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INTRODUCTION

Abstract

THE SOUTHERN ALPS of New Zealand are a mountain range that forms the backbone of the South Island of New Zealand. The range extends in a northeast to southwest direction from about latitude 42° S. to latitude 45° S. and is continued both north and south by subsidiary ranges; it is bounded on the west by the Alpine Fault. Most of the rocks are graywackes and argillites and their metamorphosed equivalents. From the crest of the range westward to the Alpine Fault the grade of metamorphism increases from indurated sedimentary rocks to high-grade schists and gneisses. Four zones of progressive metamorphism are recognized: the Chlorite, Biotite, Almandine, and Oligoclase zones. The mineralogy and petrology of these zones are described and illustrated by analyses of the rocks and their constituent minerals. The sediments were deposited in a geosyncline in Triassic (and possibly Permian and Jurassic) times. An early Cretaceous orogeny resulted in intense folding, followed by regional metamorphism. Erosion reduced the region to a low level by the end of the Cretaceous, and much of it was subjected to a marine transgression in early Tertiary times. Renewed uplift began in the Miocene and reached its peak in strong vertical movements on the Alpine Fault at the end of the Tertiary period.

Geographical Setting

The Southern Alps are the major geographical and geological feature of the South Island of New Zealand (fig. 1). They form the watershed between east and west coasts, often referred to as the Main Divide. This is generally considered as extending from Lewis Pass in the north to Mt. Aspiring in the south, a distance of some 220 miles, but is continued both north and south by subsidiary ranges. The Alps are sharply bounded on the west by a remarkable fracture, the Alpine Fault, which extends the full length of the mountains and in many places presents a wall-like appearance against the coastal plain, with a relief of several thousand feet (pl. 32). On the eastern side the Alps are flanked by subsidiary ranges and intermontane basins, many of which reflect late Tertiary and Recent faulting. Summit level ranges from about 6000 feet to a maximum of 12,439 feet in Mt. Cook. The central section is heavily glaciated, with individual glaciers up to 18 miles long. On the steep western side some of the glaciers reach almost to the coastal plain; at the maximum of the last glaciation they coalesced to form a piedmont glacier extending beyond the present coast line. The western side of the Alps is clothed in dense rain forest up to about 3500 feet; above this are subalpine scrub and then a belt of snow grass, which ends at the snow line, at about 6000 feet in the north, descending to 5000 feet in the south. The eastern leeward side has much lower rainfall; the forest is less dense and extensive, and most of this region is open grassland which is used for extensive sheep farming.

The field work was largely carried out during the summers of 1954 and 1958. The mapping was necessarily reconnaissance in nature, in order to cover an area of about 2000 square miles of rugged country in the time available, and because for much of this area the best topographical maps are on a 1:250,000 scale.

Acknowledgments

During the field work I was accompanied by a number of persons whose contribution was essential to the carrying out of the work. These included Prof. Arnold Lillie, with whom I traversed the high mountains and glaciers of the central part of the Alps, and who gave liberally from his wide experience in Alpine geology; Dr. Maxwell Gage and Messrs. A. G. Flower, J. F. Hayes, A. A. Deans, D. Deans, and R. Eggeling. I take this opportunity of thanking these men for their assistance, without which this survey could not have been carried out. I also wish to acknowledge the financial support of the John Simon Guggenheim Memorial Foundation, the American Philosophical Society, and the Higgins Fund of Columbia University. The Research Corporation provided the funds for a Frantz Isodynamic Separator, which greatly facilitated the separation of pure mineral samples from the rocks. I am also indebted to the New Zealand Geological Survey for general assist-

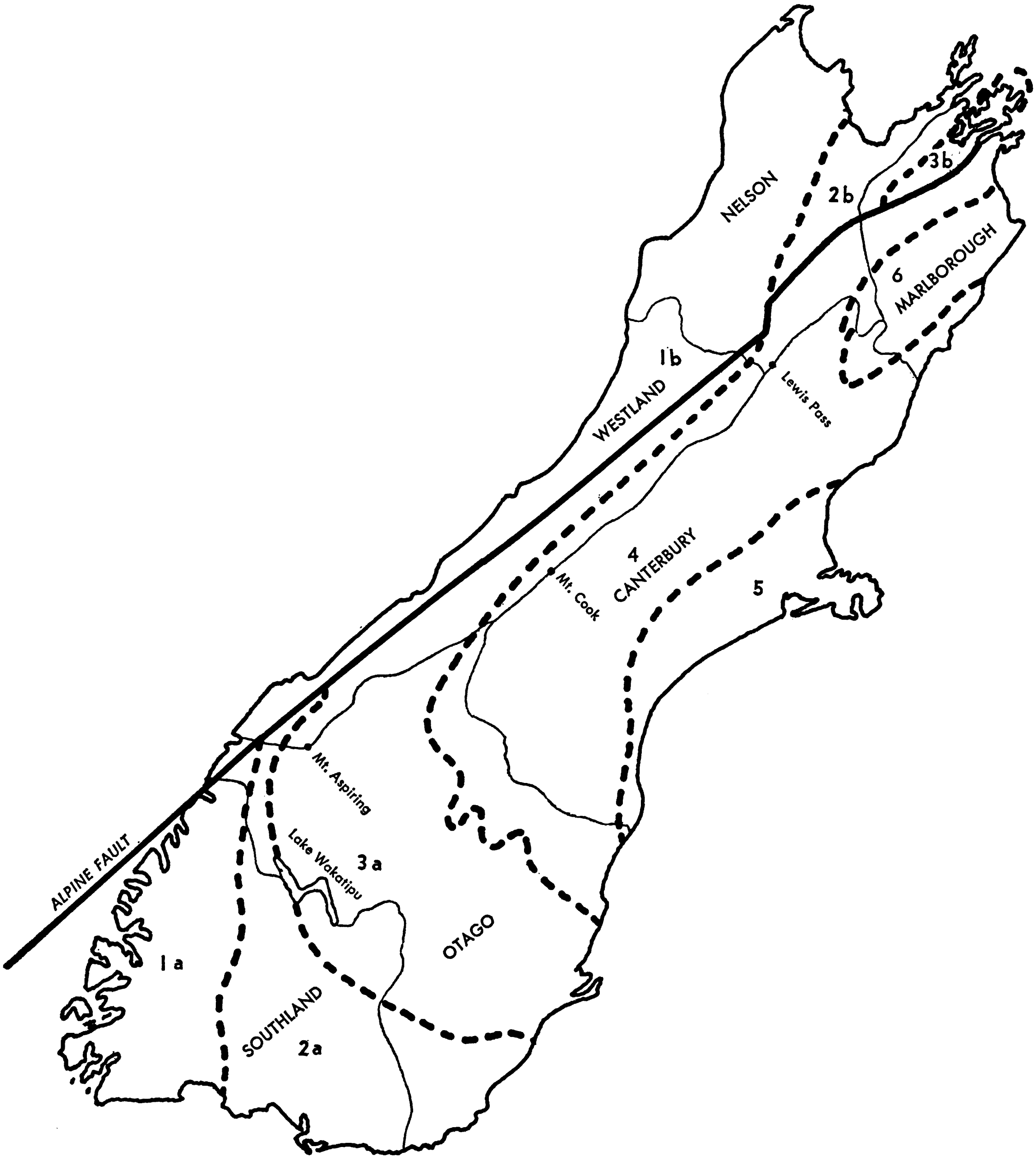


FIG. 1. The South Island of New Zealand, showing administrative provinces (outlined in thin solid lines) and structural regions (outlined in dashed lines and by heavy solid line of Alpine Fault). The structural regions are (after Wellman, 1956): 1a, Fiordland; 1b, West Coast; 2a, Southland Syncline; 2b, Nelson Syncline; 3a, Otago and Alpine Schist; 3b, Marlborough Schist; 4, Alpine Graywacke; 5, Canterbury Plains and Banks Peninsula; 6, Eastern Marlborough. The boundary of Westland Province follows the crest of the Southern Alps from Mt. Aspiring to Lewis Pass.

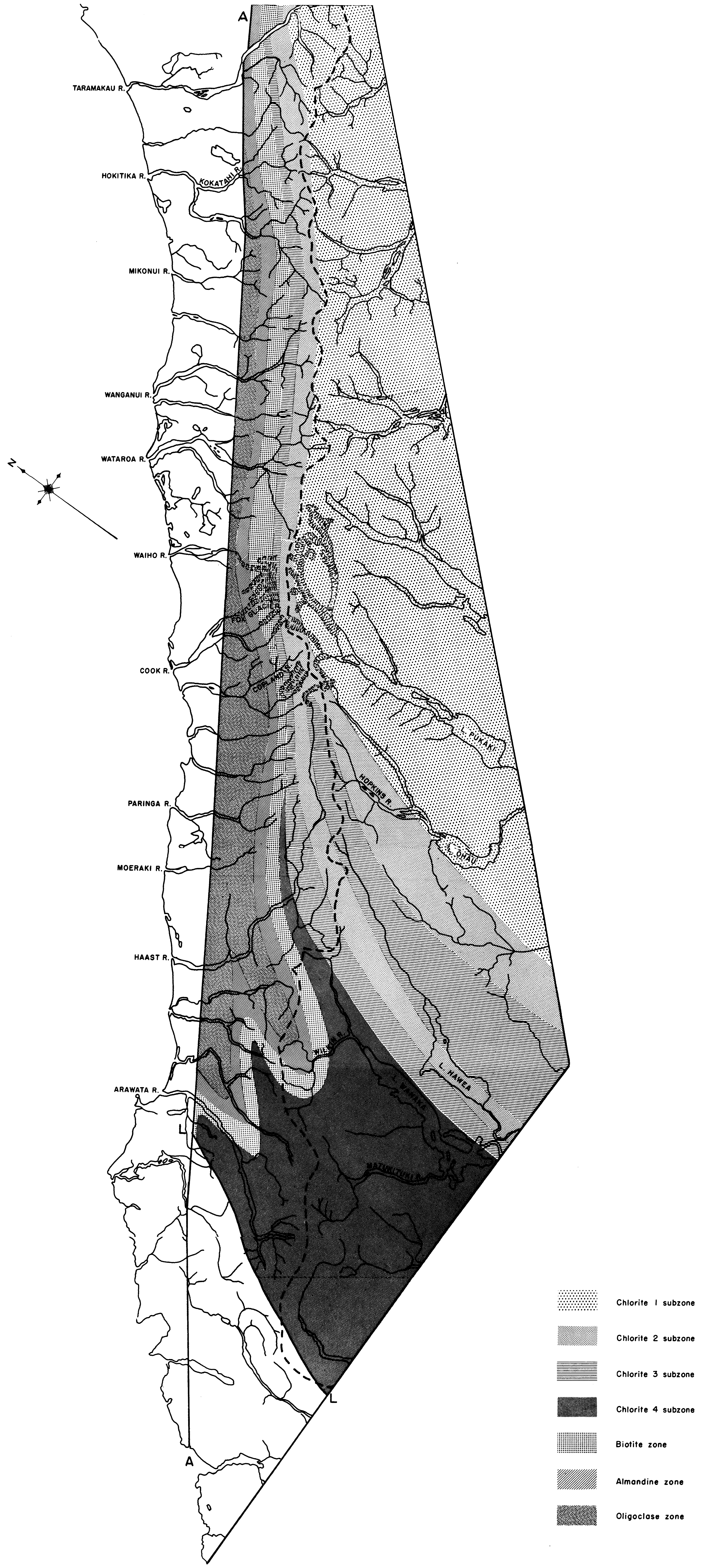


FIG. 2. Metamorphic zones in the Southern Alps. A–A, Alpine fault; L–L, Livingstone Fault. The heavy dashed line marks the watershed between the east and west coasts.

ance, especially in the provision of thin sections of many of the rocks. Dr. H. B. Wiik, Mr. M. C. Coller, and Miss M. G. Speer contributed much to this research in their chemical analyses of the rocks and minerals; Mr. H. S. Muskatt made the modal analyses of the analyzed rocks; Mr. J. Weber made the photomicrographs.

My thanks are also due to Dr. C. O. Hutton for assistance in the determination of stilpnomelane; to Dr. F. J. Turner, Dr. R. N. Brothers, and Dr. J. B. Thompson, Jr., for critical reading of the manuscript; and to Dr. P. M. Hurley and his co-workers for potassium-argon age determinations.

Previous Work

Geological investigation of this region can be said to date from the 1860's, when rich alluvial gold deposits were found along the western coastal plain. Julius von Haast, then Government Geologist of the province of Canterbury, explored large areas of the Southern Alps and summed up his observations and conclusions in a book published in 1879, accompanied by a geological map on a scale of 1:1,000,000. This was a remarkable contribution; von Haast described the progressive nature of the metamorphism in going across the Alps from east to west, and, although he did not identify the Alpine Fault as such, he clearly recognized the fundamental differences between the formations on each side of this fault.

Detailed mapping of the mountain region, coupled with some petrographic work on the rock types, began in 1905. In the next three years the New Zealand Geological Survey mapped (on a scale of 1:63,360) the region between the Taramakau and Wanganui rivers from the Main Divide to the west coast. This work was published in two bulletins (Bell and Fraser, 1906; Morgan, 1908); it established that there is a gradual transition from unmetamorphosed sediments (mainly graywackes) on the Main Divide to biotite schists and gneisses near the Alpine Fault, and that the schists and gneisses occasionally contain bands of green schists which appear to be metamorphosed basic and ultrabasic rocks.

Little further work was done until the early 1930's, when Turner (1933) made two expeditions across the Alps in their southern part. His extensive petrological investigation of the rocks collected has been the foundation of the interpretation of the metamorphic rocks of New Zealand, and the present investigation is largely the extension of his pioneer work and ideas over a much larger area. He later extended this work to the schists of Otago, to the south and east, and published a number of papers on them, some of which are referred to below. Hutton has also worked in this general region and has described in detail the metamorphism in the Lake Wakatipu region (1940). Later he made a very extensive study of the heavy detrital minerals from alluvial deposits throughout the South Island, and his published paper (1950) contains much information on minerals derived from the region described here.

Regional geological mapping on the western side of the Alps has been carried out in recent years by Wellman and Willett (1942) and Wellman (1951). In these publications, however, the authors deal only summarily with the metamorphic rocks, being principally concerned with other aspects of the geology. Detailed accounts of the geology of specific areas have been published by Wellman, Grindley, and Munden (1952), Mason and Taylor (1955), Lillie and Mason (1955), Lillie, Gunn, and Robinson (1957), and Gunn (1960). Reed (1958) has comprehensively described the metamorphic geology of the region to the north of that described here.

A brief summary of the metamorphic rocks of the Southern Alps is given in the bulletin accompanying the 1:2,000,000 geological map of New Zealand (Grindley, Harrington, and Wood, 1959).

Because of limited time for field work and the severe restriction on the number of specimens that could be brought back for laboratory examination, it was necessary to establish readily applicable macroscopic criteria for mapping these metamorphic rocks. Fortunately the earlier work of Turner (1933) had indicated the type of rocks to be expected. Mapping was based on rocks of graywacke composition, which form the common rock type throughout the region, and zones were mapped on the following criteria. Their approximate equivalence with the metamorphic zones established by Turner are given.

Unaltered graywacke	Chlorite 1 Subzone
Sheared graywacke	Chlorite 2 Subzone
Nonfoliated schist	Chlorite 3 Subzone
Foliated muscovite-chlorite schist	Chlorite 4 Subzone
Foliated biotite schist	Biotite, Oligoclase zones

(Foliation is used in the sense of macroscopically distinct lenses of quartz-plagioclase and micaceous minerals.)

The zones based on structural criteria graded one into another, and in the field it was sometimes difficult to decide the classification of an individual specimen. The field zoning was revised after an examination of thin sections, but the zone boundaries were little altered, which indicates that hand-specimen criteria are adequate for mapping metamorphic grade, at least as far as the biotite schist zone. This zone was divided into Biotite, Almandine, and Oligoclase zones on the basis of laboratory investigation of the constituent minerals. The results of the mapping are presented in figure 2.

Figure 2 shows the remarkable simplicity in the distribution of the metamorphic zones. North of Mt. Cook all sections across the mountains from east to west show a regular succession of metamorphic zones (fig. 3). Unmetamorphosed graywackes east of the Main Divide pass successively into sheared graywackes, schistose graywackes, and phyllonites (fissile unfoliated schists). The mineralogy of these rocks is that characteristic of the Chlorite Zone of regional metamorphism. Within the phyllonites the incoming of biotite indicates the passage

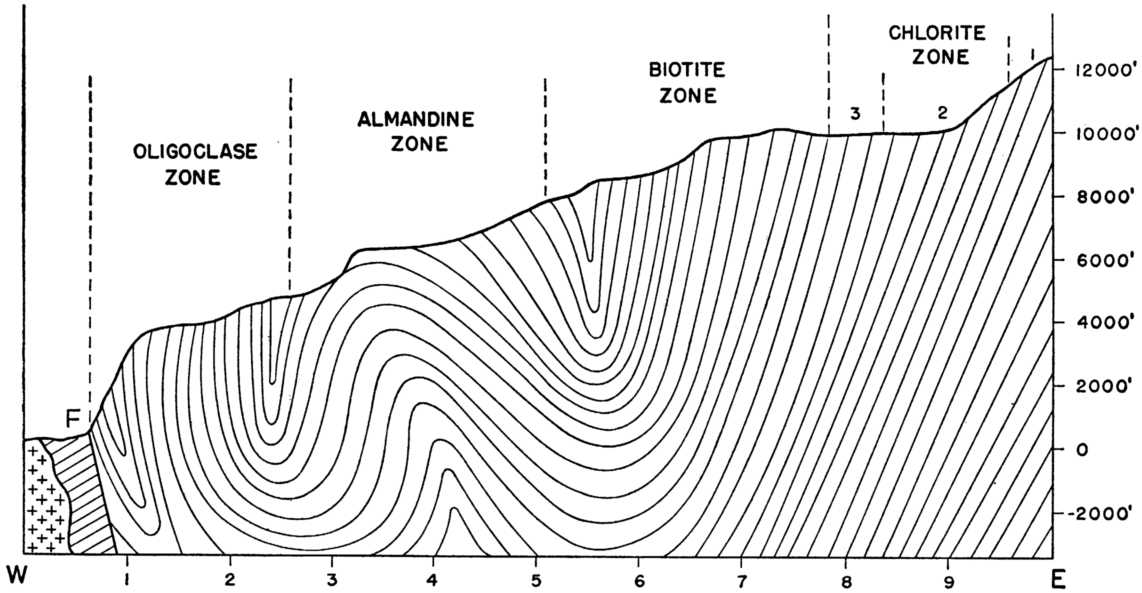


Fig. 3. Section from Alpine Fault at Cook River (W) to Mt. Cook (E).

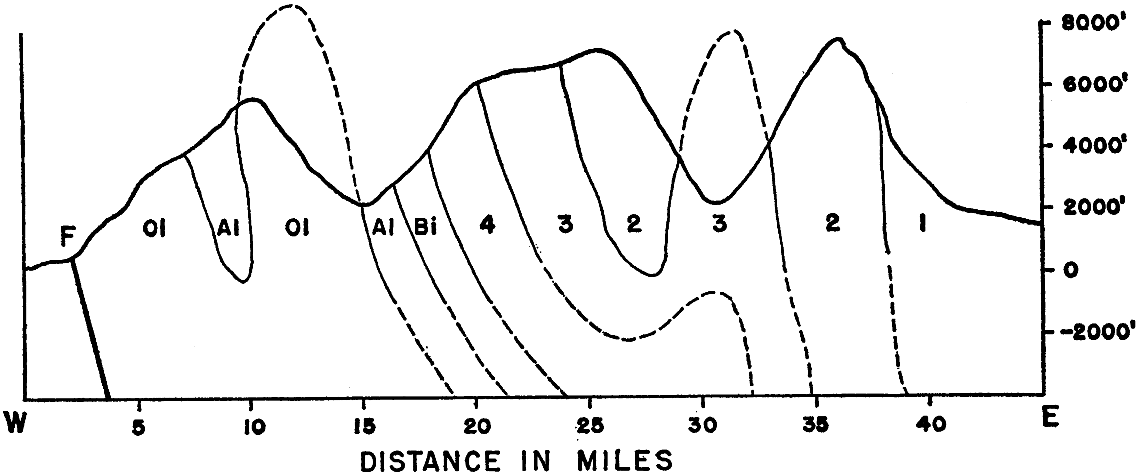


FIG. 4. Section from Alpine Fault at Haast River (W) to Lake Ohau (E), showing sequence of metamorphic zones.

from the Chlorite Zone to the Biotite Zone. The incoming of biotite is accompanied by a general increase in grain size of the constituent minerals and the development of foliation. The increasing grade of metamorphism farther west is marked by the incoming first of almandine and then of oligoclase (before the incoming of oligoclase the feldspar is albite).

South of Mt. Cook this regular succession of metamorphic zones is complicated by a repetition of some of the zones, well shown along a section from Lake Ohau to the mouth of the Haast River (fig. 4). In this region, too, biotite does not appear in the phyllonites, which are succeeded by a zone of foliated chlorite-muscovite schists (fig. 2, Chlorite 4 Subzone). This zone increases rapidly in area when followed south and southeast into Otago, at and beyond the southern boundary of the map.

The simplicity of the sequence of metamorphic zones is in marked contrast to the structural complexity of the rocks. Lillie, Gunn, and Robinson (1957) have shown that in the central part of the Alps the graywackes have been isoclinally folded, and the pattern of isoclinal folds can be traced into the more highly metamorphosed rocks. This general picture is valid for other parts of the Alps also. The graywackes strike parallel to the general direction of the Alps, i.e., northeast; the dip is 60 degrees or greater and is generally to the northwest. Previous observers have noted that schistosity planes in the metamorphic rocks are commonly parallel to bedding planes in the unmetamorphosed and slightly metamorphosed graywackes, which is certainly true. However, as Lillie, Gunn, and Robinson point out, the schistosity is parallel to the axial planes of the isoclinal folds; it thus coincides with the bedding on the limbs of the folds but diverges on the crests of the folds (where deformation has usually obscured bedding planes even in the less metamorphosed rocks). The distinction between schistosity and bedding planes can be made in some places in the phyllonite zone, but at higher metamorphic grade no trace of bedding remains, except where bands of green schists mark the original presence of sills or flows of basic igneous rocks. Throughout most of the Alpine region the schistosity planes also dip steeply. However, in south Westland and northwest Otago, areas of low-dipping and flat-lying schists are found. These areas appear in the region of the repetition of the metamorphic zones, which can plausibly be ascribed to post-metamorphism folding (fig. 4). The low-dipping and flat-lying schists occupy the axial parts of anticlinal folds. These folds plunge to the south and southeast, and when followed in this direction the biotite and schists of higher grade disappear below a broad arch of foliated chlorite schists which continues through Otago to the east coast (fig. 1).

Over the whole region the metamorphic isograds appear to be generally parallel to the schistosity planes. Such is certainly true along the direction of strike. Whether or not it also holds in the direction of dip is not so clear. On the scale of mapping, the positions of isograds have not been determined with a greater precision than within a few hundred yards horizontally, and they have not been carefully followed over large vertical distances. Nothing inconsistent with the view that isograds approximately parallel schistosity planes in the direction of dip was observed, but detailed work is necessary before categorical statements are justified.

MINERALOGY

TABLE 1 SHOWS the distribution of the more common minerals with respect to the metamorphic zones. Notes on the individual minerals follow:

QUARTZ: Quartz is present in rocks of all zones. It is a major constituent in all rocks of graywacke composition and is usually a minor constituent of schists derived from basic igneous rocks.

CALCITE: Calcite can occur in rocks of all zones. It is absent, or present only as an accessory in derivatives of graywackes and argillites, and these rocks contain no interbedded limestones. Calcite may be fairly abundant in derivatives of basic igneous rocks; in association with these rocks narrow bands consisting essentially of this mineral have been observed (Mason and Taylor, 1955).

MUSCOVITE: Muscovite can occur in all zones and is omnipresent in rocks derived from graywackes and argillites. In rocks of Chlorite 1 and 2 subzones it is present as illite, which is completely recrystallized to sericite in the Chlorite 3 Subzone and to relatively coarse-grained muscovite in higher zones. Analyses of muscovites are given in table 2.

Significant differences between these analyses are the following: Al replacing Si is 1.47 in 1, 1.86 in 2; Al in sixfold coordination is 2.96 in 1, 3.37 in 2; Fe^2 is 0.31 in 1, 0.04 in 2; Na is 0.14 in 1, 0.34 in 2; Mg is 0.48 in 1, 0.28 in 2; K is 1.66 in 1, 1.46 in 2. These differences can plausibly be ascribed to the increase in metamorphic grade from 1 to 2, since the rocks from which these muscovites have been extracted are essentially similar in composition, being metamorphosed graywackes. Thus increasing metamorphism has resulted in the practical elimination of Fe^2 and a marked decrease in Mg, coupled with an increase of Al in sixfold coordination, an increase in the replacing of Si by Al, and an increase in the replacing of K by Na. Lambert (1959) has published a number of analyses of muscovite from the Moine schists; he finds similar trends with increasing metamorphic grade.

CHLORITE: As implied in the classification, chlorite is characteristic of Chlorite-zone rocks. Nevertheless it may occur, evidently in equilibrium, in rocks of higher metamorphic grade and has been observed even in the Oligoclase Zone. Thus the Chlorite Zone is characterized not only by the pres-

TABLE 1

OCCURRENCE OF MINERALS IN RELATIONSHIP TO METAMORPHIC ZONES AND ROCK TYPE

Mineral	Rock Type	Chlorite Zone	Biotite Zone	Almandine Zone	Oligoclase Zone
Quartz	A, B	—	—	—	—
Calcite	B	—	—	—	—
Muscovite	A	—	—	—	—
Chlorite	A, B	—	—	—	—
Stilpnomelane	A, B	—			
Biotite	A, B		—	—	—
Pumpellyite	A	—			
Clinozoisite	A	—	—	—	—
Epidote	B	—	—	—	
Albite	A, B	—	—	—	
Oligoclase	A, B				—
Actinolite	B	—	—		
Hornblende	B			—	—
Almandine	A, B			—	—

A Graywacke derivatives
B Derivatives of basic igneous rocks

TABLE 2

ANALYSES (ANALYST: H. B. WIIK) OF MUSCOVITES (1) FROM QUARTZ-ALBITE-MUSCOVITE-CHLORITE SCHIST,[a] CHLORITE 4 SUBZONE, CLARKE BLUFF, HAAST RIVER; (2) FROM QUARTZ-OLIGOCLASE-MUSCOVITE-BIOTITE-ALMANDINE SCHIST,[b] OLIGOCLASE ZONE, FOX RIVER

	Analyses 1	Analyses 2		Cations per 24 (O, OH, F) 1	Cations per 24 (O, OH, F) 2
SiO_2	48.72	47.18	Si	6.53	6.14
TiO_2	0.58	0.50	Al^{IV}	1.47	1.86
Al_2O_3	28.02	33.26	Al^{VI}	2.96	3.37
Fe_2O_3	2.56	2.64	Ti	0.06	0.05
FeO	2.74	0.35	Fe^3	0.26	0.27
MnO	0.07	0.01	Fe^2	0.31	0.04
MgO	2.41	1.44	Mn	0.01	—
CaO	0.00	0.20	Mg	0.48	0.28
Na_2O	0.55	1.30	Ca	—	0.06
K_2O	9.70	8.56	Na	0.14	0.34
H_2O+	4.59	4.70	K	1.66	1.46
H_2O-	0.14	0.00			
F	0.06	0.07			
	100.14	100.21			
D	2.88	2.84			
γ	1.600	1.598			

[a] Analysis 6, table 6.
[b] Analysis 12, table 6.

ence of chlorite but also by the absence of minerals of related composition but of higher metamorphic grade, viz., biotite and almandine.

A partial analysis of chlorite from a quartz-oligoclase-muscovite-biotite-almandine schist in the Copland River gave the following results: SiO_2, 25.08; TiO_2, 0.20; Al_2O_3, 21.85; Fe_2O_3, 5.06; FeO, 20.64; MgO, 15.31; if the normal H_2O content of a chlorite analysis is assumed, the total summation would be close to 100. This chlorite is similar in composition to two from rocks of the Chlorite 4 Subzone in western Otago (Hutton, 1940). It has $\alpha = 1.621$, $\gamma = 1.625$, density 2.94. The composition corresponds to the formula

$$(Mg_{2.4}\ Fe_{1.2}^{2}\ Fe_{0.4}^{3}\ Al_{1.4})(Si_{2.6}\ Al_{1.4})O_{10}\ (OH)_8,$$

which is a ripidolite in the classification of Hey (1954).

The refractive indices of chlorite vary systematically from Chlorite-zone rocks to rocks of higher metamorphic grade. In Chlorite-zone rocks of graywacke and agrillite composition the chlorite has a gamma index of around 1.64, whereas in rocks of higher grade the index is lower, generally 1.62–1.63. This feature appears to be related to the removal of some iron from the chlorite for the formation of biotite. Chlorite from derivatives of basic igneous rocks in the Biotite and Almandine zones has a gamma index of around 1.60, and it is evidently richer in magnesium than chlorites from schists of graywacke and argillite composition.

STILPNOMELANE: This mineral is common in small amounts in rocks of the Chlorite Zone. It is often the first new mineral to appear, coming in at about the Chlorite 1 to Chlorite 2 subzone boundary. It is usually an Fe_2O_3-rich variety characterized by a strong golden yellow color in the X vibration direction (Hutton, 1938). Although widespread, this mineral is not abundant in the Alpine rocks, in contrast to the schists of Otago described by Hutton. Its occurrence seems to reflect the influence of bulk composition of the rocks; rocks with abundant stilpnomelane are generally low-silica, high-iron types probably derived from basic igneous rocks and tuffs. The Alpine graywackes have been derived from granodioritic rocks, and the accessory amount of the stilpnomelane reflects the predominance of quartz and feldspar in the parent material.

BIOTITE: The incoming of biotite indicates that the boundary between Chlorite-zone and Biotite-zone rocks has been passed. Beyond this boundary biotite is always present in rocks of graywacke and argillite composition and often in metamorphosed basic igneous rocks also.

A noteworthy feature of biotite in the Alpine schists derived from graywackes and argillites is its comparatively uniform refractive index, despite variation in metamorphic grade and in rock composition. The gamma index is always between 1.63 and 1.64, usually about 1.632, and the pleochroism is pale yellow to dark brown. Biotite in schists derived from basic igneous rocks has a gamma index of about 1.62 and is pleochroic in shades of green. One biotite from a cal-

TABLE 3

ANALYSES OF BIOTITES

	Analyses 1	2	3	4	5	6
SiO_2	36.02	36.40	38.1	37.8	38.9	39.9
TiO_2	2.42	1.70	1.17	1.49	0.53	1.01
Al_2O_3	17.34	17.73	18.9	19.4	17.0	16.3
Fe_2O_3	2.01	1.01	0.0	0.4	1.5	2.2
FeO	17.97	17.77	16.7	19.4	11.7	10.3
MgO	10.92	11.60	11.8	8.6	15.7	16.5
MnO	0.04	0.03	0.22	0.14	0.46	0.10
CaO	0.00	1.34	0.1	0.1	0.9	0.2
Na_2O	0.74	1.49	0.26	0.40	0.17	0.50
K_2O	8.27	7.37	9.10	9.00	9.50	8.65
H_2O+	3.46	3.56	4.42	3.60	4.05	3.77
H_2O-	0.00	0.00	0.07	0.05	0.04	0.20
F	0.21	0.18	—	—	—	—
Li_2O	—	—	0.03	0.03	0.01	0.02
P_2O_5	0.17	—	—	—	—	—
	99.57	100.18	100.87	100.41	100.46	99.65
D	3.06	3.04	3.05	3.05	2.94	2.88
γ	1.634	1.632	1.630	1.638	1.622	1.596

	Cations per 24 (O, OH, F) 1	2	3	4	5	6
Si	5.46	5.52	5.57	5.66	5.66	5.81
Al^{IV}	2.54	2.48	2.43	2.34	2.34	2.19
Ti	0.27	0.19	0.10	0.17	0.06	0.11
Al^{VI}	0.56	0.66	0.83	1.09	0.58	0.61
Fe^{3}	0.23	0.12	—	0.05	0.17	0.24
Fe^{2}	2.29	2.24	2.05	2.44	1.43	1.26
Mg	2.48	2.60	2.58	1.93	3.42	3.59
Mn	—	—	0.03	0.02	0.06	0.01
Ca	—	0.22	0.02	0.02	0.14	0.03
Na	0.22	0.44	0.07	0.12	0.05	0.14
K	1.61	1.41	1.70	1.73	1.77	1.61

1 Biotite from quartz-oligoclase-muscovite-biotite-almandine schist, Copland River (analyst: H. B. Wiik)
2 Biotite from quartz-oligoclase-biotite-almandine-hornblende schist (analysis 1, table 7), Callery River (analyst: H. B. Wiik)
3 Biotite from quartz-albite-biotite-muscovite schist, Kokatahi River (analyst: M. C. Coller)
4 Biotite from quartz-albite-biotite-muscovite schist, Kokatahi River (analyst: M. C. Coller)
5 Biotite from biotite-epidote-hornblende-magnetite schist, Kokatahi River (analyst: M. C. Coller)
6 Biotite from schistose marble, Kokatahi River (analyst: M. C. Coller)

careous band associated with these schists had a gamma index of 1.596 and pleochroism X = colorless, Y = Z = olive green.

A number of biotites have been analyzed. The results are given in table 3.

Of the analyzed biotites, 1 is from a graywacke-derived schist in the Oligoclase zone; 2 is from a metamorphosed basic igneous rock in the Oligoclase zone; 3, 4, 5, and 6 are from a single locality at the boundary between the Biotite and Almandine zones, 3 and 4 being from graywacke-derived schists, 5 from a green schist (metamorphosed basic igneous rock), and 6 from a calcareous band in the green schists. The compositions of the biotites in the graywacke-derived schists are rather similar, the higher metamorphic grade of 1 probably being reflected in a somewhat higher amount of substitution of Na for K; on the other hand, Al in sixfold coordination is somewhat higher in the biotites from the lower-grade schists. Biotites 5 and 6 have considerably higher Mg and lower Fe than biotites from graywacke-derived schists, evidently the result of the higher Mg/Fe ratios in their parent rocks.

Lambert (1959) has discussed the composition of biotites from regionally metamorphosed rocks and noted a consistently low value for total alkali, a noticeable feature in these Southern Alps biotites also (Na+K ranges from 1.75 to 1.85, whereas the structure requires a total of 2). He found an increase of Mg with grade, but remarked that the composition of the host rock plays a significant part in the Mg content of biotite. In the Southern Alps biotites the latter factor seems decisive in the determination of Mg content. Snelling (1957) found no significant variation in Mg content with grade in biotites from the Dalradian rocks of Scotland.

PUMPELLYITE: This mineral is a minor

and inconspicuous constituent of derivatives of graywacke in the Chlorite 2 and 3 subzones. It occurs as minute prismatic crystals, commonly penetrating quartz and albite grains. Quartz veinlets in these subzones sometimes contain pumpellyite, which is then easily recognized by its characteristic blue-green color. Hutton (1940) has described pumpellyite from rocks of this metamorphic grade in Otago.

CLINOZOISITE: This is present in minor amounts (5%–10%) in rocks of graywacke or argillite composition, in the Chlorite, Biotite, and Almandine zones; the amount is proportional to the CaO content of the rock. Rocks in the Oligoclase Zone contain little or no clinozoisite, the calcium having been taken up in the plagioclase. Clinozoisite has also been observed in quartz veinlets in rocks of the Chlorite Zone (Mason, 1959).

EPIDOTE: In schists derived from basic igneous rocks, epidote plays the same role as clinozoisite in rocks of sedimentary origin. Epidote in a quartz-albite-biotite-hornblende-epidote schist (near the boundary of the Biotite and Almandine zones) from the Kokatahi River has $\alpha = 1.735$, $\beta = 1.750$, $\gamma = 1.770$, optically negative, $2V = 69°$, corresponding to about 30 per cent of the $Ca_2Fe_3Si_3O_{12}OH$ component.

PIEDMONTITE: Hutton (1940) and Turner (1946) have described and commented on the occurrence of piedmontite in quartz schists in Otago. Similar occurrences are known in the Alpine schists (Mason, 1955). In Otago, piedmontite occurs in the Chlorite 4 Subzone; in Westland it is present in the Biotite Zone also.

PLAGIOCLASE: Incipient metamorphism rapidly converts detrital plagioclase in graywackes and argillites to a mixture of albite and clinozosite. X-ray powder photographs of rocks in the Chlorite 2 Subzone give sharp peaks for the albite phase, which indicates a uniform composition. In rocks of the Chlorite, Biotite, and Almandine zones the plagioclase is fine-grained and seldom twinned; in the Oligoclase Zone it is coarser and occasionally shows twinning. In the Chlorite, Biotite, and Almandine zones the albite contains about 5 per cent of the anorthite component, as indicated by its refractive indices. The transition to oligoclase at the boundary of the Almandine and Oligoclase zones is a rapid one, and in the Oligoclase Zone the composition is about An_{25-30}. This rapid increase in anorthite content with increasing metamorphic grade has been well documented by de Waard (1959) in the rocks of Timor.

POTASH FELDSPAR: The Alpine graywackes initially contain a variable amount (5%–15%) of potash feldspar. This is rapidly destroyed by incipient metamorphism, evidently by reaction with alumina from the clay material to give muscovite, and muscovite is the only potassium mineral in rocks of the Chlorite 3 and Chlorite 4 subzones, except for the sporadic occurrence of stilpnomelane.

TALC: Talc is found in a few occurrences of green schist in the Biotite and Almandine zones in North Westland; these occurrences were mapped and described by Bell and Fraser (1906) and Morgan (1908). They showed that these green schists are metamorphosed ultrabasic rocks.

SERPENTINE: Serpentine occurs under the same conditions as talc. It may be noted that the "type" antigorite used for the structural investigation of this mineral by Aruja (1944) and Zussman (1954) was from the Cropp River in North Westland, at about the Almandine isograd.

ACTINOLITE: Actinolite is a prominent constituent of many of the green schists mentioned above. It is frequently associated with talc. Large masses of nephrite found in fluvioglacial gravels in North Westland are evidently derived from the schist belt; this material was greatly prized by the Maoris and used for weapons, tools, and ornaments under the name *pounamu*.

Actinolite is also found, but as an unusual and inconspicuous constituent, in metamorphosed graywackes and argillites in the Chlorite and Biotite zones. The aluminous nature of these rocks favors the occurrence of clinozoisite and chlorite. Actinolite has also been found in association with kyanite.

HORNBLENDE: Hornblende-bearing schists are not uncommon in the Almandine and Oligoclase zones. Hornblende does not form in derivatives of graywacke and argillite, because of the low calcium content of these rocks, and its presence indicates derivation from basic igneous rocks and tuffs. Hornblende appears at about the same (or possibly slightly lower) grade of metamorphism as almandine and is thus a useful zone indicator.

The hornblende differs considerably in composition from one rock to another, judged from the variation in its refractive indices (measurements of the gamma index in different specimens range from 1.66 to 1.70). Two specimens have been analyzed (table 4). Of these, 1 is of lower metamorphic grade than 2. When the analyses are compared in terms of cations per 24 (O, OH, F) notable differences are: Si, 6.49 in 1, 6.04 in 2; Al^{IV}, 1.51 in 1, 1.96 in 2; Al^{VI}, 0.63 in 1, 1.09 in 2; Fe^3, 0.70 in 1, 0.25 in 2; Fe^2, 1.26 in 1, 1.96 in 2; Mg, 2.51 in 1, 1.49 in 2; Na, 0.46 in 1, 0.64 in 2. Some of these differences may be due to differences in rock composition, some to differences in metamorphic grade. To the latter can probably be ascribed the greater amount of Al in 2, both in fourfold and sixfold coordination; in fourfold coordination it approaches closely the limiting replacement of one-quarter of the Si in the (Si_4O_{11}) chains. The greater amount of Na in 2 may also reflect the higher grade of metamorphism. The differences in Mg and Fe are probably attributable to differences in original composition of the rocks.

TABLE 4

ANALYSES (ANALYST: H. B. WIIK) OF HORNBLENDE (1) FROM QUARTZ-ALBITE-HORNBLENDE-CHLORITE-EPIDOTE-BIOTITE SCHIST, ALMANDINE ZONE, KOKATAHI RIVER; (2) FROM QUARTZ-OLIGOCLASE-BIOTITE-ALMANDINE-HORNBLENDE-SCHIST,[a] OLIGOCLASE ZONE, CALLERY RIVER

	Analyses 1	Analyses 2		Cations per 24 (O, OH, F) 1	Cations per 24 (O, OH, F) 2
SiO_2	43.72	40.95	Si	6.49	6.04
TiO_2	0.65	1.03	Al^{IV}	1.51	1.96
Al_2O_3	12.21	17.54	Al^{VI}	0.63	1.09
Fe_2O_3	6.30	2.23	Ti	0.07	0.11
FeO	10.11	15.85	Fe^3	0.70	0.25
MnO	0.31	0.07	Fe^2	1.26	1.96
MgO	11.29	6.76	Mn	0.04	—
CaO	11.58	10.81	Mg	2.51	1.49
Na_2O	1.62	2.25	Ca	1.85	1.71
K_2O	0.28	0.47	Na	0.46	0.64
H_2O+	1.38	2.47	K	0.05	0.09
H_2O-	0.00	0.00			
F	0.08	0.12			
	99.56	100.55			
D	3.19	3.24			

Optical Properties:

1 $\alpha=1.649$ (pale yellow), $\beta=1.664$ (grass green), $\gamma=1.672$ (dark blue-green); $Z\wedge c=16°$, (−), $2V=70°$

2 $\alpha=1.653$ (pale yellow), $\beta=1.668$ (pale green), $\gamma=1.678$ (dark blue-green); $Z\wedge c=19°$, (−), $2V=66°$

[a] Analysis 1, table 7.

TABLE 5

ANALYSES (ANALYST: H. B. WIIK) OF ALMANDINE; (1) FROM QUARTZ-OLIGOCLASE-BIOTITE-ALMANDINE-HORNBLENDE SCHIST,[a] CALLERY RIVER; (2) FROM QUARTZ-OLIGOCLASE-MUSCOVITE-BIOTITE-ALMANDINE SCHIST, COPLAND RIVER

	Analyses 1	Analyses 2		Cations per 24 (O) 1	Cations per 24 (O) 2
SiO_2	37.28	35.92	Si	5.87	5.96
TiO_2	0.57	1.17	Ti	0.07	0.15
Al_2O_3	21.78	16.67	Al	4.05	3.26
Fe_2O_3	1.71	4.90	Fe^3	0.20	0.61
FeO	26.76	29.47	Fe^2	3.54	4.10
MnO	1.39	2.00	Mn	0.19	0.28
MgO	3.00	2.10	Mg	0.71	0.52
CaO	7.70	6.18	Ca	1.30	1.10
P_2O_5	—	0.04			
	100.19	98.45			
D	4.08	4.16			
n	1.793	1.795			
a	11.61A	11.59A			

Analyses in Terms of Garnet Components:

	1	2
Almandine	64.2	68.7
Grossularite	16.4	2.8
Andradite	5.6	16.3
Spessartite	3.4	4.9
Pyrope	10.4	7.3

[a] Analysis 1, table 7.

Hornblende (2) occurs in association with analyzed biotite (table 3, no. 2) and almandine (table 5, no. 1). The Fe^2/Fe^2+Mg ratio in these coexisting minerals is: hornblende, 0.57; biotite, 0.46; almandine, 0.83. Total Al per 24 (O, OH, F) is: hornblende, 3.05; biotite, 3.14; almandine, 3.26. The partition of ferrous iron between the three minerals favors almandine over biotite and hornblende, whereas the relative content of aluminum is similar in all of them.

CUMMINGTONITE: Mason (1953) has described and analyzed cummingtonite from the Mikonui River, in North Westland. It occurred in a quartz-rich cummingtonite-almandine schist. Similar material has since been found at other localities in the Alpine schist belt (Mason, 1955), but as river boulders, not in outcrop. However, these rocks have been found in place at the head of the Waikukupa River in the central Alpine region (J. W. Mitchell, private communication). The distribution of the cummingtonite-bearing rocks indicates that this mineral occurs in the Almandine and Oligoclase zones.

ALMANDINE: The only garnet so far found in the Alpine schists is almandine, although Hutton (1940) has described spessartite from Chlorite-zone schists in Otago. The absence of spessartite from Chlorite-zone schists in the Alps may be due to the very low manganese content of the graywackes and argillites that are the parent rocks in this region.

Almandine is common and abundant in the schists formed by the metamorphism of basic igneous rocks and in them can usually be seen with the naked eye. It is comparatively uncommon in schists formed from graywacke and argillite and in these rocks is seldom conspicuous. It is remarkably uniform in its properties, the refractive index being always close to 1.80 and the cell dimension *a* near 11.60A. Two samples of almandine have been analyzed (table 5). The comparatively high TiO_2 content in analysis 2 is partly due to ilmenite inclusions in the almandine; the TiO_2 content of this garnet is probably close to that of analysis 1.

These analyzed garnets are from rocks at approximately the same grade of metamorphism. The differences in composition are therefore to be ascribed largely, if not entirely, to differences in the bulk composition of the parent rocks. The most prominent difference is in total Fe content, 3.74 in 1, 4.71 in 2. On cursory consideration this is remarkable, because the bulk composition of 1 is considerably higher in Fe than that of 2, 1 being a derivative of a basic igneous rock or tuff, 2 being a derivative of a graywacke. However, much of the Fe in 1 is present in hornblende, a mineral that is absent from 2. Another noteworthy feature is the considerable Ca content in both garnets; garnets of similar composition are recorded from the Moine schists by Lambert (1959).

Almandine is rather uncommon in derivatives of graywackes and argillites. Indeed Turner (1933) commented on the absence of an Almandine Zone in the rocks of South Westland, even though the metamorphic grade was such that it would be expected. Better exposures and more extensive collecting have shown that this absence is only apparent, but the sporadic occurrence of almandine in small amount makes the recognition of this zone in the field somewhat difficult. The appearance of almandine in rocks of graywacke composition is conditioned by a somewhat higher than normal iron content, or a somewhat lower potassium content, or both, i.e., iron in excess of that which can be accommodated in biotite.

KYANITE: This mineral has not been found *in situ*. Detrital kyanite was recorded from South Westland by Hutton (1950), and more recently N. E. Odell (private communication) has collected kyanite schist boulders from coastal moraines in this area. This occurrence is of significance, because it indicates that part at least of the Oligoclase Zone is equivalent to the Kyanite Zone recognized in other areas of regional metamorphism.

ACCESSORY MINERALS: A number of accessory minerals also occur. Apatite is present in most, if not all, rocks, but never in amounts more than a few tenths of a per cent. Ilmenite is common. Pyrrhotite may be present in amounts up to a few tenths of a per cent, both in rocks derived from graywackes and in those from basic igneous rocks. Pyrite occurs occasionally in schists derived from basic igneous rocks. Sphene occurs occasionally, usually in hornblende schists. Some hornblende schists, however, contain rutile, in association with calcite and quartz. It thus appears that under some circumstances sphene, under others the association rutile-calcite-quartz, is stable; possibly the partial pressure of CO_2 is the determining factor. Magnetite is not uncommon in schists derived from basic igneous rocks. Tourmaline is widely distributed in accessory amounts in rocks derived from graywackes and argillites; it is usually a variety pleochroic from pale yellow to dark blue-gray. The refractive indices of a specimen from the Kokatahi River are $\epsilon = 1.626$, $\omega = 1.650$, which, according to Winchell's diagram (1951), indicates an Mg/Mg+Fe ratio of about 0.5. Axinite has been observed in a quartz veinlet cutting Chlorite-zone rocks (Mason, 1959). Prehnite has been identified in narrow veinlets cutting graywackes of the Chlorite 1 Subzone.

SIGNIFICANT ABSENCES: Paragonite has not been found in any of these rocks. Mica concentrates were made from many of them, and X-ray examination showed muscovite only, which is probably a reflection of comparatively low alumina and high potassium in the parent rocks, whereby the potassium formed muscovite and the sodium plagioclase. No hematite was found in any of these rocks, which indicates a rather low oxygen activity throughout (the localized occurrence of piedmontite, containing trivalent manganese, is not necessarily contrary to this statement). A careful search was made for jadeite and lawsonite in metamorphosed graywackes, but these minerals were not found. Coombs (1960) has recorded lawsonite-bearing metagraywackes in Nelson (structural region 2^b of fig. 1). Glaucophane has never been observed in the Southern Alps, unlike many similar areas of regional metamorphism. Neither chloritoid nor staurolite has been found; their absence is presumably due to the lack of rocks of suitable bulk composition. Even in rocks of the highest grade there is no sillimanite or potash feldspar, and in them the association quartz-calcite is present, which indicates that the grade of metamorphism was never high enough to produce wollastonite.

As MENTIONED ABOVE, the rocks of the Southern Alps are mainly graywackes (with minor amounts of argillites) and schists derived from them. The chemical and mineralogical composition of these rocks is given in table 6. Associated with these rocks are green schists derived from basic igneous rocks, their chemical and mineralogical composition being set out in table 7.

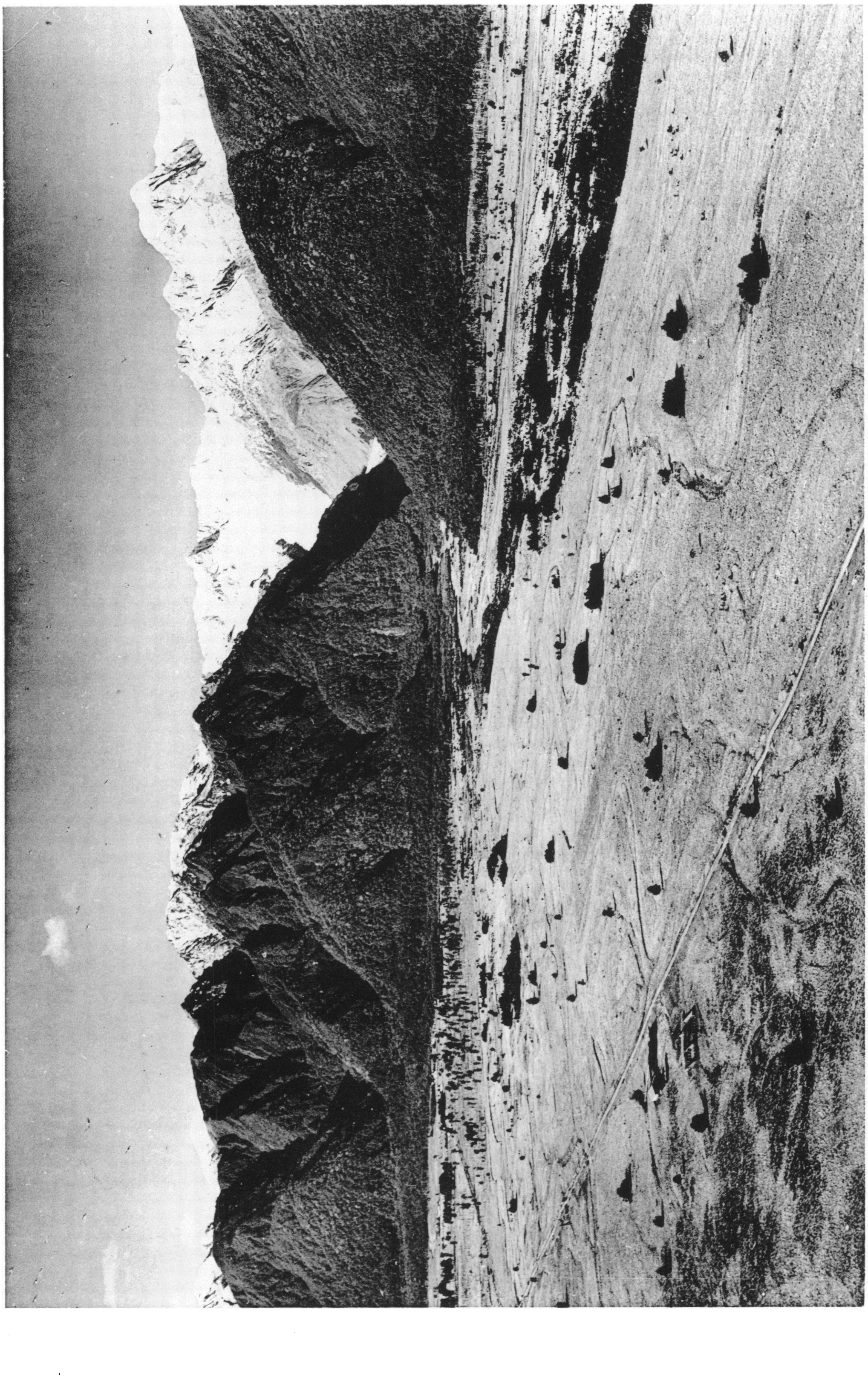
The petrology of these rocks is discussed in reference to the zones of increasing metamorphic grade, which are:

Chlorite Zone
Biotite Zone
Almandine Zone
Oligoclase Zone

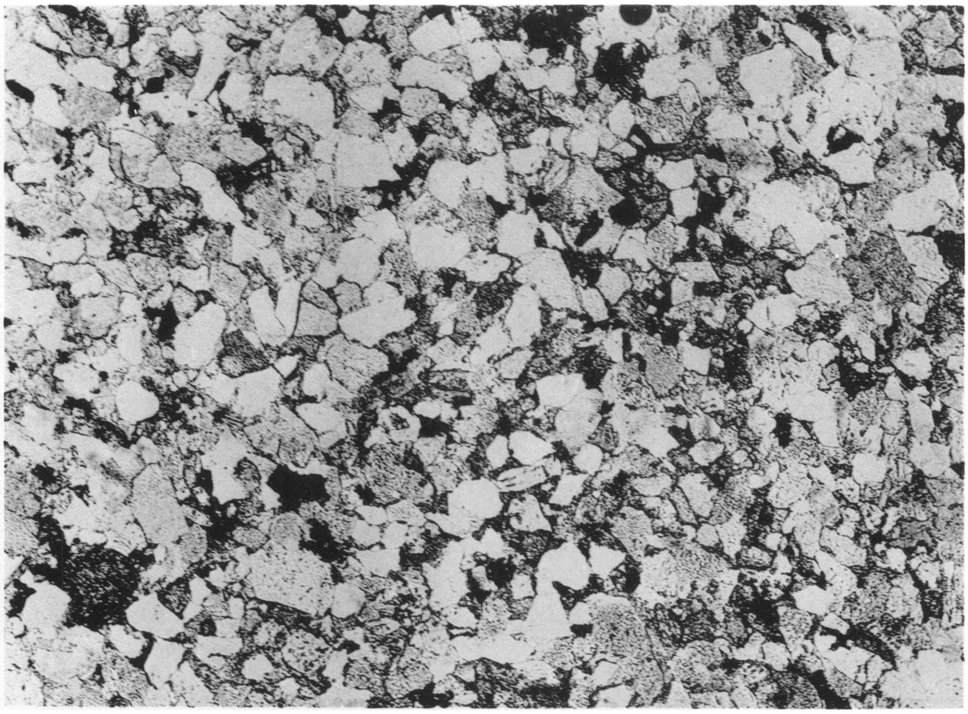
TABLE 6

ANALYSES, MOLECULAR NORMS, AND MODES OF ROCKS OF GRAYWACKE AND ARGILLITE COMPOSITION

	Analyses											
	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	70.90	68.20	65.74	60.73	58.15	69.59	63.85	70.18	68.09	71.93	69.7	70.53
TiO_2	0.50	0.31	0.50	0.76	0.89	0.54	0.61	0.46	0.66	0.49	0.80	0.64
Al_2O_3	14.33	16.63	17.36	18.72	18.95	15.20	17.40	14.15	14.34	13.39	14.8	13.48
Fe_2O_3	0.23	0.04	0.58	0.19	0.54	1.62	1.08	0.28	0.16	0.12	0.60	0.02
FeO	2.55	3.14	2.49	5.05	5.91	2.95	4.64	3.53	4.39	3.31	2.95	4.06
MnO	0.06	0.30	0.04	0.08	0.12	0.11	0.10	0.32	0.26	0.36	0.00	0.05
MgO	1.11	1.30	1.54	2.62	2.60	1.55	1.75	1.01	1.57	0.91	1.25	1.55
CaO	1.31	2.45	2.70	2.34	1.69	1.56	2.01	1.21	1.48	2.45	2.20	2.50
Na_2O	3.56	2.43	3.68	1.60	4.07	3.49	3.04	4.95	2.90	4.09	3.65	2.96
K_2O	2.73	2.33	2.81	3.92	2.95	2.06	3.26	2.48	3.23	2.20	2.40	2.42
H_2O+	1.75	1.75	2.08	3.28	2.18	1.32	0.94	1.09	2.09	0.80	0.88	1.29
H_2O-	0.36	0.55	0.03	0.02	0.05	0.00	0.40				0.02	0.00
P_2O_5	0.12	0.23	0.16	0.21	0.24	0.14	—	0.17	0.28	0.18	0.06	0.03
CO_2	0.20	0.05	0.00	0.03	0.00	0.00	0.68	0.60	—	—	0.00	0.00
	99.87	99.84	99.71	99.55	100.12	100.13	99.76	100.43	99.45	100.23	99.31	99.53
D			2.74	2.78	2.76	2.73					2.71	2.75
	Molecular Norms											
	1	2	3	4	5	6	7	8	9	10	11	12
Q	32.7	35.1	23.1	23.8	11.7	32.9	24.8	25.0	29.6	29.1	29.4	32.0
Or	16.5	14.0	17.1	24.5	18.1	12.5	20.0	15.0	19.5	13.0	14.7	14.9
Ab	33.5	22.5	34.0	15.2	38.1	32.2	28.5	45.5	27.5	37.5	33.5	27.5
An	4.5	11.5	12.7	10.8	7.0	7.1	6.0	0.5	6.5	11.5	11.3	12.9
C	4.3	7.0	4.2	9.3	7.4	5.3	7.7	3.2	4.2	0.1	2.4	1.6
En	3.2	3.8	4.4	7.6	7.5	4.4	5.0	2.8	5.0	2.6	3.6	4.5
Fs	3.4	4.8	2.9	7.0	7.8	2.8	6.0	5.0	5.8	5.0	3.1	5.6
Mt	0.2	—	0.6	0.2	0.6	1.7	1.2	0.3	0.2	0.2	0.7	—
Il	0.6	0.4	0.7	1.1	1.3	0.8	0.8	0.6	1.0	0.6	1.1	0.9
Ap	0.3	0.3	0.4	0.5	0.5	0.3	—	0.3	0.5	0.3	0.2	0.1
Py	0.3	0.3	—	—	—	—	—	—	—	—	—	—
Cc	0.6	0.2	—	—	—	—	—	1.6	—	—	—	—



Aerial view of the central part of the Southern Alps, from the west. The foreground is the coastal plain, terminated abruptly by the line of the Alpine Fault delimiting the mountain front. The high mountain on the right is Mt. Tasman, 11475 feet; the Fox Glacier is in the center of the picture. Photograph by Whites Aviation, Ltd.



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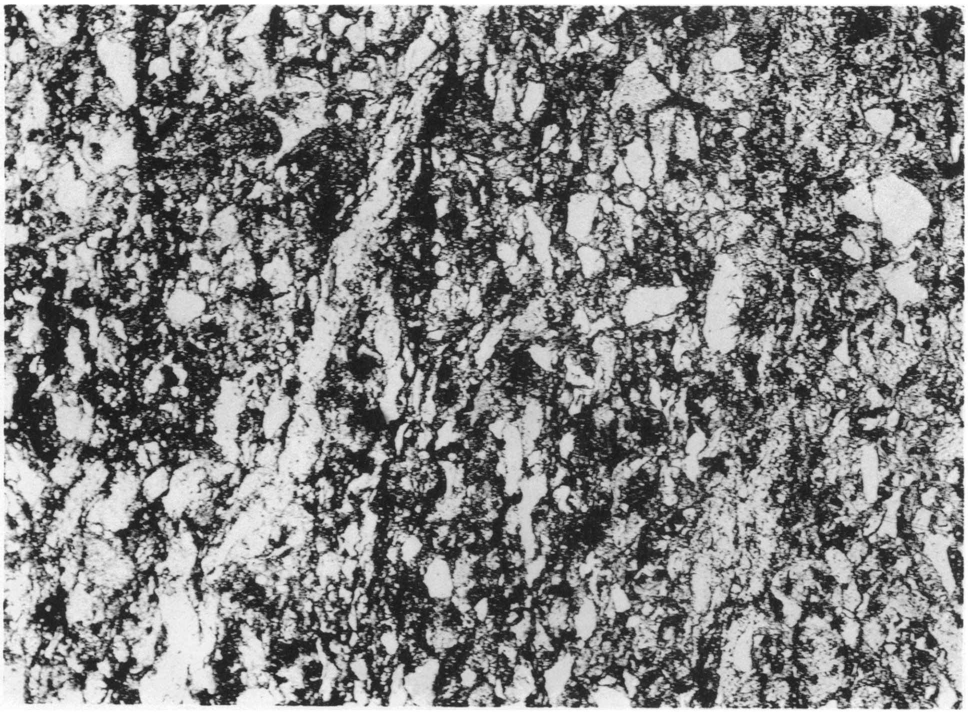
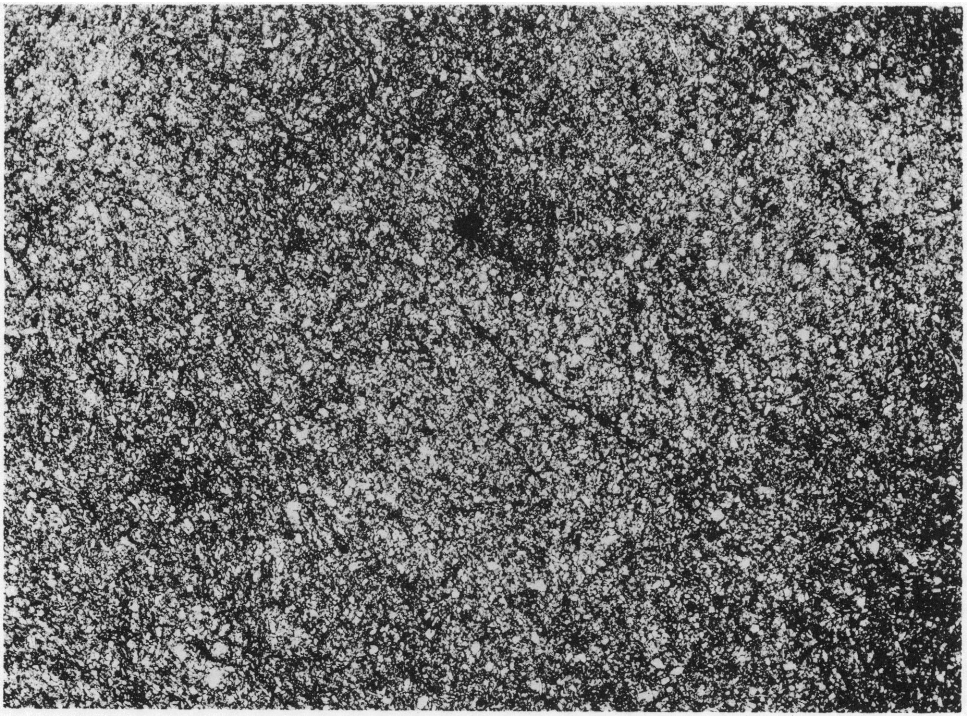


2

1. Photomicrograph of graywacke of Chlorite 1 Subzone, junction of Waimakiriri and Anti-Crow rivers. White is quartz; gray is feldspar. Photograph by J. Weber. × 30

2. Photomicrograph of graywacke of Chlorite 2 Subzone (table 6, analysis 3), junction of Hopkins and Dobson rivers; quartz grains (white) are sheared and fragmented, and the feldspathic groundmass is largely recrystallized. Photograph by J. Weber. × 30



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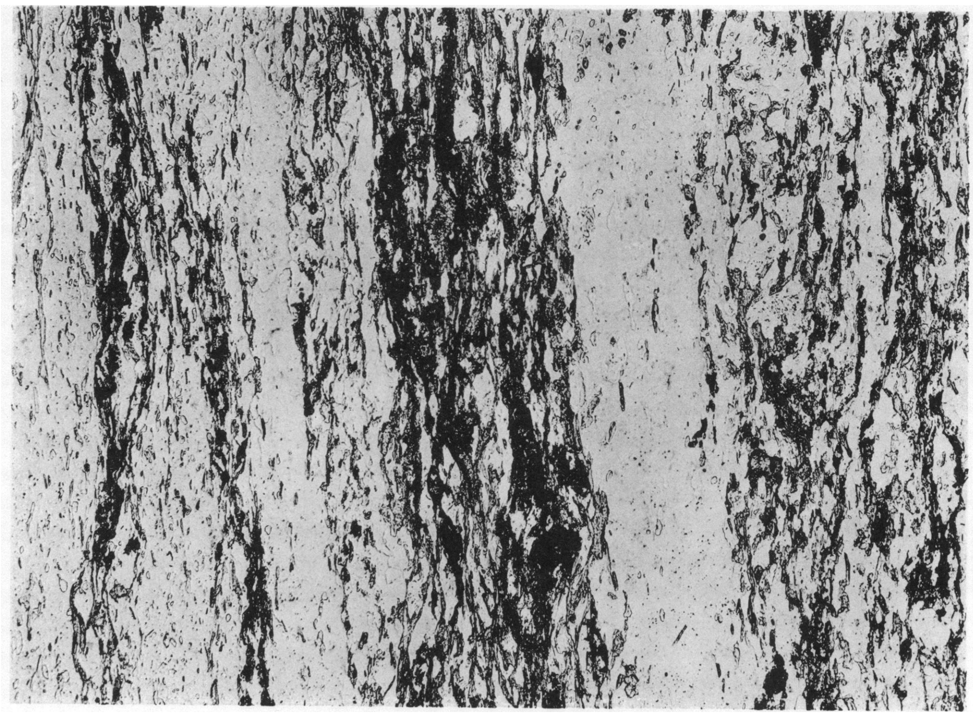
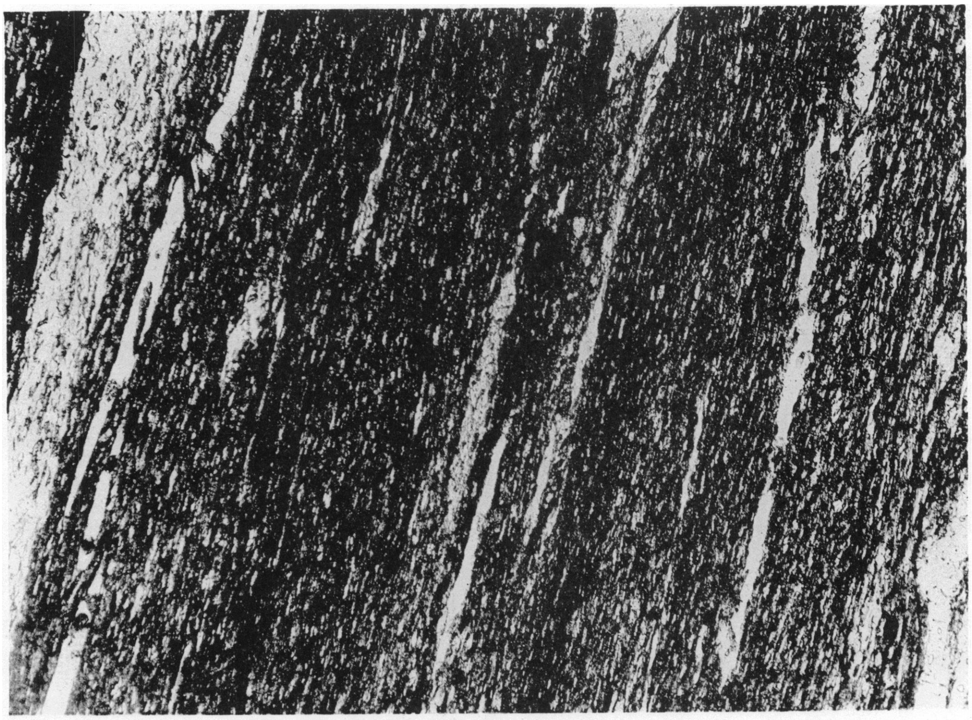


2

1. Photomicrograph of argillite of Chlorite 2 Subzone (table 6, analysis 4), junction of Hopkins and Dobson rivers. Small quartz and albite grains (white) in a feldspathic and sericitic groundmass. Photograph by J. Weber. × 30

2. Photomicrograph of schist of Chlorite 3 Subzone, Mt. Hooker, at head of Clarke River. The rock is completely recrystallized to an aggregate of quartz, albite, chlorite, muscovite, and clinozoisite, and shows incipient foliation. Photograph by J. Weber. × 30



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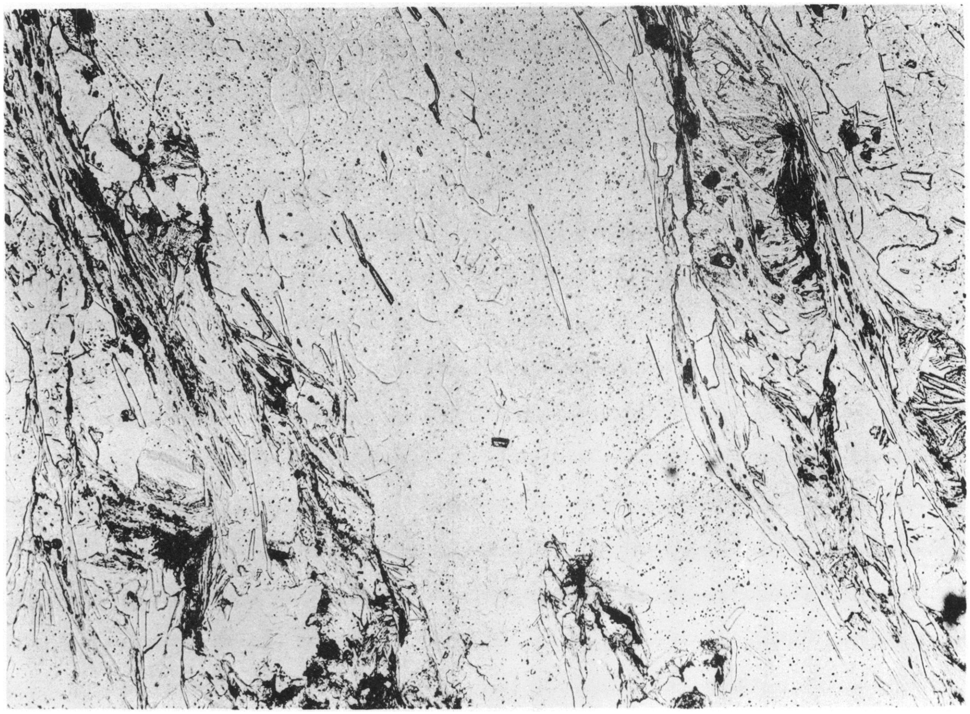
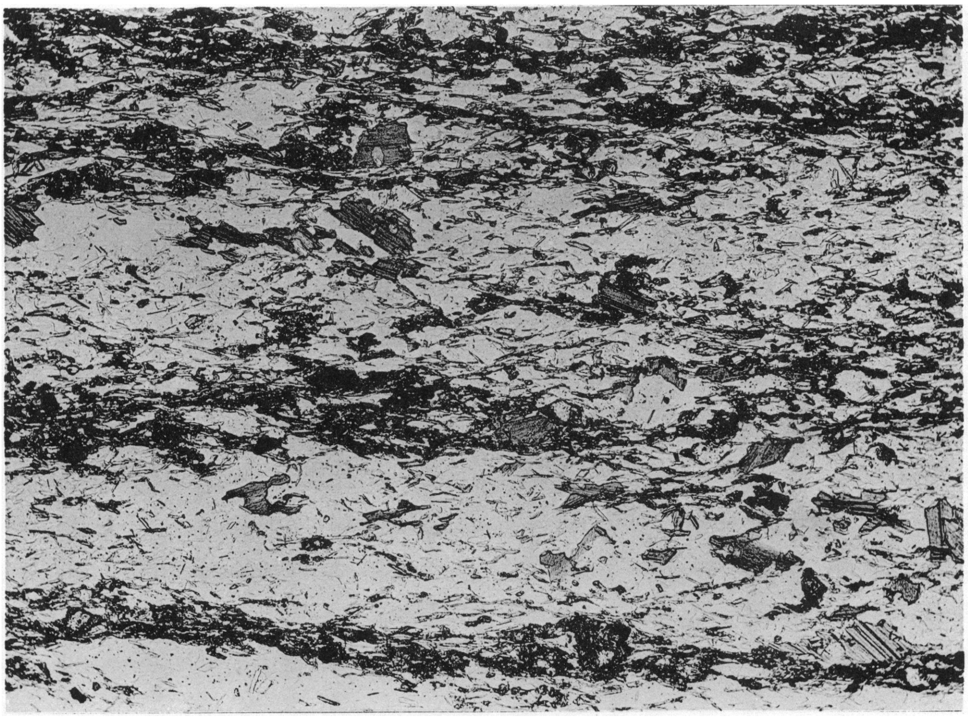


2

1. Photomicrograph of phyllite of Chlorite 3 Subzone (table 6, analysis 5), Haast River at Pyke Creek; elongated quartz grains and laminae in a feldspathic and sericitic groundmass. Photograph by J. Weber. × 30

2. Photomicrograph of schist of Chlorite 4 Subzone (table 6, analysis 6), Haast River at Clarke Bluff. The rock is coarsely foliated, quartz-albite lenses alternating with layers of muscovite and chlorite. Photograph by J. Weber. × 30



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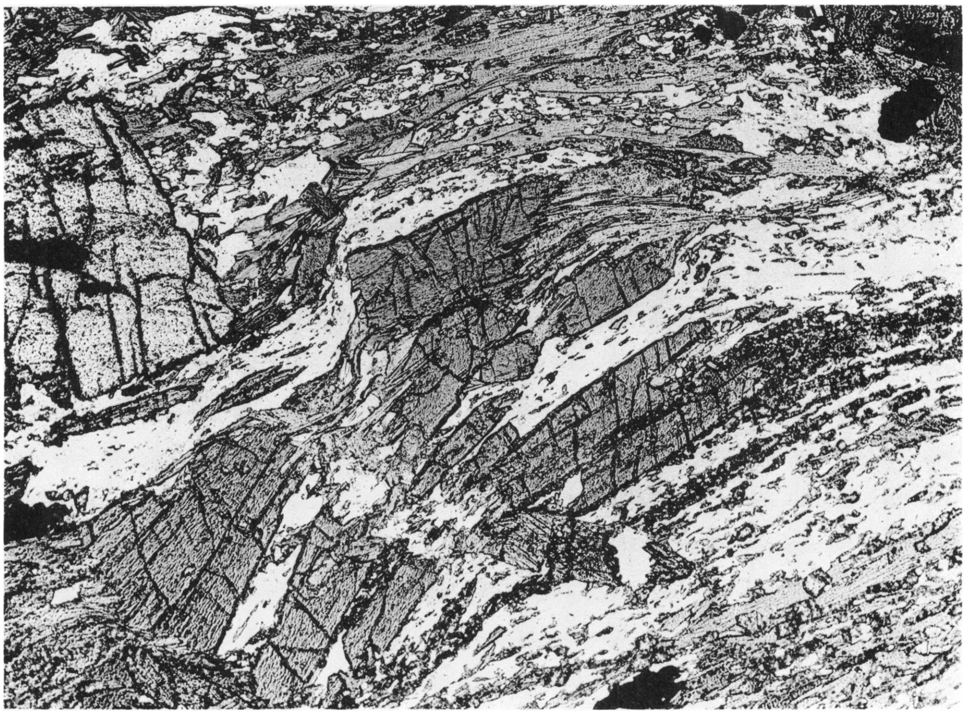


2

1. Photomicrograph of quartz-albite-biotite-muscovite-clinozoisite schist, Whitcombe River at Cat Creek. White is quartz, albite, and muscovite; light gray, biotite; dark gray to black (from opaque inclusions), clinozoisite. Photograph by J. Weber. × 30

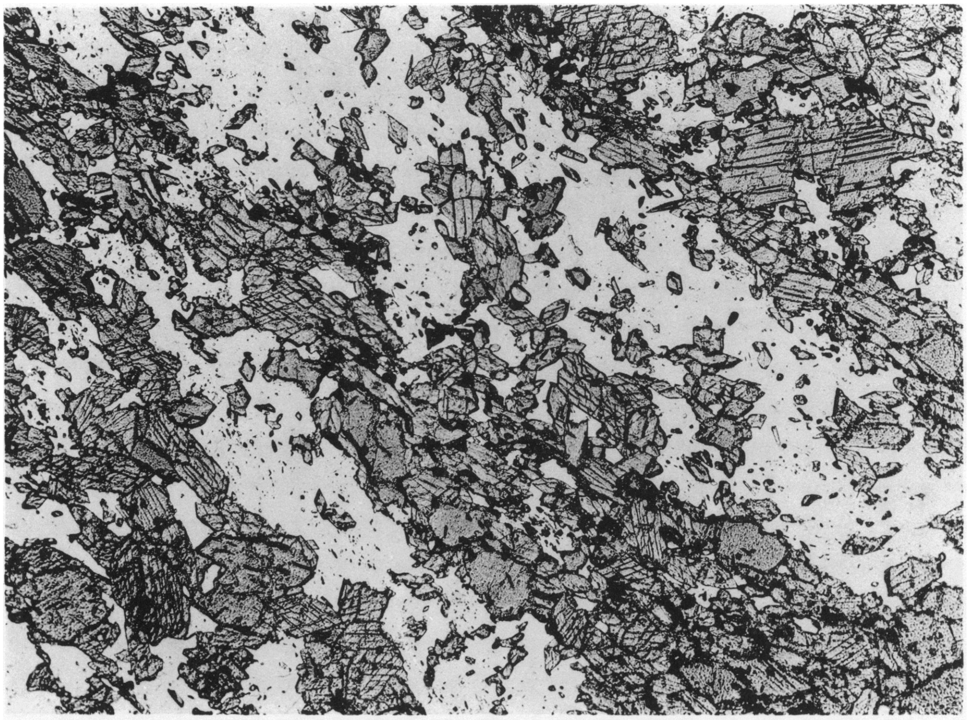
2. Photomicrograph of quartz-albite-hornblende-biotite-almandine schist (table 7, analysis 5), Styx River. White is quartz and albite; light gray, almandine; medium gray, biotite; dark gray, hornblende; black, ilmenite. Photograph by J. Weber. × 30

1

2

1. Photomicrograph of quartz-oligoclase-muscovite-biotite schist (table 6, analysis 11), Haast River at Big Bluff. Photograph by J. Weber. × 30

2. Photomicrograph of quartz-oligoclase-muscovite-biotite-almandine schist, Cone Rock, Fox Glacier. Photograph by J. Weber. × 30



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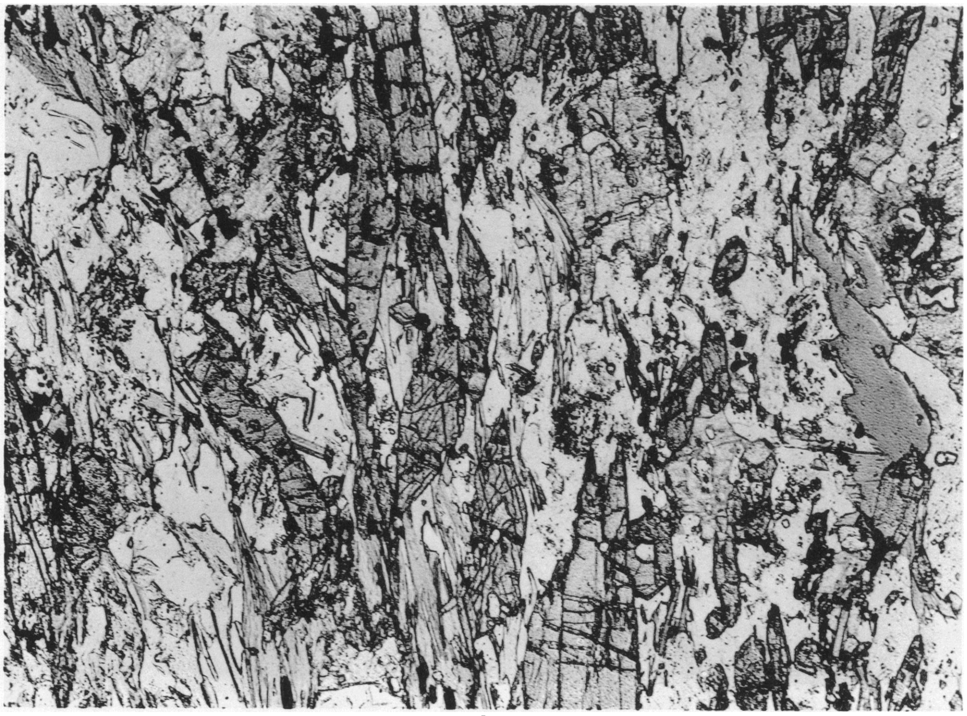
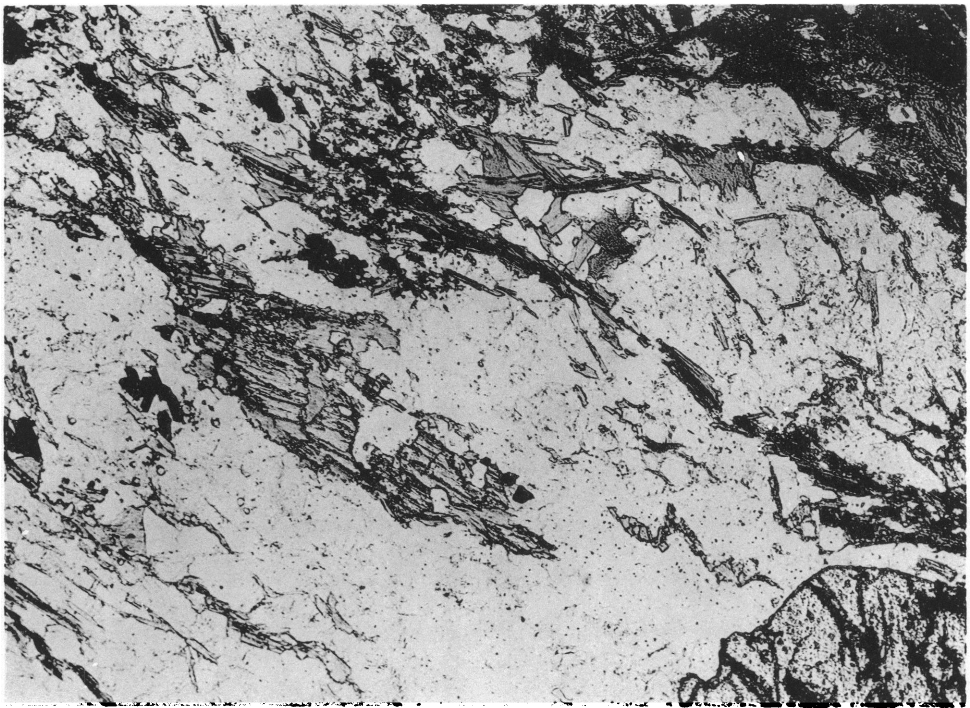


2

1. Photomicrograph of quartz-oligoclase-hornblende schist (table 7, analysis 3), Haast River at Big Bluff; contains sphene (gray rounded grains, without cleavage). Photograph by J. Weber. × 30

2. Photomicrograph of quartz-oligoclase-hornblende-biotite-clinozoisite-calcite schist (table 7, analysis 4), Cone Rock, Fox Glacier. Photograph by J. Weber. × 30



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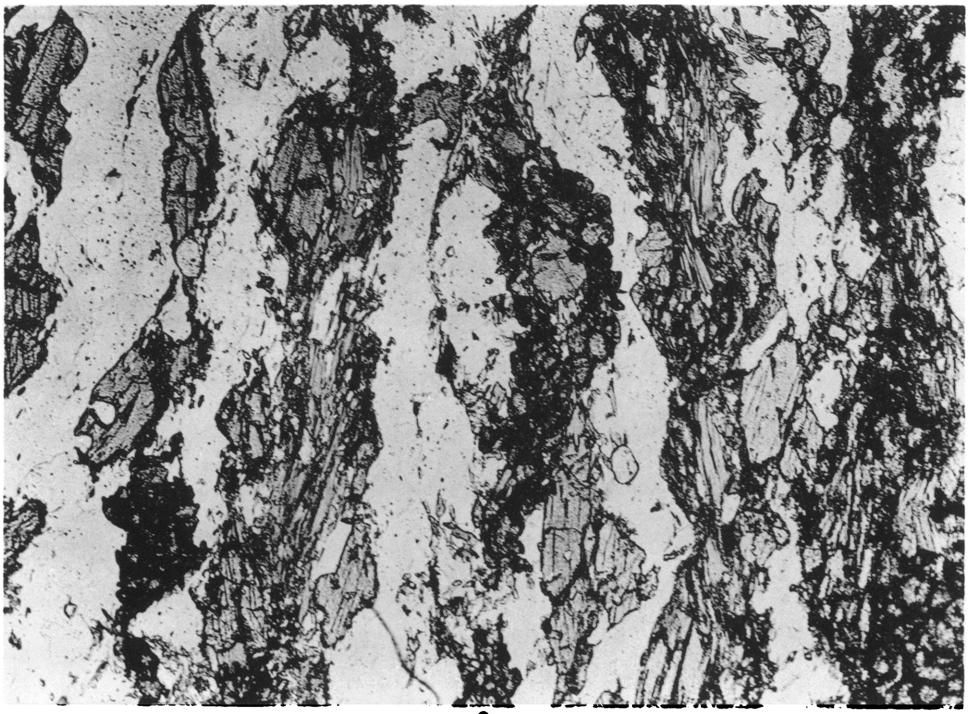

2

1. Photomicrograph of quartz-oligoclase-biotite-almandine-hornblende schist (table 7, analysis 1), Callery River, near junction with Waiho River. Photograph by J. Weber. × 30
2. Photomicrograph of quartz-oligoclase-hornblende-biotite-almandine schist (table 7, analysis 2), Cook River at road bridge. Photograph by J. Weber. × 30

TABLE 6—(*Continued*)

	Modes (Weight Per Cent) 3	4	5	6	11	12
Quartz	25	28	13	26	27	29
Plagioclase	32	14	32	29	38	36
Orthoclase	7.6	—	—	—	—	—
Muscovite	12	31	30	21	16	11
Chlorite	10	14	16	12	—	—
Biotite	—	—	—	—	15	16
Clinozoisite	10	8.5	6.5	6.0	—	—
Almandine	—	—	—	—	—	3.5
Opaque[a]	1.0	1.2	0.5	5.7	3.7	4.3
Apatite	0.4	0.5	0.5	0.3	0.2	0.1
Tourmaline	—	—	—	—	0.1	0.1
Stilpnomelane	2.0	2.8	—	—	—	—
Carbon	—	—	1.5	—	—	—

1 Graywacke, Otira Tunnel (Chlorite 1 Subzone); also S, 0.05; BaO, 0.06; SrO, 0.02; ZrO_2, 0.03. Speight (1928, p. 408)
2 Graywacke, Mungo Pass (Chlorite 1 Subzone); also SO_3, 0.13. Morgan (1908, p. 95)
3 Graywacke (pl. 33, fig. 2), Hopkins River, at junction with Dobson River (Chlorite 2 Subzone). Analyst: H. B. Wiik
4 Argillite (pl. 34, fig. 1), Hopkins River, at junction with Dobson River (Chlorite 2 Subzone). Analyst: H. B. Wiik
5 Phyllite (pl. 35, fig. 1), Haast River, opposite Pyke Creek (Chlorite 3 Subzone). Analyst: H. B. Wiik. Includes S, 0.18, and carbon 1.6.
6 Quartz-albite-muscovite-chlorite schist (pl. 35, fig. 2), Haast River at Clarke Bluff (Chlorite 4 Subzone). Analyst: H. B. Wiik
7 Quartz-albite-muscovite-biotite schist, Clarke's Creek, Arahura River (Biotite Zone). Bell and Fraser (1906, p. 71)
8 Quartz-albite-muscovite-biotite schist, Toaroha River (Almandine Zone). Morgan (1908, p. 95)
9 Quartz-albite-muscovite-biotite schist, Mt. Jumbletop (Almandine Zone). Morgan (1908, p. 95)
10 Quartz-oligoclase-muscovite-biotite schist, Mikonui River (Oligoclase Zone). Morgan (1908, p. 95)
11 Quartz-oligoclase-muscovite-biotite schist (pl. 37, fig. 1), Big Bluff, Haast River (Oligoclase Zone). Analyst: M. G. Speer
12 Quartz-oligoclase-muscovite-biotite-almandine schist (pl. 37, fig. 2), Cone Rock, Fox Glacier (Oligoclase Zone). Analyst: H. B. Wiik

[a] Pyrrhotite in analyses 5, 6, and 11; pyrrhotite plus ilmenite in analysis 12.

TABLE 7

ANALYSES, MOLECULAR NORMS, AND MODES OF SCHISTS DERIVED FROM BASIC IGNEOUS ROCKS

	Analyses 1	2	3	4	5
SiO_2	59.73	53.58	49.2	47.82	46.74
TiO_2	1.72	2.13	2.60	1.77	3.68
Al_2O_3	15.17	15.22	14.2	17.93	15.68
Fe_2O_3	0.79	0.40	2.95	0.34	1.81
FeO	7.85	10.06	8.95	9.13	14.20
MnO	0.18	0.15	0.04	0.16	0.25
MgO	2.74	4.59	6.10	6.48	2.18

TABLE 7—(*Continued*)

CaO	4.17	7.55	10.55	7.54	7.20
Na_2O	2.83	2.24	2.90	2.14	4.11
K_2O	1.78	1.24	0.45	1.94	2.16
H_2O+	2.38	2.54	1.26	2.30	1.61
H_2O-	0.15	0.07	—	0.05	0.03
P_2O_5	0.07	0.08	0.08	0.13	0.15
CO_2	0.00	0.00	0.00	2.04	0.00
	99.56	99.85	99.28	99.77	99.80
D	2.76	2.85	3.02	2.91	3.04
	Molecular Norms				
	1	2	3	4	5
Q	17.7	7.8	0.4	1.4	—
Or	11.1	7.8	2.7	12.4	13.3
Ab	26.8	21.2	27.0	19.8	27.7
An	21.8	29.2	25.2	24.7	18.9
C	1.1	—	—	3.9	—
Wo	—	3.9	11.6	—	7.0
En	8.0	13.3	17.4	18.4	2.0
Fs	10.0	13.2	8.4	12.1	5.0
Mt	0.9	0.4	3.4	0.4	1.9
Il	2.5	3.2	3.7	2.6	5.3
Ap	0.2	0.2	0.2	0.2	0.3
Cc	—	—	—	4.6	—
Fo	—	—	—	—	3.2
Fa	—	—	—	—	8.8
Ne	—	—	—	—	6.6
	(Modes Weight Per Cent)				
	1	2	3	4	5
Quartz	16	19	10	8	2.0
Plagioclase	36	22	16	27	24
Hornblende	1.8	34	68	32	20
Biotite	22	15	—	24	24
Almandine	19	1.4	—	—	14
Clinozoisite	—	2.7	—	2.8	8.0
Opaque[a]	3.3	0.7	—	—	7.7
Sphene	—	5.0	5.8	—	—
Calcite	—	—	—	4.7	—
Chlorite	1.7	—	—	—	—
Rutile	—	—	—	1.3	—
Apatite	0.2	0.2	0.2	0.2	0.3

1 Quartz-oligoclase-biotite-almandine-hornblende schist (pl. 39, fig. 1), Callery River, near junction with Waiho River. Analyst: H. B. Wiik
2 Quartz-oligoclase-hornblende schist (pl. 39, fig. 2), Cook River at road bridge. Analyst: H. B. Wiik
3 Quartz-oligoclase-hornblende-almandine schist (pl. 38, fig. 1), Big Bluff, Haast River. Analyst: M. G. Speer
4 Quartz-oligoclase-hornblende-biotite-calcite schist (pl. 38, fig. 2), Cone Rock, Fox Glacier. Analyst: H. B. Wiik
5 Quartz-albite-hornblende-biotite-almandine schist (pl. 36, fig. 2), Styx River. Analyst: H. B. Wiik

[a] Pyrrhotite and ilmenite in analysis 1; ilmenite in analyses 2 and 5.

Chlorite Zone

Rocks belonging to the Chlorite Zone cover thousands of square miles in the South Island of New Zealand, not only in the Southern Alps but also in Otago, Nelson, and Marlborough. Their petrology was first studied intensively in Otago by Turner and Hutton, who were able to divide the Chlorite Zone into four subzones, on the basis of textural and mineralogical criteria, as follows (Turner, 1948):

Chlorite 1 Subzone

Graywackes retain their original clastic structure; schistosity has not developed; slight cataclasis is evident, and an interstitial matrix of reconstituted minerals has commenced to form (epidote, chlorite, calcite, actinolite, sphene); feldspars are converted to saussurite or are much sericitized.

Chlorite 2 Subzone

Graywackes give place to semi-schist in which clastic structure has been partly obliterated, the grain size reduced by shearing, and a definite schistosity developed; chemical reconstitution is far advanced but not complete.

Chlorite 3 Subzone

Schistosity is well developed and is accentuated by incipient segregation of quartz-feldspathic and dark minerals into separate, ill-defined streaks and laminae parallel to the schistosity; the original clastic structure has disappeared, but a few relict grains persist; chemical reconstitution is virtually complete.

Chlorite 4 Subzone

Coarse schists in which the average grain size of quartz and albite ranges from 0.2 mm. to 2 mm.; schisosity and segregation banding are both highly developed; the quartz-albite bands in some places reach 8 mm. to 10 mm. in thickness.

This scheme was adopted for the mapping of the Chlorite Zone in the Southern Alps and was found generally applicable. The major difference between the Otago region and the Southern Alps is that over most of the Alps (from Paringa River north) a Chlorite 4 Subzone is not present; biotite appears in rocks of the Chlorite 3 Subzone, marking the passage to the Biotite Zone.

The absence of the Chlorite 4 Subzone over much of the Southern Alps is at first surprising, in view of its wide areal extent southeast of the Alps in Otago. However, an examination of the rocks mapped in this zone in northwest Otago shows that many of them contain traces of biotite, commonly included in flakes of chlorite. These traces of biotite appear to be relicts, which suggests that part at least, of the Chlorite 4 Subzone is the product of diaphthoresis of Biotite-zone rocks. Evidence is presented below in the present paper which indicates that the region of the rocks of Chlorite 4 Subzone underwent strong deformation in middle Tertiary times. This deformation is believed to be responsible for an extensive retrograde metamorphism which produced the Chlorite 4 Subzone, at least in part.

Rocks of the Chlorite subzones are illustrated in plates 33–35.

The least-metamorphosed rocks are graywackes, frequently interbedded with minor amounts of argillite in rhythmic sequence (a foot or two of graywacke followed by a few inches of argillite). These rocks are monotonously uniform throughout the Alpine region. I have never seen either conglomerates or limestones interbedded with these rocks anywhere in the area mapped, although these have been recorded in other regions. Fossils are extremely rare; *Monotis richmondiana*, indicating an upper Triassic (Carnic) age, has been collected at several localities. The lack of fossils and the uniform lithology of the rocks have so far discouraged the working-out of a detailed succession, and the stratigraphic thickness is unknown, but is certainly at least 20,000 to 40,000 feet. The graywackes occasionally show current bedding, which enables the tops of the beds to be distinguished and shows that the beds are sometimes right side up, sometimes inverted. Remarkable examples of subaqueous slumping are sometimes seen, and have been illustrated by Lillie, Gunn, and Robinson (1957). The general characters of the graywackes and argillites are typical of rocks deposited by turbidity currents.

The mineralogy of the graywackes is comparatively simple and uniform; they consist of grains of quartz, plagioclase, and potash feldspar, usually 0.5–1 mm. in diameter, in an argillaceous matrix. The chemical and mineralogical composition is well illustrated by the examples given in table 6. Quartz ranges from 20 per cent to 30 per cent; feldspar, from 50 per cent to 60 per cent. The amount of potash feldspar is always subordinate to that of plagioclase and is usually of the order of 5 per cent to 15 per cent. The plagioclase is usually turbid with alteration products, but it appears to have been of oligoclase or andesine composition. The potash feldspar is often sericitized but may be quite fresh. The graywackes appear to have been derived from a granodioritic terrain; they are notably free of rock fragments, and the plagioclases show twinning, characteristic of igneous rather than metamorphic rocks. In these respects they are rather different from corresponding rocks described from Otago, which contain a great deal of material of volcanic origin.

The argillites differ from the graywackes in their fine grain size, but are not fundamentally different mineralogically; in fact, many of them are essentially micro-graywackes. The similarities and differences are illustrated by nos. 3 (graywacke) and 4 (argillite) in table 6; these rocks are from two adjoining beds. The argillite contains about the same amount of quartz as the graywacke, but has less plagioclase and a greater amount of argillaceous material; X-ray examination shows that the argillaceous material is a mixture of muscovite (illite) and chlorite.

The first prominent sign of increasing metamorphic grade is the incoming of stilpnomelane, which appears in rocks at about the boundary of Chlorite 1 and Chlorite 2 subzones. At this stage, however, mineralogical reconstitution has already gone far. The argillaceous matrix has recrystallized into microscopic flakes of chlorite and muscovite, and the plagioclase is completely albitized, judged from X-ray diffraction patterns. Potash feldspar still survives, although sericitization increases. At the boundary of Chlorite 2 and Chlorite 3 subzones mineralogical reconstitution is virtually complete. The mineralogy of the completely recrystallized rocks is as follows:

Schists derived from graywackes and argillites
- Quartz-albite-muscovite-chlorite-clinozoisite
- Quartz-albite-muscovite-chlorite-clinozoisite-calcite
- Quartz-albite-muscovite-chlorite-clinozoisite-actinolite
- Quartz-albite-muscovite-chlorite-clinozoisite-stilpnomelane
- Quartz-albite-muscovite-stilpnomelane-clinozoisite
- Quartz-albite-muscovite-stilpnomelane-clinozoisite-pumpellyite

Schists derived from basic igneous rocks
- Quartz-albite-chlorite-epidote
- Quartz-albite-chlorite-epidote-stilpnomelane
- Quartz-albite-chlorite-epidote-calcite
- Quartz-albite-chlorite-epidote-actinolite
- Quartz-albite-chlorite-epidote-actinolite-calcite-muscovite

The most common association is quartz-albite-muscovite-chlorite-clinozoisite. In rocks of graywacke composition, quartz is 20 per cent to 30 per cent; albite (composition about $Ab_{95}An_5$), 25 per cent to 35 per cent; muscovite, 15 per cent to 25 per cent; chlorite, about 10 per cent; and clinozoisite, about 10 per cent. In rocks of argillite composition, albite is lower (about 10%–20%), muscovite higher (30%–35%), and chlorite higher (about 15%). A little calcite is sometimes present. Stilpnomelane is rather sporadic, and its occurrence may be conditioned by a higher-than-normal Fe_2O_3 content. Actinolite is rarely present, and, as Turner (1935) has shown, its occurrence in the Chlorite Zone is an indication of low pCO_2; at moderate pCO_2 the stable association is chlorite-calcite. Pumpellyite is widely distributed in the rocks of the Chlorite 2 and 3 subzones in small amounts and also occurs in quartz veins in these subzones. It is close to clinozoisite in composition but contains essential magnesium and ferrous iron; it appears to exist in equilibrium with clinozoisite.

Schists derived from basic igneous rocks are uncommon in the Chlorite Zone of the Alps. I have not seen them in the region north of Mt. Cook, and they are abundant only in the extreme south and southwest, in the Wilkin and Matukituki valleys. In this area the parent rocks were evidently derived largely from andesitic and basaltic volcanics. These schists are easily recognized in the field by their prominent green color, produced by the abundance of chlorite. Muscovite is usually absent (only one specimen containing muscovite was collected, and the muscovite was present in very small amount). Epidote is present instead of clinozoisite, reflecting the higher content of Fe_2O_3.

Biotite Zone

The incoming of biotite marks the boundary between the Chlorite and Biotite zones and is readily mapped, since biotite is always found in rocks of graywacke composition at the requisite grade of metamorphism. Initially the biotite may be in microscopic flakes not readily distinguished with the naked eye, but in most rocks of this zone it is present as porphyroblasts 1 mm. or more in diameter.

The mineral associations that have been observed in this zone are as follows:

Schists derived from graywackes and argillites
- Quartz-albite-biotite-muscovite-clinozoisite
- Quartz-albite-biotite-muscovite-clinozoisite-calcite
- Quartz-albite-biotite-muscovite-clinozoisite-chlorite
- Quartz-albite-biotite-muscovite-clinozoisite-chlorite-actinolite
- Quartz-albite-biotite-muscovite-chlorite-calcite
- Quartz-albite-biotite-clinozoisite-chlorite

Schists derived from basic igneous rocks
- Quartz-albite-biotite-chlorite-calcite
- Quartz-albite-biotite-chlorite-calcite-epidote
- Quartz-albite-epidote-actinolite

The common association is quartz-albite-biotite-muscovite-clinozoisite (pl. 36, fig. 1). Evidently the formation of biotite involves a reaction between muscovite and chlorite, and, as chlorite is usually subordinate to muscovite in the Chlorite-zone rocks, it may be completely removed by this reaction. A little chlorite may occur, apparently in equilibirum with muscovite and biotite. A small amount of calcite is occasionally present. As in the Chlorite Zone, the association calcite-chlorite is evidently stable in the presence of a sufficient pCO_2; at lower pCO_2 the stable phase is actinolite, which, however, is of rare occurrence in rocks of graywacke composition from the Biotite Zone.

Schists derived from basic igneous rocks are not common in this zone. Mineralogically they are identical to similar rocks in the Chlorite Zone, except that biotite is present instead of stilpnomelane.

Almandine Zone

The incoming of almandine marks the transition from the Biotite Zone to the Almandine Zone. This mineral is only occasionally present in rocks derived from graywackes and argillites and is seldom conspicuous in hand specimens. Hence the Almandine isograd is not so easily mapped as the Biotite isograd. However, in schists derived from basic igneous rocks hornblende appears close to the Almandine isograd and is always prominent in such rocks (pl. 36, fig. 2). It is readily distinguished from the actinolite of lower-grade green schists by its darker color and its less elongate crystals. The mineral associations of the Almandine Zone are as follows:

Schists derived from graywackes and argillites
- Quartz-albite-biotite-muscovite-clinozoisite
- Quartz-albite-biotite-muscovite-clinozoisite-almandine
- Quartz-albite-biotite-muscovite-clinozoisite-almandine-calcite
- Quartz-albite-biotite-muscovite-clinozoisite-almandine-chlorite
- Quartz-albite-biotite-muscovite-clinozoisite-chlorite
- Quartz-albite-biotite-muscovite-clinozoisite-chlorite-calcite
- Quartz-albite-biotite-muscovite-almandine
- Quartz-albite-biotite-clinozoisite-almandine
- Quartz-albite-biotite-clinozoisite-chlorite-calcite
- Quartz-albite-biotite-almandine

Schists derived from basic igneous rocks
- Quartz-albite-biotite-epidote-chlorite
- Quartz-albite-biotite-epidote-chlorite-calcite
- Quartz-albite-biotite-epidote-hornblende
- Quartz-albite-biotite-epidote-hornblende-almandine
- Quartz-albite-biotite-epidote-hornblende-chlorite
- Quartz-albite-biotite-epidote-hornblende-calcite
- Quartz-albite-biotite-epidote-hornblende-calcite-chlorite
- Quartz-albite-biotite-calcite-chlorite

In addition to the associations listed, a number of specimens of quartz-rich schists free of feldspar were collected; these included the associations quartz-biotite-almandine-chlorite, quartz-biotite-almandine-muscovite-calcite, and quartz-almandine-cummingtonite. These quartz schists may be the derivatives of rather pure quartz sandstones, or more probably of impure cherts. In North Westland there are local occurrences of quartz and feldspar-free green schists, evidently derived from ultrabasic igneous rocks; the association talc-actinolite is typical.

In general, the mineral associations of schists derived from graywackes and argillites are the same as in the Biotite Zone, with or without the presence of accessory to minor amounts of almandine. Thus the most common association is quartz-albite-biotite-muscovite-clinozoisite, and the rock is a schist indistinguishable from the common schists of the Biotite Zone.

The schists derived from basic igneous rocks are characterized by the presence of hornblende, although occasional specimens may be hornblende-free. The most common association is quartz-albite-hornblende-epidote-biotite, often with accessory to minor amounts of chlorite. Exceptionally specimens are found with the association chlorite-calcite; at this grade of metamorphism this probably reflects an unusually high pCO_2. Some hornblende schists contain prominent octahedrons of magnetite.

Oligoclase Zone

The Oligoclase Zone cannot be satisfactorily delineated in the field, because it is distinguished from the Almandine Zone only by the composition of the plagioclase. Nevertheless the rocks of this zone frequently have a markedly gneissose appearance, as a result of coarser crystallinity and a more pronounced segregation of quartz and plagioclase into lenticles.

The mineral associations are as follows:

Schists derived from graywackes and argillites
- Quartz-oligoclase-muscovite-biotite (pl. 37, fig. 1)
- Quartz-oligoclase-muscovite-biotite-almandine (pl. 37, fig. 2)
- Quartz-oligoclase-muscovite-biotite-clinozoisite
- Quartz-oligoclase-muscovite-biotite-clinozoisite-almandine
- Quartz-oligoclase-muscovite-biotite-clinozoisite-almandine-chlorite
- Quartz-oligoclase-biotite-almandine-clinozoisite
- Quartz-oligoclase-biotite-almandine-clinozoisite-chlorite

Schists derived from basic igneous rocks
- Quartz-oligoclase-hornblende (pl. 38, fig. 1)
- Quartz-oligoclase-hornblende-biotite
- Quartz-oligoclase-hornblende-biotite-calcite
- Quartz-oligoclase-hornblende-biotite-calcite-clinozoisite (pl. 38, fig. 2)
- Quartz-oligoclase-hornblende-biotite-calcite-clinozoisite-chlorite
- Quartz-oligoclase-hornblende-biotite-almandine (pl. 39, fig. 1)
- Quartz-oligoclase-hornblende-biotite-almandine-clinozoisite (pl. 39, fig. 2)
- Quartz-oligoclase-hornblende-biotite-almandine-clinozoisite-calcite
- Quartz-oligoclase-hornblende-biotite-almandine-chlorite
- Quartz-oligoclase-hornblende-biotite-almandine-chlorite-clinozoisite
- Quartz-oligoclase-hornblende-biotite
- Quartz-oligoclase-hornblende-clinozoisite
- Quartz-oligoclase-hornblende-clinozoisite-biotite

The plagioclase is a basic oligoclase (An_{20}–An_{30}). Frequently the association is quartz-oligoclase-muscovite-biotite, but clinozoisite may also be present, which indicates that the grade of metamorphism is insufficient for the plagioclase to take up an unlimited amount of the anorthite component. Almandine may be present in accessory to minor amounts in rocks derived from graywackes and argillites. In schists derived from basic igneous rocks the association quartz-oligoclase-hornblende is typical; biotite or almandine or both are frequently present also. Clinozoisite occurs in many of these hornblende schists, in contrast to the occurrence of epidote in similar rocks at lower metamorphic grade. Such occurrence seems not to be related to any chemical difference, so probably in the Oligoclase zone ferric iron enters perferentially into hornblende.

The kyanite schist boulders found in moraines in South Westland were evidently derived from the Oligoclase Zone. Plagioclase, when present, is of andesine composition. The association kyanite-actinolite (-quartz-muscovite) is of particular interest. The actinolite has $\gamma = 1.647$, which indicates an Fe/Fe+Mg ratio of about 0.25, according to the data of Winchell (1951). In this zone of metamorphism one might expect the associations kyanite-staurolite-epidote or kyanite-almandine-epidote rather than kyanite-actinolite. The appearance of actinolite in association with kyanite may be explained by the comparatively low Fe/Fe+Mg ratio in the rock, which favors the formation of actinolite rather than staurolite or almandine.

PETROGENESIS

Lack of Metasomatism During Metamorphism

In areas of regional metamorphism, it is a moot question whether the metamorphism has been isochemical or metasomatism has added or removed certain elements. Some geologists, especially in Europe, have maintained that there is a progressive change in composition during the metamorphism of pelitic sediments, leading ultimately to rocks of granitic composition. The Southern Alps are well suited for the testing of such a hypothesis, because they are a large area showing a continuous transition from graywackes and argillites to high-grade gneisses. With this in mind, I plotted the molecular norms in table 6 on a Q-L-M (quartz-leucoeratic-melanocratic) diagram (fig. 5). Figure 5 shows that the graywackes and argillites and the derived schists are remarkably uniform in composition and show no trend towards an increase of quartz or feldspar or both with increasing metamorphic grade. Turner (1941) showed this was true for the schists of Otago, although there the grade of metamorphism does not exceed that of the Chlorite 4 Subzone. (Analysis 5 of table 6, which appears to be anomalous, is of a phyllite selected for analysis because it appeared to be the most argillaceous rock seen.)

The bands of hornblende schist intercalated with the schists of graywacke and argillite composition provide further evidence of the lack of metasomatic action even at the highest grade of metamorphism. The boundaries of these bands are quite sharp, in spite of the considerable compositional differences across the boundary, which metasomatism would tend to erase.

Reactions Producing Key Minerals

A basic problem in the petrogenesis of a series of regionally metamorphosed rocks is the nature of the reactions that produce the key minerals, and the physicochemical conditions under which they take place. If this problem can be elucidated we have achieved a long-standing goal, viz., the establishment of a petrogenetic grid from which we can deduce the temperatures and pressures at which these important metamorphic reactions take place.

The formation of biotite is the first reaction of regional significance with increasing grade of metamorphism. In rocks of lower grade muscovite is the only potassium-bearing mineral (stilpnomelane is ordinarily absent in rocks of Chlorite 3 Subzone), so it must be involved in the production of biotite. A comparison of analyses of muscovite (table 2, no. 1) and biotite (table 3, no. 1) shows that the conversion of muscovite to biotite requires, for each 24 (O, OH) ions, the addition of 2.0 Fe^2 and 2.0 Mg, and the removal of 1.1 Si and 1.3 Al. The source of the Fe^2 and Mg can only be chlorite. Presumably the formation of biotite is a reaction between the components of muscovite and chlorite, as a result of which the chlorite changes in composition by the removal of some iron and magnesium and the concomitant addition of some silicon and aluminum. These changes should result in lower refractive indices for the chlorite in Biotite-zone rocks than in Chlorite-zone rocks, a feature actually observed.

The next reaction of regional significance is the formation of almandine, the appearance of which marks the Almandine isograd. The source material for almandine appears to be chlorite, but it is evidently chlorite of a particular composition range, because chlorite can coexist stably with almandine in Almandine-zone rocks, and some rocks in this zone contain chlorite but no almandine. The reaction presumably involves clinozoisite or epidote also, because the almandine contains a moderate amount of calcium.

The formation of almandine from chlorite is essentially the abstraction of an iron-rich component of the chlorite. The chlorite that remains must therefore be considerably richer in magnesium than the initial chlorite. A schist from the Copland River contained both almandine (table 5, analysis 2) and chlorite apparently in equilibrium; the FeO/FeO+MgO ratio in the almandine is 0.89, in the coexisting chlorite 0.43. Presumably a rock containing chlorite with an FeO/FeO+MgO ratio greater than 0.43, if recrystal-

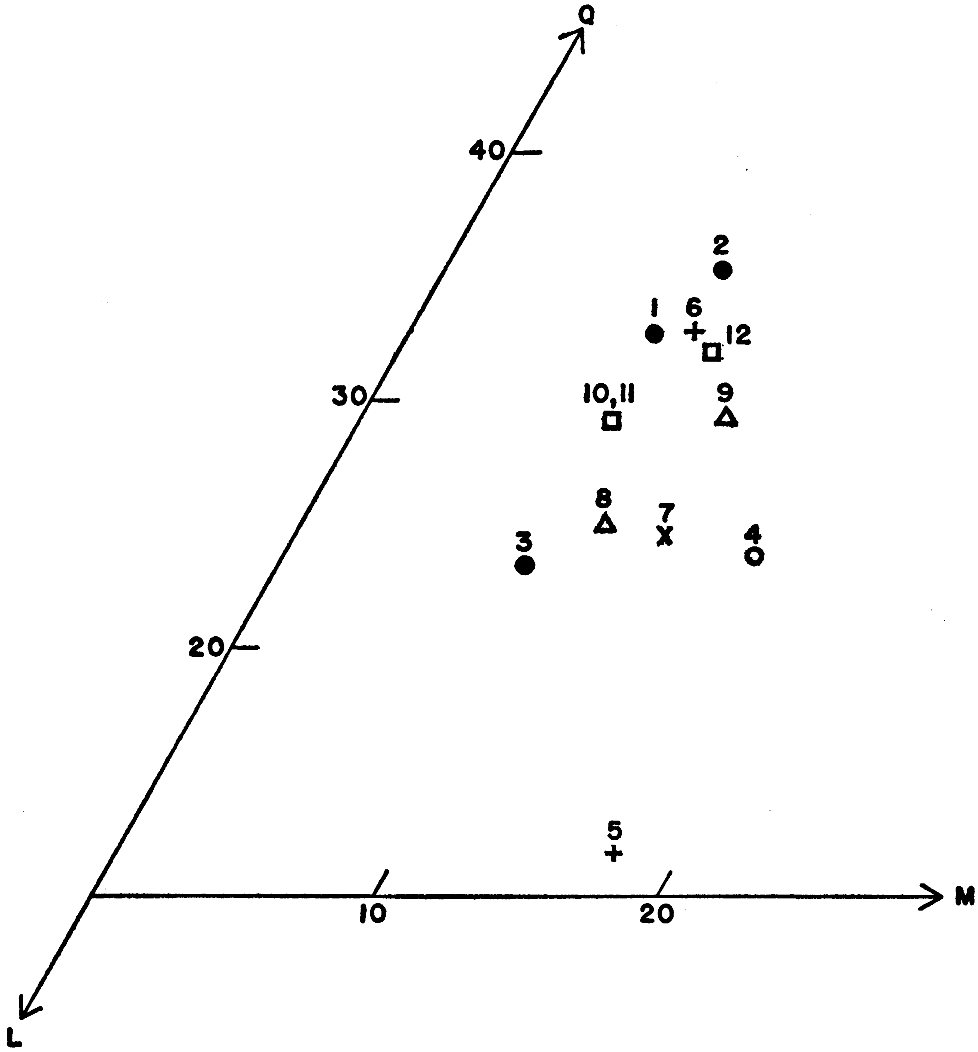

FIG. 5. Q-L-M diagram of molecular norms of graywackes and argillites and schists derived from them; ●, graywackes; ○, argillites; +, Chlorite-zone schists; ×, Biotite-zone schists; △, Almandine-zone schists; □, Oligoclase-zone schists. The figures are those of the analyses in table 6.

lized under conditions of the Almandine Zone, would give a rock containing some almandine, whereas if this ratio were less than 0.43 no almandine would form. This relationship explains why almandine is sporadic in its occurrence in schists of the Almandine Zone. In derivatives of graywacke and argillite it seems that an FeO/FeO +MgO ratio about 0.6 or greater is necessary for the appearance of almandine, if we compare analysis 11, table 6 (a schist without almandine), with analysis 12, table 6 (a schist with almandine).

The compositional relationship between coexisting almandine, chlorite, and biotite (together with quartz and muscovite) can be illustrated by a triangular diagram constructed according to the principles developed by Thompson (1957). Figure 6 was constructed by the plotting of coexisting almandine (table 5, analysis 2), chlorite (p. 224), and biotite (table 3, analysis 1) in a quartz-oligoclase-biotite-almandine-chlorite schist from the Copland River, and of coexisting almandine (table 5, analysis 1) and biotite (table 3, analysis 2) in a quartz-oligoclase-

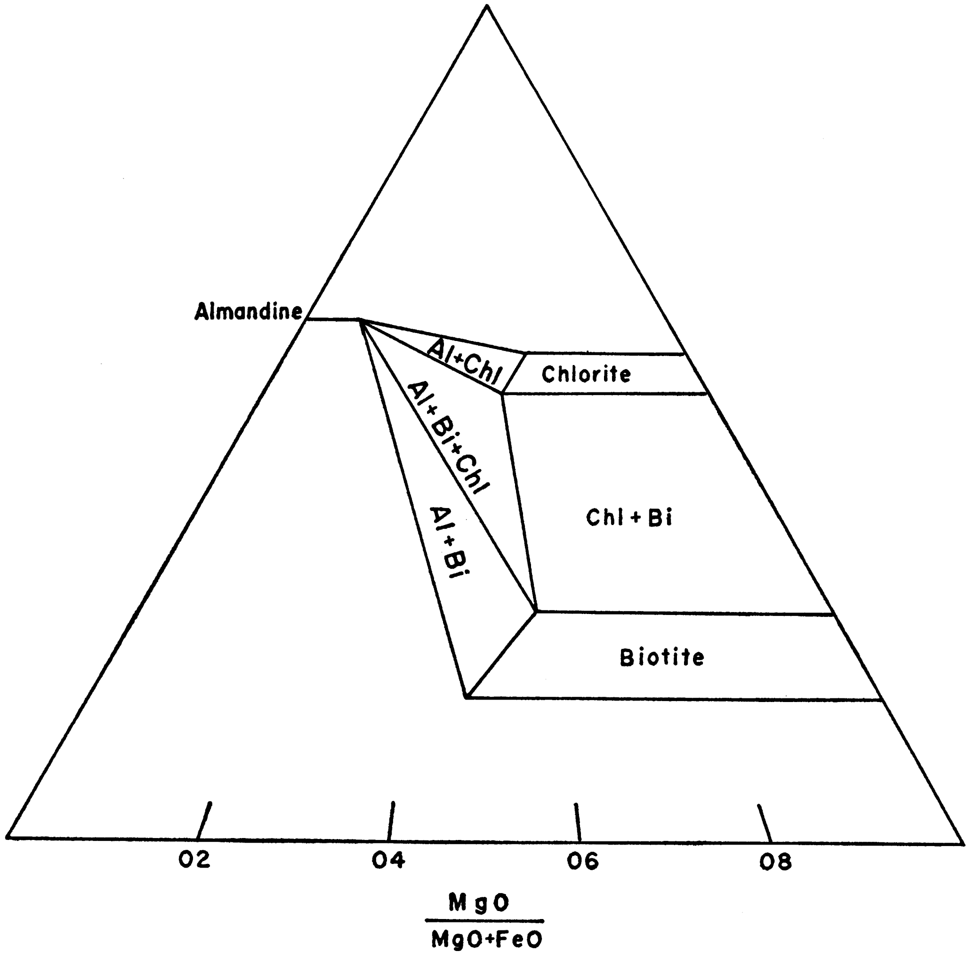

FIG. 6. Possible phases in association with quartz and muscovite in the system SiO_2-Al_2O_3-MgO-FeO-K_2O-H_2O. In the rocks of the Oligoclase Zone of the Southern Alps the associations actually observed are quartz-muscovite-biotite, quartz-muscovite-biotite-almandine, and quartz-muscovite-biotite-almandine-chlorite.

almandine-biotite-hornblende schist (table 7, analysis 1) from the Callery River. The near identity of the composition of the almandines, and of the biotites, in these two rocks strongly supports the view that we are dealing with an equilibrium relationship.

The increased anorthite content of the plagioclase when the Oligoclase isograd is passed is evidently provided by clinozoisite. The following equation can be written

$$\underset{\text{clinozoisite}}{Ca_2Al_3Si_3O_{12}(OH)} + \tfrac{1}{2}Al_2O_3 + SiO_2 = \underset{\text{anorthite}}{2CaAl_2Si_2O_8} + \tfrac{1}{2}H_2O.$$

If the reaction proceeds as written, the conversion of clinozoisite to the anorthite component of the plagioclase involves the addition of a small amount of alumina and silica. The silica is readily available from the free quartz in the rocks, but the source of the alumina is not so obvious. However, the amount required is small, and it could be provided from aluminosilicates of variable composition such as muscovite and biotite.

The formation of hornblende in the green schists can be formulated in a number of ways. The simplest might be a reaction between actinolite and albite

$$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2+NaAlSi_3O_8= NaCa_2(Mg,Fe)_5AlSi_7O_{22}(OH)_2+4SiO_2.$$

However, the association actinolite-albite is comparatively uncommon in Biotite-zone rocks; more commonly we find albite-chlorite-calcite, with or without epidote. Reaction of albite-chlorite-calcite to give hornblende involves two volatile components, H_2O and CO_2, and will clearly be conditioned by the partial pressures of these components. In view of the variety of possible reactions to give hornblende, the reality of a single Hornblende isograd may be questioned. Nevertheless it is true that in the rocks of the Southern Alps hornblende does appear at a definite metamorphic grade, which is approximately coincident with the Almandine isograd.

Correlation of Metamorphic Zones with Facies Classification

Turner and Verhoogen (1960) have recently provided a discussion and revision of the facies classification of metamorphic rocks. The relationship between their facies classification and the zones recognized in the metamorphic rocks of the Southern Alps is set out in table 8. The Chlorite, Biotite, and Almandine zones each correspond to successive subfacies of the greenschist facies. The Oligoclase Zone corresponds to part of the almandine-amphibolite facies. Turner and Verhoogen divide this facies into four subfacies, of which the two of highest grade are characterized by the presence of sillimanite. Sillimanite has not been found in rocks of the Oligoclase Zone in this region, so this zone does not include rocks metamorphosed under the higher-grade conditions of the almandine-amphibolite facies. Kyanite has been found, however, so that metamorphism reached the grade of the kyanite-almandine-muscovite subfacies. Although staurolite, the characteristic mineral of the staurolite-almandine subfacies, has not been found in the schists of the Southern Alps (presumably because they are too rich in potassium and calcium and too low in aluminum and ferrous iron to give the mineral), the association almandine-oligoclase probably signifies approximate equivalence to this subfacies.

Temperature and Pressure Conditions During Metamorphism

The only direct geothermometer that can be applied from the available data is that provided by the composition of muscovite (table 2). Analysis 1 is of a muscovite from the Chlorite 4 Subzone; analysis 2, a muscovite from the Oligoclase zone. If we can assume that the muscovites contain the maximum amount of Na at the temperature of crystallization, we can apply the muscovite geothermometer of Eugster and Yoder (*in* Abelson, 1955); this gives a crystallization temperature of about 390° C. for 1, 640° C. for 2. A partial analysis of another muscovite, in a quartz-oligoclase-muscovite-biotite-almandine schist from the Copland River, gave Na_2O, 1.78 per cent; K_2O, 8.00 per cent, which indicates a temperature of crystallization of 670° C. However, these muscovites coexist not with paragonite, but with albite. Hence they will not contain the maximum amount of Na, so these temperatures will be minimum ones. Experience has shown that the muscovite geothermometer gives unreasonably high

TABLE 8

Correlation of Metamorphic Zones with the Facies Classification

Facies	Subfacies	Zone
Greenschist	Quartz-albite-muscovite-chlorite	Chlorite
	Quartz-albite-epidote-biotite	Biotite
	Quartz-albite-epidote-almandine	Almandine
Almandine amphibolite	Staurolite-almandine Kyanite-almandine-muscovite	Oligoclase

temperatures, especially at higher grades of metamorphism (Lambert, 1959). It must be admitted, therefore, that the temperatures deduced above must be used with extreme caution, although other indicators suggest that they are of the right order of magnitude.

In North Westland lenses of serpentine are found in the schists. They occur in the Biotite Zone and in the adjoining part of the Almandine Zone. The fact that serpentine decomposes at about 500° C. into forsterite plus talc plus water vapor, and the temperature of this decomposition is virtually unaffected by pressure (Bowen and Tuttle, 1949), indicates that the temperature in the lower-grade part of the Almandine Zone did not exceed 500° C.

An indirect indicator of temperature is the presence of the association calcite-quartz and the absence of wollastonite, even in rocks of the highest metamorphic grade. If the partial pressure of CO_2 has been equal to the rock pressure the association calcite-quartz will be stable to well over 700° C. under conditions of regional metamorphism, according to the experimental data of Harker and Tuttle (1956). However, under geological conditions the rock cover is usually semipermeable to carbon dioxide. Hence the partial pressure of carbon dioxide will be lower than the rock pressure, and the formation of wollastonite will take place at lower temperatures. The absence of wollastonite from the Southern Alps rocks probably indicates that the temperature of metamorphism has not exceeded 700° C. and may have been considerably less.

Analogies from other areas of regional metamorphism provide some indication of the temperature range to be expected. Rosenfeld and Cotter (1958) have applied the calcite-dolomite geothermometer to an area of regional metamorphism in southeastern Vermont and deduce a temperature span from 375° C. in the Chlorite Zone to 625° C. in the Kyanite Zone. Turner and Verhoogen (1960) suggest a temperature range of 300° C.–500° C. for the greenschist facies and one of 550° C.–750° C. for the almandine-amphibolite facies.

On the basis of these rather vague indicators, I suggest that the Biotite isograd corresponds to a temperature between 350° and 400° C.; the Almandine isograd, to one between 450° and 475° C.; and the Oligoclase isograd, to one between 550° and 600° C. I agree with Turner and Verhoogen that significant recrystallization and the formation of new minerals in a metamorphic sequence of this kind probably begin at about 300° C., which would be the approximate temperature in the Chlorite 2 Subzone.

The pressures to which the Oligoclase-zone rocks have been subjected can be roughly evaluated from the occurrence of kyanite. Clark (1960) has determined experimentally the kyanite-sillimanite equilibrium curve. Extrapolation of his results leads to equilibrium pressures of 12.4 kilobars at 600° C., which is a reasonable temperature for the crystallization of Oligoclase-zone rocks. This implies a depth of crystallization of about 44 kilometers, if lithostatic conditions are assumed. It is conceivable that the intense folding resulted in the carrying-down of the rocks in the axis of the geosyncline to this depth. A temperature of 600° C. at this depth gives a geothermal gradient of 14° C. per kilometer, which is somewhat below average but not unreasonable.

Age of Metamorphism

The age of the metamorphism that formed the schists of the Southern Alps has been the subject of divided opinions on the part of New Zealand geologists. In the last century the schists were often considered to be Archaean, or at least pre-Devonian, because unmetamorphosed Devonian rocks occur in the northwestern part of the Alps in Nelson Province (these rocks are, however, west of the Alpine Fault and were not involved in the orogeny that metamorphosed the schists). More recently, opinion has crystallized around two viewpoints: (1) the schists are Paleozoic sedimentary rocks metamorphosed in a pre-Triassic orogeny; (2) the schists are Triassic (and possibly older) sedimentary rocks metamorphosed in an early Cretaceous orogeny. The crux of the argument between these two viewpoints is whether the fossiliferous Triassic rocks grade into the schists or are separated from them by an unconformity (an unconformity that has not, however, been recognized in the field). The second viwpoint received some support from the analysis of uranothorite from Gillespie's Beach, South

TABLE 9

POTASSIUM-ARGON AGES ON ROCKS FROM THE SOUTHERN ALPS

M.I.T. Number	Mason Number	Rock and Locality	Potassium, in Per Cent	Ar^{40}/K^{40}	Potassium-Argon Age, in Millions of Years
M-3957	762	Schist, Clarke and Haast Rivers	8.01	0.0046	76
B-3956	781	Gneiss, Haast River	7.19	0.00052±0.00008	8±2
B-3952	205	Schist, Wanganui River	6.57	0.0004 ±0.0002	7±3
B-3953	680	Schist, Franz Josef Glacier	6.50	0.0002 ±0.0001	4±2
B-3951	313	Schist, Hokitika River	6.63	0.0002 ±0.0001	4±2
B-3955	864	Pegmatite, Moeraki River	7.81	0.00153±0.00006	25±1
R-3958	133	Argillite, Hopkins River	3.72	0.102	166

Westland (Hutton, 1950). Although the uranothorite was detrital, its provenance was almost certainly from the schist belt. The Pb:U+Th age was 119×10^6 years, equivalent to lower Cretaceous.

The field evidence collected during the present investigation favors the second viewpoint. In order to test this, potassium-argon dates on a number of samples were determined by Dr. Hurley and his co-workers at the Massachusetts Institute of Technology. Their results, and a discussion of possible interpretations, have already been published (Mason, 1961). However, for the sake of completeness the information is repeated here.

Table 9 of the present paper gives the age data on the rocks from the Alpine schists. The petrological descriptions of the specimens, and their exact locations, are as follows (the numbers are the original field collection numbers):

762: Locality, Haast-Makarora road, at Clarke Bluff (junction of Haast and Clarke rivers). The rock (table 6, analysis 6) is a coarsely foliated quartz-albite-clinozoisite-chlorite-muscovite schist (Chlorite 4 Subzone); it contains accessory amounts of pyrrhotite and apatite. The potassium and argon determinations were made on separated muscovite.

781: Locality, Haast-Makarora road, at Halfway Bluff, 13.1 miles from Haast Airfield. The rock is a quartz-oligoclase-muscovite-biotite gneiss, with accessory tourmaline, apatite, clinozoisite, and opaque material.

205: Locality, south bank of Wanganui River, just below Hende Creek, Mt. Bonar Survey District. The rock is a quartz-oligoclase-muscovite-biotite schist, with accessory almandine, clinozoisite, tourmaline, and opaque material.

680: Locality, Wilson Rock, Waiho Valley, near terminal of Fraz Josef Glacier. The rock is a quartz-oligoclase-muscovite-biotite-almandine schist, with accessory opaque material.

313: Locality, east bank of Hokitika River, 4.4 miles at 202 degrees from Trig CW, Toaraha Survey District. The rock is a quartz-oligoclase-muscovite-biotite schist, with accessory almandine, clinozoisite, tourmaline, and opaque material.

864: Locality, mica mine (worked 1944–1945), Moeraki River. The sample used for analysis was cut from a large plate of biotite from a quartz-feldspar-muscovite-biotite pegmatite; the country rock is a quartz-oligoclase-muscovite-biotite schist.

133: Locality, west bank of Hopkins River, at junction with Dobson River (northwest Otago). The rock is an argillite, consisting of quartz, albite, muscovite (sericite), chlorite, and clinozoisite, with accessory stilpnomelane (table 6, analysis 4). Because it was not possible to separate the sericite mechanically, the potassium and argon determinations were made on the whole rock.

At first glance the ages of less than 10 million years for the schists and gneisses in table 9 (except specimen 762) are rather startling. It seems unreasonable on geological grounds to postulate a post-Cretaceous metamorphism for these rocks. Low-grade schist pebbles are common in Cretaceous conglomerates in Otago, as, for example, in the Naseby district (Harrington, 1955). However, high-grade (biotite) schist pebbles are unknown in Tertiary conglomerates and appear first in Pleistocene moraines in Westland (Morgan, 1908; Wellman, 1955). It seems therefore that the high-grade schists and gneisses were first exposed to erosion in Pliocene or Pleistocene times, by comparatively rapid uplift along the line of the Alpine Fault. The present relief on the fault is 12,000 feet in the central part of the Alps, and the total uplift has certainly been much greater, to provide the immense amount of fluvioglacial debris on the Westland coastal strip. It is therefore conceivable that the biotite-bearing schists have been at considerable depths during most of the Tertiary period, hence at a temperature at which argon would diffuse out of the mineral as it was formed. Hurley and his co-workers believe that temperatures of 300° C. or greater are required for the loss of argon in this way. If geothermal gradient of 30° C. per kilometer is assumed, a temperature of 300° C. would correspond to a depth of 30,000 feet; if a geothermal gradient of 20° C. per kilometer is assumed, that temperature would correspond to a depth of 45,000 feet. These data suggest an uplift of between 30,000 and 45,000 feet on the Alpine Fault since the beginning of the Pliocene.

The potassium-argon ages of the schists and gneisses record the time since the radiogenic argon was retained within the crystal structure of the biotite. In the case of these rocks, this is evidently much later than the time at which the biotite crystallized, i.e., the time of metamorphism. The only clue to the time of the metamorphism is provided by the 76-million-year age of the chlorite-muscovite schist (specimen 762). This rock is of much lower grade of metamorphism than the biotite-bearing schists and gneisses, so that its original temperature of metamorphism was lower, and it lies farthest from the Alpine Fault. However, it is quite improbable that the potassium-argon age for this rock is the actual age of the metamorphism; some argon loss since crystallization of the muscovite has probably occurred. The figure of 76 million years does indicate that the metamorphism is pre-Tertiary; the geological evidence suggests that the metamorphism was probably early Cretaceous.

The significance of the 25-million-year age of the biotite from the Moeraki River pegmatite depends upon the interpretation of the geological environment of the pegmatite. Wellman (1955, p. 16) writes: "The origin of these pegmatites is somewhat uncertain. They do not transgress the schistosity planes, show no contact effects, and appear to grade laterally into the enclosing schist. They seem to have formed by recrystallization of particular bands in the schist rather than by intrusion." My own observations agree with those of Wellman, and I interpret these pegmatites as formed by the segregation of a low-melting fraction of the country rock during the regional metamorphism, which would make the probable age of pegmatites early Cretaceous. The 25-million-year age would then be due to argon loss as a consequence of deep burial during most of the Tertiary era. The somewhat higher age for the pegmatite biotite in comparison to the biotite from the schists may perhaps be ascribed to the greater retentivity for argon of the large biotite crystals in the pegmatite.

The potassium-argon age of the argillite poses a number of problems. The rock belongs to the graywacke-argillite formation that makes up the Southern Alps east of the Main Divide and that grades into the metamorphic rocks to the west. In the field the argillite and the interbedded graywacke are indurated but apparently unmetamorphosed. However, thin sections show accessory stilpnomelane, evidently produced by mild metamorphic recrystallization. These rocks are mapped as belonging to the Chlorite 2 Subzone, but are close to the boundary between the Chlorite 1 Subzone and Chlorite 2 Subzone. The simplest interpretation would be to consider the potassium in the argillite to have been incorporated in the sericite during diagenesis, and the potassium-argon age to give the elapsed time since diagenesis. The age of 166 million years, on the current time scale, would be near the Triassic-Jurassic boundary, which is not inconsistent with the sparse fossil evidence. The presence of accessory stilpnomelane suggests that these rocks were affected by the later regional metamorphism, which would tend to cause some argon loss and hence lower the potassium-argon age. No detrital potassium feldspar was detected in the argillite, so that the possibility of "inherited" argon in the rock is unlikely.

Causes of Metamorphism

Two contrasted hypotheses have been proposed for the cause of the metamorphism which produced the schists of Otago and Westland. Hutton (1939) and Turner (1941) believed that the Chlorite-zone schists in Otago were underlain at depth by a major granitic intrusion. To this intrusion were attributed widespread introduction of tourmaline into schists of all compositions, the local disseminations of pyrite, occurrences of piedmontite, and the development of quartz veins carrying gold, sulphides, or scheelite in a large number of widely separated localities [later Turner (1946) suggested that the piedmontite-bearing schists were probably originally manganiferous cherts and that this mineral was not the product of magmatic emanations]. The contrasting hypothesis has been put forward by Wellman (1956) and Grindley (1957), who maintain that the metamorphism is the result of depth of burial of an enormously thick sedimentary sequence, estimated by Grindley as 50 miles down to the base of the Chlorite Zone.

Neither of these hypotheses is satisfactory in explaining the metamorphism which formed the schists of the Southern Alps. A weakness of the theory of an underlying granitic intrusion is that it nowhere outcrops —neither in Otago nor in the Southern Alps, where high relief over thousands of square miles might be expected to reveal some offshoot. A few small quartz-feldspar-muscovite-biotite pegmatites do occur in the high-grade schists between the Paringa and Haast rivers, but these may be segregation pegmatites. Turner and Hutton mention the granites of South Westland as parts of their subjacent granite batholith, but these granites all lie on the west side of the Alpine Fault outside the schist region. The widespread occurrence of tourmaline, which Hutton cited as specific evidence of metasomatism by granite-derived solutions, can be explained as representing the boron content of the parent rocks. The boron content of New Zealand graywackes and argillites is often of the order of 100 to 800 p.p.m., quite sufficient to account for the quantity of tourmaline present in the schists, as pointed out by Reed (1958).

The hypothesis of Wellman and Grindley that the metamorphism is due to the burial of the sediments in the axial part of the geosyncline to the depth of many miles is also unsatisfactory. It is based on the belief that, since schistosity planes in the more highly metamorphosed rocks are parallel to bedding planes in the less-altered graywackes and argillites, measurements across the strike will give true stratigraphic thicknesses—hence, the estimate of 50 miles to the base of the Chlorite Zone. They do not allow for the intense isoclinal folding *prior* to metamorphism, which makes any estimates of stratigraphic thickness by measurements across schistosity planes quite illusory.

I believe with Wellman and Grindley that the cause of the metamorphism is to be sought in deep burial rather than in the supply of heat from a subjacent granite batholith. I differ from them in ascribing this deep burial to the compression of the geosyncline and the piling up of isoclinally folded beds, not to simple accumulation of a great thickness of sediments. I believe that the belt of highest-grade schists exposed in the Alps represents the rocks nearest the axis of the geosyncline, which are not necessarily those stratigraphically lowest. These rocks were subjected to the greatest intensity of heat, pressure, and deformation by the focusing of the orogenic forces at the axis of the geosyncline.

GEOLOGICAL HISTORY

1. In the Permian and Triassic a geosynclinal trough existed on the present site of the Alps. It was bordered on the east by a land mass of generally granodioritic composition from which large quantities of sediment were derived and which were carried into the geosyncline largely by turbidity currents. This sediment formed the graywackes (quartz, plagioclase, potash feldspar, clay) and argillites that, with their metamorphosed equivalents, form the main part of the Southern Alps.

The western and southwestern side of the geosyncline was probably a volcanic island arc from which the sediments were mainly tuffaceous graywackes of andesitic composition. Such graywackes form the major part of the Permian and Triassic sequence in southwest Otago and Southland, and the schists of far South Westland are notably more chloritic than those of the main part of the Alps.

2. Sedimentation came to an end in Jurassic times and was followed by intense orogeny. The sediments were folded into a complicated series of anticlinoria and synclinoria, themselves made up of isoclinal folds. The rocks nearest the axis of the geosyncline were subjected to the greatest degree of deformation and were carried down to a sufficient depth to produce the regional metamorphism now observed on the western flank of the Alps.

3. During the Cretaceous the land area produced by the orogeny was reduced to a surface of low relief.

4. Partial transgression of the sea in the Eocene followed. Terrigenous sediments of Eocene age are succeeded by Oligocene limestones, which suggests complete marine transgression at that time.

5. At the end of the Oligocene the trend was reversed, and renewed uplift of the region probably began. Post-Oligocene sediments in areas flanking the Alps are notably terrigenous, in contrast to the clear-water limestones of Oligocene times. This renewed uplift was most marked in South Westland and northwest Otago, and in this region was accompanied by folding, which was quite intense in northwest Otago (a band of Oligocene limestone a few feet thick and more than 20 miles long is infolded and infaulted in the schists of this region). The folding was accompanied by minor intrusions of gabbroic and feldspathoidal rocks in the Paringa, Haast, and Makarora valleys. A considerable amount of Biotite-zone rocks were retrogressively metamorphosed to rocks of the Chlorite 4 Subzone.

Erosion probably more or less kept pace with uplift; there is no evidence of the formation of high mountains in this region during the Miocene and Pliocene.

6. At the end of the Pliocene strong vertical uplift began along the whole length of the Alpine Fault and continued throughout the Pleistocene. The total uplift is probably of the order of 30,000 to 40,000 feet. This uplift brought the high-grade schists and gneisses to the surface for the first time and exposed them to erosion.

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