p. 420).

CORRELATION.

The gneisses of Doubtful Sound are continuous with the dominantly hornblendic gneisses of Lake Manapouri which the writer has recently correlated with Professor Park's Dusky Sound Series of

probable Palaeozoic age (Turner, 1937b, pp. 245, 246). Though the latter have as yet been only incompletely described (Marshall, 1907; Speight, 1910; Park, 1921, pp. 35, 36), they appear to resemble the more strongly metamorphosed of the Doubtful Sound rocks in many respects. For example, the mineral assemblages recorded by Professor Speight *(loc. cit.)* include the following from Dusky Sound: garnet-quartz-plagioclase-microcline-hornblende-epidote-biotite-sphene (D 1); garnet-diopside-plagioclase-quartz-hornblende with minor orthoclase, biotite and rutile (D 3) (also S 24 of Marshall, 1907, p. 501); hornblende-feldspar-rutile (D 15); quartz-microcline-biotite (D 16). The similarity confirms the correlation previously made for the Manapouri gneisses.

ACKNOWLEDGEMENTS.

The writer wishes to acknowledge gratefully his indebtedness to the Australian and New Zealand Association for the Advancement of Science for supplying a grant to defray the cost of field work. His thanks are also due to Drs H. L. Briggs and C. M. Focken for assistance in the field, to Professor W. N. Benson for advice and suggestions during laboratory investigations, and especially to Mr F. T. Seelye of the Dominion Laboratory for the nine chemical analyses that are published in this paper, and to Dr J. Henderson, Director of the N.Z. Geological Survey, who kindly made arrangements for carrying these analyses out.

LOCALITY LIST.

Specimen Number.	Locality.
4554-4568	W. coast of Deep Cove, ½ mile from Head.
4569-4572	E. coast of Deep Cove, 1 mile from Head.
4573-4576	E. coast of Deep Cove, ¾ mile from Head.
4577-4581	E. coast of Deep Cove, ½ mile from Head (at the base of prominent bare bluff).
4582-4599	Great waterfall at E. side of Head of Deep Cove.
4600	E. side of Elizabeth Island, 1 mile from S. end.
4601	E. coast of Sound, opposite middle of Elizabeth Island.
4602-4603	Elizabeth Island, near South end.
4604-4608	E. coast of Sound, opposite S. end of Elizabeth Island.
4609	E. coast of Sound, opposite middle of Hall's Arm.
4610-4611	E. coast of Sound, opposite southern headland at entrance to Hall's Arm.
4612-4613	W. coast of Sound, 1 mile from Head.
4614-4617	W. coast of Sound, ¼ mile S. of entrance to Hall's Arm.
4618-4649	W. coast of Sound, at S. side of entrance to Hall's Arm.
4650-4653	W. coast of Sound, ¾ mile S. of entrance to Hall's Arm.

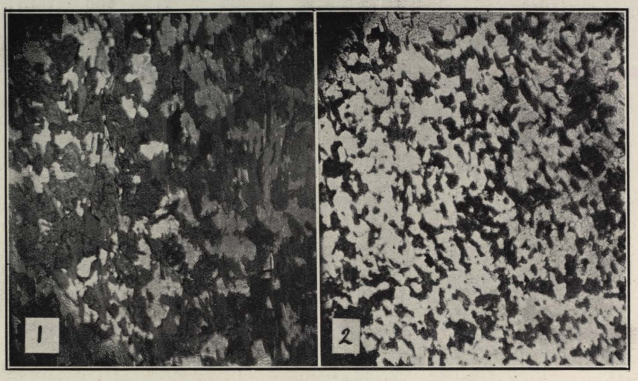

FIG. 1.—Hornblende-plagioclase-biotite-gneiss ("dioritic" type), No. 4599.
FIG. 2.—Fine-grained hornblende-plagioclase-gneiss, No. 4596.

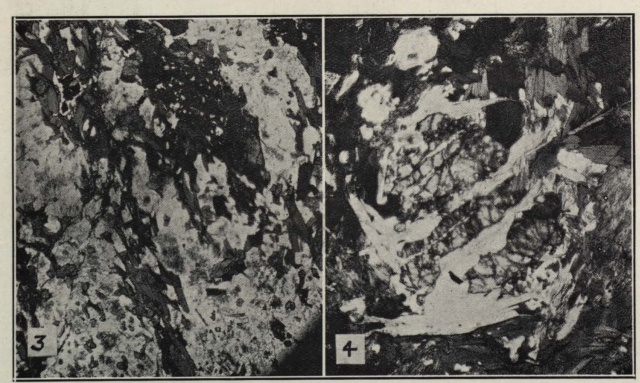

FIG. 3.—Coarse-grained hornblende-plagioclase-epidote-biotite-gneiss, No. 4601. The large sieved crystal in the top centre is hornblende; remaining dark crystals are mostly biotite.

FIG. 4.—Garnet-biotite-gneiss, No. 4554. A large central grain of garnet is surrounded and crossed by colourless chlorite; dark crystals around border of photograph are biotite.

All figures × 12.

To face page 596.

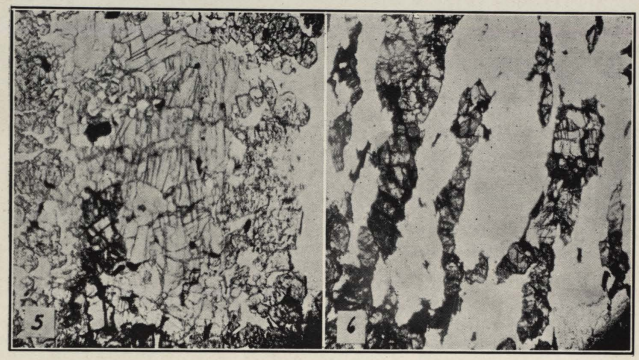

FIG. 5.—Diopside-garnet-gneiss, No. 4694. Diopside at centre (showing cleavage) surrounded at sides of photograph by garnet and interstitial quartz.

FIG. 6.—Diopside-hypersthene-gneiss, No. 4687. The colourless clear mineral is plagioclase.

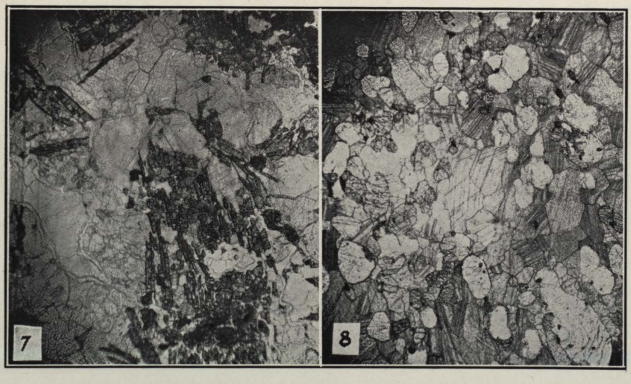

FIG. 7.—Prismatic zoisite surrounded by scapolite and quartz, No. 4678.

FIG. 8.—Marble with rounded grains of diopside, feldspar and scapolite.
All figures × 12.

4654-4657	Boulders from beach, W. coast of Deep Cove, ¾ mile from Head.
4658	W. shore of Secretary Island, 1 mile N. of The Gut.
4659	N. side of entrance to First Arm.
4660-4664	S. side of entrance to First Arm.
4665	W. coast of Sound, ¾ mile N. of Crooked Arm.
4666-4678	Kellard Pt., ¼ mile inside Crooked Arm.
4679-4681	W. coast of Sound, 1 mile S. of Kellard Point.
4682-4684	W. coast of Sound, halfway between Kellard and Brigg Pts.
4685-4688	W. coast, 1½ miles N. of Brigg Pt.
4689	W. coast, 1 mile N. of Brigg Pt.
4690	Brigg Point.
4691	N. shore of Hall's Arm, 1 mile from entrance.
4692-4694	N. shore of Hall's Arm, 1½ miles from entrance.
4695	S. side Hall's Arm, ¾ mile from Head.

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