The Metamorphic and Intrusive Rocks of Southern Westland.

PART II.

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DISCUSSION OF THE METAMORPHIC PROCESS.

PROGRESSIVE METAMORPHISM.

Establishment and Definition of the Metamorphic Zones: In his pioneer work upon progressive metamorphism in the Scottish Highlands, Barrow (1893 and 1912) established a sequence of metamorphic zones based upon the mineralogical changes observed to take place in sediments of pelitic composition, with gradually increasing metamorphism. Each zone was named after an index mineral, the first appearance of which defined the outer limit of the zone in question. The more recent investigation of Tilley (1925a) upon rocks south-west of the area studied by Barrow were also confined mostly to pelitic rocks. Tilley accepted the sequence of zones put forward by Barrow in 1912, except that he included the two outermost zones (Barrow's zones of clastic mica and digested clastic mica respectively) in a single zone characterised by chlorite. Modern workers (e.g., Tilley, 1925a; Elles and Tilley, 1930) now recognise for pelitic or psammo-pelitic rocks six zones characterised respectively by the following index minerals, in order of increasing metamorphic grade: chlorite, brown biotite, almandine, staurolite, kyanite, sillimanite. It is generally recognised, however, (e.g., Elles and Tilley, 1930, p. 622) that staurolite is formed only under rather special circumstances, so that the staurolite zone is not as clearly defined as the other five.

The effects of progressive metamorphism upon the green beds of the Scottish Dalradian have also been worked out recently (Phillips, 1930), and the mineral associations characteristic of all zones from that of chlorite to the kyanite-sillimanite boundary, as defined for pelitic rocks, have been determined.

From the petrological details given in the previous pages it is apparent that the rocks of the area between the Haast and Cascade Rivers also furnish an example of progressive metamorphism on a regional scale. Pelitic rocks are only rarely developed, however, and cannot therefore be used as the basis for zoning. By far the greater portion of the schists and gneisses of this region are of the quartzo-feldspathic type, derived ultimately from sandstones and grits of greywacke composition, and characterised by abundant quartz and sodic plagioclase, together with constant but small amounts of mica or chlorite. An attempt has therefore been made to establish a sequence of zones based upon the effects of progressive metamorphism of the quartzo-feldspathic rocks. In a later section the probable correlation with the zones as defined by Barrow and Tilley for pelitic rocks will be discussed.

In the Haast-Cascade area three zones are recognisable on this basis, and are characterised respectively by chlorite, biotite, and oligoclase. This sequence of zones is thus somewhat comparable with that established by T. Vogt (1927) for the progressively metamorphosed sediments of the Sulitelma area of Norway. The indices of Vogt's zones are chlorite, biotite, almandine, and oligoclase.

Distribution of Metamorphic Zones: The approximate positions of the isograds which limit the three zones recognised above, as deduced from examination of several extensive critical sections, are shown upon the accompanying map. These lines are no more than approximations, since their exact determination would involve some months of additional field work in exceedingly difficult and inaccessible country.

The zone of chlorite occupies the greater part of the map, and continues south-east beyond its limits for many miles into the great belt of schists of low metamorphic grade, which underlie Central Otago and constitute the Maniototo Series of Professor Park. In the north-east corner of the area mapped, however, the complete chlorite zone is limited to a width of about 10 miles. Here there is relatively rapid transition from coarse quartz-albite-chlorite-schists near the biotite isograd, through the phyllites of the upper Haast Gorge, to slates, which appear in the vicinity of Haast Pass and are the least metamorphosed rocks of the chlorite zone.

The biotite zone constitutes a narrow belt of schists which flank the rocks of the chlorite zone on the north-west. They are well exposed along the southern side of the Haast Valley, between Thomas Bluff and the Landsborough Junction, and may also be observed on the south-eastern side of the Jackson Valley. In this latter locality the biotite zone is not fully developed, but is cut off sharply on the north-west by the Cascade-Jackson Valley Fault, which here constitutes the boundary between the zones of biotite and oligoclase.

The typical feldspar of the biotite zone, as defined above, is albite containing 5% to 7% of anorthite. As the metamorphic grade increases the plagioclase becomes richer in anorthite until the composition of oligoclase ($Ab_{90}An_{10}$ to $Ab_{70}An_{30}$) is attained. An oligoclase isograd has therefore been drawn, marking the first appearance of feldspar containing 10% of anorthite, and an oligoclase zone is recognised, including the area occupied by oligoclase-biotite schists, hornfelses, and gneisses. In those portions of the oligoclase zone where metamorphism has been most intense—e.g., the area of gneisses one mile inland from Mr J. Cron's homestead, near the mouth of the Haast River—basic oligoclase, oligoclase-andesine, and even in one case andesine of composition $Ab_{60}An_{40}$ may be developed. Normally, however, the composition of the feldspar of the oligoclase zone lies between $Ab_{90}An_{10}$ and $Ab_{80}An_{20}$.

The zone of oligoclase forms a wide belt of intensely metamorphosed rocks lying north-west of the biotite zone and stretching right to the coast. In the Haast Valley section the oligoclase isograd cuts the valley on its south side, not far east of Thomas Bluff, and from this point to the sea within the oligoclase zone there is a steady increase in intensity of metamorphism. Ten miles east of Thomas

Bluff, however, there is a small isolated area in the vicinity of Douglas Creek which certainly lies well within the oligoclase zone, for the feldspar varies from medium oligoclase to oligoclase-andesine. The exact limits of this area have not been determined, but its approximate extent is indicated on the map.

The rocks of the oligoclase zone are also developed in considerable variety in the south-western portion of the map, between the sea coast and the Cascade-Jackson Valley Fault, which has here brought them into juxtaposition with some of the less metamorphosed of the schists of the biotite zone. Transition between the two zones, such as may be seen in the Haast Valley section, is therefore not apparent in this southern area. Indeed, the abrupt change in metamorphic grade at the outcrop of the fault is so conspicuous that in an earlier paper (Turner, 1930, p. 186) the rocks of the oligoclase zone (north-west of the fault) were provisionally separated as a distinct series from the quartz-albite-biotite-schists and the schists of the chlorite zone to the south-east.

MINERALOGICAL AND TEXTURAL CHANGES INVOLVED.

(a.) *In the Quartzo-feldspathic Rocks:* In order of increasing metamorphic grade the rocks of the quartzo-feldspathic group lying within the chlorite zone have been classed as slates, phyllites, and quartz-albite-chlorite-schists. The most conspicuous effects of progressive metamorphism within the limits of the zone concern the structure and texture of the rocks, rather than the nature of the component minerals which constitute a remarkably constant assemblage of quartz, almost pure albite, delessitic chlorite, muscovite, and epidote in varying proportions. During the transition from slate to fully crystallised quartz-albite-chlorite-schist, the average grain-size increases rapidly from about 0.01 mm. to between 0.1 mm. and 0.5 mm., and at the same time the foliation becomes gradually more pronounced. One of the first definitely metamorphic minerals to crystallise is tourmaline, which appears as scattered relatively large idioblastic prisms in even the most finely crystalline slates, and remains as a constant accessory in the more highly metamorphosed schists. The white mica of the slates, as observed by Brammall (1921, pp. 212, 213) in the case of Bolivian rocks, is a distinctly greenish, rather poorly birefringent variety. In the phyllites and schists this mineral gradually loses its green colour, and the birefringence increases to that of a typical muscovite, though the optic axial angle may sometimes remain abnormally small. An unusual feature is the development of actinolite at an early stage in one of the phyllites (No. 1290) much as in some of the green schists of the chlorite zone. A gradual diminution in the amount of epidote is apparent in the transition from slate to schist, but this is probably due rather to differences in original composition of these rocks than to progressive metamorphism.

Transition from the zone of chlorite to the biotite zone is marked by the incoming of brown biotite, as a result of reaction between muscovite and chlorite, much as described by Tilley (1926, p. 40) for schists of pelitic composition. Chlorite is therefore usually absent or present in small amount, though in rare cases (e.g., No. 1288), where there was an initial deficiency in muscovite, considerable quantities of chlorite may survive even into the oligoclase zone. Where it first appears the biotite is pale yellowish to deep golden brown (e.g., No. 1325), and is developed as scattered knots upon the foliation planes; but as the metamorphic grade increases the mineral becomes much more plentiful, and the colour for vibrations parallel to Z changes first to deep sepia and finally, near the oligoclase isograd, to dark reddish brown. As a result of reaction with epidote the feldspar of the biotite zone is typically considerably more calcic than in the zone of chlorite. It ranges from nearly pure albite (e.g., No. 1283, one mile east of Thomas Bluff, Haast Valley) to albite-oligoclase, but usually contains about 7% of anorthite. Epidote is always present in rather diminished amounts, and is always a poorly birefringent type approaching clinozoisite, in contrast with the often highly ferriferous epidote of the chlorite zone. In the transition from the chlorite to the biotite zone textural changes are not conspicuous. In general the grain-size of the biotite-schists is much the same as that of the quartz-albite-chlorite-schists, but the foliation is more perfectly and regularly developed than in these latter rocks.

The rocks of the oligoclase zone include biotite-hornfelses, biotite-andalusite-hornfels, hornfelsic paragneisses, composite gneisses, and the more strongly metamorphosed of the quartz-plagioclase-biotite-schists.

The transition from the zone of biotite to that of oligoclase is best observed in the continuous section along the southern side of the Haast Valley. The schists of Thomas Bluff (No. 1282), lying just within the oligoclase zone, are distinguished from those further east (e.g., No. 1283) by the fact that the anorthite content of the feldspar has now reached 10%, while the biotite is somewhat coarser, and is definitely dark reddish brown for light vibrating parallel to Z. The rocks of Big Bluff (Nos. 1280, 1281), three or four miles west of Thomas Bluff, are coarse gneisses which lack the perfect fissility of the schists further east, and contain oligoclase of medium composition. The most advanced stage of metamorphism is shown by gneisses (e.g., Nos. 1278 and 1279) collected about one and a-half miles from the mouth of the Haast River. The foliation of these rocks is now rather imperfectly developed in comparison with that of the schists of Thomas Bluff. The grain size is consistently coarse, averaging about 0.3 mm. to 1 mm. for quartz and feldspar and from 0.5 mm. to 1.5 mm. for the micas. The anorthite content of the feldspar has reached from 33% to 40%, indicating that a high grade of metamorphism has been attained, while epidote is absent, having been completely used up in production of andesine from more sodic feldspar. The gneisses between Big Bluff and the mouth of the river frequently show such features as development of myrmekite or introduction of orthoclase, coarse apatite, and coarse muscovite, all of which are believed to be due to the influence of invading pegmatites, and for this reason they have been grouped with the composite gneisses. These effects are much less pronounced, though more widely and regularly distributed, than in the Cascade-Arawata area further south.

In this latter locality the rocks of the oligoclase zone are again distinguished by the presence of oligoclase and intensely pleochroic reddish brown biotite, and by absence of epidote and chlorite, except as products of later retrogressive metamorphism. In texture, however, they differ conspicuously from the schists and gneisses of the Haast Valley, since they have been subjected to the hornfelsing action of a subjacent mass of granite which invaded the rocks of this southern area during their metamorphism, but which did not similarly influence the rocks north of Okuru. In the south-western part of the oligoclase zone, therefore, such features as granoblastic texture, porphyroblastic texture, and sieve-structures (especially in the case of biotite) are extremely characteristic. A further peculiarity of the oligoclase zone as developed in the Cascade and Arawata Valleys is the local restricted formation of composite gneiss as a result of the influence of invading dykes of pegmatite. In an earlier section the mineralogical and textural changes characteristic of this intrusive phase of the metamorphism have been fully discussed, and it has been pointed out that these changes were effected under conditions of high-grade metamorphism, i.e., while the rocks in question still lay within the zone of active formation of oligoclase.

(b.) *In the Micaceous Schists:* Bands of highly micaceous schist representing initial sediments of pelitic composition were only rarely observed. With the exception of mica-rich laminae and thin bands in the hornfelsic paragneisses of the Cascade Valley, they include a single specimen from the chlorite zone, and several from the zone of oligoclase. Judging from these, however, the mineralogical changes involved in their progressive metamorphism are much the same as in the case of the quartzo-feldspathic rocks.

(c.) *In Green Schists:* The green schists occurring within the chlorite zone include chlorite-albite-epidote-schists and chlorite-calcite-albite-epidote-schists, which occur mainly as plentiful boulders in the Jackson River and its eastern tributaries, and have doubtless been derived from a source not far outside the biotite isograd, along the range which flanks the Jackson Valley on the south-east. The feldspar of these rocks is albite with an anorthite content below 5%, and the mica, when present, is always muscovite. In specimens of chlorite-schist from Central Otago (Clyde, Queenstown, and the Kawarau Gorge)—well within the limits of the chlorite zone as defined above—golden brown biotite has developed, however, as scattered patches along the planes of foliation. This early appearance of biotite in the progressive metamorphism of muscovite-bearing green schists has been commented upon by Tilley (1925a, p. 103) and Phillips (1930, pp. 244, 245) in the case of the green beds of the Scottish Dalradian. Pale green or colourless actinolite, though not common, is sometimes developed in small amounts in rocks of the chlorite zone (e.g., No. 1319), though strongly coloured amphiboles are confined to rocks of considerably higher metamorphic grade. This agrees with the observations of Tilley (1923, p. 185) and

Phillips (1930, p. 253) upon the green schists of the Start area and the Scottish Dalradian respectively. The epidote of the chlorite zone is nearly always a highly ferruginous type with a birefringence varying from 0.035 to 0.040.

Though collected only from boulders in the Jackson River and its tributary, Turnley Creek, the biotite-calcite-albite-epidote-schist No. 1326 and the amphibole-schists Nos. 1312 and S.W. 19 may be assumed with reasonable certainty to have been brought down from localities lying within the zone of biotite on the range which flanks the Jackson on the south-east. The metamorphic grade of the schists in question is obviously higher than that of the chlorite-schists, while their perfect schistosity excludes the possibility of origin among the hornfelsic rocks, which in this area are developed over the whole of the oligoclase zone.

One of the first minerals to appear within the biotite zone is biotite itself—a deep golden brown to pale yellow variety, lacking the intense red-brown colour so characteristic of the biotite in the more highly metamorphosed of the quartzo-feldspathic rocks. As would be expected, however, from the comparative rarity of muscovite in the green schists of the chlorite zone, biotite is usually present in accessory amount only, in the corresponding rocks of the zone of biotite. In one case, however, this mineral makes up 25% of the rock (No. 1326), indicating admixed argillaceous material in the initial unmetamorphosed rock. As with the quartzo-feldspathic rocks, the feldspar is noticeably more calcic in the zone of biotite, the composition varying from medium albite ($Ab_{95}An_5$) to oligoclase-albite ($Ab_{90}An_{10}$). The anorthite content appears actually to be slightly higher than in isogradic quartzo-feldspathic schists. An amphibole of the actinolite-glaucophane series, having deep greenish blue absorption for light vibrating parallel to Z, first appears in the biotite zone and becomes increasingly abundant as metamorphism becomes more intense. There appears to be complete transition from almost colourless actinolite (of the chlorite zone), through rather pale amphibole, to the intensely pleochroic actinolite-glaucophane, which appears to be characteristic of the more metamorphosed rocks of the biotite zone and the schists belonging to the zone of oligoclase. In all these cases the amphibole appears from its constant close association with chlorite to have arisen mainly by reaction between chlorite and epidote or calcite, much as described by Tilley (1923, pp. 187, 197) in the schists of the Start area. It is probable, however, that the glaucophane molecule, which enters into the composition of the blue-green amphibole, owes its presence to some such reaction involving albite, as that given by Phillips (1930, p. 252): epidote + albite ——> amphibole + more calcic plagioclase.

The most intensely metamorphosed members of the green schist group are Nos. 1287 and 1291, which appear to have been derived from either just within or just outside the oligoclase isograd. The anorthite content of the plagioclase is 10% in one case and 12% in the other, indicating that the source of the rocks probably lay just inside the zone of oligoclase. The amphibole is now very strongly coloured, and is so plentiful as to impart a nematoblastic texture to the rock in some instances. A noticeable feature is the relatively low iron content of the epidote, which has become progressively poorer in iron during transition from the zone of chlorite to that of oligoclase. In specimens Nos. 1287 and 1291 the percentage of the clinozoisite molecule present in the epidote is about 90%. The actual quantity of epidote has also diminished considerably, as a result of its having been used up during the formation of amphibole and anorthite.

Grades of Metamorphism Attained in the Three Zones: In the following paragraphs an attempt will be made to estimate the degree of metamorphism reached in each of the three zones, which may thus be compared with the standard metamorphic zones as defined for pelitic schists of the Scottish Highlands.

The literature dealing with the progressive metamorphism of the schists of the Scottish Dalradian contains many references to quartzo-feldspathic rocks, in some of which sodic plagioclase is one of the main constituents. Nevertheless details of the mineralogical changes which have taken place during the progressive metamorphism of such rocks, and accurate correlations of these with the changes occurring in pelitic schists under similar conditions have seldom been recorded.

One of the best known accounts is that given by Cunningham-Craig (1904), who describes in detail the progressive metamorphism of the Ben Ledi Grits in the Loch Lomond area, where recrystallisation (constructive metamorphism) has followed closely upon destructive or dynamic metamorphism due to shearing during intense folding. In order of increasing constructive metamorphism four zones are recognised:—

(1) The zone in which grits predominate.

(2) The zone of mica-schists in which, owing to their resistance to initial dynamic metamorphism, a few of the coarser grits still survive.

(3) The zone of mica-schists composed entirely of authigenic minerals.

(4) The zone of coarse albite-gneisses.

In the first and second zones (Cunningham-Craig, 1904, pp. 17-21) biotite—believed by Cunningham-Craig to be authigenic—is plentiful in the Ben Ledi Grits; but in the second and third zones this mineral becomes progressively chloritised, while the coarse albite-gneisses typically contain no biotite, the place of which is taken by chlorite and muscovite. The stable mineral association in the zone of albite-gneiss is thus albite-chlorite-muscovite, just as in the chlorite zone of South Westland, and it therefore appears unlikely that Cunningham-Craig is correct in his suggestion that the biotite of the less metamorphosed rocks is authigenic. The hypothesis has also been put forward (Cunningham-Craig, 1904, pp. 26-27) that the albite-gneisses of Loch Lomond are isogradic with garnetiferous schists and gneisses of the Ben Ledi group in the Aberfeldy district, and that the development of albite is a consequence of hydro-thermal metamorphism, while garnet has been generated under conditions of purely thermal metamorphism. More recently Bailey (1922, p. 92; 1923, pp. 326-327) adopted similar views. On the assumption that albite and garnet are antipathetic, this writer recognises in the Cowal area three zones according to the following scheme:—

1. Mica inconspicuous.
2. Mica conspicuous.
3. (a) Mica with garnet.
   (b) Mica with albite.

Bailey's views in this connection have, however, been severely criticised by Tilley (1925, pp. 108, 112), who states that the albite-gneisses of Loch Lomond owe their mineralogical composition to peculiarities in the initial chemical composition, and maps them as lying well within the zone of biotite.

Following Tilley's mapping, it must still be admitted that in rocks of the albite-gneiss type originating from greywackes or greywacke-shales (Bailey, 1923, p. 325), biotite develops considerably later than in schists of pelitic composition. The chlorite-muscovite association is therefore stable well within the biotite zone as defined for pelitic rocks.

In southern Westland the biotite isograd, drawn on the accompanying map, marks the first appearance of biotite in rocks which resemble in mineral composition and origin the albite-gneisses of the Loch Lomond area. The " chlorite zone " of Westland and Otago is therefore equivalent, as regards the metamorphic grade attained therein, to the chlorite zone and part of the zone of biotite, as defined for pelitic rocks in the Scottish Highlands.

In the schists of southern Westland the most conspicuous mineralogical change induced by regional progressive metamorphism, once biotite has fully developed, is a gradual change in composition of the plagioclase. As a result of reaction with epidote this mineral becomes more calcic as the grade of metamorphism rises. The anorthite content of the plagioclase may therefore be taken as index of intensity of metamorphism, provided the mineral is in equilibrium with excess of epidote. This last qualification is important, since when once the epidote has been used up in the reaction the composition of the plagioclase remains constant during progressive metamorphism beyond this point. It is therefore evident that a rock such as No. 1329, containing feldspar of composition $Ab_{93}An_7$, but no epidote, is not necessarily of lower grade than one in which basic oligoclase and epidote are in mutual equilibrium. In general the rocks in which the composition of the plagioclase may serve as a metamorphic index must therefore be rich initially in both plagioclase and epidote. Such rocks include many green schists and certain of the schists of greywacke composition, e.g., most of the quartzo-feldspathic schists of South Westland.

A detailed account of the changes in composition of plagioclase which take place during the progressive metamorphism of green schists has recently been given by Dr. Phillips (1930, pp. 247-250) in his description of the green beds of the Scottish Dalradian. Within the chlorite zone (as defined for pelitic schists) the anorthite content never rises above 3% to 4%. " The anorthite molecule only begins to enter noticeably into the composition of the plagioclase when the garnet isograd is passed. Measurements of material from localities around West Loch Tarbert, Loch Fyne, and south of Aberfeldy (all well within the garnet zone) give compositions of $Ab_{95}An_5$ to $Ab_{90}An_{10}$. As the grade increases farther the plagioclase is taking part actively, and the composition changes rapidly. The most calcic feldspars measured occur near the summit of the Hill of Strone, south-west of Glen Clova, near the kyanite-sillimanite boundary, with a composition of $Ab_{63}An_{37}$, medium andesine. At the north-east side of Glen Clova, near Loch Brandy, the average composition of a large number of measurements was $Ab_{68}An_{32}$ " (Phillips, 1930, p. 258).

In applying these results to the quartzo-feldspathic schists of southern Westland it must be remembered that the ultimate chemical and mineralogical compositions of the two groups of rocks in question are not the same. In each case the reaction involving the production of more basic plagioclase from albite may be expressed in part by the following relation: albite + epidote ——> more calcic plagioclase.

There appear to be three cases, however:—

(1) In the case of the Dalradian green beds the reaction is essentially bound up with the production of hornblende, and has been expressed by Phillips (1930, p. 252) by the relation: epidote + albite ——> amphibole + more calcic plagioclase.

(2) It has already been shown that in the green schists of Westland, while the above reaction may account for the formation of the glaucophane component of the characteristic blue-green amphibole, the latter mineral appears to have been developed mainly by interaction between chlorite and either epidote or calcite. The full reaction may thus be written: chlorite + epidote + albite ——> amphibole + more calcic plagioclase. This does not differ greatly from the reaction given under (1).

(3) During progressive metamorphism of the quartzo-feldspathic schists of Westland the low-grade association albite-chlorite-epidote-muscovite passes over to the high-grade assemblage oligoclase-biotite-muscovite. The two reactions involved are: chlorite + muscovite ——> biotite; and albite + ferriferous epidote ——> oligoclase + iron (which presumably enters into the biotite). It is, of course, conceivable that production of increasingly calcic plagioclase by this reaction would not follow a course exactly parallel with reactions (1) and (2), though, since the composition of plagioclase is known to be sensitive to changes in metamorphic grade, the divergence is not likely to be large. In support of this latter contention it may again be pointed out that the green schists of southern Westland, throughout their range from the zone of chlorite to just beyond the oligoclase isograd, contain plagioclase of approximately the same composition as isogradic quartzo-feldspathic schists.

In the Haast-Cascade area the composition of the plagioclase ranges from $Ab_{95}An_5$ to $Ab_{90}An_{10}$ in the zone of biotite, and from $Ab_{90}An_{10}$ to $Ab_{60}An_{40}$ in the oligoclase zone. If these figures are compared with the compositions determined by Phillips for the Dalradian green beds, and due allowance is made for the possibility that in the latter case the anorthite content of the plagioclase may increase more slowly than in the case under consideration, it must still be admitted that the rocks of the oligoclase zone of Westland are of high metamorphic grade. The writer therefore suggests that the inner part of the biotite zone and a considerable portion of the oligoclase zone of Westland may be regarded as metamorphically equivalent to the zone of almandine as defined for pelitic rocks in the Scottish Dalradian. The relatively basic plagioclase (sodic to medium andesine), which is characteristically a constituent of the highly metamorphosed gneisses in the vicinity of the mouth of the Haast River, points to the possibility that these rocks may even be isogradic with those of the staurolite or kyanite zones of Scotland. This conclusion is borne out by the presence of sillimanite in some of the more intensely metamorphosed gneisses of the oligoclase zone.

The amphibole-schists Nos. 1287 and 1291 which occur in the vicinity of the oligoclase isograd show certain features, in addition to the presence of sodic oligoclase, indicating a metamorphic grade comparable with that of the garnet zone of Scotland. These rocks contain plentiful blue-green strongly coloured amphibole in association with from 10% to 15% of brown biotite. In his account of the Start green schists, Tilley (1923) records that while pale or colourless hornblende is abundantly developed within the zone of chlorite in the absence of muscovite, when the latter mineral is initially present, hornblende appears only at a later stage in metamorphism after the formation of biotite. Phillips (1930, pp. 252-253) comes to a similar conclusion in the case of Dalradian green beds, and states: " In the non-potassic green schists of the Start, South Devon, as in the altered spilites of Cornwall and Finland, hornblende appears before biotite. With admixed sericitic material, as in a tuff or derived sediment of the nature of the green beds, the higher potash-content leads to the formation of biotite, and hornblende appears much later often after garnet. . . . In this connection material from localities in the Loch Earn district . . . although occurring in the middle of the chlorite zone of pelitic rocks, shows the development of amphibole. The mineral is finely fibrous, pale green or almost colourless (lacking the characteristic blue-green axial tint of the hornblende of higher-grade rocks . . . A bulk analysis of one of these rocks is given, and shows a molecular ratio for CaO to K_2O of 27, this ratio for the Cowal rock (biotite-epidote-albite-schist) being only 8. An alkali estimation of the other Loch Earn rock showed a K_2O content of only 0.41." The association of abundant strongly pleochroic blue-green amphibole, brown biotite, and acid oligoclase in the amphibole-schists of Westland is thus almost exactly comparable with the assemblage of minerals typical of green schists of the garnet zone in the Scottish Dalradian, except that garnet itself is absent in the former case.

This conclusion is strongly supported by Vogt's (1927) researches, which show clearly that in the Sulitelma rocks anorthite enters notably into the plagioclase only within the zones of almandine and oligoclase. In the sedimentary schists of Vogt's zone of oligoclase the anorthite-content of the plagioclase is 20% to 34%, while in the green schists of the epidote-amphibolite-facies (isogradic with those of the zone of almandine) this figure is only 10% to 26%.

A singular feature which calls for some explanation is the complete absence of garnet from both quartzo-feldspathic and green schists in the higher zones of metamorphism in the Haast-Cascade area. The mineral occurs only in a single specimen of unusual composition—the garnetiferous quartz-magnetite-haematite-schist represented by sections Nos. 1316 and 1317.

The genesis of almandine garnet in regionally metamorphosed sediments has recently been discussed by Tilley (1926, pp. 41-44), who concludes that within the almandine zone it is formed from chlorite, often with exchange of magnesia for ferrous oxide. Where manganese is present spessartite-almandine forms at an even earlier stage of metamorphism, while the presence of lime also appears to favour early genesis of garnet, into which the grossularite molecule may enter to a not unimportant extent.

During progressive metamorphism of the quartzo-feldspathic schists of southern Westland, chlorite is almost invariably completely used up in the production of biotite before the zone of oligoclase is reached. Beyond the oligoclase isograd these rocks contain biotite and excess muscovite, but no chlorite such as might give rise to garnet, except in such rocks as the chlorite-hornfelses, where chlorite has subsequently developed from biotite by retrogressive metamorphism. The composition of the quartzo-feldspathic rocks is therefore sufficient in itself to account for the non-appearance of almandine within the zone of oligoclase.

The same reasoning applies also to the rocks grouped as micaceous schists. Where these occur within the zone of oligoclase they contain abundant biotite and a plentiful excess of muscovite, so that almandine (accompanied by orthoclase) could arise only by interaction between biotite and quartz, a reaction which, according to Tilley (1926, p. 44), is restricted to the highest grades of metamorphism well beyond the zone of almandine.

The case of the green schists is different, however. Chlorite is still present even in rocks occurring near the oligoclase isograd, but is gradually used up in the production of blue-green amphibole, not of garnet. Except for the complete absence of this latter mineral, the assemblage of minerals in the Westland green schists corresponds exactly with the association typical of the Dalradian green beds where these lie within the almandine zone. Of these rocks Phillips (1930, p. 252) writes: "It has been noted that garnet has been sporadically developed . . . The variable degree to which excess of chlorite survives and recrystallises in higher zones may be correlated with this variability of occurrence of garnet." In the case of the Westland schists no such explanation can be advanced.

Tilley (1926a) has also shown that the nature of the metamorphic process has a profound influence upon the crystallisation of garnet. Almandine is typically absent from the thermal assemblages of large-scale contact zones such as those of Kristiania and Comrie, though when manganese is present spessartite forms readily enough in contact aureoles. In cases where almandine-schists have been subjected to thermal metamorphism, the garnet is unstable, and breaks down to cordierite and magnetite.

It will be shown in a later section that there is considerable evidence to indicate that the intrusion of a subjacent batholith of granite was one of the essential factors in the metamorphism of the Haast-Cascade area of Westland. The influence of magmatic fluids and of high temperature induced by this invading mass appear to have been very far-reaching, and undoubtedly extended into the outer part of the zone of chlorite. The writer therefore suggests that this " contact " influence has perhaps been a sufficiently important factor in the metamorphic process to render crystallisation of almandine impossible, even in rocks such as the green schists, the composition of which favoured its development. The fact that the garnet of the only garnetiferous schist (No. 1317) collected by the writer proved to contain plentiful manganese accords with this view in the light of Dr Tilley's observations.

The following table summarises the conclusions reached by the writer in comparing the metamorphic grade of the three zones of South Westland with that of the Scottish zones as defined for pelitic rocks.

Zones of South Westland.	Zones of Scottish Highlands.	Grubenmann's Depth Zones.
Chlorite.	Chlorite + outer portion of Biotite.	Epi-Zone.
Biotite.	Inner portion of Biotite + outermost portion of Almandine.	Meso-Zone.
Oligoclase.	Middle and inner portions of Almandine possibly + Staurolite and Kyanite.	

Additional Note on Progressive Metamorphism of Green Schists.

Since the completion of this paper a detailed account of the progressive metamorphism of basic and basic-intermediate volcanic rocks of the Misaka Series of Japan has come to hand (K. Sugi, 1931*). The following brief comparison between Sugi's results and the present writer's observations upon the green schists of Westland has therefore been added.

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* "On the Metamorphic Facies of the Misaka Series in the Vicinity of Nakagawa, Prov. Sagami." *Jap. Jour. Geol. and Geogr.*, vol. IX, No. 1-2, 1931, pp. 87-142.

In the district studied by Sugi, schists belonging to four distinct facies have been formed by metamorphism of basic pyroclastic rocks:

(1) Greenschist-Facies. Essential constituents are albite (Ab_{98} to Ab_{90}, averaging Ab_{95}), ferriferous negative chlorite and highly ferriferous epidote, accompanied by minor leucoxene, and sometimes sericite, calcite, or quartz.

(2) Actinolite-Greenschist-Facies. Essential constituents are albite (Ab_{94} to Ab_{91}), actinolite, clinozoisite, and ferriferous epidote, accompanied by minor leucoxene, poorly ferriferous epidote, and quartz. The epidote is often zoned, the outer zones being rich in clinozoisite (p. 108).

(3) Transitional Facies. Essential constitutents are albite (Ab_{90}) and actinolite, with minor amounts of clinozoisite, pale chlorite, leucoxene, and quartz. Oligoclase-andesine (Ab_{70}) and green hornblende are developed to a minor extent, usually constituting distinct augen.

(4) Amphibolite-Facies. Essential minerals are basic plagioclase (Ab_{42} to Ab_{15}) and common green hornblende.

The less metamorphosed members of the Misaka Series resemble isogradic green schists of South Westland, in the gradually increasing anorthite content of the plagioclase, and decreasing iron content of epidote and chlorite (with resultant zoning in the case of epidote) as the grade of metamorphism advances. Actinolite is less commonly and biotite more usually developed in the Westland rocks than in those described by Sugi.

In the schists of the Misaka Series the anorthite content of the plagioclase is perhaps slightly higher than in the corresponding low-grade green schists described by the present writer. It will be noticed, however, that in the schists of the Amphibolite-Facies and the facies transitional to the Actinolite-Greenschist-Facies, as described by Sugi, the entry of coloured amphibole (green hornblende) is accompanied by very rapid rise in the anorthite content of the plagioclase. This feature is not parallel in the amphibole-schists of Westland, where deep blue-green amphibole of the actinolite-glaucophane series typically is associated with sodic oligoclase. The reason for this discrepancy lies partly in the somewhat lower metamorphic grade of the Westland rocks, and partly in the complex nature of the metamorphic process which affected the Misaka Series. According to Sugi (1931, pp. 139-142) the present mineralogical constitution of the rocks of the Greenschist and Actinolite Greenschist-Facies was determined by dynamic metamorphism assisted by the effects of minor intrusions of basic rocks, while the amphibolites, on the other hand, are products of subsequent purely contact action of a quartz-diorite intrusion upon the invaded green schists.

RETROGRESSIVE METAMORPHISM.

As was pointed out in the previous paper referred to (Turner, 1930a, p. 184), the final stage in the metamorphic history of the Cascade Valley was marked by minor retrogressive metamorphism, when the schists, gneisses, and hornfelses were subjected to conditions typical of Grubenmann's epi-zone. In some cases the result was more or less complete diaphthoresis involving the formation of characteristic low-grade rocks—the chlorite-hornfelses and certain contorted quartz-albite-muscovite-chlorite-schists. More commonly, however, only partial recrystallisation in localised patches of small extent has occurred, as in many of the biotite-hornfelses. As would be expected from the nature of the process, the effects of retrogressive metamorphism are most marked in rocks lying within the oligoclase zone. They are especially conspicuous in specimens collected from along the outcrop of the Cascade-Jackson Valley Fault, and in its immediate vicinity where shearing has been most intense. Breaking down of high-grade minerals to a low-grade association has proceeded further in rocks of small grain size (e.g., hornfelses) than in coarser rocks such as the gneisses of the same district. The latter have been affected mechanically, however, just as much as rocks of finer grain.

The effects of retrogressive metamorphism in the Haast-Cascade region have already been discussed in the sections dealing with the petrography of the chlorite-hornfelses, biotite-hornfelses, and contorted quartz-albite-muscovite-chlorite-schists, and compared with the observations of Eleanora Knopf (1931) upon diaphthoresis. A summary of the effects observed by the present writer may conveniently be given at this stage as follows:—

(1) One of the most easily detected and frequent changes observed is replacement of biotite by chlorite. The pseudomorphs often contain grains of sphene or needles of sagenetic rutile, representing the titanium content of the parent biotite.

(2) Plagioclase is often replaced by sericitic mica, either partially or completely. It should be noted, however, that in other cases sericitisation of plagioclase has occurred at an earlier stage during the formation of composite gneiss from hornfels, under the influence of pegmatitic solutions.

(3) In some of the hornfelses, epidote has been generated in small amounts at the expense of biotite, especially where these rocks are traversed by small shatter planes.

(4) In hornfelses and hornfelsic paragneisses containing andalusite (Nos. 1211, 1212, 1343) this mineral has been partially or in one instance (No. 1343) completely altered to " shimmer-aggregates " of sericitic mica.

(5) Mechanical effects of retrogressive metamorphism are often very pronounced even when mineralogical changes have not been effected. They include:—

- (a) Production of undulose extinction in crystals of quartz, feldspar, and sometimes even mica.
- (b) Bending of twin lamellae in grains of feldspar, and of cleavage laminae in micas.
- (c) Development of secondary twinning in microcline and possibly in plagioclase.
- (d) Recrystallisation of large grains of quartz or sometimes feldspar, as a mosaic of small grains with sutured margins.

(e) Development of small shear-planes, along which secondary quartz, calcite, or even epidote may be deposited.
(f) In rare cases the formation of contorted highly foliated schists (e.g., No. 1334) from non-foliated rocks such as hornfelses.
(g) Possibly the development of strain-slip cleavage in the slates of Haast Pass is to be attributed to this process.

CAUSES OF METAMORPHISM.

In the previous account of the hornfelses and gneisses of the Cascade Valley it was stated (Turner, 1930a, p. 184) that three processes had been concerned in the crystallisation of these rocks as they now exist, the first being the most important. In chronological order these were:—(1) Intense dynamo-thermal metamorphism under meso-zone conditions; (2) invasion and local modification by granite pegmatites, also under meso-zone conditions; (3) retrogressive metamorphism under epi-zone conditions. As a result of evidence obtained during subsequent work, certain modifications, referring especially to the first of the above three processes, are now put forward.

The dominant process has been one of regional progressive metamorphism involving two distinct factors. The first is dynamo-thermal metamorphism in the sense employed by Tyrrell (1930, p. 255), resulting from powerful stress and high temperature controlled by folding movements and depth of burial. As frequently observed in similar instances (e.g., Barrell, 1921), this was aided and modified by a second factor, namely, contact effects resulting from contemporaneous invasion of the folded strata by a subjacent batholith, with accompanying further rise in temperature and permeation of the overlying rocks by volatile magmatic fluids.

The effects of this second phase are especially conspicuous within the zone of oligoclase in the Cascade, Arawata, and Jackson Valleys, in the immediate vicinity of the still unexposed batholith. Here there has been extensive development of hornfelses, hornfelsic paragneisses and hornfelsic mica-schists, the non-foliated or poorly foliated texture of which indicates that high temperature was a much more important factor in their crystallisation than directed pressure. The occasional presence of andalusite has similar significance. In these rocks, too, the presence of porphyroblastic muscovite, occasional minor microcline, and widely disseminated tourmaline and apatite is doubtless to be attributed to the effects of magmatic fluids rising from the subjacent intrusive mass. It has already been pointed out that tourmaline and apatite are also very widely distributed through the schists of the biotite and chlorite zones, many miles beyond the limits of the area where hornfelsing has taken place. Even in the least metamorphosed rocks of the zone of chlorite—the Haast Pass slates—relatively large idioblastic crystals of tourmaline are constantly present, and bear witness to the far-reaching influence of magmatic fluids rising from the depths.

The question now arises as to whether the distribution of the zones of progressive metamorphism in South Westland was governed by dynamo-thermal conditions dependent upon folding, or by the

" contact " influence of the subjacent batholith, or by a combination of these factors.

If the progressive metamorphism of the schists of South Westland were entirely a dynamo-thermal process dependent upon folding and depth of burial, some degree of parallelism between the isograds and the strike of the rocks may reasonably be expected. Actually the isograds cut obliquely across the strike, and, as far as can be gathered from the evidence at present available, their courses are probably highly irregular. Of special significance in this connection is the small isolated area of oligoclase-bearing schists in the vicinity of Douglas Creek, Haast Valley. Though the oligoclase isograd crosses the Haast Valley some eight miles west of this area, and a broad belt of schists lying within the biotite zone intervenes, the rocks of Douglas Creek certainly lie within the zone of oligoclase. It is obvious, therefore, that the distribution of the zones has been considerably influenced by the distribution of subjacent magma. On this assumption the quartz-oligoclase-biotite-schists of Douglas Creek, which, as already noted, are unusually rich in tourmaline and apatite, owe their high metamorphic grade to the existence in this vicinity of an upward-projecting cupola of granite, at no great depth below the surface.

The distribution of hornfelsic rocks is also of considerable significance, since their presence in any locality may be taken to indicate proximity to the granite contact. As would be expected, the hornfelses are strictly confined to within the zone of oligoclase. In the Arawata, Jackson, and Cascade Valleys hornfelses, hornfelsic paragneisses, and hornfelsic mica-schists are developed consistently throughout the whole of the oligoclase zone. In the Haast Valley on the other hand, relatively well foliated quartz-oligoclase-biotite-schists are characteristic of most of the zone of oligoclase; the foliation becomes indistinct only when the composition of the feldspar is relatively calcic (oligoclase-andesine), while true hornfelses are never developed even where the metamorphic grade attains its maximum value. There is thus no approach to parallelism between the outer boundary of the hornfelsed " zone " and the oligoclase isograd, such as might be expected if uprise of a granite batholith alone were responsible for the progressive metamorphism of the area. In the south the subjacent intrusion has evidently approached more closely the biotite-oligoclase boundary surface than in the vicinity of the Haast Valley further north.

The conclusion is therefore put forward that the distribution of the metamorphic zones of the Haast-Cascade area was governed by dynamo-thermal metamorphism combined with contemporaneous invasion in depth by an extensive subjacent batholith of granite. This conclusion is supported by the hypothesis advanced by Finlayson (1908a, p. 120) and later adopted by Professor Park (1921), that the schists of Central Otago are arched over a subjacent granite batholith, with which the auriferous and scheelite-bearing veins of this district are genetically connected.

The second process involved in the metamorphism of the South Westland schists and hornfelses, namely, invasion and modification of the more deep-seated of these rocks by veins of pegmatite, has already been discussed fully in a previous section. It was then shown that while this phase definitely post-dated the hornfelsing, it nevertheless occurred while the invaded rocks were still subjected to meso-zone conditions. It should here be noted that the mineralogical changes resulting from pegmatitic injection are not always distinguishable in a particular instance from the more widespread effects of the initial uprise of magma.

The third process was minor retrogressive metamorphism, the effects of which have been summarised in the previous section. In her recent summary of the phenomena of retrogressive metamorphism, Eleanora Knopf (1931, pp. 6, 7) emphasises the fact that when a mineral assemblage in mutual equilibrium under high pressure-temperature conditions is subjected to conditions of decreasing temperature and pressure, there is normally a very marked lag in adjustment to the new conditions. Consequently katagneisses are frequently exposed at the earth's surface by denudation, without any attempt at readjustment of the mineral assemblage to an association in mutual equilibrium at ordinary temperatures and pressures. Diaphthoresis or retrogressive metamorphism occurs only when the rocks in question have suffered deformation involving strong differential movement of the constituent parts. This acts as a trigger force, and instigates readjustment to the new conditions. The rocks of the Haast-Cascade area which show the effects of diaphthoresis must then have been subjected to fairly severe deformation under epi-zone conditions. The resultant shearing was especially intense in the vicinity of the Cascade-Jackson Valley Fault which presumably first came into existence about this time. There is no petrological evidence to show whether this second deformation was simply a late phase of the main orogenic movement responsible for the original metamorphism, or an independent event occurring at a subsequent period in the history of the area. This question will be discussed later.

To summarise the position, it may be stated in conclusion that three phases are involved in the metamorphism of the rocks of South Westland:—

(1) Progressive regional metamorphism resulting from the combined effects of dynamo-thermal metamorphism due to folding, and " contact " metamorphism on a large scale following upon invasion of the lower levels by a subjacent batholith.

(2) Invasion of the lower zones by granite pegmatites and local development of composite gneisses under meso-zone conditions.

(3) Later deformation and resultant retrogressive metamorphism under epi-zone conditions.

DATE OF METAMORPHISM.

In the previous paper referred to (Turner, 1930a, pp. 185, 186) the quartz-albite-chlorite-schists of the Olivine Range were correlated with the Maniototo Series of Central Otago, and provisionally separated from the more intensely metamorphosed gneisses and hornfelses of the coastal belt, which were grouped as an Older Metamorphic Series believed to antedate the Maniototo Schists.

Subsequent field work has shown, however, that in the Haast Valley there is perfect gradation, as a result of progressive metamorphism, from quartz-albite-chlorite-schists of the Central Otago type, through quartz-plagioclase-biotite-schists, to oligoclase-biotite-gneisses similar to the most metamorphosed members of the " Older Metamorphic Series " of the Cascade Valley. In the Cascade, Jackson, and Arawata Valleys this transition is completely masked by the fact that the Cascade-Jackson Valley Fault has brought into juxtaposition rocks of widely different metamorphic grade.

It is therefore not possible to separate the schists of southern Westland from the Maniototo Series of Central Otago, and the term Older Metamorphic Series as applied to the Cascade Valley rocks must lapse. It is, of course, possible that the South Westland schists are stratigraphically either older or younger than those of Central Otago, while the latter may themselves include strata of different ages. At present all that can be stated is that the schists of Central Otago and those of the Haast-Cascade area owe their present condition to contemporaneous progressive metamorphism.

Judging from the observations of Haast (1879) and Cox (1877a), the belt of highly metamorphosed schists, which extends along the western flank of the main alpine chain north of the area under consideration, is probably continuous with the area of schists and gneisses south of the Haast River. These northern schists have been mapped and examined at various points between Hokitika and north-west Nelson, and are classed as the Arahura or Aorere Series in the various Geological Survey Bulletins dealing with this region. It appears extremely probable that the schists of northern Westland and Nelson, the Maniototo schists of Central Otago, and the rocks described in this paper from South Westland were all metamorphosed contemporaneously during a single period of regional progressive metamorphism.

The date of this metamorphic period is still uncertain, but a certain amount of evidence bearing on the problem has gradually accumulated, and may conveniently be examined at this stage. Some of the more significant points may be summarised as follows:—

(1) The schists of Central Otago " are flanked to the north-east and south-west by a semi-schistose series of greywackes and argillites into which they merge apparently imperceptibly. These are in turn succeeded without obvious break by the Permian (?) fossiliferous sediments at Clinton in the south and the late Middle Triassic beds at Mount St. Mary, near Kurow, in the north " (Benson, 1928, p. 56).

(2) In North Westland and Nelson there is apparently no break between the argillites and greywackes of the main divide and the highly metamorphosed rocks of the Arahura Series further west (e.g., Morgan, 1908, p. 77). In the Haast-Cascade area there is also perfect transition from slates in the vicinity of Haast Pass, through schists of intermediate grade, to the highly metamorphosed gneisses and schists of the coastal belt.

(3) It has been demonstrated by Marshall (1917) that in the Tuapeka district there is perfect transition, by progressive metamorphism, from unaltered greywackes to the schists of Central Otago.

(4) Triassic and Jurassic conglomerates in many localities throughout New Zealand contain very plentiful boulders of granite and other plutonic rocks.

(5) In the Parapara district of Nelson, Bell, Webb, and Clarke (1907, p. 46) record the presence of boulders of schist in conglomerates of the Haupiri Series, which are usually correlated with the Te Anau Series of Permo-Carboniferous age (e.g., Benson, 1921, p. 17). A pebble of tourmaline-schist was also collected by the present writer from a large boulder of Te Anau breccia in the Routeburn Valley (north-west of Lake Wakatipu).

(6) Professor J. Park has informed the writer that he has observed boulders of mica-schist in the Triassic conglomerates of Nelson.

From consideration of items 1, 2, and 3 above, it would appear, on the assumption that no break of major importance separates the schists from the fossiliferous Permian and Triassic beds, and in view of the substantial continuity of the Triassic-Jurassic sequence in New Zealand, that the metamorphism must have occurred in Lower Cretaceous times and coincided with the post-Hokonui orogeny. Writing in support of this hypothesis, Professor Benson (1921, p. 28) has stated that " this also would afford an explanation of the absence of pebbles of the schist, or quartz-pebbles derived from the schists, and of micaceous sands, from the Mesozoic semiglomerates and greywackes adjacent to the areas of schist."

On the other hand it is equally evident from items 4, 5, and 6 above, that during Triassic and Jurassic times, and apparently even as early as the middle or later Palaeozoic, an extensive area of strongly metamorphosed rock invaded by granites was already exposed by denudation. Whether the boulders of these Palaeozoic and Mesozoic conglomerates were worn from schists and granites of the same age as those now so extensively developed in Nelson, Westland, and Otago, it is impossible to state. They, nevertheless, constitute undoubted evidence of ancient metamorphism.

Two alternative hypotheses, neither of which can be regarded as proved beyond doubt, therefore present themselves:—

(1) That two periods of intense metamorphism and granite intrusion must be recognised—an early period affecting rocks now represented in Palaeozoic and Mesozoic conglomerates, and a later period (Lower Cretaceous) responsible for the metamorphism of the schists of Central Otago, Westland, and Nelson.

(2) That there was a single, very ancient period of intense metamorphism, at least as remote as Palaeozoic. The writer favours this second hypothesis, though it necessitates the existence of an as yet undiscovered major break between the Central Otago schists and the overlying Triassic and Permian sediments. In a

later section, when the tectonic significance and age of the great peridotite intrusion has been discussed, further evidence in support of this view will be brought forward.

It will also be shown later that the subsequent epi-zone deformation, which brought about partial retrogressive metamorphism of the schists and hornfelses of the Cascade Valley, also considerably affected the peridotites and associated intrusive rocks, the age of which is probably Lower Cretaceous. If the writer's view as to the date of the main metamorphism is correct, the movements giving rise to retrogressive metamorphism must therefore belong to a much later period of orogeny than that during which the main progressive metamorphism was brought about. It is highly probable that both the diaphthoresis of the schists and dynamic metamorphism of the peridotites are to be attributed to the Lower Cretaceous orogeny, which so profoundly affected the New Zealand region.

IGNEOUS ROCKS INTRUSIVE INTO THE METAMORPHIC SERIES.

Pegmatites.

Dykes and veins of pegmatite, ranging from one inch to two or three feet in width, invade the rocks of the oligoclase zone in the Cascade, Jackson, and Arawata Valleys, where they are often extremely abundant. In the Haast Valley, pegmatites are absent from all but the most highly metamorphosed of the gneisses of the oligoclase zone, which they invade on a minor scale about 1 mile south of Mr J. Cron's homestead.

These rocks have already been described in the previous paper dealing with this area (Turner, 1930a, pp. 181, 182). There is little to add to the previous descriptions except a brief statement with reference to the composition of the plagioclases. Detailed examination of their optical properties* has shown them in some cases to be slightly more calcic than previously stated. The actual redetermined values now given are:—

No. 1219 (1 ml. S.W. of Martyr Br.)—between $Ab_{85}An_{15}$ and $Ab_{80}An_{20}$

No. 1220 (S. end Martyr Br.)—$Ab_{90}An_{10}$

No. 1221 (S. end Martyr Br.)—$Ab_{67}An_{33}$

No. 1222 (Gorge of Creek on N. side of Martyr Ford)—$Ab_{83}An_{17}$

No. 1356 (Gorge of Creek on N. side of Martyr Ford)—$Ab_{90}An_{10}$

It is frequently asserted that the abundant pegmatite veins, which often are associated with highly metamorphosed schists in other parts of the world, are not of magmatic origin, but are " a product of metamorphism, and have been derived from the sediments

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* Comparison of principal refractive indices where possible with those of quartz and Canada balsam; determination of optic sign and approximate estimation of optic axial angle; determination of maxium extinction angle with reference to albite twinning plane in sections perpendicular to 010, and of extinction angles X to 001 cleavage and Z to 001 cleavage in sections perpendicular to Z and X respectively.

which they traverse " (Bailey, 1923, p. 322). There can be no doubt, however, that the pegmatites of the Haast-Cascade area represent the crystallisation-products of volatile magmatic extracts rising from the subjacent granite batholith, the presence of which has already been inferred from other evidence. Not only have the pegmatites of this area had an obvious and often profound " contact " influence upon the invaded hornfelses, but their composition, especially their high content of potash feldspar definitely precludes any possibility of derivation from the adjacent metamorphic rocks.

As previously stated, the pegmatite injection occurred shortly after the period of hornfelsing, but while conditions of maximum metamorphism still prevailed. They certainly antedate the final period of retrogressive metamorphism, when they suffered very severe crushing often accompanied by chloritisation of biotite and partial sericitisation of plagioclase. Cataclastic effects of this nature are especially well shown by a tourmaline-pegmatite (No. 1356), recently collected from the gorge of the small creek, which drains into Martyr Creek just below the ford across the latter stream. In this rock crystals of quartz, albite-oligoclase and tourmaline originally 5 mm. in diameter have frequently been reduced to a completely crushed and partially recrystallised mosaic of tiny granules, through which larger angular fragments are scattered irregularly.

PERIDOTITES AND ASSOCIATED ROCKS.

The Material Studied: An account of the peridotites and associated dyke-rocks which are extensively developed along the western flank of the Olivine Range, from the Jackson Valley to Red Mountain, some 25 miles south-west (see map), has already been published (Turner, 1930a, pp. 186-199), and will not be unnecessarily recapitulated in the present paper. To this, however, are now added descriptions of further material collected on the 1930 expedition, and of certain additional specimens from the vicinity of Red Mountain, collected by Dr G. Moir, and presented by him to the Geology Department of the Otago University. The following observations are therefore intended to supplement the account already recorded, and to modify those of the original conclusions and descriptions which have been found as a result of further work to be incorrect or incomplete.

The rocks of the South Westland peridotite belt include a considerable variety of types, which may be grouped for convenience of description into eight classes, of which the first is by far the most extensively developed:—

(1) Peridotites and altered derivatives.
(2) Pyroxenites and altered derivatives.
(3) Chromite rocks.
(4) Hornblendites and related rocks.
(5) Altered " Gabbros."
(6) Nephrites.
(7) Veins of hydrothermal origin.
(8) Epidote-hornfelses developed by contact metamorphism of the invaded schists and hornfelses.

Peridotites and Altered Derivatives: A number of additional specimens were collected from the large morainic boulders which mantle the surface of the Cascade Plateau, and from the boulders in the bed of Laschelles Creek derived directly from the Plateau moraines. Since this material represents detritus brought down from almost the full extent of the peridotite belt, examination of it throws valuable light upon the nature of the peridotites beyond the limits of the area mapped.

The most abundant rock type from this locality is harzburgitic dunite (Nos. 1239, 1240, and 1241 previously described; Nos. 1378, 1381, 1382, 1383), consisting mainly of olivine with from 3% to 10% of fairly coarsely crystalline allotriomorphic enstatite. There are always minor but constant amounts of deep brown chromite, or less commonly yellowish brown picotite (No. 1378). With increasing enstatite the dunites pass into true harzburgites, such as No. 1380, which, in addition to plentiful scattered crystals of enstatite, contains large clots of this mineral, as much as 3 cm. in diameter, easily distinguishable in hand-specimen. The olivine of this specimen shows only incipient alteration to antigorite, but minor patches of very fine antigorite and talc have already developed along the cleavage planes of the pyroxene. Chromite is not abundant. No. 1396 is a lherzolitic dunite containing both augite and enstatite, each to the extent of about 5%, while No. 1384 is a true lherzolite, the composition of which is olivine 70%, enstatite 10%, clear monoclinic pyroxene 20%, and accessory chromite. Though all the peridotites from this locality show the effects of intense shattering, they are consistently free from alteration which has never advanced beyond the incipient stage.

Supplementary material from various points on Red Spur and Martyr Spur confirms the conclusion formerly reached, that the rocks of the northern end of the peridotite belt are mainly partially serpentinised wehrlites and wehrlitic dunites, in which the olivine shows all stages of replacement by antigorite, while augite typically is altered to a semiopaque brownish substance which appears to have a moderately high birefringence. No. 1400 (Red Spur) is a type hitherto unrecorded, however. It is a deep green semitranslucent serpentine obtained from one of the major shatter planes, which both here and elsewhere were frequently observed to be lined with similar material. The original rock must have been a much crushed wehrlitic dunite containing about 5% of augite. About one-half of the olivine has been converted to chrysotile serpentine (optically + with small axial angle), which now builds up clear patches several millimeters in width, showing perfect mesh structure, while the augite is either clear and unaltered, or partially replaced by pseudomorphous bastite. The serpentinisation of the rock has thus proceeded along lines totally different from those normally followed in the peridotites of this area, and doubtless was effected by passage of magmatic waters along the major crush planes, after shearing had ceased. Veinlets of chrysotile asbestos of similar origin commonly occupy fractures of this type along the full extent of the peridotite belt.

Specimens collected by Dr Moir from the Red Mountain area include, in addition to previously described types, a dark grey opaque serpentine (No. 1413, margin of Red Mt. intrusive mass), which is seen in thin section to consist almost entirely of fine-grained antigorite with perfectly developed " thorn structure " (compare Bonney and Raisin, 1905, p. 702; Pl. XLV, Fig. 3). There are scattered small grains of secondary magnetite, and several crystals of bastite partly or almost completely converted into antigorite (compare Benson, 1914, pp. 674, 675; Turner, 1930a, p. 190), and presumably pseudomorphous after original enstatite. From analogy with previously described specimens, the rock may probably be classed as an antigorite-serpentine derived from original harzburgite.

A serpentine hitherto unrecorded from this area is No. 1385 collected from a single boulder in the bed of Martyr Creek, at the ford where the track crosses this stream. It is a homogeneous, fine-grained black serpentine, which is seen in section to consist of almost totally isotropic serpentine, charged with abundant small granules of secondary iron-ore. With intense convergent illumination some of the serpentine was observed to be very feebly birefringent, giving anomolous blue interference tints between crossed nicols, and showed rather imperfect " thorn structure."

With reference to hydrothermal alteration of the peridotites of the Olivine Range, examination of new material has merely confirmed the conclusions originally reached (Turner, 1930a, p. 197).

Pyroxenites and Altered Derivatives: The pyroxenites occur as clear-cut veins and dykes, often only a few inches, but sometimes several feet in width, which invade the peridotites and serpentines of the Olivine Range. Along the peridotite belt itself the relation of pyroxenite to peridotite is usually obscured by the fact that the rocks of the outcrop are intensely shattered by frost action, but the sharply defined boundaries of the veins and their undoubtedly intrusive nature may clearly be observed in some of the larger boulders of peridotite (frequently five or six feet wide) which mantle the Cascade Plateau.

Relatively unaltered pyroxenites so far recorded (Turner, 1930a, p. 191) include an enstatite-pyroxenite (No. 1246) with minor augite and olivine from the Cascade Plateau boulders, a somewhat similar rock from Red Mountain (No 1247) containing about 25% of augite and a little green chrome-diopside, and an augite-pyroxenite (No. 1245) collected from Martyr Spur and containing in addition to monoclinic pyroxene a small amount of enstatite and about 20% of antigorite replacing olivine. To these may be added three additional records: Nos. 1376 and 1377 from veins in morainic boulders of peridotite, Cascade Plateau, and No. 1369 collected from a small dyke invading the wehrlite of Red Spur. No. 1376 is a dark green comparatively fine-grained pyroxenite, the composition of which is monoclinic pyroxene with schiller structure 90%, olivine 8%, and enstatite 2%. The pyroxenes occur in clear, unaltered allotriomorphic crystals about 2 mm. in length, among which the olivine, showing incipient alteration to antigorite is interstitially distributed (Pl. 28a,

Fig. 13). No. 1377 is a coarse enstatite-pyroxenite containing small amounts of interstitial olivine and accessory chromite, and resembles No. 1246 from the same locality. No. 1369 is an augite-pyroxenite, consisting almost entirely of coarse schillered augite and small patches of decomposition products possibly representing original olivine.

The pyroxenites of the Olivine Range have in many cases undergone intense hydrothermal alteration, the mineralogical changes observed being considerably more diverse than those involved in serpentinisation of the peridotites of the same region. Seven types of altered pyroxenites may be recognised: antigorite rocks, antigorite-talc rocks, chrysotile rocks, garnetiferous chlorite-antigorite rocks, garnetiferous diopside-chlorite-magnetite rocks, chlorite rocks, and diopside-vesuvianite rocks.

(1) Antigorite rocks. As in the peridotites, enstatite and any olivine which may be present in the pyroxenites normally alter to antigorite with perfect " thorn structure," while monoclinic pyroxene is in this case also commonly affected in a similar way. Rocks which have been conspicuously altered in this manner are Nos. 1375, 1381, 1401, and 1403, in addition to Nos. 1244, 1252, and 1261 already described (Turner, 1930a, pp. 190-194).

No. 1401 (dyke near eastern margin of peridotite intrusion, Martyr Hill, Olivine Range) is a coarse grey augite-pyroxenite consisting of plates of pyroxene sometimes as much as 5 cm. to 6 cm. in length. In section some of these crystals are seen to be relatively fresh, but many have been replaced by a felt of antigorite, throughout which cleavage prisms of residual pyroxene and secondary magnetite are scattered in variable amounts. A few crystals are dusted with the opaque brownish decomposition product so commonly observed coating the aluminous pyroxene of the wehrlites, and enclose long streaks of granular magnetite which has been deposited along the cleavage cracks.

A relatively early stage in alteration is seen in No. 1375 (boulder, Laschelles Cr.), a pale coloured pyroxenite, which in thin section is seen to consist entirely of colourless monoclinic pyroxene and antigorite. The latter mineral builds up clear patches constituting perhaps 25% of the total composition of the rock, and surrounding crystals of pyroxene which fray out terminally into cleavage prisms still in optical continuity with the main crystal, but separated from one another by fine-grained encroaching antigorite. No. 1261 (Red Mountain intrusion) represents a more advanced stage in serpentinisation of an augite-enstatite-pyroxenite, in which both pyroxenes are now rather more than half converted to antigorite and accessory magnetite. No. 1403, from the same locality, is a coarse-grained light green semi-translucent serpentine with flaky fracture, and appears originally to have been an enstatite-pyroxenite with very little augite. Transformation of enstatite to antigorite is almost complete, but residual cleavage prisms, and occasional larger fragments stabbed through with antigorite blades, still persist throughout most of the section.

Apple-green, semi-translucent serpentines, which break with the flaky or splintery fracture characteristic of antigorite rocks, and macroscopically closely resemble nephrite but for slightly inferior hardness (5 to 5½), are represented by two specimens both collected from boulders—No. 1244 (Turner, 1930a, p. 190), and No. 1386 obtained from the bed of Martyr Creek, 1½ miles above its junction with the Cascade River. No. 1386 consists entirely of blades of antigorite 0.1 mm. to 0.2 mm. in length showing most perfect "thorn structure," though there are several somewhat ill-defined patches which appear originally to have been bastite, now almost completely replaced by antigorite. No. 1244 also consists mainly of antigorite, but contains in addition a minor amount of a pale greenish mineral identified as a serpentine between chrysotile and xylotilite, together with occasional crystals of bastite showing partial replacement by antigorite. It is possible that these rocks are derivatives of original peridotites, but it seems more probable that they are actually completely serpentinised pyroxenites.

(2) Antigorite-talc rocks. These are represented by a single specimen, No. 1249, obtained from a dyke in the serpentine of Martyr Spur, about three-quarters of a mile above the bush line (Turner, 1930a, p. 192). Augite and olivine have both been replaced to a large extent by fine-grained antigorite, but enstatite, which was fairly abundant in the original pyroxenite, has been altered either to talc or to a mixture of talc and antigorite. Macroscopically chlorite, magnetite, and garnet are all visible in minor amount, so that the rock differs from the garnetiferous chlorite-antigorite rocks only in the presence of abundant talc.

(3) Chrysotile-serpentines. Pyroxenites which have been altered to chrysotile-serpentines are of rare occurrence and were obtained only from boulders in Martyr Creek, 1½ miles above its junction with the Cascade River. Of these, No. 1253 (Turner, 1930a, p. 194) consists mainly of colourless monoclinic pyroxene now half converted to chrysotile, together with occasional large pseudomorphs of bastite after enstatite. In No. 1389, from the same locality, the pyroxene has been completely destroyed, and the rock now consists of chrysotile and bastite, throughout which well cleaved granular masses of a carbonate mineral, about 1 mm. in diameter, are abundantly dispersed, together with about 1% of secondary magnetite, which seems to be especially concentrated in the carbonate-rich areas.

(4) Garnetiferous chlorite-antigorite rocks. Rocks of this type were obtained from dykes invading the peridotite of Martyr Spur, and are represented by specimens Nos. 1248 and 1250 (Turner, 1930a, pp. 192, 193). They are augite-pyroxenites in which the pyroxene has been replaced by pennine and minor antigorite, while small grains of deep red garnet and larger crystals of magnetite are constantly present in relatively small quantities. In No. 1250 the development of prisms of diopside in addition to the other minerals mentioned marks a transition towards the next group.

(5) Garnetiferous diopside-chlorite-magnetite rock. No. 1366 (small dyke, Red Spur) is an extremely altered rock consisting in hand-specimen of well defined patches of white and green material enclosing abundant irregular masses of bright magnetite, often more than 10 mm. in diameter. The most abundant mineral, apart from magnetite, is diopside, which takes the form of well crystallised slender prisms often over 1 mm. in length, scattered among which are interstitial flakes of a colourless chlorite, which also occurs in coarser crystals building up clear diopside-free areas often 2 mm. in diameter. The chlorite is uniaxial, positive, and poorly birefringent, with strong dispersion, and thus appears to be a colourless variety of pennine. It also occurs as coarse crystals with the characteristic anomolous blue interference tint, enclosed within the large grains of magnetite. Pale yellowish garnet, though not abundant, is consistently present in all three sections examined, in the form of small rounded grains which are especially numerous along sparsely distributed fracture lines. Though there is no trace of residual pyroxene, it is concluded from analogy with the rocks of the previous group that the specimen in question is an extreme type of completely altered augite-pyroxenite. The formation of secondary diopside from augite recalls a similar instance described, in the case of a lherzolite from the Shetland Islands, by Phillips (1927, p. 628), who states in this connection that " the secondary production of pyroxene, rather than amphibole, in an altered serpentine is not common. Merrill (1888, p. 489) has described a case. Here original augite is surrounded more or less completely by a narrow irregular border, projecting in the form of sharp teeth for a considerable distance into the serpentine. The new growth, however, is (in all cases) in optical continuity with the original augite."

(6) Chlorite-rocks. No. 1251 (Red Spur) has already been described as a rock showing transition from monoclinic pyroxene to finely crystalline pennine, which develops as well defined bands along the cleavage cracks. The end-product of this type of alteration is exemplified by specimen No. 1414, a fine-grained green rock from the eastern margin of the Red Mountain peridotite mass, resembling the clear green antigorite-serpentines such as No. 1244, but for its greatly inferior hardness. In section, over 99% of the rock consists of minute plates of colourless or very pale green pennine often showing anomolous blue interference tints, and having a structure closely resembling the " thorn structure " so typical of antigorite rocks. There are several small highly irregular granular aggregates of secondary iron ore and greenish yellow garnet.

(7) Diopside-vesuvianite rock. In the previous paper referred to (Turner, 1930a, pp. 196, 197), the writer described an interesting vein rock from Red Mountain, consisting essentially of colourless diopside and a somewhat inferior amount of pale pink vesuvianite. The pyroxene occurs in crystals ranging between 1 mm. and 2 mm. in length, and appears upon careful examination to be undergoing replacement by the vesuvianite. The only other minerals are scattered flakes of green pennine, and colourless zoisite in narrow well defined veinlets cutting irregularly across one of the sections.

The reactions involved in the alteration of the pyroxenites of this area were previously summed up (Turner, 1930a, p. 198) as follows: " Olivine, if present, is always altered partly or wholly to antigorite. The enstatite is usually altered to the same mineral just as in the normal peridotites, but sometimes it has been replaced by talc, a mixture of talc and antigorite, or rarely by bastite. The augite is frequently converted into pennine, with which grains of garnet and prisms of diopside may be associated. Sometimes it is altered to antigorite, . . . while rarely it may be decomposed to the opaque brownish substance which is so commonly met with in the wehrlites of the main intrusion. In one case conversion of augite to diopside was observed." To the above may be added replacement of monoclinic pyroxene by vesuvianite.

The secondary minerals thus produced by alteration of pyroxenes include antigorite, chlorite, talc, diopside, garnet, magnetite, and vesuvianite. Most of these are typical stress minerals, and shearing stress must therefore have had a profound influence upon the alteration process. The importance of the part played by water is indicated by the prevalence among the reaction products of minerals such as antigorite, chlorite, talc, and vesuvianite whose molecules contain OH groups. It is obvious that in some cases, e.g., during the change from augite to antigorite or to chlorite, the reaction was more than simple hydration, and involved removal of lime in solution, while in other instances, such as the replacement of pyroxene by vesuvianite, lime, and probably alumina must have been added and magnesium removed during the reaction. Similarly the formation of the diopside-chlorite-magnetite rock No. 1366 doubtless involved addition of considerable amounts of iron. Other instances might be quoted.

In conclusion, it may therefore be stated that the alteration of the original pyroxenes was a hydrothermal process which took place under conditions of marked shearing stress, and which frequently involved subtraction or addition of such bases as lime, alumina, magnesia, and iron.

Chromite Rocks: The peridotites of the Cascade Valley and their altered derivatives normally contain chromite in accessory proportions, while in rare instances picotite has been observed in these rocks. In the proxenites, on the other hand, chromite is often completely absent, though occasionally present as sparsely scattered grains of small size. Rocks containing a high percentage of chromite also occur, however, and may be grouped into three classes, viz., chromite-olivine rocks, altered chromite-pyroxene rocks, and chromite-serpentine rocks.

The genesis of these chromite rocks is of some interest in view of recent investigations bearing upon the origin of chromite deposits in general (e.g., Sampson, 1929; Ross, 1929; Fisher, 1929). These writers agree that deposits of chromite have not all originated by segregation of early-formed crystals separating out from a basic magma, but in many cases must be due to crystallisation at a much later stage. Fisher (1929, p. 692) thus recognises three distinct periods of crystallisation of chromite: " (1) Chromite of the early magmatic period is the first mineral to crystallise . . . (2) Chromite of the late magmatic period is later than the ground-mass minerals, and occurs in zones of crushed olivine, in cleavages of the cleavable minerals, and as replacements of the earlier pyrogenic silicates of the groundmass. (3) Chromite of the hydrothermal period is definitely later than the pyrogenic silicates, and is associated with deuteric minerals; the chromite of this period was formed by early or late hydrothermal solutions."

Chromite-olivine rocks or chromite-rich dunites occur *in situ* about a quarter of a mile south-west of the crest of Martyr Hill, not far from the eastern boundary of the peridotite belt, in the bed of the tributary creek which drains the southern slope of Martyr Hill, and falls into the gorge of Woodhen Creek. No. 1235 is a typical specimen, consisting of olivine which has undergone incipient alteration to antigorite, and chromite which makes up about 30% of the total composition. The latter mineral is concentrated in parallel bands from 1 mm. to 3 mm. in thickness, interspersed with olivine-rich bands of somewhat greater width. It occurs in unfractured noticeably rounded grains varying between 0.5 mm. and 1 mm. in diameter, which are surrounded by and enclosed in olivine. There is perfect transition from normal dunite to chromite-olivine rock, the extent of which is thus ill-defined and quite limited. From the field occurrence alone it is obvious that the chromite rocks of this type owe their existence to accumulation of early-formed crystals of chromite, a conclusion that is borne out by the relation of olivine to chromite as seen in thin section, and by the rounded form and unfractured nature of the individual chromite crystals, both of which are regarded by Fisher (1929, pp. 711, 719) as criteria of the " early magmatic period " of crystallisation.

Dark coloured rocks consisting of chromite and altered pyroxene (e.g., Nos. 1361, 1373) occur at several points along the crest of Martyr Spur about half a mile above the bush line. Their relation to the enclosing peridotite could not be observed, since masses of broken talus resulting from frost action conceal the outcrop. The hand-specimen consists of coarsely granular chromite set in a soft apple-green serpentinous matrix. In section the most abundant mineral is chromite, which occurs as idiomorphic or subidiomorphic crystals between 0.2 mm. and 0.5 mm. in diameter, usually aggregated into composite unfractured masses ranging from 2 mm. to 3 mm. in width. In section No. 1361 the chromite individuals are enclosed in or enwrapped by coarse allotriomorphic crystals of monoclinic pyroxene, which is sometimes almost unaltered, but usually shows partial or complete replacement by a fine-grained aggregate of serpentine and zoisite. The serpentinous material is colourless, uniaxial, and positive, with a birefringence between 0.005 and 0.01, and often shows distinct cleavage; its optical properties thus agree well with those of chrysotile, but it lacks the fibrous habit characteristic of that mineral. The zoisite is mainly in minute, almost isotropic, highly refringent, grains, but occasionally the individual crystals reach about 0.2 mm. in diameter, in which case the mineral is seen to be definitely biaxial and positive, with a small optic axial angle, while the dispersion is sufficiently marked to produce greenish yellow anomolous interference tints. Alteration of the pyroxene is always especially conspicuous in the immediate vicinity of the chromite grains, which are often separated from relatively unaltered pyroxene by a narrow fringe of zoisite and serpentine. Many of the grains of chromite are partially bordered by irregularly developed rims of a clear, deep yellowish green isotropic mineral with only moderately high refractive index. The only minerals with similar properties listed by Winchell (1929, p. 106) are garnierite and the rare hydrated nickel carbonate zaratite, both of which may occur associated with chromite and serpentine. Secondary veinlets 0.1 mm. to 0.2 mm. wide, consisting of relatively coarse serpentine optically similar to that developed throughout the matrix of the rock, are fairly common. In No. 1373 some of the secondary veinlets consist largely of a clear colourless mineral the exact nature of which is uncertain. The refractive index is high and the double refraction weak; the interference figure is biaxial and negative, the optic axial angle being definitely small; there appears to be no cleavage. The negative optic sign and lack of cleavage distinguish the mineral from zoisite and clinozoisite. It appears most probably to be vesuvianite, for though it is definitely biaxial Winchell (1927, p. 344) states that in some cases vesuvianite may have an optic axial angle ranging from 30° to 60°.

Though the chromite-pyroxene rocks have been profoundly affected by hydrothermal solutions, there seems to be no evidence that deposition of chromite was connected with the alteration process. On the contrary, the texture of the less altered portions of the rock is most reasonably explained on the assumption that both the chromite and the enclosing pyroxene are primary magmatic minerals, the former being first to crystallise. It may also be pointed out that the distribution of the chromite bears no relation to the degree of serpentinisation of the pyroxene. The tendency for alteration to be especially pronounced in the immediate vicinity of chromite grains has already been commented upon, and was considered by Fisher (1929, pp. 701, 703) in the case of American rocks to indicate "a genetic relationship between the chromite and the deuteric minerals." It seems more probable, in the present instance at any rate, that this phenomenon may be traced ultimately to local crushing of pyroxene immediately adjacent to grains of chromite during shearing, as a result of differences in mechanical properties of these two minerals.

The evidence available suggests that the chromite-pyroxene rocks and their serpentinised derivatives have originated as dykes invading the peridotite. Both chromite and pyroxene have crystallised from the same magma at a late stage, subsequently to the consolidation of the main peridotite mass.

The chromite-serpentine rocks occur as small dykes or veins invading the peridotite of Martyr Spur (No. 1374) and Red Spur (Nos. 1363, 1368, 1372). In every case the principal constituent is feebly translucent deep reddish brown chromite, in the form of allotriomorphic much shattered grains set in a finely crystalline matrix of serpentine, which also occupies the cracks traversing the chromite grains. Whenever the serpentine is sufficiently coarse for its optical properties to be determined, it is found to be uniaxial, positive, and poorly birefringent. Section No. 1374a shows the sharply defined boundary between the completely serpentinised material of a chromite-serpentine vein, and the invaded rock—in this case a partially serpentinised dunite (Pl. 28a, Fig. 14).

In many respects the chromite-serpentine rocks of the Olivine Range resemble closely the chromite rocks which Fisher (1929) believes to be of hydrothermal origin. Nevertheless they are distinguished from the completely serpentinised phase of the chromite-pyroxene rocks only by absence of zoisite and the allotriomorphic form and shattered state of the chromite itself. The writer therefore suggests that they are probably the completely altered equivalents of rocks consisting originally of pyroxene and chromite. That serpentinisation took place subsequently to crystallisation of the chromite is clearly indicated by the presence of serpentine matrix occupying cracks in the chromite grains.

Hornblendites and Related Rocks: Small dykes and veins of fine-grained dark coloured rocks, in which primary magmatic hornblende is the dominant constituent, invade the rocks of the peridotite belt at several points in the vicinity of Red Mountain, from which locality a number of specimens have been collected by Dr Moir. Similar rocks were obtained by the writer from a small dyke on the crest of Martyr Spur, and from a boulder in the bed of Martyr Creek. In some cases hornblende was apparently the only primary constituent, but many of the rocks originally contained a considerable amount of plagioclase, now represented by zoisite or albite. Augite is sometimes present in small quantities. The following descriptions illustrate the characteristics of this group of rocks:—

No. 1415 (near eastern margin of peridotite intrusion, Red Mountain). The original constituents of the rock were strongly pleochroic reddish brown hornblende and a somewhat less amount of plagioclase. The hornblende occurs in allotriomorphic or subidiomorphic crystals about 1 mm. in length, now largely bleached to a pale amphibole feebly pleochroic from pale yellowish (X) to pale green (Z). The feldspar was originally idiomorphic, but is now completely replaced by opaque, white granular saussurite, in which the Prussian blue interference tint of zoisite may occasionally be distinguished, while minute grains of clear albite occur interstitially among the saussurite pseudomorphs and hornblende crystals. The bleached hornblendes sometimes enclose secondary sphene, while iron ore occurs as a minor accessory.

No. 1259 (dyke, Red Mountain) is a more intensely altered rock, the original composition of which must have been close to that of the previously described specimen. The hornblende is pinkish brown, and occurs in ragged, often bent and twisted prismatic crystals which fray out terminally into tufts and sheaves of tremolite needles. Colourless transparent zoisite, accompanied by minor interstitial albite and quartz, have entirely replaced the original feldspar, the crystal form of which has also been completely destroyed.

Nos. 1258 and 1408 (dykes, Red Mountain) are hornblende-zoisite rocks with small amounts of interstitial quartz and albite. The hornblende is a much paler variety than in the previous specimens, the pleochroic scheme being:—

X = very pale yellow
Y = pale yellowish green
Z = pale brownish green
$X < Y < Z$

It is sometimes partially bleached to a colourless amphibole in optical continuity with the normal green hornblende. The zoisite is clear, colourless, biaxial, and positive, and shows the usual Prussian blue tint between crossed nicols. Though much of the zoisite doubtless represents original plagioclase, in some parts of the section it appears definitely to be replacing hornblende.

No. 1410 was collected from a hornblendite dyke which cuts a zoisite-albite rock (No. 1411) close to the eastern margin of the peridotite mass near Red Mountain. The rock consists mainly of pale greenish hornblende, which has suffered partial alteration to coarsely crystalline serpentine in some parts of the section. The serpentine is a nearly uniaxial, positive variety close to chrysotile. Interstitial rounded masses of granular zoisite from 0.5 mm. to 1 mm. in diameter are scattered throughout the section, and appear to represent original feldspar.

No. 1412 (Red Mountain). About 60% to 70% of the rock is pale green hornblende, which usually either frays out terminally into colourless amphibole or contains a central bleached zone of similar material. The hornblende crystals are enclosed in a matrix of finely crystalline shapeless grains of untwinned albite (Pl. 28a, Fig. 15). Zoisite with the usual Prussian blue anomolous interference tint is by no means abundant, and its development is confined to the immediate vicinity of hornblende crystals. Distinctly pleochroic pink sphene occurs as an accessory.

No. 1402 (dyke, Martyr Spur, Olivine Range). Strongly pleochroic deep reddish brown to pale pinkish hornblende, now largely bleached, or frayed out into pale green actinolite needles, makes up about 60% of the rock. It is set in a matrix the chief constituent of which is colourless isotropic serpentine, containing abundant inclusions of pale green actinolite and colourless granular garnet, as well as scattered irregular masses of sphene ranging from 0.1 mm. to 1 mm. in diameter. The latter mineral exhibits strong pleochroism from colourless to deep pink. Epidote and zoisite are present only as accessory grains of small size. There are also several allotriomorphic crystals of almost unaltered augite, which are sometimes enclosed in hornblende, but may also occur free in the serpentine matrix.

No. 1390 (boulder, ford across Martyr Creek, 1½ miles above Cascade junction). This is a relatively coarse-grained rock of rather striking appearance, in which dark crystals of hornblende are set in a green altered matrix. The principal constituent is hornblende in coarse crystals ranging from 1 mm. to 3 mm. in diameter, which are strongly pleochroic according to the following scheme:—

X = pale pink
Y = deep reddish brown
Z = slightly deeper reddish brown
$X < Y < Z$

The larger crystals sometimes enclose small rounded cores of colourless augite. The brown amphibole is frequently bordered with an optically continuous fringe of green hornblende which is pleochroic from fairly deep bluish green (Y and Z) to very pale yellow (X). The large hornblendes are enclosed for the most part in a mass of unoriented diopside prisms and fibrous remnants of green hornblende, throughout which occur small patches consisting of coarsely crystalline pennine or coarse allotriomorphic pink garnet. The chlorite is a pale variety of pennine, uniaxial, positive, and poorly birefringent, giving anomolous yellowish brown interference tints between crossed nicols. The pleochroic scheme is

X = Y = pale bluish green
Z = very pale yellow
$X = Y > Z$

Undoubted examples of transition from green hornblende to chlorite or a mixture of chlorite and diopside, and from both varieties of hornblende to diopside have all been observed in this section. In one or two places colourless transparent zoisite also appears to be replacing green hornblende. The mode of origin of the garnet is not clear. It occurs in large masses ranging up to 3 mm. in diameter, which sometimes contain small but conspicuous interstitial crystals of a mineral, the properties of which agree exactly with those of bowlingite. It is strongly pleochroic from pale golden yellow (X) to deep brownish yellow (Y = Z). The birefringence is relatively high, and there is a single well-marked cleavage perpendicular to X. The only primary minerals in the rock are brown hornblende and augite—the latter in very small quantity—and the rock is therefore classed as a much altered hornblendite.

In a previously published description of a hornblende-zoisite rock (No. 1258) from Red Mountain (Turner, 1930a, p. 196) the suggestion was made that the rock probably represented a completely recrystallised gabbroid dyke, in which augite had been converted to green hornblende, and labradorite to zoisite and albite. Examination of many additional sections of related rocks nevertheless has failed to yield any evidence of secondary origin for the hornblende. On the contrary, when augite is present, its relation to the enclosing hornblende indicates clearly that the latter is also a primary mineral, which has crystallised directly from a basic magma, as a result of reaction, according to Bowen's well-established principle, between earlier formed crystals of augite and the melt itself. The hornblendic dyke-rocks thus consisted originally of hornblende, variable amounts of plagioclase, and sometimes a little augite.

The observed mineralogical transformations involved in the alteration of these rocks after their consolidation may be summarised briefly as follows:—

(1) Brown hornblende —> green hornblende.
(2) Hornblende —> tremolite or actinolite.
(3) Hornblende —> serpentine.
(4) Hornblende —> chlorite.
(5) Hornblende —> zoisite.
(6) Hornblende —> diopside.
(7) calcic plagioclase —> zoisite + minor albite and quartz.
(8) calcic plagioclase —> albite + minor zoisite.

As in the altered pyroxenites, the reaction products are mostly stress minerals, and in many of them, e.g., zoisite, serpentine, chlorite, and according to modern authorities (Warren, 1929; Kunitz, 1930; Posnjak and Bowen, 1931) tremolite, OH groups enter conspicuously into the composition of the molecule. Here, too, then alteration has been brought about by aqueous solutions acting under conditions of stress. It is obvious, however, that during the alteration of hornblende as outlined above, certain bases, especially lime, have sometimes been added, and in other cases have been removed in solution. Similarly while replacement of calcic plagioclase by zoisite implies addition of some lime and removal of soda, this process must have been exactly reversed during the replacement of calcic plagioclase by albite observed in specimen No. 1412.

In addition to the products of the mineralogical changes described above, there are other secondary minerals such as the garnet of Nos. 1390 and 1402, and the serpentine of specimen No. 1402, the exact mode of origin of which is not yet clear.

Altered "Gabbros": Under this heading are included certain intensely altered white or blotched green and white rocks, which, whenever observed *in situ,* occur as dykes and veins invading the peridotite mass. Except in rare instances the primary minerals have been completely destroyed, and the rocks are now made up of a fine-grained aggregate of secondary minerals, among which one of the calcium aluminium silicates epidote, zoisite, or garnet always predominates. Three main types may be recognised, viz., epidote rocks, zoisite rocks, and garnet-zoisite rocks.

Epidote rocks of this group are known from two specimens (Nos. 1257 and 1388) collected from boulders in the bed of Martyr Creek, 1½ miles above its junction with the Cascade River. Macroscopically they are white or pale grey homogeneous, very fine-grained rocks, which break with a splintery or flaky fracture, recalling that of antigorite-serpentines. About 70% of the rock consists of very small grains of yellow epidote, which is only determinable as such under high magnification. In specimen No. 1388 there are also scattered large, irregular grains of deep yellow highly birefringent epidote, evidently rich in iron. Minute granules of albite occur interstitially among the epidote grains. Highly irregular lenses and streaks consisting entirely of albite and quartz make up the remaining 30% of the section in each of the specimens examined. In section No. 1257 several minute crystals of brown hornblende and a little zoisite were noted, while in No. 1388 very small pale green laminae and fibres of chlorite are constantly present in the epidote-rich areas. This latter section is crossed by a veinlet 1 mm. in width consisting mainly of relatively coarse, intensely strained quartz enclosing idiomorphic crystals of albite. Vermicular colourless chlorite is plentifully developed along one side of this veinlet.

The zoisite rocks are massive white or blotched greenish rocks represented by specimens Nos. 1256 and 1387 obtained from boulders in the bed of Martyr Creek, No. 1294 from boulders alongside the track one mile north of Martyr Bridge, and Nos. 1406, 1409, and 1411 collected *in situ* by Dr Moir from veins invading the peridotite mass of Red Mountain east of Awarua Bay. They are marked by the universal abundance of zoisite, which is typically accompanied by notable amounts of both tremolite and antigorite.

No. 1406 contains conspicuous crystals of residual colourless augite, always enclosed in patches of felted antigorite. The bulk of the rock consists of very small stumpy prisms and granules of zoisite, with a little interstitial antigorite, and possibly a very small amount of albite. The zoisite in this section is elongated parallel to X, and has a relatively high birefringence of about 0.01, these properties indicating a comparatively high iron content unusual in this mineral (compare Winchell, 1927, pp. 353, 354).

Specimen No. 1387 consists of aggregated prisms of zoisite and tremolite with interstitial antigorite, and irregularly developed intervening patches composed entirely of felted plates of this latter mineral. Most of the tremolite is colourless, and is distinguishable from the zoisite by its lower refractive index, but two crystals of pale brown faintly pleochroic amphibole were also noted. The zoisite occurs mainly in small slender prisms with straight extinction and a single vertical cleavage, but there are also clusters of coarser crystals, sometimes over 1 mm. in length, having similar optical properties. The optic axial angle is small, the sign positive, the elongation is positive, and the birefringence is again relatively high—about 0.01 to 0.012—indicating the presence of appreciable Fe_2O_3 in the molecule.

No. 1409 is a coarsely blotched green and white rock in which tremolite is particularly well crystallised as prisms over 1 mm. in length, which, together with minor interstitial antigorite and albite, build up colourless patches of considerable extent, which contrast conspicuously with the pale yellowish areas of granular zoisite. The zoisite is mainly in the form of small idiomorphic prisms with negative elongation, fairly low birefringence, and strong dispersion, but there are also coarser less perfectly shaped crystals with positive elongation, the optic axial angle being small and the optic sign positive. No. 1394 is unusual in that, in addition to coarser tremolite and zoisite which are the main constituents, there are minor quantities of prismatic diopside, conspicuous on account of its high refractive index, medium birefringence, and strongly oblique extinction. There are also areas built up of felted laths of a colourless serpentine with negative elongation.

No. 1256, previously described (Turner, 1930a, p. 195) as a tremolite-antigorite rock, has since been found to contain in addition a high proportion of prismatic zoisite, which was previously confused with the tremolite. It somewhat resembles No. 1387 described above.

Garnet-zoisite rock is known from a single specimen, No. 1254, which was obtained from a dyke of resistant white rock several feet wide, cutting the serpentine of Martyr Spur not far below the bush line. In the previously published description of this rock (Turner, 1930a, p. 194), the zoisite was incorrectly identified as enstatite. The refractive index is too high for enstatite, however, while on careful re-examination interference figures were obtained in several cases, showing the small optic axial characteristic of zoisite. The rock is obviously related to the grossularite-pyroxene rocks of the peridotite belt of Nelson to which Marshall (1911) gave the name rodingite, and which, according to Grange (1927, pp. 162-163), frequently contain zoisite and diopside in addition to garnet.

The recorded occurrences of lime-silicate dyke-rocks intrusive into ultrabasic rocks have been summarised by Benson (1918, pp. 722-723), who has himself traced every gradation from eucrite-gabbros to pure grossularite rocks in the Bingara district of New South Wales (Benson, 1914, pp. 686-688). This supports the original conclusion of Murgoci (1900), that certain of the lime-silicate masses included in the Paringû serpentines of Roumania were altered gabbros. The " rodingites " of the Dun Mountain, Nelson, have also been shown by Benson (1926, p. 43) and Grange (1927) to be due to garnetisation of originally gabbroid rocks, under the influence of " concentrated magmatic water " acting probably at high pressures. Recently Tyrrell (1931, p. 29) has drawn attention to the occurrence in the Ural Mountains of dykes of garnet-pyroxene, garnet-vesuvianite, and garnet-chlorite rocks, which invade serpentinised harzburgites. These rocks have been described fully by Arshinov and Merenkov (1930), who believe that they have originated by " the garnetisation of micro-diorites and the alteration of pyroxenite schlieren by calcium metasilicate solutions liberated in the process of serpentinisation."

The lime-silicate rocks of the peridotite belt of South Westland are believed to have originated in a similar way, by alteration under pressure of basic dyke-rocks, by aqueous solutions rich in lime, rising from the cooling peridotite mass. The alteration was probably effected by the same waters as were responsible for serpentinisation of the rocks of the main intrusion, and their lime content was no doubt derived from monoclinic pyroxenes during this latter process.

The universal abundance of zoisite suggests that the original unaltered rocks must have contained a high percentage of calcic plagioclase. Augite was certainly present in some cases, and may occasionally still persist as residual crystals, which always have undergone partial replacement by antigorite or other serpentine. It is thus reasonable to assume that the clear patches of serpentine which invariably occur in the zoisite and garnet rocks represent completely altered augite. It will be noticed that the lime removed during this latter reaction would also be available for development of lime-rich secondary silicates. The tremolite, which occurs so plentifully in many of the zoisite rocks, must probably be regarded as a derivative of hornblende; for, while alteration of pyroxene to tremolite has never been observed in any of the rocks of this area, replacement of hornblende by colourless amphibole commonly occurs in the hornblendites and related rocks described in the previous section. The lime-silicate rocks are therefore regarded as much altered gabbros and hornblende-gabbros, comparable with the " rodingites " of the Dun Mountain, Nelson.

Nephrites: Boulders and pebbles of nephrite occur sparsely in the gravels of the Jackson River, while a single specimen (No. 1379) of a rock evidently allied to nephrite was obtained from a boulder alongside the track leading from Martyr Bridge to the Martyr-Jackson Saddle, about one mile north of the bridge. From their distribution and from comparison with other New Zealand occurrences, it is highly probable that these boulders have been brought down from veins in the northern portion of the peridotite belt.

No. 1370 (Upper Ford, Jackson River). Macroscopically the rock is highly schistose, corresponding to the " fissile nephrites " of Finlayson (1909, pp. 367, 368), translucent, and rather pale green in colour, lacking the deep green tint which is so commonly shown by much of the nephrite of New Zealand. In section it is seen to be made up entirely of a colourless fibrous amphibole with the properties of tremolite or actinolite, in minute prisms or fibres which are usually interwoven in tufts and sheaves, in which the form of the individual crystals may often be obscured. It closely resembles sections of nephrite from the Teremakau River in the Otago University collection, and agrees well with the descriptions and figures of typical New Zealand nephrites published by Finlayson (1909, pp. 366-380).

No. 1364 (Upper Ford, Jackson River) is a beautiful pale green translucent highly schistose rock, approaching in appearance the variety termed *inanga* by the Maoris. The hardness, estimated on a polished surface cut parallel to the foliation, is approximately 5.5, and is thus inferior to that of most nephrites, for which the figure 6.5 is usually quoted (e.g., Finlayson, 1909, p. 367). Microscopically the rock consists of slender prisms of colourless tremolite or actinolite, which are often considerably coarser than in the previous specimen, and vary from 0.2 mm. to 0.8 mm. in length. They universally show traces of cross fracture transverse to the direction of elongation. The maximum extinction angle in sections parallel to the vertical axis is 20°, and the optic sign is negative. Only the smaller crystals are grouped in tufts, the larger prisms being perfectly formed and developed independently of any such felted structure.

No. 1379 is a tough, pale greenish grey or almost white opaque rock, much softer than the nephrites described above, and having only poorly developed schistosity. The section consists largely of colourless amphibole, which occurs partly as felted fibres as in section No. 1370, but mainly in the form of much coarser prismatic crystals averaging 0.5 mm. × 0.05 mm., arranged in haphazard fashion. In some parts of the section prisms of amphibole are set in patches of matted, fibrous, very feebly birefringent serpentine. This latter mineral is optically negative, as in the case of antigorite. from which it differs, however, in its small optic axial angle and complete lack of " thorn structure." It thus appears to be similar both in optical properties and in texture to the serpentine of which the Milford Sound bowenite is composed (compare Finlayson, 1909, p. 362). The only remaining constituent of the rock is a cloudy yellowish sphene, occurring in scattered minute irregular granules.

In the paper already quoted, Finlayson (1909, pp. 376, 377) has summarised the various theories which have been put forward to account for the origin of nephrite, the most generally accepted view being that which involves derivation from original pyroxene. He states further that, while uralitisation of pyroxene is the normal mode of origin of most New Zealand nephrite, nevertheless contact-action, deep-seated metamorphism of serpentine-talc-carbonate rocks, and direct transformation of olivine to nephrite have all been responsible for the formation of nephrite in particular instances. The last of these processes is illustrated by a single specimen (Finlayson, 1909, p. 374) believed to have come from the peridotite belt of the Olivine Range, but no such material has since been obtained from this locality by the present writer. Since residual remnants of the primary constituents are completely lacking in the nephrite rocks from the Jackson Valley, it is impossible to be certain as to the nature of the initial rocks from which they originated. From their mineralogical composition and foliated texture it is obvious, however, that shearing stress was one of the main factors involved in their crystallisation.

Veins of Hydrothermal Origin: Under this heading are included veins consisting respectively of chlorite, zoisite, and quartz-albite, which are believed to have been deposited at a late stage, directly from rising magmatic waters.

The first of these three types is represented by specimen No. 1358, which was collected by Dr Moir from a vein of almost pure coarsely crystalline chlorite, 3 cm. to 5 cm. in width, cutting the peridotite of Red Mountain. Macroscopically the mineral is deep green in colour, and occurs in idiomorphic or subidiomorphic hexagonal tables from 1 mm. to 10 mm. in diameter. The section consists almost entirely of well crystallised very pale chlorite, with minor amounts of colourless to pale green serpentine, occupying the interstices between the chlorite crystals. The chlorite is uniaxial and positive, frequently twinned parallel to 001, and in vertical section shows brownish yellow anomolous interference tints when viewed between crossed nicols, indicating weak birefringence and strong dispersion.

In some crystals zones or irregular bands giving Prussian blue interference tints may also be developed. The pleochroism, though faint, is very distinct, and of a type most unusual in chlorites, in that the absorption for light vibrating parallel to the vertical axis (Z) is definitely stronger than that for vibrations parallel to the cleavage.* The pleochroic scheme is

$$X = Y = \text{colourless}$$
$$Z = \text{pale brownish yellow}$$
$$X = Y < Z$$

Basal sections are thus colourless and non-pleochroic. Except for the unusual pleochroism the properties agree perfectly with those of pennine. The serpentine which occurs interstitially between the chlorite crystals is optically positive and nearly uniaxial, and has a lower refractive index but much stronger birefringence than the chlorite. It appears to be chrysotile, but lacks the fibrous habit usually developed in that mineral. Both chlorite and serpentine show strongly undulose extinction, indicating that at the time of crystallisation shearing had not yet entirely ceased.

No. 1407 is a hard white rock collected by Dr Moir from a vein in the serpentine east of Big Bay in the Red Mountain area. Over 95% of the rock consists of fairly coarsely crystalline zoisite in subidiomorphic or allotriomorphic crystals ranging from 0.5 mm. to 1 mm. in diameter. The optic axial plane is parallel to the 010 cleavage, and the elongation of prismatic crystals is always negative, properties corresponding with iron-free or alpha-zoisite (Winchell, 1927, p. 354). There are scattered crystals of a uniaxial, optically positive serpentine with micaceous habit, identical with the variety already described in the altered chromite-pyroxene rock No. 1361. The serpentine of the chlorite-rock No. 1358 just described is also probably of this type. Interstitial albite occurs as an accessory. It is admittedly possible that this zoisite vein may be a completely altered anorthosite, and thus comparable with the zoisite-bearing rocks of the " altered gabbro " group. The appearance of the rock, both in hand-specimen and beneath the microscope, nevertheless strongly supports the view that the zoisite has been deposited directly from aqueous solution. Minute veinlets of similar composition, which appear almost certainly to have been formed in this manner, have already been noted cutting some of the more highly altered rocks of the peridotite belt.

A narrow dyke of intensely sheared quartz-albite rock (No. 1255) invading the peridotite mass on the north side of Woodhen Creek Gorge has already been recorded (Turner, 1930a, p. 195), and compared with closely similar rocks described by Benson (1914, p. 691) from the Great Serpentine Belt of New South Wales. The presence of this rock, deep within the heart of the peridotite intrusion, indicates that aqueous solutions rich in soda and silica must have been expelled from the underlying magma towards the close

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* A chlorite having closely similar properties has recently been described as a constituent of altered peridotites from Northern Norway by S. Foslie (*Norsk. geol. tids.* B. xii, 1931, pp. 219-245).

of the period of intrusive activity. Benson (1914, p. 691; 1918, p. 715) mentions a number of cases where similar emission of sodic solutions from peridotite magmas has been recorded, and calls attention to albitisation of mica-schists of the Maniototo Series adjacent to a serpentine dyke in the vicinity of Cromwell, Central Otago, observed by Park (1908). It may be pointed out that the Cromwell serpentine is probably of the same age as the peridotites of the Olivine Range of Westland.

Epidote-hornfelses: The western flank of the peridotite belt is bordered by a zone of epidote-hornfelses, which have apparently been produced by contact action of the peridotite upon the adjacent biotite-hornfelses of the Metamorphic Series. Owing to the fact that the outcrop is obscured by dense forest, the exact extent of this zone has not been determined, but specimens have been collected close to the contact on both Martyr and Red Spurs, and from boulders in Martyr Creek. Epidote-hornfelses appear to be absent from the eastern margin of the peridotite belt.

No. 1359 (boulder, Martyr Creek) is a very fine-grained green rock, minutely laminated but only imperfectly fissile, and breaking with the rather even fractive characteristic of finely crystalline hornfelses. The essential constituents are epidote 40%, albite-quartz 40%, muscovite 10%, and chlorite 10%. The grain-size is remarkably uniform, about 0.05 mm., but there is a tendency towards porphyroblastic development of albite, some crystals of which reach 0.1 mm. or 0.2 mm. in diameter. The banding is due to alternation of ill-defined laminae 1 mm. to 5 mm. in width, in which epidote is concentrated or diminished respectively. The epidote is a yellow, highly birefringent ferruginous variety. Pale green chlorite and colourless sericite occur abundantly as minute flakes and wisps, lying interstitially between the grains of the other minerals. The relative proportions of quartz and albite are difficult to determine, since interstitial chlorite and mica prevents application of the Becke refractive index test. There are several fair-sized grains of magnetite.

No. 1360 (Red Spur, west of peridotite contact) is similar to the previous specimen, but somewhat more fissile. Yellow epidote is even more plentiful than in the preceding section, and occasionally occurs as large grains ranging up to 0.2 mm., set in the usual fine-grained matrix of epidote, albite, quartz, and chlorite. One of the laminae contains a number of xenoblastic grains of strongly pleochroic deep green hornblende. Sphene and magnetite occur as minor accessories.

The high epidote content of the hornfelses suggests that lime-bearing solutions emitted from the cooling intrusion must have been active during their crystallisation. The transformation of coarsely crystalline biotite-oligoclase hornfelses and schists into fine-grained epidote-hornfelses containing albite, sericite, and chlorite involves breaking down of a mineral assemblage characteristic of a relatively high grade of metamorphism to a typically low-grade assemblage. From the mineralogical composition of the contact rock it therefore follows that the intrusion of the peridotite mass was affected under low-grade metamorphic conditions.

In conclusion it may be pointed out that the epidote-hornfelses of the Olivine Range recall similar rocks described by Greenly (1919, pp. 108, 109) from the contact aureole which surrounds some of the serpentines of Anglesey.

Tectonic Significance and Date of Intrusion: In his report of 1887, Professor Park stated that the peridotite mass of Red Mountain had risen up along a great fault plane, separating the Maniototo schists of Central Otago from the breccias of the overlying Te Anau Series further west. In the present area (Turner, 1930a, p. 199) intrusion has been effected along a major fault which runs north-east along the middle portion of the Cascade Valley, and continues down the full length of the Jackson for at least ten miles beyond the north-eastern end of the peridotite belt. This fault has been referred to elsewhere in this paper as the Cascade-Jackson Valley Fault. On the Olivine Range the south-eastern margin of the intrusion dips steeply south-east. Judging from the relative intensity of metamorphism exhibited by the rocks on either side of the Jackson Valley, the upthrow is on the north-western side of the fault.

It has already been shown that intrusion of the peridotite mass and associated dykes was accompanied by shearing movements, which continued to operate throughout the subsequent period of hydrothermal alteration. This accords with the generalisations advanced by Benson (1926) regarding the tectonic conditions accompanying the intrusion of ultrabasic rocks, and with Suess's (1909, p. 564 view that " the green rocks are sills in dislocated mountains which sometimes follow the bedding planes and at others the planes of movement."

In considering the probable age of the South Westland peridotites, it is necessary also to take into account the available evidence bearing upon the age of other ultrabasic intrusions of the South Island, since these in all probability belong to a single orogenic period (e.g., see Finlayson, 1909, pp. 364, 365; Benson, 1926, p. 44). As pointed out by Finlayson, there is a strong petrographic similarity between all these rocks, while all have been considerably affected by subsequent shearing during serpentinisation. This similarity is all the more apparent when the South Island peridotites are contrasted with the early Tertiary serpentines and peridotites of North Auckland. In the second place the ultrabasic masses of Nelson, Central Westland, and South Westland are all linear intrusions, which lie west of and parallel to the main axial mountain chain. Where the main arc of folding bifurcates in the southern portion of the South Island (Benson, 1924, p. 129), other linear intrusions of ultrabasic rocks, according to the observations of McKay (1881, p. 143) and Marshall (1906), continue to be developed on the western side of the Central Otago fold in the rugged country between Lake Wakatipu and the Hollyford River. Thus as pointed out by Finlayson (1909, p. 365) " the structural significance of the magnesian belt is too evident to be overlooked in this connection."

Discussing the age of the peridotites of the South Island, Benson (1926, p. 44) sums up the situation thus: " The upper limit of the possible age of these beds is fixed by the occurrence of pebbles of serpentine in the ' Miocene ' beds overlying the ancient rocks (Morgan, 1908) . . . During the last decade the ultrabasic and accompanying basic intrusions have been generally considered to have been injected during the late Mesozoic orogeny, but more recently Park (1921) has declared his belief that they were injected during the early part of the Triassic, accompanying the orogeny he believes to have occurred then, and he considers that all other occurrences in the South Island are probably of the same age.'' During the interval extending from the Middle Cretaceous to the later part of the Tertiary, the South Island of New Zealand was not affected by folding movements of any importance, and it is thus safe to conclude that the ultrabasic intrusions of the South Island are certainly not younger than Lower Cretaceous. Furthermore, since as stated above the trend of the peridotite intrusions approximates to that of the ancient folds, and since the latter are believed to be products of the great Lower Cretaceous orogeny, it is reasonably certain that the intrusions themselves are of Lower Cretaceous age.

Earlier in this paper the suggestion was put forward that the main metamorphism of the schists and gneisses of Central Otago and Westland may have occurred in conjunction with folding movements much more ancient than those of the Lower Cretaceous. If it be admitted that the ultrabasic intrusives of the South Island are not younger than Lower Cretaceous, additional evidence in support of this hypothesis may now be brought forward. In the first place it has already been established that in the Cascade-Haast area uprise of a subjacent granite batholith accompanied the metamorphism during the period of its maximum intensity. Intrusion of the peridotite mass took place at a much later date, when meso-zone conditions of metamorphism had given place to conditions typical of the epizone. If both granites and peridotites belong to the same intrusive cycle, then the well-established principle of decreasing basicity of successive intrusions is reversed in this instance. In the second place the distribution of granites and peridotites has considerable significance in this connection. During a folding movement, linear intrusions of peridotite usually rise up at an early stage, in the outer portion of the folded range, while masses of granite normally invade the core of the fold at a somewhat later stage (e.g., Benson, 1926, p. 76). The distribution of the ultrabasic intrusives of the South Island along the outside of the main arc of folding agrees perfectly with this principle, but if the granites belong to the same orogenic cycle they should lie within, i.e., east of the peridotite line. Actually the reverse is always the case.

The writer therefore concludes that the peridotite intrusions of the South Island are probably of Lower Cretaceous age, and that the progressive metamorphism of the schists of Otago and Westland and accompanying uprise of granite intrusions belong to a distinct and much more ancient period of orogeny. The partial retrogressive metamorphism of some of the schists and hornfelses of the Cascade and Arawata Valleys are attributed to the same shearing forces as affected the peridotite mass immediately after intrusion in Early Cretaceous times.

DIORITIC ROCKS.

The dioritic rocks are confined to the area of hornfelses and schists which lies south of the Arawata River, between Laschelles Creek and the Jackson Valley, where they occur as minor dykes and as boulders in the stream beds. Their precise age is unknown, but as they are only slightly affected by shearing, it is reasonably certain that they post-date the much more highly altered ultrabasic rocks.

The essential constituents of these rocks are brown or green hornblende and plagioclase (ranging from oligoclase to andesine), in more or less equal proportions, always accompanied by a notable amount of interstitial quartz. In one specimen (No. 1393) augite, biotite, and ilmenite are also plentiful. The accessory minerals include extremely abundant apatite, variable amounts of iron ores, and minor sphene. Most of the dioritic rocks have suffered considerable alteration—probably of an auto-pneumatolytic kind—involving partial chloritisation of hornblende and biotite, sericitisation of feldspar and crystallisation of minor amounts of secondary calcite, epidote, and sphene.

One of the least altered of these rocks is specimen No. 1333 collected from a narrow dyke which invades the hornfels on the southern side of the Arawata River, 1½ miles west of the mouth of the Jackson. It is a holocrystalline, rather fine-grained non-porphyritic rock, consisting of feldspar 55%, hornblende 35%, quartz 5% to 10%, and accessory apatite, magnetite, and pyrite. The hornblende is for the most part a brown variety occurring in perfectly idiomorphic crystals about 0.8 mm. long (Pl. 28a, Fig. 16), which often show simple orthopinacoidal twinning, and have a maximum extinction angle (Z to c) of 20°. The pleochroic scheme is

X = light yellowish brown
Y = deep yellowish brown
Z = deep yellowish brown
$X < Y < Z$

The crystals are frequently rimmed with a narrow border of deep green to very pale yellowish hornblende, while in some instances an almost colourless or very pale green amphibole partially replaces the normal coloured mineral. Pale green pennine occurs as an alteration product of hornblende, but it not nearly so plentiful as in some of the other dioritic rocks from this area. The feldspar is oligoclase-andesine approximating to $Ab_{70}An_{30}$, and occurs in slightly sericitised, subidiomorphic or allotriomorphic crystals, about 0.5 mm. in diameter, enclosing or enwrapping the hornblendes. Quartz occurs as highly irregular interstitial grains among the crystals of feldspar and hornblende.

A much more altered type, briefly described in the previous paper dealing with this area (Turner, 1930a, p. 200), is represented by boulders from Laschelles Creek (Nos. 1262, 1392), and from the small creek which joins Martyr Creek about 1½ miles above its junction with the Cascade River (No. 1263). The hornblende crystals average about 3 mm. in length, and are perfectly idiomorphic.

They are often simply twinned, and show strong pleochroism according to the following scheme:—

X = pale yellowish brown
Y = dark yellowish brown
Z = dark brown, sometimes with a distinct reddish tinge
$X < Y < Z$

As in the previous section, the brown hornblende crystals are usually rimmed with a fringe of green hornblende. Partial or complete alteration of the amphibole to deep green pennine, often enclosing grains of secondary sphene or calcite, is common in all the rocks of this type. The feldspar appears to be mainly medium oligoclase, but since it is almost completely replaced by sericitic mica it is impossible to determine the composition exactly. Alkali feldspar is probably also present in subsidiary amounts. Quartz is relatively abundant, both as interstitial grains and very commonly as a micropegmatitic intergrowth with the feldspar. Slender prisms of apatite ranging up to 3 mm. in length are very plentiful, while the iron ores include both magnetite and pyrite. Calcite and deep yellowish green epidote are sometimes associated with the chlorite.

No. 1393 (boulder, Laschelles Creek) is unusual in that the ferromagnesian constituents include abundant augite and biotite as well as hornblende. The mineral composition is feldspar 40%, augite 20%, hornblende 15% to 20%, biotite 5% to 10%, quartz 5% to 10%, ilmenite 5% to 10%, apatite 1%, accessory sphene, and secondary calcite. The feldspar is largely basic andesine, in well-twinned subidiomorphic crystals which are usually considerably altered to sericite. This is accompanied by minor amounts of sericitised alkali-feldspar. The quartz occurs mainly as interstitial grains, but occasionally it may be intergrown on a fine scale with the feldspar. The most abundant ferromagnesian silicate is pale pink relatively unaltered augite, which typically takes the form of rounded allotriomorphic crystals, rarely showing marginal reaction rims of hornblende or biotite. It sometimes ophitically encloses laths of plagioclase. The hornblende is almost entirely the pale yellow to deep green variety, and is considerably altered to pennine. It occasionally shows marginal resorption to biotite. The latter mineral is in the form of ragged flakes from 0.1 mm. to 0.3 mm. in length, with very strong pleochroism from pale golden brown to very deep chocolate brown (almost black), and is sometimes partially replaced by pennine. Ilmenite in skeletal crystals, rods, and parallel growths is unusually plentiful, while slender prisms of apatite are constantly present in all parts of the section.

No. 1264, obtained from boulders in the Cascade River, is an unusually coarse-grained rock consisting of large idiomorphic crystals of pale green hornblende from 3 mm. to 4 cm. in length, and occasional coarse apatite grains, enclosed in a mass of completely altered plagioclase, which appears to have been andesine.

No. 1327 is an extremely fine-grained rock macroscopically resembling a fine hornfels, obtained *in situ* from a small dyke invading the hornfels on the south side of the Arawata River, 1½ miles west of the Jackson. The rock consists of a holocrystalline groundmass of completely altered feldspar and hornblende, the grain-size of which ranges from 0.01 mm. to 0.05 mm., enclosing rare phenocrysts of acid andesine near $Ab_{65}An_{35}$ in composition. Secondary calcite is developed throughout the groundmass, and there are several inclusions consisting of relatively coarse aggregates of quartz and calcite grains. The rock is classed as an unusually fine-grained porphyrite.

With the exception of the porphyrite just described the dioritic rocks are believed to be of pegmatitic origin, having crystallised from a residual dioritic magma unusually rich in soda and potash, and in water and other volatile constituents. They are therefore classed as quartz-diorite-pegmatites.

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Literature Cited.

The following is a list of works to which reference has been made in the text:—

Adams, F. D., 1895. Further Contribution to our Knowledge of the Laurentian, *Am. Jour. Sci.*, Ser. 3, Vol. 50, pp. 58-69.

Adams, F. D., and Barlow, A. E., 1910. Geology of the Haliburton and Bancroft Areas, *Mem. Geol. Surv. Canada*, No. 6.

Alling, H. L., 1921. The Mineralography of the Feldspars, *Jour. Geol.*, vol. 29, no. 3, pp. 193-294.

Arshinov, V. V., and Merenkov, B. J., 1930. Petrology of the Chrysotile Asbestos Deposits of the Krasnouralky Mine in the Ural Mountains, *Trans. Inst. Econom. Min.*, No. 45, Moscow.

Bailey, E. B., 1922. The Structure of the South-west Highlands of Scotland, *Q.J.G.S.*, vol. 78, pp. 82-131.

—— 1923. The Metamorphism of the South-west Highlands, *Geol. Mag.*, vol. 60, pp. 317-331.

—— 1925. *In* The Pre-Tertiary Geology of Mull, Loch Aline and Oban, *Mem. Geol. Surv. Scotland.*

Barrell, J., 1921. Relations of Subjacent Igneous Invasion to Regional Metamorphism, *Am. Jour. Sci.*, ser. 5, vol. 51, pp. 1-19, 174-186, 255-267.

Barrow, G., 1893. On an Intrusion of Muscovite-Biotite Gneiss in the South-east Highlands of Scotland, and its Accompanying Metamorphism, *Q.J.G.S.*, vol. 49, pp. 330-358.

—— 1912. On the Geology of Lower Dee-side and the Southern Highland Border, *Proc. Geol. Assn.*, 1912, pp. 1-17.

BECKE, F., 1908. Ueber Myrmekit, *T.M.P.M.*, Bd. 27, pp. 377-390.

—— 1909. Ueber Diaphthorite, *T.M.P.M.*, Bd. 28, pp. 369-375.

BELL, J. M., WEBB, E., AND CLARKE, E. DE C., 1907. The Geology of the Parapara Subdivision, *N.Z. Geol. Surv. Bull.*, No. 3.

BENSON, W. N., 1914. The Geology and Petrology of the Great Serpentine Belt of New South Wales; pt. 3, Petrology, *P.L.S. N.S.W.*, vol. 38, pt. 4.

—— 1918. The Origin of Serpentine, a Historical and Comparative Study, *Am. Jour. Sci.*, ser. 4, vol. 46, pp. 693-731.

—— 1921. Recent Advances in New Zealand Geology, *Rept. Austr. Assn. Adv. Sci.*, sect. c, pp. 1-89.

—— 1924. The Structural Features of the Margin of Australasia, *Trans. N.Z. Inst.*, vol. 55, pp. 99-137.

—— 1926. The Tectonic Conditions Accompanying the Intrusion of Basic and Ultrabasic Igneous Rocks, *Mem. Nat. Acad. Sci.*, vol. 19, No. 1, Washington.

—— 1928. Metamorphic Rocks of New Zealand, *Rept. Austr. Assn. Adv. Sci.*, sect. c, pp. 56-68.

BONNEY, T. G., AND RAISIN, C., 1905. The Microscopic Structure of Minerals Forming Serpentine, *Q.J.G.S.*, vol. 61, pp. 690-714.

BOWEN, N. L., 1922. The Behaviour of Inclusions in Igneous Magmas, *Jour. Geol.*, vol. 30, No. 6, pp. 513-570.

BRAMMALL, A., 1921. Reconstitution Processes in Shales, Slates, and Phyllites, *Min. Mag.*, vol. 19, No. 94, pp. 211-224.

BRUCE, E. L. AND MATHESON, A. F., 1930. The Kisseyenew Gneiss of Northern Manitoba and Similar Gneisses occurring in Northern Saskatchewan, *Trans. Roy. Soc. Canada*, ser. 3, vol. 24, pt. 1, sect. 4, pp. 119-132.

COLE, G. A. J., 1916. A Composite Gneiss near Barna, *Q.J.G.S.*, vol. 71, pp. 183-188.

COLEMAN, A. P., 1907. The Sudbury Laccolithic Sheet, *Jour. Geol.*, vol. 15, No. 8.

COLLINS, W. H., 1917. Onaping Map-area, *Mem. Geol. Surv. Canada*, No. 95.

COX, S. H., 1877a. Report on Westland District, *Repts. Geol. Expl. N.Z.*, 1874-1876, pp. 61-93.

—— 1877b. Report on Coal Measures at Jackson's Bay, *Repts. Geol. Expl. N.Z.*, 1874-1876, pp. 94, 95.

CUNNINGHAM-CRAIG, E. H., 1904. Metamorphism in the Loch Lomond District, *Q.J.G.S.*, vol. 60, pp. 10-29.

DALE, T. N., 1914. Slate in the United States, *U.S. Geol. Surv. Bull.*, No. 586.

DANA, E. S., 1922. *A Text-Book of Mineralogy*, 3rd Edition, New York, John Wiley & Sons.

ELLES, GERTRUDE L., AND TILLEY, C. E., 1930. Metamorphism in Relation to Structure in the Scottish Highlands, *Trans. Roy. Soc. Edinburgh*, vol. 56, pt. 3, No. 25, pp. 621-646.

FENNER, C. N., 1914. The Mode of Formation of Certain Gneisses in the Highlands of New Jersey, *Jour. Geol.*, vol. 22, pp. 594-612, 694-702.

—— 1926. The Katmai Magmatic Province, *Jour. Geol.*, vol. 34, No. 7, pp. 673-772.

FINLAYSON, A. M., 1908. Some Observations on the Schists of Central Otago, *Trans. N.Z. Inst.*, vol. 40, pp. 72-78.

—— 1908a. The Scheelite of Otago, *Trans. N.Z. Inst.*, vol. 40, pp. 110-122.

—— 1909. The Nephrite and Magnesian Rocks of the South Island of New Zealand, *Q.J.G.S.*, vol. 65, pp. 351-381.

FISHER, L. W., 1929. Origin of Chromite Deposits, *Econ. Geol.*, vol. 24, No. 7, pp. 691-721.

GARDINER, M. I., 1890. Contact-alteration near Galloway, *Q.J.G.S.*, vol. 46, pp. 569-581.

GHOSH, P. K., 1927. Petrology of the Bodmin Moor Granite (eastern part), Cornwall, *Min. Mag.*, vol. 21, No. 118, pp. 285-309.

GOLDSCHMIDT, V. M., 1920. Geologisch-petrographische Studien in Hochgebirge des Südlichen Norwegens, *Vidensk. Skr., 1, Math. Nat. Kl., Kristiania*, No. 10.

GRANGE, L. I., 1927. On the "Rodingite" of Nelson, *Trans. N.Z. Inst.*, vol. 58, pp. 160-166.

GREENLY, E., 1919. The Geology of Anglesey, *Mem. Geol. Surv. Gt. Britain.*

GRUBENMANN, U., 1910. *Die Kristallinen Schiefer*, Berlin.

HAAST, J., 1879. *Geology of the Provinces of Canterbury and Westland*, Christchurch.

HARKER, A., 1919. The Present Position and Outlook of the Study of Metamorphism in Rock Masses *Q.J.G.S.*, vol. 74. No. 293, Anniversary Address.

HOLMES, A., 1920. *The Nomenclature of Petrology*, London, Murby & Co.

HUNTER, J. F., 1925. Pre-Cambrian Rocks of Gunnison River, Colorado, *U.S. Geol. Surv. Bull.*, No. 777.

HUTCHINGS, W. M., 1890. Notes on the Probable Origin of Some Slates, *Geol. Mag.*, 1890, pp. 264-273, 316-322.

—— 1892. Notes on Ash-Slates and Other Rocks of the Lake Districts, *Geol. Mag.*, 1892, pp. 154-161, 218-228.

IDDINGS, J. P., 1906. *Rock Minerals*, New York, John Wiley & Sons.

KIESLINGER, A., 1926. Geologie und Petrographie der Koralpen I, *Wien. Akad. Sitzber., Math. Nat. Kl.*, 135, Abt. 1.

KNOPF, ELEANORA B., 1931. Retrogressive Metamorphism and Phyllonitisation, Pt. 1, *Am. Jour. Sci.*, ser. 5, vol. 21, No. 121, pp. 1-27.

KUNITZ, W., 1930. Die Isomorphieverhältnisse in der Hornblende Gruppe, *Neues Jahrb. Min.*, 40, Abt. A, pp. 171-250.

MCKAY, A., 1881. District West and North of Lake Wakatipu. *Rept. Geol. Expl. N.Z.*, 1879-1880, pp. 118-147.

MARSHALL, P., 1906. Geological Notes on the Country North-west of Lake Wakatipu, *Trans. N.Z. Inst.*, vol. 38, pp. 561-568.

—— 1907. Geological Notes on the South-west of Otago, *Trans. N.Z. Inst.*, vol. 39, pp. 496-503.

—— 1911. *In* The Geology of the Dun Mountain Subdivision, Nelson, *N.Z. Geol. Surv. Bull.*, No. 12, pp. 31-35.

—— 1917. The Geology of the Tuapeka District, *N.Z. Geol. Surv. Bull.*, No. 19.

MARWICK, J., 1925. Upper Palaeozoic (Permian) Fossils at Clinton, *N.Z. Jour. Sci. and Tech.*, vol. 7, No. 6, pp. 362-363.

MERRILL, G. P., 1888. Note on the Secondary Enlargement of Augites in a Peridotite from Little Deer Isle, Maine, *Am. Jour. Sci.*, ser. 3, vol. 35, pp. 488-490.

MORGAN, P. G., 1908. The Geology of the Mikonui Subdivision, *N.Z. Geol. Surv. Bull.*, No. 6.

—— 1911. The Geology of the Greymouth Subdivision. *N.Z. Geol. Surv. Bull.*, No. 13.

MURGOCI, G. M., 1900. Ueber die Einschlüsse von Granatvesuvianfels in dem Serpentine des Paringû Massif, *Bulletinul de Sounte, Bukarest*, 9.

—— 1905. On the Genesis of Riebeckite and Riebeckite Rocks, *Am. Jour. Sci.*, ser. 4, vol. 20, pp. 133-145.

—— 1906. Contribution to the Classification of the Amphiboles, *Bull. Dept. Geol. Univ. California*, vol. 4, No. 15, pp. 359-386.

PARK, J., 1887. On the District between the Dart and Big Bay, *Rept. Geol. Expl. N.Z.*, 1886-1887, pp. 121-137.

—— 1906. The Geology of the Alexandra Sheet, *N.Z. Geol. Surv. Bull.*, No. 2.

—— 1908. The Geology of the Cromwell Subdivision, *N.Z. Geol. Surv. Bull.*, No. 5.

——1909. The Geology of the Queenstown Subdivision. *N.Z. Geol. Surv. Bull.*, No. 7.

——1921. The Geology of Western Southland, *N.Z. Geol. Surv. Bull.*, No. 23.

PHEMISTER, J., 1926. *In* The Geology of Strath Oykell and Lower Loch Shin, *Mem. Geol. Surv. Scotland.*

PHILLIPS, F. C., 1927. The Serpentines and Associated Rocks and Minerals of the Shetland Islands, *Q.J.G.S.*, vol. 83, No. 332, pp. 622-652.

—— 1930. Some Mineralogical and Chemical Changes Induced by Progressive Metamorphism in the Green Bed Group of the Scottish Dalradian, *Min. Mag.*, vol. 22, No. 129, pp. 239-256.

POSNJAK, E., AND BOWEN, N. L., 1931. The Role of Water in Tremolite, *Am. Jour. Sci.*, ser. 5, vol. 22, pp. 203-214.

READ, H. H., 1923. The Geology of the Country round Banff, Huntly, and Turriff, *Mem. Geol. Surv. Scotland.*

—— 1923a. The Petrology of the Arnage District in Aberdeenshire: A Study in Assimilation, *Q.J.G.S.*, vol. 79, pp. 446-486.

—— 1926. *In* The Geology of Strath Oykell and Lower Loch Shin, *Mem. Geol. Surv. Scotland.*

—— 1931. The Geology of Central Sutherland, *Mem. Geol. Surv. Scotland.*

RENARD, A. F., 1882. Recherches sur la Composition et la Structure des Phyllades Ardennais, *Mus. Roy. Hist. Nat. Belgique Bull.*, vol. 3.

ROSS, C. S., 1929. Is Chromite always a Magmatic Segregation Product, *Econ. Geol.*, vol. 24, No. 6, pp. 641-645.

SAMPSON, E., 1929. May Chromite Crystallise Late, *Econ. Geol.*, vol. 24, No. 6, pp. 632-641.

SCHALLER, W. T., 1925. The Genesis of Lithium Pegmatites, *Am. Jour. Sci.*, ser. 5, vol. 10, pp. 267-279.

SEDERHOLM, J. J., 1916. On Synantetic Minerals and Related Phenomena, *Com. Geol. Finlande Bull.*, No. 48.

SIMPSON, E. S., 1915. On Chloritoid and its Congeners, *Geol. Surv. West. Austr. Bull.*, No. 64, pp. 64-78.

SMITH, J. PERRIN, 1907. The Paragenesis of the Minerals in the Glaucophane-bearing Rocks of California, *Proc. Amer. Phil. Soc.*, vol. 45, pp. 183-242.

SPEIGHT, R., 1910. Notes on the Geology of the West Coast Sounds, *Trans. N.Z. Inst.*, vol. 42, pp. 255-267.

STILLWELL, F. L., 1918. The Metamorphic Rocks of Adelie Land, *Repts. Australasian Antarctic Exped.*, ser. A, vol. 3, pt. 1.

SUESS, E., 1909. *The Face of the Earth*, vol. 4, Oxford, Clarendon Press (*Das Antlitz der Erde*, English Translation by Sollas).

SUGI, K., 1930. On the Granitic Rocks of Tsukuba District and their Associated Injection-rocks. *Jap. Jour. Geol. & Geogr.*, vol. 8, Nos. 1-2, pp. 29-112.

TATTAM, C. M., 1929. The Metamorphic Rocks of North-east Victoria, *Bull. Geol. Surv. Victoria*, No. 52.

THOMAS, H. H., 1925. *In* The Pre-Tertiary Geology of Mull, Loch Aline and Oban, *Mem. Geol. Surv. Scotland.*

TILLEY, C. E., 1921. Pre-Cambrian Para-Gneisses of Southern Eyre Peninsula, South Australia, *Geol. Mag.*, vol. 58, pp. 251-259, 305-312.

—— 1921a. The Granite Gneisses of Southern Eyre Peninsula (South Australia) and their Associated Amphibolites, *Q.J.G.S.*, vol. 77, pp. 75-134.

—— 1923. The Petrology of the Metamorphosed Rocks of the Start Area (South Devon), *Q.J.G.S.*, vol. 79, pp. 172-204.

—— 1925a. Metamorphic Zones in the Southern Highlands of Scotland, *Q.J.G.S.*, vol. 81, pp. 100-112.

—— 1926. Some Mineralogical Transformations in Crystalline Schists, *Min. Mag.*, vol. 21, No. 113, pp. 31-46.

——1926a. On Garnet in Pelitic Contact Zones, *Min. Mag.*, vol. 21, No. 113, pp. 47-50.

TURNER, F. J., 1930a. The Metamorphic and Ultrabasic Rocks of the Lower Cascade Valley, South Westland, *Trans. N.Z. Inst.*, vol. 61, pp. 170-201.

—— 1930b. Physiographic Features of the Lower Cascade Valley and the Cascade Plateau, South Westland, *Trans. N.Z. Inst.*, vol. 61, pp. 524-535.

TYRRELL, G. W., 1930. *The Principles of Petrology*, 2nd ed., London, Methuen & Co.

—— 1931. Recent Advances in Science—Geology, *Science Progress*, vol. 26, No. 101, pp. 26-34.

VAN HISE, C. R., 1904. A Treatise on Metamorphism, *U.S. Geol. Surv. Monogr.*, No. 47.

VOGT, T., 1927. Sulitelmafeltets geologi og petrografi, *Norges Geologiske Undersökelse*, Nr. 121, Oslo. [Abstract, *Neues Jahrbuch*, Ref., 1929 5, pp. 455-478.]

WARREN, B. E., 1929. The Structure of Tremolite, *Zeits. Krist.*, vol. 27, pp. 42-57.

WATT, W. R., 1914. Geology of the Country Around Huntly, *Q.J.G.S.*, vol. 70, pp. 266-293.

WINCHELL, A. N., 1927. *Elements of Optical Mineralogy—Part 2*, New York, John Wiley & Sons.

—— 1929. *Elements of Optical Mineralogy—Part 3*, New York, John Wiley & Sons.

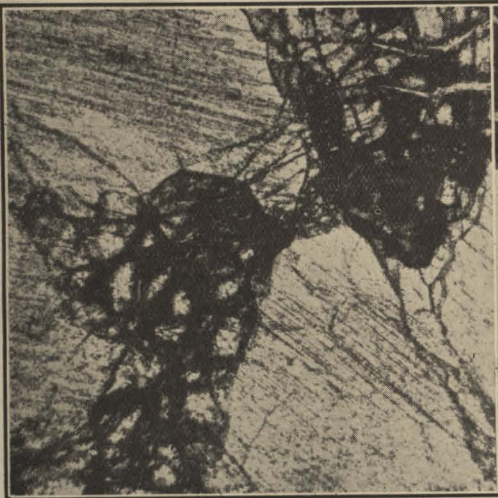

FIG. 13.—*Diallage and interstitial olivine in pyroxenite (No. 1376).*

FIG. 14.—*Contact between partially serpentinised peridotite and chromite vein (No. 1374a).*

FIG. 15.—*Hornblende-albite rock (No. 1412).*

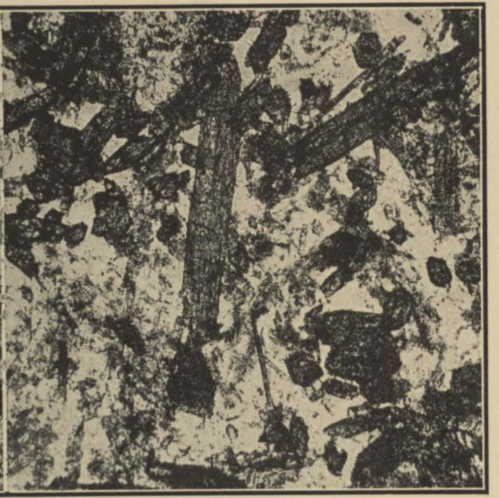

FIG. 16.—*Fine-grained diorite-pegmatite (No. 1333).*

All magnifications 37 diameters.