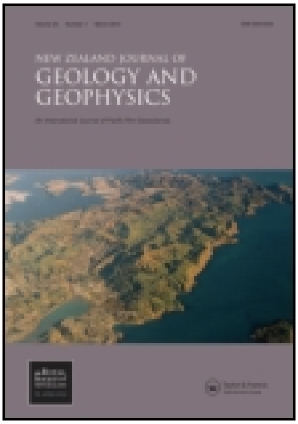


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# OBSERVATIONS ON THE GEOLOGY OF AN AREA NEAR LAKES THOMSON AND HANKINSON, FIORDLAND

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ABSTRACT

The physiography of the area is dominated by glaciated landforms carved in gneiss of the Fiordland Complex. The gneiss is generally dioritic, with gradations to quartzo-feldspathic and amphibolitic varieties, and is cut by mainly barren pegmatite veins; epidote is abundant. The rocks commonly show signs of post-consolidational shearing and crushing. There is a well defined zone of strongly crushed rocks, trending approximately north, which cuts obliquely across the northern end of Lake Hankinson. In general the rocks are petrographically similar to those near Lake Manapouri. Chemical analyses of a microcline-bearing gneiss, a hornblende-biotite gneiss, and an amphibolite are compatible with derivation of these from acid and intermediate volcanic or tuffaceous sedimentary rocks and mildly alkaline olivine basalts respectively. Geometric analysis of foliation attitudes, lineations, and minor fold axes, shows that there is a statistical fold axis plunging gently to the south-west.

## INTRODUCTION

This account is the product of some 10 days work in the region of Lakes Hankinson and Thomson, carried out during the 1962 annual field expedition of the Otago University Science Students Association. The geological party consisted of the authors, together with B. D. Fahey and R. J. Ryburn, who also assisted in preparation of this paper, and R. J. Cavaney, L. R. Dodds, R. J. King, and H. Rimmer. The party was based at Thomson hut for two-thirds of the period and at Hankinson hut for the remainder. Lakeside and creek outcrops were thoroughly examined, and as much as possible of the outcrop above the bush line was visited. A one-day trip was also made to the Henry Pass.

Compilation of the accompanying map (Fig. 1) was greatly facilitated by a preliminary copy of the Wakatipu sheet (Wood, 1962), on which the topography had been plotted from aerial photographs. Study of aerial photographs showed that revision of form lines was necessary in some places.

## PREVIOUS WORK

Little previous geological work has been done in this area. There is a brief account of muscovite pegmatite on Mount Elmwood (Willett, 1946), from which small amounts of commercial mica were taken in the early

years of the century, but which has long since been abandoned. The only geological information published since then is on the Wakatipu sheet (Wood, 1962).

The gneiss of the area forms part of the Wet Jacket Formation of Wood (1960, 1962), which he mapped as a unit composed largely of dioritic rocks, distinguishable from the dominantly quartzo-feldspathic Bradshaw gneiss below and the Long Sound calc-silicate gneiss above. Wood (1962) has recognised a broad synformal structure plunging gently to the south-west across this region.

## PHYSIOGRAPHY

The rocks of the region are dominantly coarse-grained banded gneisses and are thus relatively resistant to erosion. This has been reflected in the topography, which is steep and youthful. Glaciation has resulted in notable over-steepening of the valley walls, the truncation of tributary valleys giving rise to numerous waterfalls, the formation of many valley-head or cirque lakes (for example, Lake Wade), and the scouring and mamillating of exposed rock surfaces. Drainage is directly consequent upon the pattern imposed by glaciation, and is characterised by master rivers following the main U-shaped glaciated valleys, commonly excavated along the strike of the gneisses. They are fed by numerous discordant tributaries and innumenable small runnels and guts which, although dry in fine weather, discharge large quantities of water into the main valleys after heavy rain.

Although the dominant influence on drainage has been that of the Pleistocene glaciations, the internal structure of the rocks themselves also has an effect. For example, immediately up stream from Lake Thomson hut the whole force of the Wapiti River thunders against a major joint face in the gneiss and is diverted 20 to 30 yards sideways before continuing its southern course though a deep narrow canyon cut along another joint surface.

In some places deep furrows have been gouged out of the floors of the valleys to subsequently become lakes, many held up at one end by morainic debris. As emphasised by Cotton (1948, pp. 61–2), these lakes are essentially ephemeral features of the landscape and are fast being silted up. Locally, as at the head of Lake Thomson, aggradation is occurring and deltas are being built.

Deadwood Lagoon, which at first sight might be considered a small glacial lake, appears to have been produced by a relatively recent slip from Mount Murrell damming the Rugged Burn (Hall-Jones, 1959; and relevant aerial photographs).

## PETROLOGY

### *Gneiss*

The gneisses are foliated biotite- and hornblende-bearing feldspathic varieties, generally with some quartz. A single band of quartz-feldspar gneiss about 100 ft thick was seen on the western shore at the extreme southern

end of Lake Thomson, and thin intercalations of similar rock were seen among more basic gneiss at a few other places. Muscovite-bearing gneiss was found *in situ* at one place only—on the ridge north of Hankinson hut.

The foliation is defined by preferred orientation of minerals, especially hornblende and biotite, and is generally fairly regular, although in some places the rocks are massive and practically unfoliated. Well defined gneissic layering is in some places parallel to the foliation, with 1- to 2-in. thick bands of biotite- or hornblende-rich rock alternating with quartzo-feldspathic or feldspathic bands of similar width.

Concordant lenses of contrasted lithology, ranging from a few inches to several feet in length, and up to 3 ft in thickness, are particularly well exposed in slip scars on the west shore of Lake Thomson. Hornblende- and biotite-rich rocks as well as leucocratic quartzo-feldspathic types occur. Less regular inclusions of biotite-rich material were found on the west shore of Lake Hankinson near the isthmus of the peninsula (Fig. 2). Irregular pegmatoid veining is also common (see p. 92).

On the basis of microscopic examination of some 30 thin sections the gneisses are divided into four main groups:

(1) Plagioclase-biotite-hornblende-microcline gneiss (OU 18334, 18321, 18314, 18317)
(2) Plagioclase-biotite-hornblende gneiss (OU 18333)
(3) Plagioclase-biotite gneiss (OU 18326, 18313)
(4) Plagioclase-hornblende-biotite gneiss (OU 18336, 18316, 18315, 18327)

The dominant type appears to be the fourth group, the plagioclase-hornblende-biotite gneiss, which occurs throughout the area. Microcline-bearing biotite-hornblende gneisses are next in abundance, but have been recorded only from the western shores of Lake Thomson, although microcline occurs sporadically in a hornblende-free gneiss (OU 18313) from bluffs just south-west of Hankinson hut.

Where it occurs, *microcline* is subordinate to plagioclase and is non-perthitic; myrmekite has developed at replacement boundaries with plagioclase. Under crossed polars, many plagioclase grains are seen to have albitic borders along junctions with the microcline (cf. Tuttle and Bowen, 1958, p. 140).

*Plagioclase* compositions as determined in the zone perpendicular to {010} in the direction [100] (van der Kaaden, 1951), have a range of only 8%. All measured values fell between $An_{24}$ and $An_{32}$, with the majority $An_{26-27}$. In some gneisses the plagioclase has been extensively sericitised, often preferentially along cleavages.

Green *hornblende* generally occurs as elongate subidioblastic crystals showing sieve structure with quartz (OU 18315). Hornblende usually has $Z$ blue-green, $Y$ olive-green, $X$ pale olive, $2V\alpha$ 53°–57°, $\beta$ = 1·683–4, $Z : c$ = 15°. A significant number of grains in the slide of OU 18336 have the optic axial plane in the plane of the section (which was cut perpendicular to the foliation), indicating a tendency to parallelism of (010) planes perpendicular to foliation, as well as of *c axes* to lineation. The hornblende of a few gneisses (OU 18327), like that of some amphibolites (see p. 92), is paler and less strongly pleochroic than in most specimens.

Brown *biotite* occurs as subidioblastic grains, many showing alteration to chlorite, which was seen in one rock (OU 18333) to be associated also with muscovite and prehnite. Vermicular quartz inclusions were sometimes seen (OU 18317).

*Epidote* was found in all but the two most northerly specimens collected, OU 18327 north-east of Thomson hut and OU 18315 on the Henry Saddle. The epidote is a colourless variety, but pleochroic cores of allanite (Fig. 3A) were found in practically all slides examined (cf. Turner, 1937, p. 239), and vermicular plagioclase inclusions were often seen.

Additional minerals include quartz, which is common but not ubiquitous, sphene, sometimes in large crystals, opaque oxides, and rare zircon (OU 18333).

Textures are typically metamorphic: highly irregular interlocking grains of feldspar and quartz, with crude alignment of subidioblastic hornblende and biotite defining the gneissic structures. Grain size is between 1 and 3 mm in practically all rocks, although in some specimens the texture is finer and more nearly equigranular (OU 18316, a mafic intercalation west of Lake Thomson).

### *Amphibolite*

*Concordant amphibolites* are well represented in the Wapiti Creek section for about 100 yards up stream from Thomson hut. A 15-ft-thick band is exposed at lake level on the north-west shore of Lake Hankinson, and there is a 40-ft-thick band of north-easterly trending coarse amphibolite with quartz veining and gradational boundaries to surrounding gneiss, on the ridge north of Hankinson hut. Quartz-biotite veins, varying from ¼ in. to 1ft in width, were found near the centre of this mass, which at its north-eastern limit has been incorporated as sub-rectangular agmatitic blocks 1 to 2 ft across in quartz-feldspar pegmatite.

OU 18328 from Waipiti Creek near Thomson hut is a hornblende-rich gneiss transitional towards the amphibolites, although its hornblende is of the less common pale green variety, and the rock contains accessory pyrrhotite. The amphibolites proper are characterised not only by predominance of hornblende (which is sometimes pale green, see p. 92), but also by paucity of plagioclase and abundance of epidote, again generally of the colourless variety. Where present, plagioclase has the same composition as that in the gneisses—ranging from $An_{26}$ to $An_{33}$. In the coarse plagioclase amphibolite just described from above Hankinson hut, the plagioclase is very coarsely sericitised and contains ragged epidote. In the amphibolites accessory brown rutile occurs instead of sphene as scattered granular inclusions.

A series of three closely spaced specimens (OU 18329–31) was collected from an amphibolite band in Wapiti Creek a few yards from Thomson hut. They form an interesting sequence that merits closer examination: from top to bottom the essential composition changes from an epidote amphibolite with subordinate quartz and magnetite, through a plagioclase- and quartz-bearing hornblende-epidote rock with muscovite and brown rutile, to almost monomineralic epidotite with quartz and accessory brown rutile.

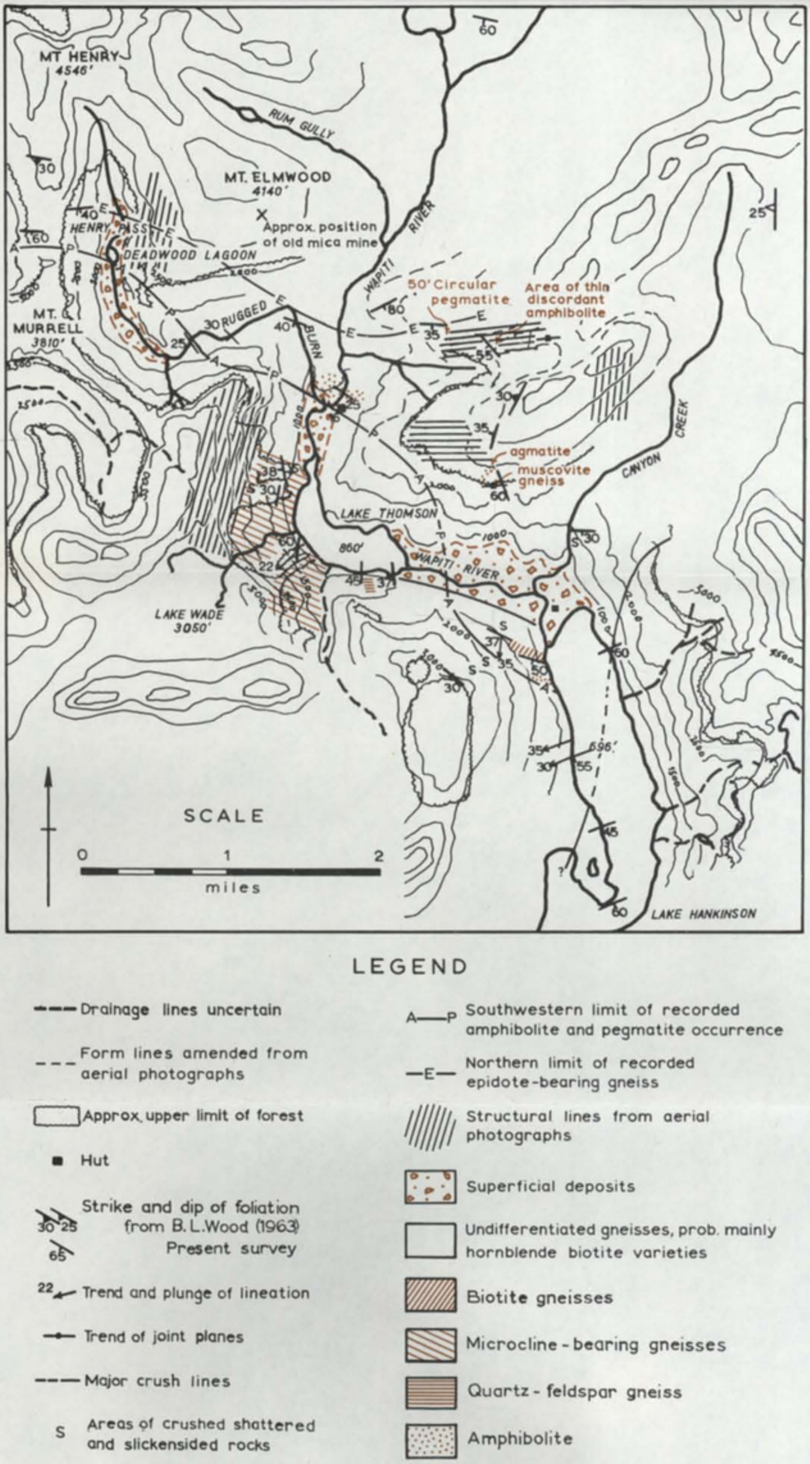




FIG. 1—Geological sketch map of the area near Lakes Thomson and Hankinson.

FIG. 2—Irregular biotite-rich inclusion in leucocratic gneiss, Hankinson pennisula isthmus.

In the top member (OU 18330), hornblende, a normal green variety like that in most of the gneisses, occurs mainly as elongate subidioblastic crystals, but some irregular and much larger grains, up to 6 mm in diameter, enclose epidote, which appears to have been partly resorbed with precipitation of oxide dust (Fig. 3B). The opaque mineral in this rock appears to consist mainly of ilmenite with blebs and lamellae of titanhematite exsolved parallel to {0001}. Pseudobrookite (?) and rutile were also identified, the latter in part replacing titanhematite lamellae. The scattered oxide dust (Fig. 3B) appears to be magnetite. Sparse, scattered grains of pyrite are also present.

In the second specimen (OU 18329), there is also some embayment of epidote by a paler green hornblende (see below), towards which it is otherwise usually idioblastic. Where interstitial quartz occurs near muscovite, the latter has developed a skeletal habit, apparently due to preferential solution along cleavages. The interstices are here filled by quartz, with potash feldspar as a discontinuous selvedge between quartz and mica, and as small inclusions in the quartz (Fig. 4A).

The association of skeletal muscovite, quartz, and potash feldspar in specimen 18329 calls for additional comment. Since the muscovite is in skeletal form *only* where in association with quartz, the presence of the latter is considered to have been directly connected with production of the skeletal form. Reaction between silica and muscovite commonly leads to the formation of potash feldspar and sillimanite:

$$KAl_3Si_3O_{10}(OH)_2 + SiO_2 \rightarrow KAlSi_3O_8 + Al_2SiO_5 + H_2O.$$

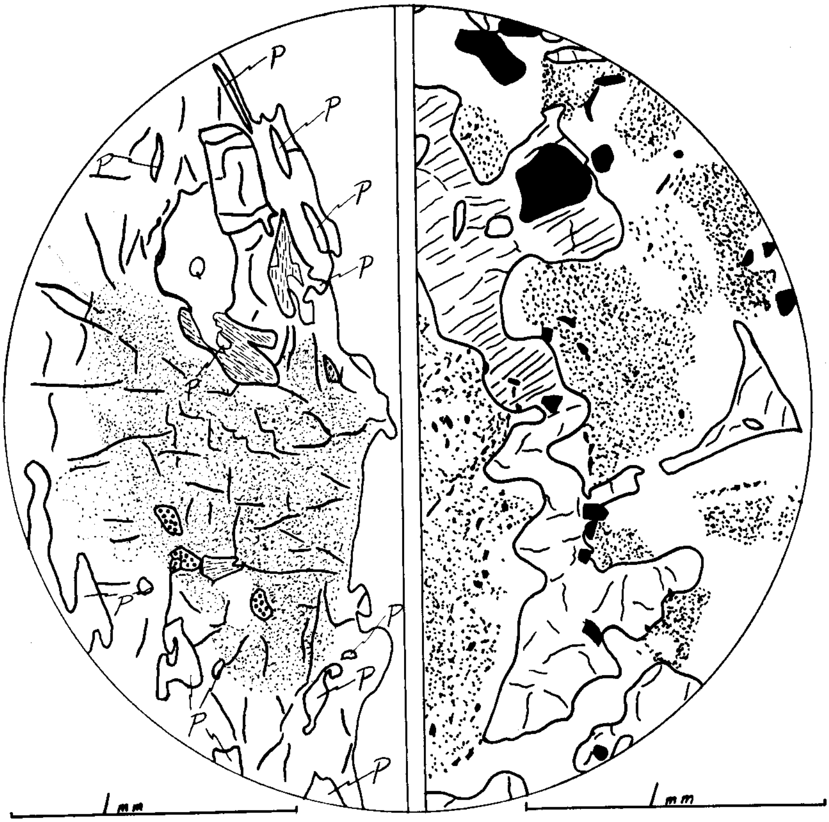


FIG. 3A (*left*)—Epidote crystal in OU 18333, showing well developed allanite core (close stippling), with gradational margin (light stippling), to epidote. Inclusions of plagioclase (P), quartz (Q), chlorite (lined), and apatite (dots).

FIG. 3B (*right*)—Hornblende in OU 18330 (blank) with irregular, possibly partially digested inclusions of epidote (heavy outline, cleavage and fractures); also magnetite (black) and iron oxide dust (stippled).

No sillimanite occurs, however, and the potash feldspar forms only a discontinuous selvedge between muscovite and quartz, the latter often filling in most of the space in the skeletal mica. It seems possible therefore that there were small amounts of silica-rich pore fluid available in the later stages of recrystallisation. Where such fluids encountered the muscovite, reaction resulted in the removal in solution of such components as alumina, water, and perhaps potash. This removal would be accompanied by the precipitation of quartz and potash feldspar in the available pore space.

Benson and Bartrum (1937, p. 115) followed older workers in attributing the vermicular quartz–muscovite intergrowths they found in schists to reaction between potash feldspar and water expelled from invading granite.

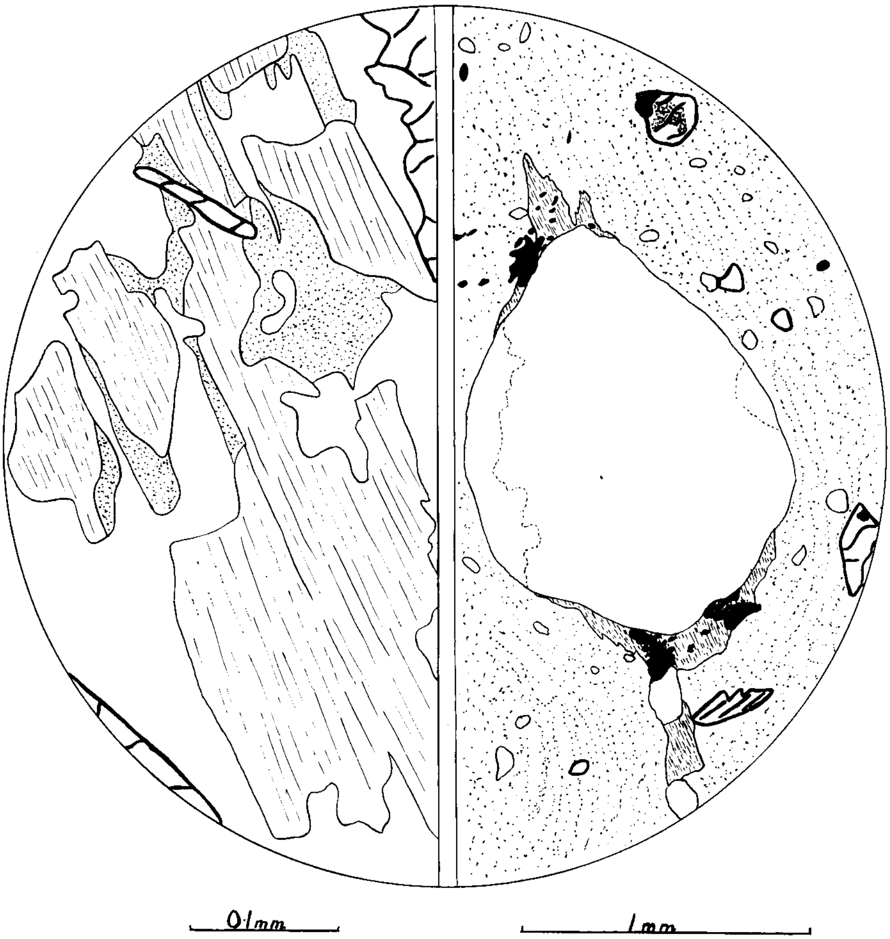


FIG. 4A (*left*)—OU 18329, showing corroded muscovite (lined), quartz (blank), and partial selvedges of potash feldspar (stippled) between the two; also epidote (heavy outline).

FIG. 4B (*right*)—OU 18319, semi-mylonite with oxide dust in groundmass giving effect of flow-banding round plagioclase ovoid (blank—dotted lines delimit marginal cataclasis), with sericite (lined) at either end. Also small fragments of plagioclase, quartz, epidote, hornblende (blank, last two with heavy outline, stippling for allanite core in epidote), and magnetite (black).

Although this is a possible explanation for the textures they observed, it would seem to be inapplicable here since in this case it is apparently the muscovite that has suffered attack.

The hand specimen of OU 18335 from the west shore of Lake Hankinson contains a small biotite-rich knot, but is otherwise a normal plagioclase amphibolite, differing from those just described in containing no quartz, rutile, or opaque oxides. The hornblende is of the less common paler green variety (cf. OU 18327), which has optical characters distinct from the variety usually encountered (p. 87): absorption and pleochrism are similar but less pronounced, and blue tints more obvious; $2V\alpha = 80°–84°$, $\beta = 1{\cdot}654$.

Increase in 2V and decrease of refractive index in hornblendes appears to be correlatable with decreased absorption and increase in $Mg^{2+}$ relative to $Fe^{2+}$ (Deer, Howie, and Zussman, 1963, p. 236; see also Table 2).

*Discordant amphibolites* were mapped on the ridge north-east of Thomson hut as thin east-south-easterly trending bands making an angle of about 30° with the foliation. One of them appears to have a sub-central vein of nearly pure feldspar (OU 18325), but otherwise they differ little from concordant amphibolites, except in the occasional presence of interstitial apatite (OU 18324). Hornblende is of the more strongly coloured variety.

### *Pegmatite*

Pegmatite occurs predominantly as irregular coarse-grained quartz-feldspar veining in gneisses, ranging from an inch to over a foot in thickness, and with sharp contacts (Fig. 5). Such veining, both concordant and cross-cutting, was recorded especially from the western side of Lake Thomson, although not confined to this region.

Two larger pegmatite masses were also seen. The first is a circular mass of quartz-feldspar-biotite rock, some 50 ft in diameter, cutting coarse leucocratic gneiss on the ridge north-east of Thomson hut. The other is on the ridge north of Hankinson hut, where, as noted previously, a quartz-feldspar--biotite pegmatite incorporates part of the amphibolite as agmatitic blocks.

Petrographically the pegmatites contain the same minerals as the gneisses in which they occur, though much coarser grained and more leucocratic. Abundant microcline was found only in pegmatite collected from the microcline-bearing gneiss on the west shore of Lake Thomson (OU 18322), and trace amounts occur exsolved from plagioclase in a quartz-feldspar vein cutting gneiss on the ridge north-east of Thomson hut (OU 18309).

Thin veins of coarsely crystalline quartz were found filling some joint fractures.

### *Crush Rock*

Differential movement in gneiss, recorded from a variety of localities, is manifested by zones of pale grey-green coloration in which there is a general loss of gneissic structure and development of close-spaced angular fractures, so that the rocks readily break into small blocky fragments. Where movement

FIG. 5—Concordant pegmatitic segregation in gneiss above north-west shore of Lake Thomson.

has been less intense there may be only a general appearance of alteration in the ferromagnesian minerals, with no sign of cataclasis other than a few irregular pale green veins cutting the rock. The most important zone of crushed rock cuts obliquely across the north-east shore of Lake Hankinson, with a possible continuation across the Hankinson peninsula—the Hankinson Fault (see p. 102).

Slight shearing in the gneiss has mainly caused chloritisation of ferromagnesian minerals, sericitisation of plagioclase, and strain effects in the pale yellow epidote (OU 18312, 18314, 18320). Thin pale yellow-green veins cutting the rocks consist of comminuted quartz, feldspar, abundant yellow pleochroic epidote, subhedral zoisite (OU 18320), and sericite (OU 18312). Where crushing has been more intense, as in a sample from the Hankinson peninsula (OU 18323), the whole rock asumes an appearance similar to the veins in less affected rocks, with angular fragments of altered plagioclase, strained quartz, and epidote, in a sericitic base.

In all these rocks subjected to a greater or less degree of shearing stress, the epidote is a yellow pleochroic variety, possibly richer in iron than the colourless epidote in unaffected gneisses (cf. Wahlstrom, 1955, p. 183). The allanite cores in such yellow epidote are also more obvious and more richly pleochroic.

Epidote fragments in a semi-mylonite from the main Hankinson fault (OU 18319) are colourless and contain little allanite. This rock has a very fine oxide-dusted, almost flow-banded groundmass, deformed round plagioclase ovoids up to more than 3 mm across, showing clear signs of marginal cataclasis. Small rounded fragments of hornblende and sphene are also present (Fig. 4B).

### *Distribution of Metamorphic Lithologies*

Lithological correlation in an area such as this is made difficult by the scarcity of exposures below the bush line, and by the essential similarity of the gneisses. However, with the assistance of petrographic data it has been possible to draw some *tentative* boundaries (see Fig. 1). One marks the north-east limit of the epidote-bearing specimens collected; the other demarcates both the south-west limit of recorded amphibolites and larger pegmatites, and the north-east limit of microcline-bearing gneisses.

Additional information on the distribution of rock types is afforded by a study of sand specimens from river and lake shores. These were collected from three localities, and their approximate composition is shown in Table 1.

TABLE 1—Composition of Sand Specimens

| Locality | Major Constituents | Minor Constituents |
|---|---|---|
| Wapiti River, near Thomson hut | oligoclase–andesine<br>quartz<br>hornblende | epidote<br>biotite<br>sphene<br>chlorite<br>zircon |
| Canyon Creek, lower reaches | oligoclase–andesine<br>microcline<br>quartz<br>hornblende | epidote<br>biotite<br>sphene<br>chlorite<br>rutile<br>hypersthene |
| Lake Hankinson, north shore | oligoclase–andesine<br>microcline<br>quartz<br>hornblende | epidote<br>biotite<br>sphene<br>rutile |

The composition of the sands presumably reflects that of the gneisses drained by the streams from which they were collected. Relative abundances of plagioclase, hornblende, biotite, and epidote, and lesser amounts of sphene, rutile, and chlorite accord well with petrographic results from the gneisses. It is, however, of interest to note that the area drained by the upper Wapiti River must be poor in microcline-bearing rocks; whereas Canyon Creek and the lower Wapiti drain areas where the gneisses are

relatively rich in microcline. Such rocks are recorded from the west shore of Lake Thomson (p. 87), but not in the Canyon Creek valley, which was only briefly visited.

A more interesting feature is the presence of hypersthene in the sand from Canyon Creek, which indicates that noritic rocks or hypersthene granulites may crop out in the region north-east of the area studied.

A pebble of coarse quartz-almandine rock (OU 18307) was collected from the Wapiti River just above its confluence with the Rugged Burn. It is composed of sub-rounded pink garnet with strained and granulated quartz, and although it is the only garnetiferous rock found during the survey, it indicates that garnet-bearing rocks may not be far away from the north-west.

A small rounded boulder of unusual composition (OU 18332) was collected at Deadwood Lagoon. It is leucocratic, with feldspar and randomly oriented white mica conspicuous, and a little biotite, chlorite, and pink garnet also visible in hand specimen. The thin section shows andesine and a nearly uniaxial white mica; also muscovite and a very pale green chlorite, as well as dominant epidote in relatively well formed colourless crystals. The epidote grains have irregular overgrowths of colourless zoisite (?), with low anomalous interfence tints and small $2V_\gamma$, containing vermicular plagioclase inclusions. This boulder suggests the presence of some unusual calc-silicate rocks near Mount Henry.

## *Comparison with Other Areas*

The rocks described from the Lake Hankinson region are generally similar to gneisses described from the Lake Manapouri region by Turner (1937), who observed allanite cores in the epidote of some rocks. Benson and Bartrum (1935, pp. 138–39, fig. 2) also described allanite in epidote of granitic rocks invading schists and hornfelses in the Preservation Inlet and Chalky Point region.

Grindley (1958, p. 17) has briefly described dioritic microcline-free gneisses from the Fiordland Complex of northern Lake Te Anau, and noted that many contain small xenolithic blocks of darker coloured microdiorite (1958, fig. 4). Similar rocks were noted above the bluffs west of Hankinson hut.

The reconnaissance mapping of Wood (1962) has established that the dioritic rocks of the Hankinson area form part of the more extensive Wet Jacket Formation of the Fiordland Complex. He has mapped younger basic and granitic intrusives, which is consistent with indications provided by examination of sand and pebbles samples, and in addition he records the frequent occurrence of crush zones in most members of the complex.

## *Chemical Analyses*

Analyses for three representative specimens of gneiss from the area are listed in Table 2, together with calculated norms and measured modes.

TABLE 2—Chemical Analyses Norms and Modes (Analyst: W. Kitt, Chemistry Division, D.S.I.R.)

| | OU 18334 | OU 18336 | OU 18335 |
|---|---|---|---|
| $SiO_2$ | 63·9 | 53·6 | 46·8 |
| $Al_2O_3$ | 15·8 | 18·9 | 18·0 |
| $Fe_2O_3$ | 1·7 | 3·2 | 2·3 |
| FeO | 3·2 | 4·4 | 6·6 |
| MgO | 2·3 | 2·4 | 9·6 |
| CaO | 4·4 | 7·9 | 9·3 |
| $Na_2O$ | 4·5 | 4·8 | 3·0 |
| $K_2O$ | 2·2 | 1·1 | 0·6 |
| $TiO_2$ | 0·80 | 0·97 | 0·19 |
| $P_2O_5$ | 0·26 | 0·55 | 0·13 |
| MnO | 0·06 | 0·12 | 0·13 |
| $H_2O+$ | 0·87 | 1·31 | 3·25 |
| $H_2O-$ | 0·05 | 0·08 | 0·07 |
| | 100·04 | 99·33 | 99·97 |
| NORMS | | | |
| *Q* | 16·5 | 2·6 | — |
| or | 13·0 | 6·5 | 3·6 |
| ab | 38·1 | 40·6 | 23·3 |
| an | 16·4 | 26·8 | 33·9 |
| ne | — | — | 1·1 |
| di | 3·1 | 7·1 | 9·7 |
| hy | 7·5 | 6·5 | — |
| ol | — | — | 21·2 |
| mt | 2·5 | 4·6 | 3·3 |
| ilm | 1·5 | 1·8 | 0·4 |
| ap | 0·6 | 1·2 | 0·3 |
| an % (calc.) | 30 | 40 | 38 |
| (meas.) | 24–26 | 31–32 | 26–31 |
| MODES | | | |
| Quartz | 19·9 | 10·8 | — |
| Plagioclase | 54·1 | 57·2 | 28·9 |
| Microcline | 8·4 | — | — |
| Hornblende | 5·8 | 22·3 | 68·4 |
| Biotite | 10·2 | 4·2 | 0·5 |
| Epidote | 1·2 | 4·4 | 2·1 |
| Magnetite | tr. | 0·5 | tr. |
| Apatite | tr. | 0·6 | tr. |
| Sphene | 0·4 | tr. | — |
| | 100·0 | 100·0 | 100·0 |

*Localities:*

OU 18334 Slip scar exposure, 3–400 ft above lake level, west side Lake Thomson, northern end.
OU 18336 Lake level, west shore, Lake Hankinson, 1 mile north of southern tip of peninsula.
OU 18335 Lake level, west shore, Lake Hankinson, ½ mile south of Hankinson hut.

The high magnesia in the analysis for OU 18335 is reflected in the hornblende, which as already noted (see p. 92) has optical characteristics of more magnesian varieties. The norm for this analysis also shows a little nepheline, a not uncommon feature of such rocks (e.g., Evans and Leake, 1960, p. 348).

### *Metamorphism and Nature of Original Rock*

The mineral assemblages of the specimens described are appropriate to rocks of dominantly basic to intermediate composition in the almandine–amphibolite facies of regional metamorphism (Fyfe, Turner, and Verhoogen, 1958, pp. 202 and 229).

Turner (1937, p. 237) considered that the microcline-free gneisses of the Lake Manapouri region were derived from basic and semi-basic igneous rocks, and Grindley (1958, p. 19) concluded that the dioritic gneisses of the Fiordland Complex round northern Lake Te Anau were probably originally basic lavas, shallow intrusives, tuffs, and tuffaceous sediments. The analyses do not contradict such conclusions, and that for the amphibolite is consistent with an origin from a rather olivine-rich, mildly alkaline basalt or dolerite, probably present as intercalated flows, or as minor intrusives. The microcline-bearing rocks may well represent gradations to original more acid volcanic rocks (e.g., dacite or dacitic tuff) from which the more quartzo-feldspathic gneisses could also be derived. Alternatively, they may represent metamorphosed sediments of greywacke or arkose composition (as suggested by Turner, 1937, p. 237). The analytical data are consistent with both alternatives. The restriction of microcline to gneisses and pegmatites west of Lake Thomson is noteworthy. It is possible that there was little movement of potash during metamorphism, and the occurrence of microcline in a gneiss may indicate that there was potash in the original rocks (cf. Turner, 1937, p. 239).

The thin, often discordant pegmatitic veins cutting the gneisses are composed almost entirely of the lower-melting quartzo-feldspathic constituents in the host rocks. They are regarded as auto-segregation material, "sweated out" during late-stage build-up of volatiles and reinjected locally. Their characteristically irregular form suggests emplacement while the gneiss still retained some degree of plasticity. By contrast, the larger bodies are of coarser-grained rock, perhaps intruded at a still later stage, when the country rocks were less mobile and when there had been greater concentration of volatiles to facilitate the development of large crystals.

The discordant amphibolite and plagioclase amphibolite sheets recorded in the gneiss east of Lake Thomson show no apparently significant textural or mineralogical differences from the concordant varieties. Their regular form would indicate emplacement in mainly solidified rock. Wood (pers. comm.) has recorded both concordant and discordant amphibolitic bands, and notes that in places a concordant sheet may ramify irregularly through the surrounding gneiss.

These amphibolites might represent dikes of basaltic composition, intruded fairly late in the metamorphic history. Yoder and Tilley (1962, pp. 459

*et seq.*) have shown that basalts may metamorphose to amphibolites at temperatures as low as 600°C in the presence of water, at confining pressures between 1 and 10 kilobars.

## STRUCTURE

### *Mesoscopic features*

*Foliation* is defined by preferred orientation of minerals, especially biotite, and is generally well displayed in the gneisses, sometimes emphasised by banding of alternate light and dark layers. It is generally regular over the span of an outcrop and in places is consistent over several, as on the west shore of Lake Thomson, where measurements and structural lines from aerial photographs indicate a uniformity of foliation strike over about 2 miles.

*Lineations* are manifested either as corrugations or in alignment of dark minerals, and some were found parallelling the axes of minor folds (Fig. 6).

FIG. 6—Minor folding in mesocratic gneiss, west shore of Lake Hankinson, near northern end. Strong lineations were observed parallel to fold axes.

*Minor folds* (Fig. 7), generally affect the foliation and vary from folds with tightly appressed limbs, sometimes asymmetrical, through more open varieties, to gentle flexures. Most are of the order of a few feet in amplitude, but one seen at the northern end of Lake Hankinson was about 90 ft across. A single slip fold, in a thin discordant quartz-feldspar vein, was recorded west of Lake Thomson.

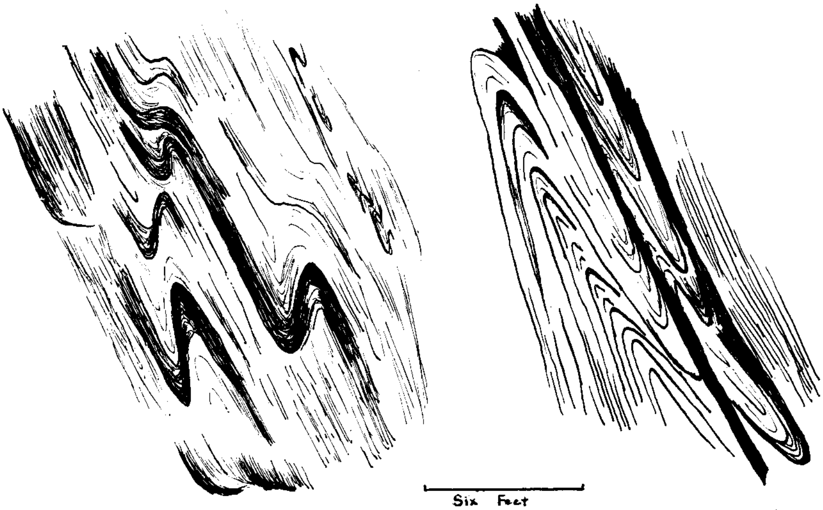


FIG. 7—Examples of asymmetrical minor folds in banded gneiss, northern end of Lake Hankinson, eastern shore. Note minor displacement by the vein parallel to the axial plane of the fold in the right-hand drawing.

*Statistical analysis*

A plot of poles to foliation is shown in Fig. 8, on which lineations and minor fold axes have also been plotted. The foliation poles fall in a reasonably well defined great circle whose pole lies well within the scatter of lineations and minor fold axes. It would appear that only one phase of folding has taken place and that the area is statistically homogeneous, with monoclinic symmetry and a regional axis plunging about 20° to the south-west.

Foliation trends suggest that there is a synform and an antiform with south-westerly plunging axes in this area, in agreement with the results of geometrical analysis and with the findings of Wood (pers. comm.) whose mapping shows that boundaries of major units within the sequence he has determined are generally parallel to the gneissic foliation.

There is, however, not enough evidence to be certain that the foliation everywhere parallels original compositional layering. The parallelism of foliation with boundaries of concordant amphibolites and quartzo-feldspathic lenses, and the often regular foliation banding in the gneisses are suggestive of control by original lithological layering. But it is possible that an original axial-plane foliation could have been rotated into parallelism with the lithological layering during continued folding, and this foliation could then have been folded into the forms seen today. No signs of lithological boundaries transgressing foliation were seen during the survey to lend support to this view. Accordingly it is concluded that foliation was developed at least mainly parallel to original compositional layering.

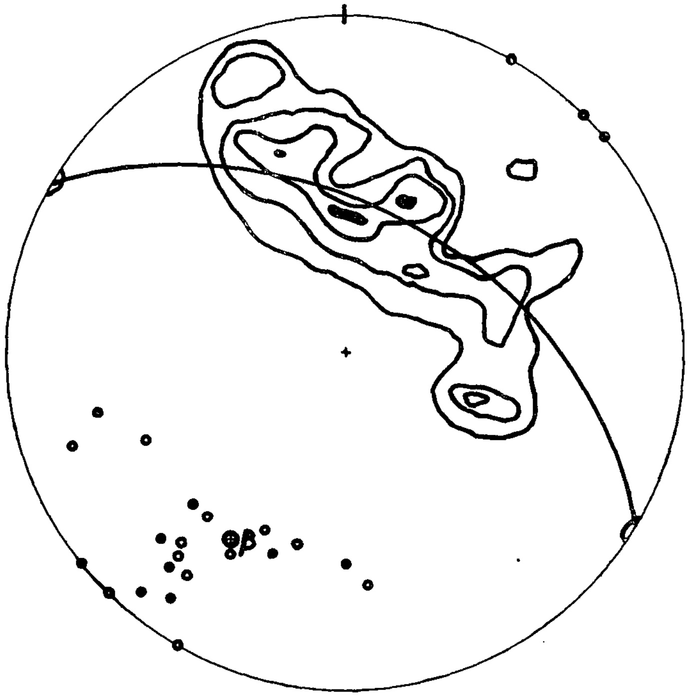

FIG. 8—Contoured stereogram of poles to gneissic foliation lineations (●), minor folds axes (○), and statistical regional axis β. Contours 8%, 6%, 4%, and 2% per 1% area; 90 points.

*Joints*

Most joint planes measured were vertical or steeply dipping, but showed no obviously simple pattern when plotted stereographically.

*Faults*

The trend of crush zones appears to be variable, but may well be controlled either by the foliation to which they are occasionally parallel, or by regional joint patterns. Slickensides are common in such fracture zones.

A belt of sheared rock trending 130° was found near the foot of the slopes west of the Hankinson hut. Its continuation is probably the marked scarp that separates the gneiss from superficial Pleistocene deposits and has been mapped as a fault.

Another larger crush zone—the Hankinson Fault (Fig. 9)—was found in a belt, up to 300 ft across, cutting obliquely across the north-east shore of Lake Hankinson. This zone was followed up to, and slightly above, the bush line, but could not be traced any further north. It acts as a channel for a small stream that has in places exposed an actual fault plane. In one part a length of 400 ft of the plane is exposed, with an average height of 20 ft.

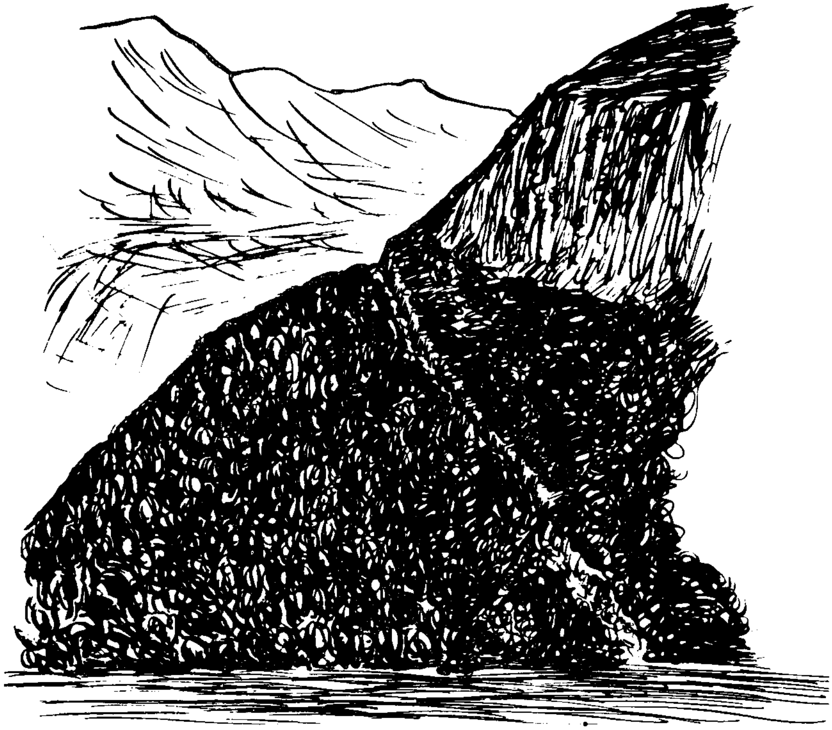

FIG. 9—The Hankinson Fault, drawn from Lake Hankinson, looking north-east; Canyon Creek valley in background.

The fault strikes 053° and dips 56° south-east. A strong grooving on its surface trends due north and plunges 50° south, indicating that the latest movement was predominantly vertical, not lateral.

Close to the fault, minor flexures and small faults are consistent with movement of the east block over the west, i.e., with reverse faulting.

As the sense of movement on the Hankinson Fault is not known, the orientation of the stress ellipsoid cannot be unambiguously determined. However, following the method of Means (1963), it can be demonstrated that for the above data, and assuming a value for $\theta$* between 30° and 40°, the stress ellipsoid approximates to one of the special cases where two of the three axes lies in the plane of the earth's surface and the third is normal to this plane.

A further strong crush zone crossing the isthmus of the peninsula on Lake Hankinson may be a southerly extension of the 300 ft belt described above. At the northern end of this zone, the regional southerly-dipping foliation swings round to parallel the direction of the crush belt. The

*$\theta$ = the angle between the direction of greatest principal stress and a fault plane.

latter is marked by closely spaced vertical joint fractures and appears to be between 75 and 100 ft wide. Near the probable centre of this belt there is a vertical wall some 10 to 20 ft high, parallel to the joint fractures, and the rocks are most affected near this, having a strongly cataclastic appearance with virtually no trace of original gneissic structure.

On the southern side of the isthmus, this belt is again marked by vertical fractures, but the rocks seem to be less crushed and the belt of dislocation is narrower. A vertical wall forming the south-west side of the peninsula here is not related to the crush belt, for it is cut in uncrushed gneisses and trends obliquely across the belt. The trend of the crush zone here was measured as 195° magnetic (215° true), which is markedly at variance with the trend as shown on the map (Fig. 1), where it is drawn in from aerial photographs. Either the map is greatly distorted here, or there is some local magnetic disturbance.

A small area of less shattered rocks was seen in a small bay on the south-eastern side of the peninsula. It appeared to be oriented parallel to the main belt described above, but the fracture pattern was less simple. It was not seen on the other side of the peninsula where its continuation would be expected.

*Structural lines on aerial photographs*

These show up well in five small areas (see Fig. 1). Two sets are parallel to measured foliation, west of Lake Thomson and in Canyon Creek, but the others probably represent joint directions.

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