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DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

BULLETIN 107

METAMORPHIC AND IGNEOUS ROCKS OF THE LAMBOO COMPLEX, EAST KIMBERLEY REGION, WESTERN AUSTRALIA

BY

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SUMMARY

The Lamboo Complex is a metamorphic and igneous complex in the East Kimberley region of Western Australia. Its rocks range from 1940 to 1700 million years old. The complex forms the centre of an area of intense deformation and tectonic activity known as the Halls Creek Mobile Zone.

The Tickalara Metamorphics have been formed by regional metamorphism of the geosynclinal sediments and volcanic rocks of the Halls Creek Group. Basic and ultrabasic rocks were emplaced in the Halls Creek Group just before the regional metamorphism. They were emplaced as homogeneous dolerite and ultrabasic sills, or as thick differentiated gabbroic sills with subordinate ultrabasic segregations at the base. The largest sills have been metamorphosed only on the margins, but the smaller bodies have been completely altered.

The Tickalara Metamorphics comprise schist, quartzite, paragneiss, granite gneiss, calc-silicate rocks, amphibolite, and pyroxene granulite. Three progressive zones of metamorphism have been established on the basis of the mineralogical and textural changes in pelitic, arenaceous, and basic igneous rocks. The appearance of biotite and sillimanite has been used to demarcate the zonal boundaries in the pelitic and arenaceous rocks. The grade of metamorphism in the basic igneous rocks is indicated by the change in colour of the calciferous amphiboles. The Tickalara Metamorphics range from the greenschist facies to granulite facies, and belong to the low-pressure intermediate group of Miyashiro (1961). High shearing stress and relatively low temperatures governed the crystallization of the low-grade metamorphic rocks. The high-grade rocks were produced under conditions of low pressure and high temperature. However, the partial pressure of water was sufficiently high to restrict the formation of the pyroxene granulite facies in the pelitic rocks, and sufficiently high to remobilize the sillimanite and cordierite-rich gneisses into migmatites and an anatectic granodiorite/tonalite magma (the Mabel Downs Granodiorite). The granodiorite intrudes the Tickalara Metamorphics but is structurally concordant with them. After its formation by anatexis it was intruded as a mobile magma at a higher level in the crust.

A later group of discordant igneous rocks intrudes the Tickalara Metamorphics and Halls Creek Group. These are surrounded by contact aureoles. The Bow River Granite and the associated co-magmatic Castlereagh Hill Porphyry form a large discordant batholith on the western margin of the Lamboo Complex. The Bow River Granite includes coarse-grained porphyritic granite with tabular or oval feldspar phenocrysts, granodiorite, and granite-gabbro breccias.

Numerous smaller granitic plutons intrude the Halls Creek Group. Copper occurs in the vicinity of one pluton and tin-bearing pegmatite dykes are associated with the others.

Tonalite and granodiorite plutons intrude the Bow River Granite and Halls Creek Group. They are the youngest of the large magmatic intrusions in the Lamboo Complex. Thin dykes of dolerite, diorite, pegmatite, aplite, and quartz-feldspar porphyry post-date these plutons.

INTRODUCTION

This Bulletin describes the geology of the igneous and metamorphic rocks of the Lamboo Complex in the eastern part of the Kimberley Division of Western Australia (Fig. 1). The area encompasses the western halves of the Lissadell,

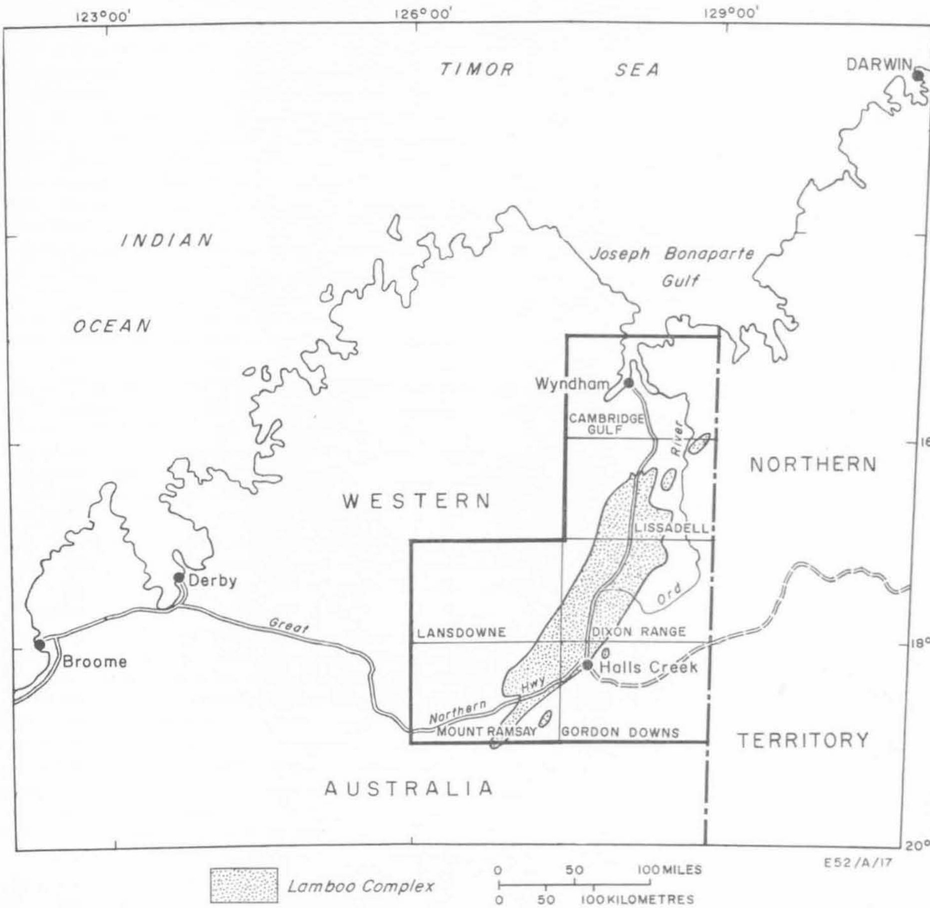


Figure 1
Locality map and 1:250,000 Sheet index.

Dixon Range, and Gordon Downs 1:250,000 Sheet areas, the eastern half of the Mount Ramsay Sheet area, and the southeastern corner of the Lansdowne Sheet area. It is bounded on the east by longitude 128°30′E and 129°E (on the Lissadell Sheet), on the west by longitude 127°30′E and 126°45′E (on the Mount Ramsay Sheet), and by latitude 16°00′S and 19°00′S.

The mapping of the Lamboo Complex is part of a current investigation of the Kimberley Division by the Geological Survey of Western Australia and the Bureau of Mineral Resources. The geology of the area within which the Lamboo Complex lies has been described by Dow & Gemuts (1969) and maps and explanatory notes on parts of the area are also available (Dow & Gemuts, 1967; Dunnet & Plumb, 1968; Dow, Gemuts, Plumb, & Dunnet, 1964; Roberts, Halligan, & Gemuts, 1967; and Smith & Gemuts, 1967).

I wish to acknowledge the field observations of D. B. Dow and H. L. Davies, of the Bureau of Mineral Resources, who helped in the initial subdivision of the Lamboo Complex. Other acknowledgments have been inserted in the text where appropriate.

I am grateful to Professor C. E. Marshall, and Drs A. F. Trendall, J. L. Daniels, and T. G. Vallance for helpful discussions and encouragement. Mr L. H. Fimmell took the photomicrographs and Mr K. Gayski prepared the thin sections. The silicate analyses were made by the Western Australian Government Chemical Laboratory and the Australian Mineral Development Laboratories in Adelaide.

V. M. Bofinger, formerly of the Bureau of Mineral Resources, is studying the isotopic age of the rocks from the area, and his preliminary results have been incorporated in this Bulletin.

Topography, Access, and Climate

The Lamboo Complex has a rugged topography and is enclosed by high ridges of Proterozoic sediments to the east and west. The crystalline rocks have an open-textured drainage, with subdued strike ridges and low rounded bouldery hills up to 300 feet high (Pl. 1, fig. 1). The granitic horsts rise above the low-lying plains which are underlain by basic igneous and metamorphic rocks or by zones of intense shearing. The plains provide easy access to the north and form the main pastoral areas.

Halls Creek, the only town in the area, is situated about 380 miles from Derby and 250 miles from Wyndham. Originally a gold mining centre, it is now a small supply town for cattle stations in the surrounding district. Halls Creek and most of the cattle stations have all-weather airstrips which are regularly served by aircraft which connect at Wyndham with airline services from Perth and Darwin.

The Great Northern Highway from Derby to Wyndham passes through Halls Creek. Most of the area can be traversed by Land Rover along station tracks or across country. Areas difficult of access to the north and west of Mabel Downs homestead were mapped by means of a helicopter.

The region has a tropical savannah climate with a wet season from December to March and a long dry season from June to September. The annual rainfall ranges from 13 inches in the south to 35 inches in the north. Daily temperatures are very high all through the year, and in the summer may average over 110°F for many days.

OUTLINE OF THE GEOLOGY OF THE LAMBOO COMPLEX (Fig. 2)

The igneous and metamorphic rocks of the Lamboo Complex form a north-northeasterly belt nearly 200 miles long and about 30 miles wide, between Mount Hawick in the south and Pompeys Pillar to the north. Farther north, the complex is covered by Proterozoic sediments, except for a number of inliers of granite near the Halls Creek Fault. The western margin of the complex is unconformably overlain by, and faulted against, Proterozoic sediments. On the Lissadell and Dixon

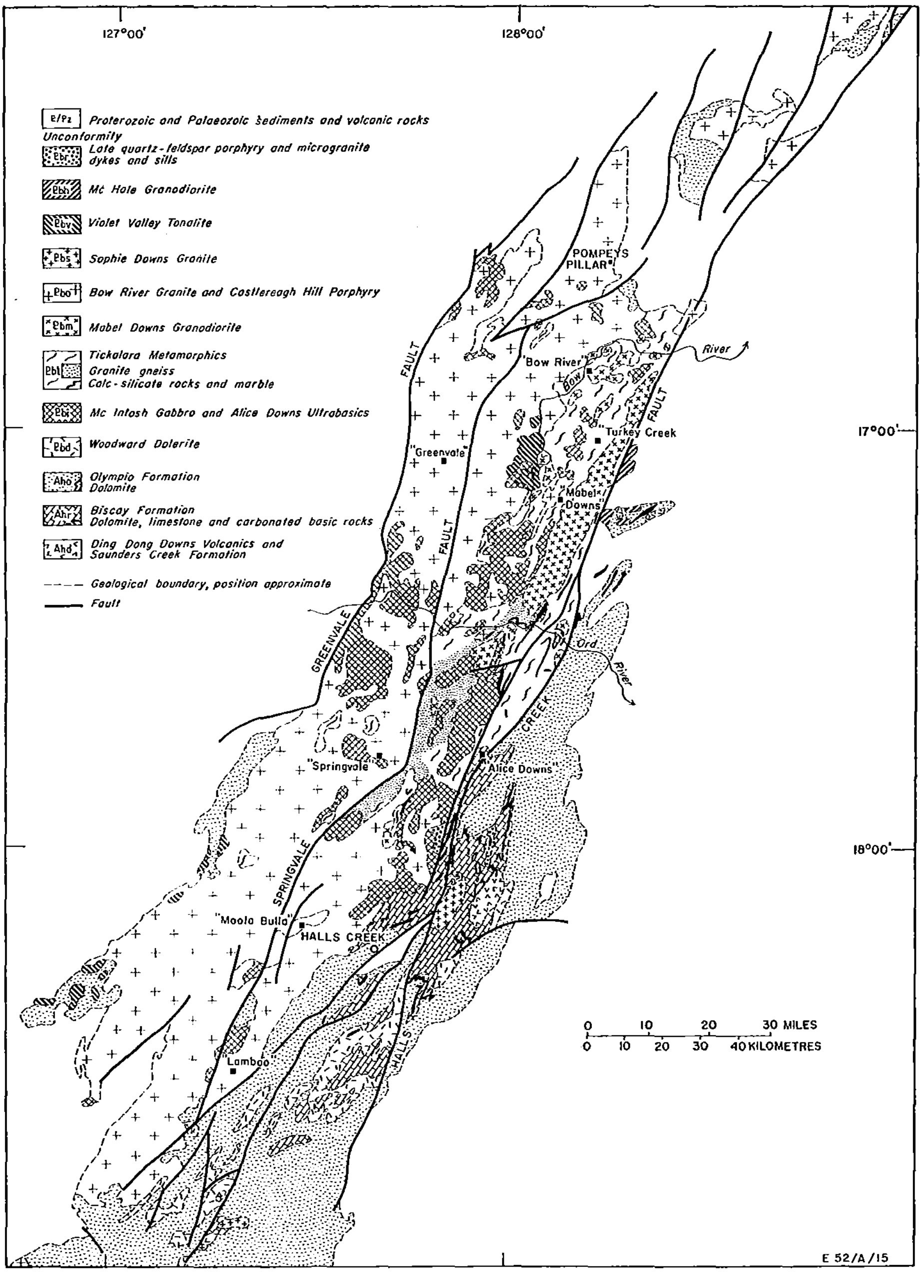


Figure 2

Geological map of the Lamboo Complex and Halls Creek Group.

Range Sheet areas the eastern margin is defined by the Halls Creek Fault, but on the Gordon Downs and part of the Mount Ramsay Sheet areas the eastern margin is not entirely controlled by faults, and igneous rocks of the Lamboo Complex intrude the sedimentary and volcanic rocks of the Halls Creek Group. The granites intruding the Halls Creek Group in the Osmond Range, and in the Sophie Downs area and along the McClintock and Cummins Ranges, have also been mapped as part of the Lamboo Complex.

Hardman (1884, 1885) was the first geologist to examine the complex. He recognized varieties of gneiss and schist intruded by granite, syenite, and 'trap rock'. Some of the areas he investigated were so complex that the 'ramifications of the different igneous and metamorphic rocks become so complicated that even on a map of a very large scale it would be extremely difficult to represent them correctly' (1885, p. 27).

Since Hardman's investigation, the complex has been subdivided by various authors as shown in Table 1.

HARDMAN (1884, 1885)	MATHESON & GUPPY (1948)	TRAVES (1955)	DOW & GEMUTS (1969)
Varieties of gneiss and schist intruded by granite syenite, and trap rock	Lamboo Complex (granite, gneiss, and metasediments)	Lamboo Complex (granitic rocks)	Lamboo Complex: Basic and acid plutonic rocks; High-grade metamorphic rocks (Tickalara Metamorphics)
	Halls Creek Group (metasediments and volcanics); McLintock Greenstones (mainly basic lavas)	Halls Creek Metamorphics	Halls Creek Group (unmetamorphosed and low-grade metamorphic, sedimentary, and volcanic rocks)

M(S)79

Table 1

Subdivision of the Lamboo Complex and Halls Creek Group.

The complex is named after Lamboo homestead 30 miles southwest of Halls Creek. The name was first used by Matheson & Guppy (1949), and was defined by Guppy et al. (1958) to include granite, granitic gneiss, and undigested remnants of metasediments. The older rocks in the area were designated as the Halls Creek Group (metasedimentary and volcanic rocks) and McClintock Greenstones (mainly basic lavas). Traves (1955) included only the granitic rocks in the Lamboo Complex, and placed the metasediments and the Halls Creek Group and McClintock Greenstones in the Halls Creek Metamorphics. Dow & Gemuts (1967), following Guppy et al. (1953), included only the high-grade metamorphic rocks (Tickalara Metamorphics) and the basic and acid plutonic rocks in the Lamboo Complex. The low-grade metasedimentary and volcanic rocks were placed in the Halls Creek Group of which the Tickalara Metamorphics are regarded as the metamorphosed equivalents.

Geological History

The geological history of the Lamboo Complex can be summarized as follows (see Table 2):

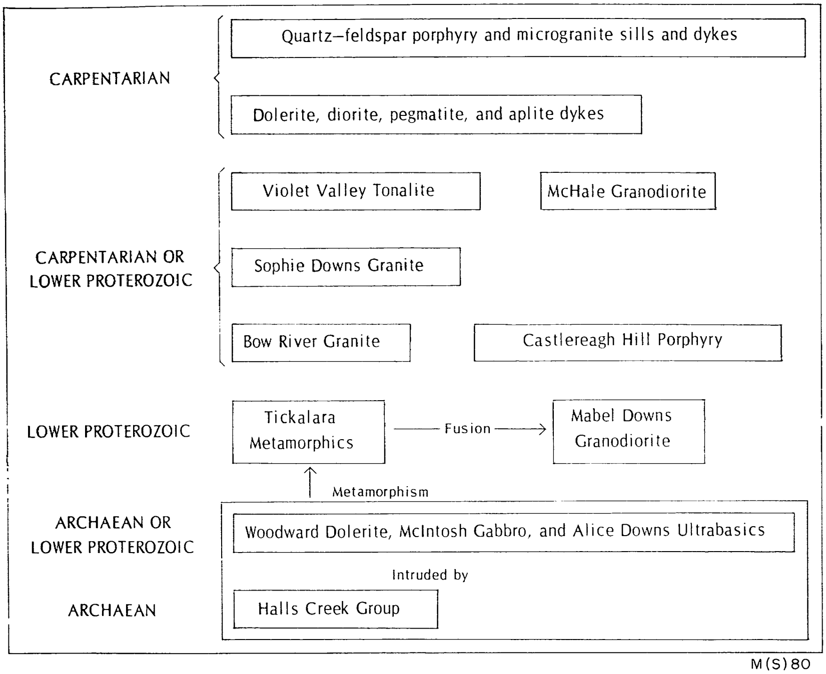


Table 2

Sequence of events in the Lamboo Complex.

(i) In Archaean times, the geosynclinal sediments and associated basic and acid volcanic rocks of the Halls Creek Group were deposited. In the early Proterozoic, they were intruded by ultrabasic and basic sills and dolerite dykes which are known collectively as the Woodward Dolerite. The Halls Creek Group has been divided into the Ding Dong Downs Volcanics, and the Saunders Creek, Biscay, and Olympio Formations.

(ii) The geosynclinal pile was then deformed and metamorphosed. The grade of metamorphism increased from the greenschist facies in the south to the granulite facies in the north. In the south, features such as bedding, ripple marks, load casts, and graded bedding have been preserved in the low-grade metasediments of the Halls Creek Group, and the Woodward Dolerite has been uralitized or completely reconstituted to form low-grade amphibolite.

In the north and to the west of the Halls Creek Fault, the Halls Creek Group has been converted into high-grade metamorphic rocks known as the Tickalara Metamorphics. The greywacke and shale of the Olympio Formation and the acid volcanics of the Biscay Formation were changed to schist and gneiss and the dolomites and limestones in the Biscay Formation were converted to calc-silicate rocks. The amphibolites are thought to have been formed by the reconstitution of the Woodward Dolerite and of the interbedded basic lava flows and dolomites in the Biscay Formation. Some of the pyroxene granulites represent higher-grade equivalents of the amphibolites, but others were derived directly from calcareous sediments and basic igneous rocks. The Tickalara Metamorphics contain large sill-like bodies of differentiated basic and ultrabasic rocks. Although they appear to be of the same age as the Woodward Dolerite, they have been given separate names—the Alice Downs Ultrabasics and McIntosh Gabbro. The largest sills have been metamorphosed only on the margins, but the smaller bodies have been completely altered to rocks ranging from the greenschist to granulite facies.

(iii) In the regions of the highest metamorphic grade partial fusion of the Tickalara Metamorphics gave rise to the anatectic gneissic Mabel Downs Granodiorite which intrudes the Tickalara Metamorphics and the McIntosh Gabbro.

(iv) The Bow River Granite, which locally grades into the Castlereagh Hill Porphyry, was intruded as a batholith along the western margin of the Lamboo Complex during the waning stages of metamorphism. It incorporated pendants of the basic and ultrabasic rocks, and of the Tickalara Metamorphics and Halls Creek Group. Aplite and pegmatite dykes are associated with the Bow River Granite. The batholith was emplaced in the early Proterozoic.

(v) The Sophie Downs Granite was intruded into anticlines in the Halls Creek Group. The copper mineralization in the Sophie Downs area is related to the granitic intrusions, and tin-bearing pegmatites are present in the Cummins and McClintock Ranges. The gold mineralization in the Halls Creek Group may also be related to the Sophie Downs Granite. The age of the Sophie Downs Granite is unknown, and the intrusions may be older or younger than the Bow River Granite.

(vi) The Violet Valley Tonalite was intruded into the Halls Creek Group and Bow River Granite. The McHales Granite, which intrudes the Halls Creek Group in the Osmond Range area, may be related to the Violet Valley Tonalite intrusion.

(vii) Dykes of dolerite, diorite, pegmatite, and aplite were intruded into the Bow River Granite and Tickalara Metamorphics.

(viii) The youngest intrusions in the Lamboo Complex are the quartz-feldspar porphyry dykes in the Bow River Granite and the quartz-feldspar porphyry and microgranite sills and stocks in the Halls Creek Group. The minimum age of these intrusives is Middle Proterozoic.

Structural Setting

The major structural unit in the Kimberley region is an arcuate tectonic belt of intensely deformed sedimentary and volcanic rocks of the Halls Creek Group and the associated metamorphic and igneous rocks of the Lamboo Complex. The eastern arm of this belt has been called the Halls Creek Mobile Zone (Traves, 1955). The zone lies between two structural basins which have been stable since Cambrian times—the Kimberley and Ord-Victoria River Basins. The Halls Creek Mobile Zone extends for 500 miles from Mount Hawick in the south to Darwin in the north. The width of the zone is variable, and the eastern and western limits are defined by the gently dipping rocks in the structural basins to the east and west. The Lamboo Complex forms the nucleus of the Halls Creek Mobile Zone.

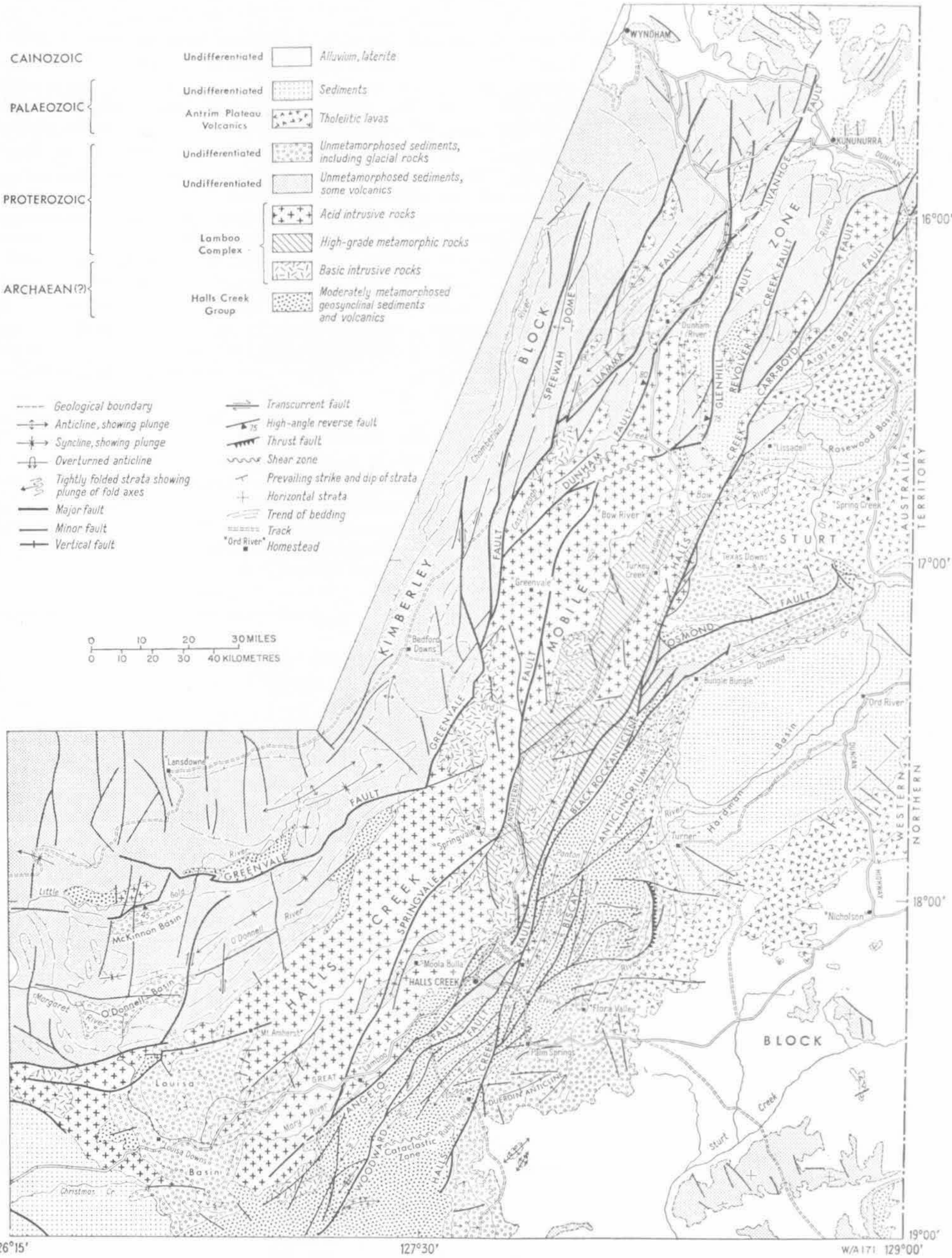


Figure 3

Structural map of the Lamboo Complex and Halls Creek Group.

The margins of the Halls Creek Mobile Zone are paralleled by great fundamental faults (De Sitter, 1956) which represent zones of major crustal weaknesses in the Precambrian shield. They include the Halls Creek, Greenvale, Springvale, Woodward, Angelo, Ivanhoe, Revolver Creek, Carr Boyd, and Cockatoo Faults. Recurrent vertical and lateral movements along these faults have produced folds in the zone itself and in the overlying Proterozoic rocks. Some of the structures in the Proterozoic rocks are controlled by folds and faults that began in the Archaean.

A structural sketch map of the Lamboo Complex and Halls Creek Group is given in Figure 3.

Halls Creek Group and Tickalara Metamorphics

The Halls Creek Group has been subdivided by Smith (1963) into four formations:

The *Ding Dong Downs Volcanics* are the oldest rocks in the East Kimberley area. The formation consists predominantly of amygdaloidal epidotized basalt intercalated with basic crystal tuff and tuffaceous greywacke. Carbonaceous phyllite, quartz-sericite schist, epidotized quartz-muscovite schist, and quartz-biotite schist are interbedded with the volcanic rocks. The formation is intruded by thin rhyolite sills.

The *Saunders Creek Formation* consists of medium to coarse-grained quartz sandstone and feldspathic sandstone with interbeds of fine to coarse-grained greywacke and subgreywacke. In places, a quartz conglomerate is present near the base.

The *Biscay Formation* comprises basalt and andesite with minor basic agglomerate, greywacke, tuffaceous greywacke, siltstone, slate, carbonaceous slate, chert, and quartzite. Limestone, dolomite, and calc-silicate rocks occur in the middle and at the top of the formation.

The *Olympio Formation* comprises a thick sequence of quartz-rich and feldspathic subgreywacke intercalated with arkose, siltstone, shale, and carbonaceous siltstone. Conglomerate bands with pebbles of quartzite and jasper occur throughout the sequence. In places, the top of the formation is defined by a bed of dolomite.

Structure of the Tickalara Metamorphics

In the low-grade metamorphic rocks of the Tickalara Metamorphics, the structural style is similar to that in the Halls Creek Group. Axial-plane cleavage folds and numerous small shear zones and faults are common. In the high-grade rocks the structural style is more complex and many of the rocks have been deformed plastically. The folding was accompanied by the intrusion of igneous rocks and both have contributed to the development of the high-grade metamorphic assemblages.

To the south of the Ord River, the folds in the Tickalara Metamorphics have steep northerly plunging axes. The anticlines are overturned to the east and the synclines are sheared out along faults branching from the Halls Creek Fault. The major fold axes and axial planes trend north-northeast. These folds are similar to the axial-plane cleavage folds in the Halls Creek Group. The regional structure is disturbed to the west by intrusive granites and numerous shear zones.

The structure of the area to the north of the Ord River is very complex, and both ptygmatic and isoclinal folds have been developed in the metamorphic rocks on the margins of the gneissic Mabel Downs Granodiorite. Transposition of folded layers and plastic flow have been the dominant processes of deformation in the migmatites. Flowage is a conspicuous feature in the marble bands which have been plastically deformed, whereas the intercalated layers of gneiss and amphibolite have been shattered and disoriented.

In the least deformed areas, the minor folds are generally accompanied by steeply plunging lineations caused by the intersection of bedding and the axial-plane cleavage. The orientation of the lineations is constant over large areas. In the Black Rock Anticline and in the metamorphic rocks enveloping the basic sills in the McIntosh Hills a later strain-slip (crenulation) cleavage cuts across and deforms the earlier folds and lineations. In these areas there is a maximum development of knotted schist and pencil gneiss.

In the migmatites, the plunge of the dominant lineations (formed by the alignment of acicular sillimanite and biotite laths) are most variable.

The Tickalara Metamorphics are bounded on the east by the Halls Creek Fault which trends north-northeast for a distance of 250 miles. The fault has a large vertical component, with the downthrow to the east. It also has a large horizontal component, and in the south it appears to have displaced the Halls Creek Group horizontally for at least 16 miles, west block south. With the exception of this fundamental fault and the Springvale Fault, which defines part of the western boundary of the Tickalara Metamorphics, no other large faults are known to affect these rocks.

Structure of the Igneous Intrusives

The igneous rocks which were intruded before or during the development of the Tickalara Metamorphics are generally concordant with the host rocks. The later intrusives are discordant and generally fault controlled.

The *Alice Downs Ultrabasics* and the *McIntosh Gabbro* were intruded into the Halls Creek Group before the development of the Tickalara Metamorphics. During metamorphism they remained as competent bodies which were relatively unaffected by the folding processes.

The intrusions form large, roughly circular or elliptical, sill-like, layered bodies which are folded into synclines parallel to the axial trend of the structures in the Tickalara Metamorphics. Many of the structures have been disrupted by later intrusive granites, but two of them are well preserved—the Panton Sill, which is composed of layered ultrabasic rocks preserved in a tight southerly plunging faulted syncline, and the McIntosh Sill, which is an elliptical syncline of rhythmically banded gabbros.

The *Mabel Downs Granodiorite* is a gneissic intrusive which was introduced into the Tickalara Metamorphics during the final phase of their deformation; the structures in the intrusion are concordant with the enveloping rocks. South of the Ord River, the granodiorite occupies the core of a faulted anticline with its eastern limb overturned to the west. To the north, a larger sill-like mass is folded into a tight syncline, but the structure disappears into a limb of a dragfold farther north where the granodiorite has the same steep westerly dipping foliation as the enclosing rocks. The minor isoclinal folds, schlieren, and lineations of mineral laths have a constant steep northerly plunge. The structure of the other granodiorite masses shown in Figure 2 is unknown.

The *Bow River Granite* and *Castlereagh Hill Porphyry* are coarse-grained intrusives which were introduced during and after the waning stages of metamorphism. Away from fault zones, where a marked secondary foliation is present, the rocks are massive and seldom exhibit any primary structures. Some of the granites have a primary foliation, defined by the orientation of the feldspar laths, which seems to have no regional significance. Faulting has played a large part in the emplacement of these rocks and horst-graben structures are common. Wide zones of mylonite occur along large faults cutting the igneous rocks in the Lissadell and Mount Ramsay Sheet areas.

The Bow River Granite, along the western margin of the Tickalara Metamorphics, was intruded during the final stage of metamorphism. The granite is gneissic and lit-par-lit injection of the paragneiss is a common feature. One of the larger bodies of granite gneiss occurs in the core of an anticline which is overturned to the east.

The trend of the joints in the intrusives is controlled by the faults in their immediate vicinity; the dominant directions are 330° and 070°.

EARLY INTRUSIVE ROCKS

The Woodward Dolerite is restricted to the Halls Creek Group and was intruded before the formation of the Tickalara Metamorphics. The Alice Downs Ultrabasics and McIntosh Gabbro in the Tickalara Metamorphics are the equivalents of the Woodward Dolerite in the Halls Creek Group. They are partly metamorphosed and foliated and are concordant with the country rocks. They were probably emplaced just before or during the main phase of deformation.

WOODWARD DOLERITE

The Woodward Dolerite comprises numerous basic and ultrabasic sills and dykes which intrude the Halls Creek Group; most of them are restricted to the top of the Biscay Formation, but in the Mount Ramsay Sheet area they also intrude the Olympio Formation. In places, the sills intrude the basic volcanic rocks interbedded with the Halls Creek Group sediments, and it is impossible to differentiate between them as most of the primary structures have been obliterated by low-grade metamorphism.

The Woodward Dolerite sills are folded and are concordant with the Halls Creek Group. The folding probably took place during or after the intrusion of the sills. Most of the sills were intruded along the bedding of the sediments, but the sediments are intruded by dyke-like apophyses in places.

Although there is little petrographic similarity between the ultrabasic and basic sills in the Halls Creek Group and the Alice Downs Ultrabasics and McIntosh Gabbro in the Tickalara Metamorphics, it is believed that the latter are the metamorphosed equivalent of Woodward Dolerite.

The Woodward Dolerite sills range from hundreds of feet to 12 miles long and from 50 to 2000 feet thick. The thickest sills are concentrated to the west of the Halls Creek Fault, between Ruby Plains homestead and the Black Elvira River, where the closely spaced sills intrude the Biscay Formation which has been folded into a large dome. There is a concentration of thin sills in the Olympio Formation to the east and west of the Woodward Range, to the east of Mount Dockerell, and in the McClintock Ranges. Another large folded sill extends from Mount Dockerell to Willy Willy Creek. The small sills to the east of the Halls Creek Fault are tightly folded and intrude the boundary between Olympio and Biscay Formation. Close to the Bow River Granite and Sophie Downs Granite the sills intruding the sediments are sheared, metamorphosed, and attenuated parallel to the granite contact.

The contacts between the sills and the country rock are not well exposed, but in places the sediments are altered to green hornfels, and chilled margins up to 20 feet wide have been observed in the intrusives. The texture of the sills ranges from fine-grained and massive at the margin to vesicular, coarse-grained, and porphyritic towards the centre.

The least altered dolerite sills are massive dark green rocks with a relict coarse-grained allotriomorphic granular texture, or medium-grained ophitic texture. Most of the rocks have been thoroughly uralitized and contain no trace of the original minerals. The altered rocks are composed of light green decussate and rosette-like actinolite or tremolite, spongy albite, epidote, and quartz. In places the primary laths of labradorite have been replaced by fine-grained aggregates of epidote, and chlorite replaces the amphibole. The accessories include skeletal ilmenite and sphene.

The ultrabasic rocks are poorly exposed, and the contact relationships are unknown. The least altered rocks are dark green and massive with a red pitted weathered surface. They have an allotriomorphic granular texture, and are composed of clinopyroxene and amphibole relics set in a fine-grained decussate serpentine-rich groundmass. The most common type is completely altered and consists almost entirely of serpentine.

ALICE DOWNS ULTRABASICS

The ultrabasic rocks represent the differentiated basal fraction of the basic sills which were intruded into the Halls Creek Group before the development of the Tickalara Metamorphics. The sills have been completely or partially metamorphosed and are surrounded by metamorphic rocks. The compositional layering in the ultrabasic rocks is a primary structure, but the original attitude has been modified by folding and shearing. The sills have been folded into tight anticlines and synclines. The largest ultrabasic segregations are the Panton Sill and an elliptical body 4 miles north of Lamboo homestead. To the north of the Panton Sill, smaller bodies crop out along the faulted margins of the gabbros in the McIntosh Sill or form large lenticular bands within the gabbros. Small lenticular segregations in gabbro are also present south of Tickalara Bore.

Panton Sill (Field geology by J. W. Smith)

The Panton Sill has been folded into a southerly plunging syncline 7 miles long, 2 miles wide, and about 3300 feet thick. It contains Tickalara Metamorphics in the synclinal core. The sill is broadly layered and consists of altered peridotite and tremolite-chlorite schist at the base, which grade into alternating bands of uralitized gabbro and leucogabbro towards the top. Individual bands range from 100 to 300 feet thick, and rhythmic mineral banding parallel to the layering is present in some localities. The dip of the banding ranges from 50° on the western flank to 70° on the eastern flank of the syncline.

Most of the rocks in the Panton Sill contain secondary minerals derived from pyroxene and olivine during deformation and metamorphism.

Altered Peridotites. The massive dark green altered peridotite contains small closely spaced reddish pits which represent weathered-out olivine grains.

The relict ragged olivine crystals are pseudomorphed along fractures by cryptocrystalline serpentine, and are set in a groundmass of decussate tremolite and chlorite laths. Irregular grains of chromite and magnetite are common accessories, and shredded aggregates of talc are present in some rocks.

The peridotites contain disseminated grains of chromite, and in places the grains are concentrated in thin layers or as larger bands up to 6 inches across associated with magnesite. The chromite is euhedral and generally pentagonal, but in some cases it is embayed by the chlorite-rich groundmass. The olivine has been completely serpentinized, but the original crystals are outlined by sharp termination of chromite grains. An analysis of a chromite-rich band indicated 11.5 percent chromium and 20.1 percent iron.

Tremolite-Chlorite Schist. The tremolite-chlorite schists are dark green; they have a fibrous and decussate fabric and generally possess a secondary foliation. They were derived from peridotite or troctolite.

The schists contain ragged tremolite laths intergrown with and replaced by pale green or colourless chlorite. Magnetite and chromite grains outline the boundaries of olivine crystals, which are pseudomorphed by decussate clusters of tremolite and chlorite laths. Similarly, chain-like spinel grains enclose decussate tremolite laths and probably represent pre-existing boundaries of pyroxene or olivine crystals. Granulated or lath-like labradorite containing tiny acicular amphibole inclusions is present in some of the schists.

Uralitized Gabbro. The dark-green coarse-grained uralitized gabbros and cream-coloured uralitized leucogabbros from the top of the Panton Sill contain no trace of the original mafic minerals. Rhythmic banding is preserved and ragged amphibole-rich bands up to 5 cm thick are common.

The texture ranges from coarse-grained allotriomorphic granular to ophitic. The presence of bands of severely granulated minerals indicates that cataclastic action was prevalent during the alteration of the rocks.

The anhedral to euhedral zoned plagioclase laths range from andesine to bytownite. Small hornblende needles are distributed randomly through the feldspar and some of the plagioclase is saussuritized and contains granular epidote-rich cores.

The hornblende forms large ragged plates which are pleochroic from light green to dark green or blue-green. The amphibole contains regularly distributed opaque aggregates which may outline the margins of the original pyroxene. The amphibole may be replaced along the cleavage by red-brown biotite.

A little quartz and calcite are also present.

Ultrabasic Rocks North of Lamboo Homestead

An elliptical body of ultrabasic rocks, 6 miles long and 4 miles wide, which is surrounded by gabbros, crops out 6 miles north of Lamboo homestead. The rhythmic banding on the southern margin of the intrusion dips to the south at 60°. This banding is marked by chromite-rich (6 inches wide and 150 feet long) and chromite-poor laminae (Pl. 1, fig. 2). On the eastern and western margins, the primary structures have been disrupted by shearing; the foliation strikes north-northeast and dips 40°E. This foliation is defined by pod-like, yellow, magnetite-ensheathed chrysotile-asbestos veins.

The ultrabasic rocks are fine to coarse-grained and dark green or black. They are composed almost entirely of decussate serpentine pseudomorphs after olivine and pyroxene. The chromite bands consist of closely set euhedral chromite grains interspersed with a dark red unidentified opaque mineral.

Ultrabasic Rocks in the McIntosh Sill (Field geology by H. L. Davies)

In the southern segment of the McIntosh Sill, large lenses of relatively unaltered ultrabasic rocks are surrounded by gabbroic rocks. The bands may represent ultrabasic segregations in situ, or xenoliths which have been incorporated in the gabbro.

One of the bands is composed of olivine and hypersthene. The small poikilitic olivine anhedra are enclosed in large hypersthene crystals, and the small interstitial anhedral plagioclase grains are surrounded by symplektites of spinel and tremolite. The hypersthene has been partly altered to tremolite.

Ultrabasic lenses ranging from anorthosite to pyroxenite are present in separate faulted bodies on the northwestern, western, and southern margins of the McIntosh Sill. They probably represent the basal ultrabasic fraction of the McIntosh Sill. The body immediately to the west of the sill is about 1300 feet thick and has a vertical primary foliation. It grades from anorthosite in the east to altered pyroxenite (spinel-amphibolite) in the west. A similar body northwest of the sill ranges from anorthosite in the west to ultramafic rocks in the east.

Small Outcrops of Ultrabasic Rocks

North of the Panton Sill small isolated remnants of ultrabasic rocks are enclosed in paragneiss. One of them contains chromite. Other outcrops occur in association with altered gabbro on the margins of the Toby Sill, and as small roof pendants in granite to the north of Halls Creek.

Lenticular uralitized hypersthene peridotites are enclosed in gabbro to the south of Tickalara Bore. The olivine is remarkably well preserved and usually forms cracked subhedral aggregates with schillerized orthopyroxene rims, surrounded by dark green hornblende. Some of the olivine has secondary coronas of decussate tremolite, surrounded by decussate colourless chlorite (Pl. 2, fig. 1). Chlorite is absent in some of the coronas and a symplektite of green spinel and tremolite has developed in its place. Plagioclase is usually absent, but small poorly twinned grains, peppered with acicular tremolite needles, may be present.

MCINTOSH GABBRO

Differentiated basic sills, with or without ultrabasic segregations, constitute about one-quarter of the Lamboo Complex. The sills were intruded before the formation of the Tickalara Metamorphics. They are metamorphosed, and do not have contact aureoles. They include xenoliths of gneiss and calc-silicate rocks which represent altered enclaves of the Halls Creek Group sediments.

Some of the basic intrusions form large circular or elliptical sill-like bodies which have been folded into shallow synclines or basins. The more symmetrical bodies include the McIntosh and Toby Sills, the large body near Springvale homestead, and the elliptical sill on the Armanda River. Many small remnants of sills and other less regular bodies constitute most of the basic intrusives. They occur in a belt trending north-northeast from Lamboo homestead in the south to the O'Donnell Range in the north.

The McIntosh Gabbro crops out in subrounded dark green or black hills, or as discrete boulders in black soil. The rock types include gabbro, troctolite, norite, uralitized basic rocks, amphibolite, and pyroxene granulite. Most of the rocks have been partly or wholly altered by metamorphism, shearing, or late granitic intrusives.

McIntosh Sill (Field geology by H. L. Davies)

The elliptical McIntosh Sill is the best preserved example of a differentiated basic intrusion in the Lamboo Complex. It crops out over an area about 9 miles by 3 miles, and its thickness has been estimated at 5000 feet. It consists of alternating layers of melagabbro, leucogabbro, norite, and troctolite. Anorthosite and hypersthenite occur as lenses within the sheet and in separate faulted bodies on the northwestern, western, and southern margins. The faulted bodies possibly represent the basal layers of this differentiated intrusion.

The sill has been folded into a structural basin (Pl. 3) in which the poorly preserved rhythmic layering dips inwards at 10° to 75°. The presence of concentric ridges and gullies suggests compositional banding, but the sill appears to be remarkably uniform.

The centre of the McIntosh Sill is unaltered, but the margins of the intrusion have been uralitized. The alteration was caused by regional metamorphism and late granite intrusion.

Xenoliths of contorted sillimanite gneiss and calc-silicate rocks occur in the northwestern segment of the sill.

The following rock types were found in the McIntosh Sill: (i) at the top — hypersthene troctolite and olivine norite; (ii) less than a quarter of the thickness from the top — gabbro and olivine gabbro; (iii) about a quarter of the thickness from the base — olivine gabbro; and (iv) near the base of the sill — olivine gabbro.

The texture of all rock types is medium to coarse-grained allotriomorphic granular. Rhythmic mineral banding, outlined by single or cumulative layers of irregular olivine crystals, are present in places.

Olivine forms euhedral to anhedral fractured crystals or glomeroporphyritic aggregates. The margins of the crystals have been replaced by brown hornblende, or yellow coronas of spinel may be present. The fractures in the olivine contain a yellow or brown opaque mineral. The composition of the olivine ($2V_X \approx$ 80°-90°) ranges from chrysolite to hyalosiderite.

The anhedral schillerized hypersthene ($2V_X \approx$ 70°-80°) is strongly pleochroic (reddish brown (X) through pale brown (Y) to pale green (Z)) and contains exsolution lamellae or myrmekitic intergrowths of clinopyroxene. In rare cases hypersthene pseudomorphs euhedral olivine crystals.

Slightly green, but non-pleochroic clinopyroxene anhedra ($2V_z \approx 60°$ and $Z \wedge c = 41°-44°$) are partly schillerized and have a prominent diallage parting. Some grains are twinned and in rare cases small poikilitic hypersthene grains are enclosed by clinopyroxene.

The large anhedral and tabular plagioclase laths range from labradorite to anorthite. The feldspar is cloudy and usually has a pinkish tinge.

Some of the mafic minerals have been partly altered to pale brown and greenish brown amphibole associated with iron oxide and green spinel.

Armanda Sill

The Armanda Sill is a composite igneous intrusion situated 20 miles north of Halls Creek. It is 6 miles long, 2 miles wide, and elliptical in shape (Fig. 4).

The sill contains uralitized gabbro and dolerite, porphyry, and granite. It has been intruded into the Halls Creek Group, and along the eastern margin the dolerite and porphyry contain large deformed xenoliths of metamorphic rocks.

The sill has been deformed, and the eastern, northern, and western margins are defined by faults. The faults are inferred from the presence of shear zones and from displacement of the rocks forming the sill. Movement along the faults has given the sill an anticlinal structure which is outlined by the steeply dipping foliation around its margin, but the core of the sill has not been affected.

Basic Rocks. The core of the Armanda Sill consists of dark green or grey coarse-grained uralitized gabbro. Alternating layers (50-150 ft wide) of melagabbro and leucogabbro are paralleled by rhythmic banding (6 in. wide) of feldspar and mafic minerals. The layering and banding dip to the east at 25°. In places, the gabbro is cut by coarse-grained hornblende-rich pegmatitic-gabbro schlieren which do not have the same attitude as the primary layers.

The gabbros have a coarse-grained allotriomorphic granular fabric. Broad tabular laths of labradorite or bytownite are interlocked with ferromagnesian minerals. Primary anhedral olivine, hypersthene, or clinopyroxene crystals may be present. Olivine is rimmed by a symplektite of an opaque mineral, a light green amphibole, and spinel (Pl. 2, fig. 2). More rarely, the olivine has a corona of clinopyroxene or forms irregular fractured crystals in schillerized hypersthene. The amphibole is derived from pyroxene and olivine. It forms irregular ragged plates composed of tiny randomly oriented hornblende laths; but in polarized light it seems to be homogeneous. Its pleochroism ranges from colourless to olive green.

Dark green fine to medium-grained uralitized ophitic dolerite forms the outer margin of the gabbro. On the western and northern margins of the sill the dolerite is foliated. The unsheathed dolerite is vesicular and contains small amygdales filled with zeolite(?), calcite, and epidote. Rare schlieren and veins of gabbroic pegmatite are present in places.

The dolerites have an ophitic or fine-grained allotriomorphic granular texture. The plagioclase ranges from andesine to bytownite. Andesine is usually present in the more intensely altered rocks in which abundant epidote replaces the plagioclase. The interlocking plagioclase laths are fractured and altered to sericite, kaolin, clinozoisite or epidote, and calcite. Some of the relatively unaltered grains are zoned.

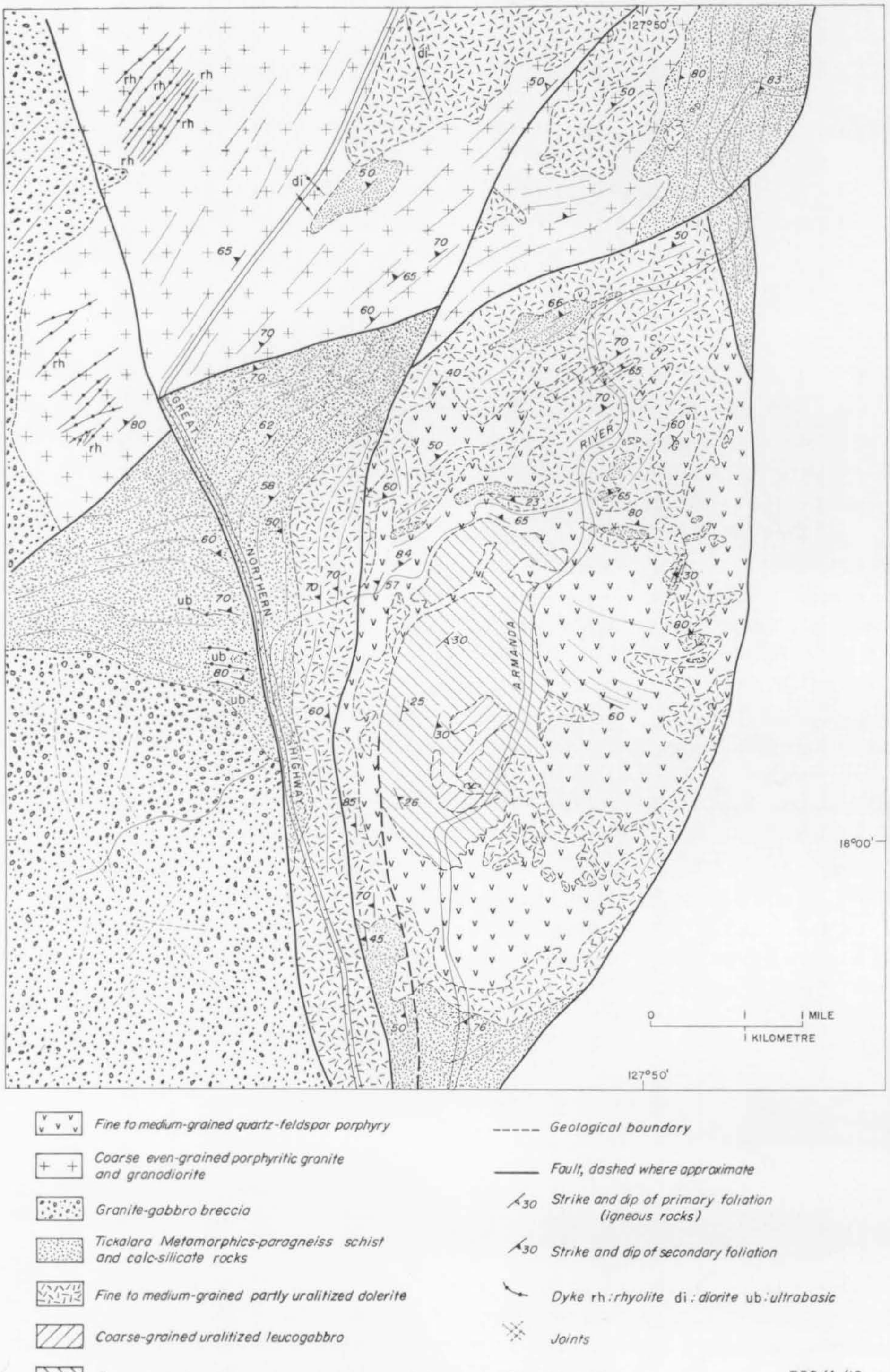


Figure 4
The Armanda Sill.

Most of the ferromagnesian minerals have been uralitized, but relict pyroxene crystals are preserved poikilitically in large hornblende phenocrysts. Some of the clinopyroxene is surrounded by coronas of hypersthene. No olivine was noted. Amphibole forms large irregular plates or aggregates of decussate laths. The pleochroism ranges from light yellow to dark green. Tiny dark brown biotite laths replace amphibole along the cleavage. In places, the ferromagnesian minerals have been replaced by chlorite, and amphibole is absent.

Granules of ilmenite with coronas of sphene are the main accessories. Small amounts of anhedral quartz are present in the more highly altered rocks. Veins of quartz and calcite cut all the minerals.

Discussion. The dolerite and gabbro probably represent parts of the same intrusion. On the eastern side of the sill where the dolerite forms the top of the gabbro, many deformed enclaves of skarn and quartzite derived from the Halls Creek Group are present. It is conceivable that the dolerite is the chilled margin of the gabbro, and as Poldervaart (1953) has suggested, the border facies of metagabbros can be recrystallized to homogeneous granoblastic aggregates which may or may not be finer in grain than the central metagabbros.

On the eastern and northern margins of the sill, sheared basic rocks with a relict ophitic or granular texture, pass imperceptibly into coarse-grained gabbros. The sheared rocks were derived from dolerite and gabbro during the deformation of the sill by movements along the marginal faults. The originally flat-lying compositional banding in the gabbros was tilted at the same time. Mobilized basic material derived from the basic rocks during deformation was intruded as basic pegmatite schlieren into the dolerite and gabbro.

Some of the basic rocks were uralitized during their emplacement, but most of the alteration was caused by hydrothermal solutions from the porphyry and granite intrusives. Subsequent shearing and deformation further contributed to the breakdown of the primary ferromagnesian minerals to secondary hornblende.

Porphyries. The basic rocks of the Armanda Sill are intruded by fine to medium-grained quartz-feldspar porphyry.

In plan, the porphyry forms an irregular but continuous ring around the gabbro and dolerite. The shape of the porphyry intrusion in section is unknown. An easterly dipping contact was observed on the western side of the structure. The porphyry intrusion is probably dish shaped; the base of the intrusion is probably almost conformable with the gabbro, but the sides are probably intrusive and discordant. Small apophyses and stocks intrude the basic rocks. The porphyry contains irregular xenoliths, up to half a mile across, of fine-grained dolerite on its eastern margin. In the north, isolated masses of porphyry intrude the medium-grained dolerite, and both are sheared. Many small porphyry dykes intrude the basic rocks along the margins of the sill.

The porphyries are generally composed of phenocrysts of feldspar and quartz set in a fine-grained siliceous base. The feldspar phenocrysts consist of large spongy crystals of microcline microperthite; a few irregular laths of albite are also present. The feldspars are faintly sericitized. Clots, lenticles, or wisps of ragged hornblende are generally present. They are probably altered basic xenoliths. The hornblende is pleochroic from light brown-green to dark blue-green. Dark brown biotite flakes replace amphibole along the cleavage. The groundmass consists of a crypto-crystalline mosaic of quartz, feldspar, and mica, with a little sphene, epidote, magnetite, and spongy garnet.

Contact Relationships. On the southern margin, the contact between the basic rock and the porphyries is knife-sharp. The basic rocks are chilled and the porphyries have been metamorphosed to quartz-feldspar-biotite-muscovite hornfels. Four hundred feet from the contact the porphyry contains irregular xenoliths of fine-grained basic rocks and tiny mafic clots, some of which have crenulated margins.

Small fine-grained porphyry dykes intrude the coarse-grained gabbro in the southern quadrant (Fig. 5a). The contact is sharp and the porphyry contains round xenoliths of gabbro and silica-rich schlieren oriented parallel to the contact. Many of the dykes contain no basic inclusions.

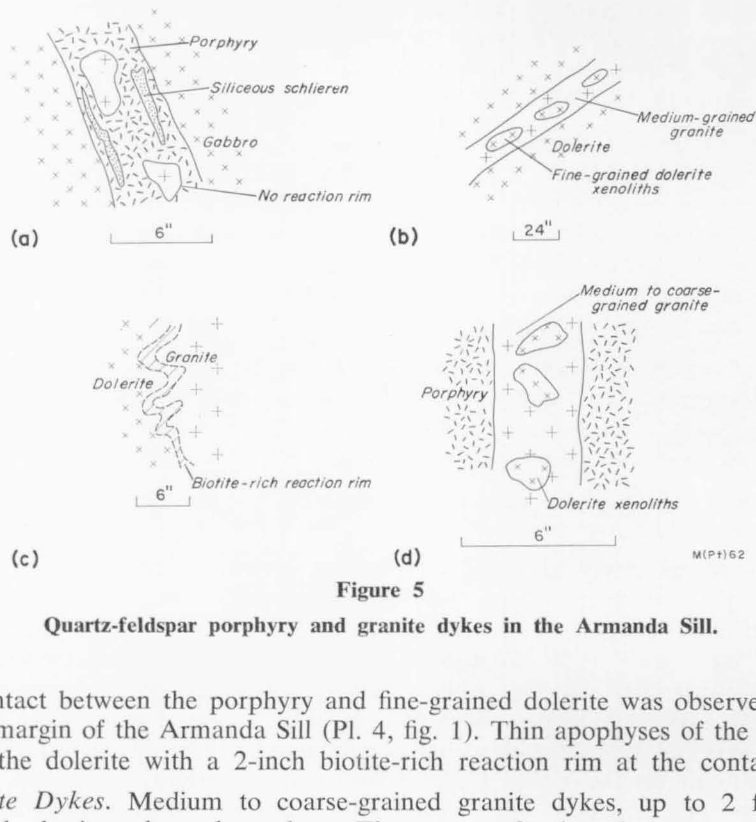


Figure 5

Quartz-feldspar porphyry and granite dykes in the Armanda Sill.

A contact between the porphyry and fine-grained dolerite was observed on the eastern margin of the Armanda Sill (Pl. 4, fig. 1). Thin apophyses of the porphyry intrude the dolerite with a 2-inch biotite-rich reaction rim at the contact.

Granite Dykes. Medium to coarse-grained granite dykes, up to 2 feet wide intrude the basic rocks and porphyry. They are confined to the eastern margin of the sill.

On the eastern margin of the main porphyry intrusion, a medium-grained granite dyke intrudes fine-grained dolerite (Fig. 5b). The contact is sharp and neither rock type is chilled at the margins; the granite contains round fine-grained basic xenoliths. In another dyke in this locality a biotite reaction rim has been formed at the contact (Fig. 5c).

On the northern margin of the main porphyry intrusion, a medium to coarse-grained granite dyke intrudes fine-grained porphyry. The contact is sharp and the dyke contains fine-grained dolerite xenoliths (Fig. 5d).

Discussion. Blake et al. (1965) have described the association of acid and basic magmas in intrusive and extrusive rocks in Iceland and Great Britain. Their observations are similar to the relationships in the Armanda Sill.

The basic and acid components of the Armanda Sill appear to have been emplaced almost contemporaneously. Since the gabbro and dolerite have been chilled against the porphyry it seems that the acid magma was emplaced when the basic magma was only partially crystallized (Blake et al., 1965, p. 34). The absence of chilled margins at the gabbro-porphyry contacts, and the alteration of the gabbro to a biotite-rich hybrid at the contacts 'can be explained by supposing that the acid component remained liquid longer than the basic' (Blake et al., 1965, p. 34).

The granite dykes intrude both the basic and acid components of the sill. They may represent the final phase of the porphyry intrusion (analogous to aplite dykes) or are directly associated with the Bow River Granite which intrudes the Armanda Sill in the northwestern quadrant.

Other Uralitized Basic Rocks

Uralitized gabbro and norite are predominant in the other basic bodies of the Lamboo Complex. The pyroxene and olivine of the gabbro, norite, or troctolite have commonly been altered to green hornblende or actinolite, but the plagioclase has generally not been altered. In some cases it appears that calcium enrichment of the feldspar has taken place during alteration. Other reactions noted include (i) the development of granular epidote in the plagioclase; (ii) the addition of sodic rims to the plagioclase; (iii) the development of acicular crystals of secondary amphibole in the feldspar; and (iv) the development of symplektites of amphibole and spinel around the olivine or plagioclase.

The alteration of the ferromagnesian minerals may have been caused by regional metamorphism or by hydrothermal solutions derived from the late intrusive granites. Both hypotheses would explain why the margins of the larger basic intrusives (e.g., the McIntosh Sill) have been uralitized while the centres remain relatively unaltered.

The texture of the uralitized rocks ranges from subophitic to allotriomorphic granular. Remnants of the original ferromagnesian minerals are present in many of the rocks. The clinopyroxene is surrounded by secondary amphibole, and the pyroxene commonly interfingers with the hornblende along prominent cleavage traces. In the norites, the subhedral olivine is surrounded by schillerized hypersthene, which in turn has been altered to ragged dark green hornblende.

In the more highly altered rocks, amphibole is the dominant ferromagnesian mineral. The amphibole commonly consists of a light green variety with a rim of a dark green type, and in some cases they are intergrown parallel to the cleavage. Shido (1958) has also observed similiar relationships in the Nakoso district in Japan, and has suggested that the dark green margins are hornblende and the pale green centres actinolite. She also states that actinolite disappears with the increase in the grade of metamorphism, and this has also been observed in the Lamboo

Complex. Both types of amphibole are replaced by dark brown biotite. The plagioclase laths are euhedral to subhedral; some are zoned and others have saussuritized cores. The plagioclase ranges from andesine to bytownite. Andesine is present where the plagioclase has been severely epidotized; the bytownite is cloudy and cracked but still euhedral and zoned. Some of the feldspars contain small inclusions of acicular amphibole similar in composition to the amphibole megacrysts. A little magnetite, pyrite, ilmenite, and chlorite are also present.

Sheared Basic Rocks

Many of the basic rocks have been converted to amphibolite by shearing and deformation. Foliated amphibolite occurs on the margins of the McIntosh Sheet and in shear zones in the smaller basic bodies. These amphibolites are darker and more massive than those derived from sedimentary or basic volcanic rocks. The amphibolites of uncertain origin have been included in the Tickalara Metamorphics.

The sheared basic rocks are generally composed of plagioclase, hornblende, and quartz. Remnants of zoning in the bytownite support the conclusion that these rocks were derived from basic igneous rocks. Laths of idioblastic hornblende oriented parallel to the slight foliation (which in many cases is represented only by cataclastic zones), and microcrysts of the amphibole are included in plagioclase. Up to 30 percent of anhedral strained quartz may be present. The rocks also contain magnetite, a little ilmenite, epidote, and calcite.

GENESIS OF THE BASIC AND ULTRABASIC INTRUSIVE ROCKS

The main features of the basic and ultrabasic rocks are as follows:

(i) Intrusion of thin dolerite and ultrabasic sills (Woodward Dolerite) into the Halls Creek Group. The sills are homogeneous and there is no evidence of magmatic differentiation.

(ii) Intrusion of thick differentiated gabbroic sills into the Halls Creek Group (McIntosh Gabbro and Alice Downs Ultrabasics), some of which have subordinate basal ultrabasic segregations.

(iii) The absence of contact aureoles in the country rocks.

(iv) All the intrusives occur in the Halls Creek Mobile Zone — a zone of intense deformation and orogenic activity.

These observations can be related by modifying a hypothesis put forward by Smith (1958) to explain the genesis of the Bay of Islands Igneous Complex in Western Newfoundland.

Differentiation was important in the initial development of the Alice Downs Ultrabasics and McIntosh Gabbro. They were probably differentiated at depth into a continuous sill-like body composed of an ultrabasic basal zone and an overlying gabbroic zone. During this state of partial crystallization the primary pluton was subjected to orogenic forces and dismembered by faulting and folding, and was then intruded higher into the crust. The more mobile and less viscous parts of the pluton were intruded as thin sills of dolerite and ultrabasic rocks (pyroxenite?) in the Halls Creek Group. The partly solidified and differentiated portion of the magma was intruded into the Halls Creek Group as large differentiated sills of varying compositions. The Panton and the McIntosh Sills have basal ultrabasic layers, but the Armanda Sill consists entirely of gabbro. Deformation of the partially solidified magma has only partly destroyed the original compositional layering. Many of the sills were wholly or partly uralitized by the regional metamorphism and shearing which accompanied their emplacement.

The lack of contact aureoles in the country rocks can be explained by the fact that the magma was partly solidified during intrusion. The magma did not have enough volatiles and was too cool to have any effect on the wall rocks. In places there is some hornfelsing of the country rocks, but the true relationships have generally been obscured by regional metamorphism and deformation.

TICKALARA METAMORPHICS

The distribution of the Tickalara Metamorphics is shown in Figure 2. The grade of metamorphism ranges from the greenschist facies in the south to the amphibolite and granulite facies in the north. The formation comprises schist, quartzite, paragneiss, granite gneiss, calc-silicate rocks, amphibolite, and pyroxene granulite. The boundaries between many of the rock types are gradational, but calc-silicate and amphibolite bands form useful markers.

The deformed roof pendants of calc-silicate rocks (skarns) and other metasediments within the granitic and basic rocks of the Lamboo Complex have been included in the Tickalara Metamorphics.

With the exception of the granite gneiss, the Tickalara Metamorphics can be regarded as the metamorphic equivalents of the Halls Creek Group, but it is uncertain whether the metamorphic rocks were derived entirely by regional metamorphism or whether contact metamorphism also played a part. Numerous syntectonic igneous intrusives are present in the metamorphics, and it is probable that they supplied much of the heat responsible for the deformation of the Halls Creek Group. Perhaps both contact and regional metamorphism were involved in the formation of the metamorphic rocks. The styles of folding and mineral relationships show that there has been more than one period of deformation and metamorphism.

The deformation, metamorphism, and igneous activity in the Halls Creek Mobile Zone was operative for at least 150 million years (V. M. Bofinger, pers. comm.). The high-grade metamorphic rocks were formed 1940 million years ago, and the Bow River Granite was emplaced during a period of regional deformation 1800 million years ago. The granite was one of the last phases of igneous activity in the Lamboo Complex.

ZONES OF PROGRESSIVE REGIONAL METAMORPHISM

The Halls Creek Group and Tickalara Metamorphics can be subdivided into three broad metamorphic zones on the basis of the mineralogical and textural changes in the pelitic, arenaceous, and basic igneous rocks.

The chloritic siltstone and subgreywacke of the Halls Creek Group grade into biotite schist and finally into sillimanite gneiss of the Tickalara Metamorphics. The appearance of biotite and sillimanite has been used to demarcate the zonal boundaries in the pelitic and arenaceous rocks. The biotite zone also contains garnet and staurolite, but the density of sampling is not sufficient to outline zones by the appearance of these minerals.

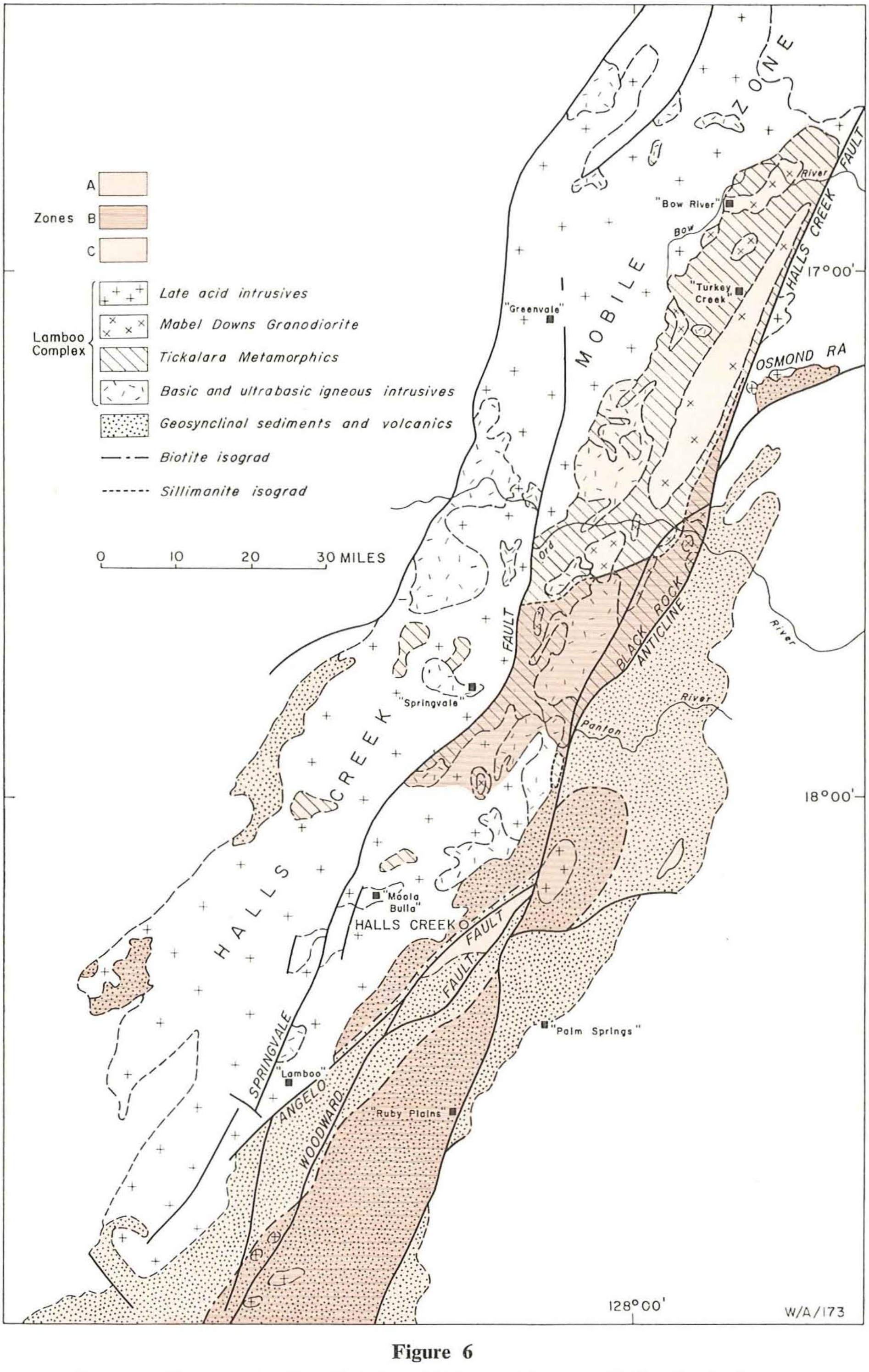


Figure 6
Metamorphic zones in the Tickalara Metamorphics and Halls Creek Group.

ROCK	MINERAL	ZONE A	ZONE B	ZONE C
PELITIC AND ARENACEOUS ROCKS	Quartz	Detrital	———	———
	Chlorite	———	— — — — — —	Retrograde
	Muscovite	———	———	Retrograde
	Biotite		———	———
	Garnet		———	———
	Chloritoid		— — — — — —	
	Staurolite		———	— —
	Kyanite			— — — — —
	Andalusite		— — — — — —	———
	Sillimanite			———
	Cordierite			———
	Plagioclase	Detrital — — —	Increase in An content	⟶
	Microcline		— — —	———
	Hornblende			— — — — —
CALCAREOUS ROCKS	Dolomite	———		
	Calcite	———	———	———
	Tremolite		———	
	Diopside-hedenbergite		— —	———
	Wollastonite			— — — — —
	Garnet		— — —	———
	Epidote		———	———
	Scapolite			— — — — —
	Plagioclase			Bytownite to anorthite
	Quartz	Detrital or diagenetic	———	———
	Chlorite	———		
	Hornblende			———
BASIC IGNEOUS ROCKS	Actinolite-tremolite	———		
	Hornblende		Blue-green to dark-green	Green-brown to brown
	Cummingtonite			— — — —
	Clinopyroxene			———
	Orthopyroxene			— — —
	Calcite	———	— — — — — —	
	Sphene	———	———	— —
	Epidote	———	— — — —	
	Plagioclase	Primary — — —	Increase in An content	⟶
	Chlorite	———	— — —	
	Biotite			— - Secondary — —
	Quartz	———	Decrease in quartz content	⟶ — — —

M(Pt)61

Note: Full line indicates that the mineral is common to abundant
Broken line indicates that it is rare to common
Arrangement after Miyashiro (1958)

Table 3

Mineralogical variations with increasing grade of metamorphism in the Halls Creek Group and Tickalara Metamorphics.

The basic igneous rocks of the Halls Creek Group change from slightly altered dolerite to amphibolite and basic granulite with increasing metamorphic intensity. The grade of metamorphism is indicated by the change in absorption colour in the Z direction of the calciferous amphiboles. This change is consistent with mineralogical changes in the associated arenaceous and pelitic rocks. Thus, the biotite-rich schists are associated with amphibolites containing green or blue-green hornblende, and the sillimanite-rich gneisses with amphibolites or basic granulites containing greenish brown or brown hornblende.

The metamorphic zones are shown in Figure 6, and the changes in mineral assemblages with increasing grade of metamorphism are shown in Table 3.

Zone A

Zone A comprises the Halls Creek Group, and is confined to the following areas (Fig. 6): (i) east of the Halls Creek Fault, in a belt extending from Palm Springs in the south to the Ord River in the north—the eastern margin of the zone is obscured by Proterozoic sediments; and (ii) west of the Halls Creek Fault, in a belt bounded by the Angelo and Woodward Faults.

The pelitic and arenaceous rocks in Zone A are slightly metamorphosed and include siltstone, shale, carbonaceous shale, subgreywacke, arkose, and subarkose. Although the rocks are tightly folded and cleaved, bedding and other sedimentary structures have been preserved. In the phyllitic siltstone and slate, mica and chlorite have been formed along the cleavage planes. The matrix of the arenaceous rocks has generally been reconstituted to sericite or muscovite and chlorite, but the larger detrital grains are unaltered except for slight marginal corrosion.

The calcareous rocks include limestone, dolomite, and brecciated dolomite, or their silicified equivalents. The carbonate mosaic consists of irregularly shaped grains with sutured boundaries; interstitial chlorite and sericite are common, and in some cases they form veins and clots. Rare lenses of chert and detrital quartz indicate the bedding in the siliceous varieties.

Two types of altered basic igneous rocks are present in Zone A:

(i) Altered basic volcanic rocks; they have a decussate texture and there is generally no relict primary fabric. They are composed of light green rosettes of actinolite or tremolite which interfinger with chlorite, quartz, and a little carbonate. Plagioclase is rare; it ranges from primary labradorite or andesine to secondary albite. The primary plagioclase is generally pseudomorphed by epidote and sphene.

(ii) Altered dolerite and gabbroic sills of the Woodward type, which have a relict allotriomorphic granular or ophitic texture. Light green decussate tremolite or actinolite, or in rare cases hornblende, which pseudomorph the primary ferromagnesian minerals, is randomly distributed among spongy albite, epidote, and quartz. The labradorite may be pseudomorphed by sericite, kaolin, and clinozoisite, or by epidote. More rarely, the secondary amphibole may be replaced by chlorite. Skeletal ilmenite and sphene are abundant.

Zone B

Zone B occurs in both the Halls Creek Group and Tickalara Metamorphics. Its distribution is as shown in Figure 6. The main areas are: (i) In a fault wedge between the Woodward and Halls Creek Faults; this area is intruded by late

PLATE 1

Fig. 1. Low rounded bouldery hills of igneous rocks in the Lamboo Complex, 24 miles north-northeast of Halls Creek.

Fig. 2. Chromite-rich (to right of hammer) and chromite-poor laminae in serpentine-rich Alice Downs Ultrabasics, 6 miles north of Lamboo homestead.

PLATE 2

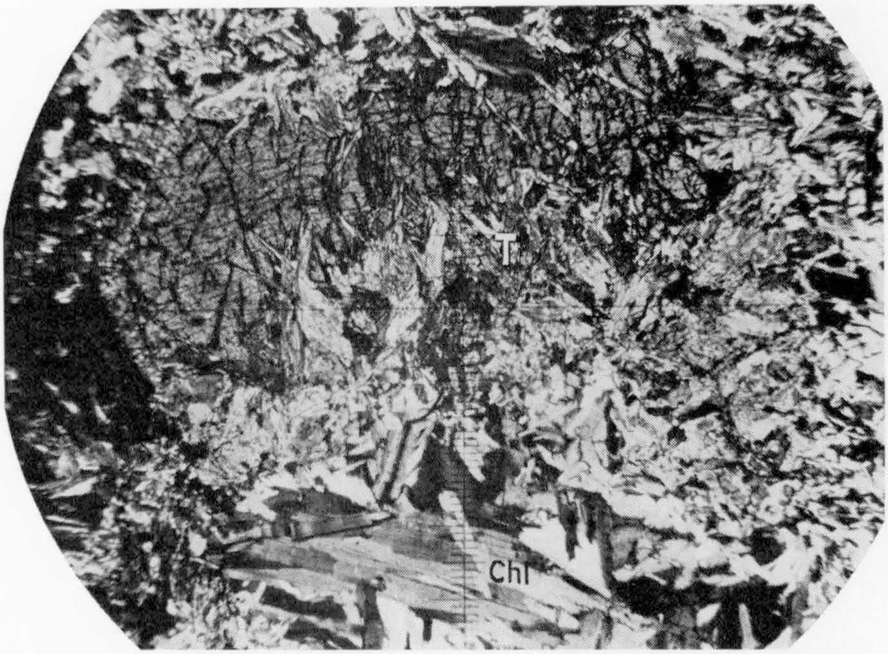


Fig. 1. Uralitized hypersthene peridotite, 8 miles south of Tickalara Bore, showing anhedral fractured olivine crystal embayed by decussate tremolite (T) laths, which in turn are surrounded by decussate colourless chlorite (Chl) laths.

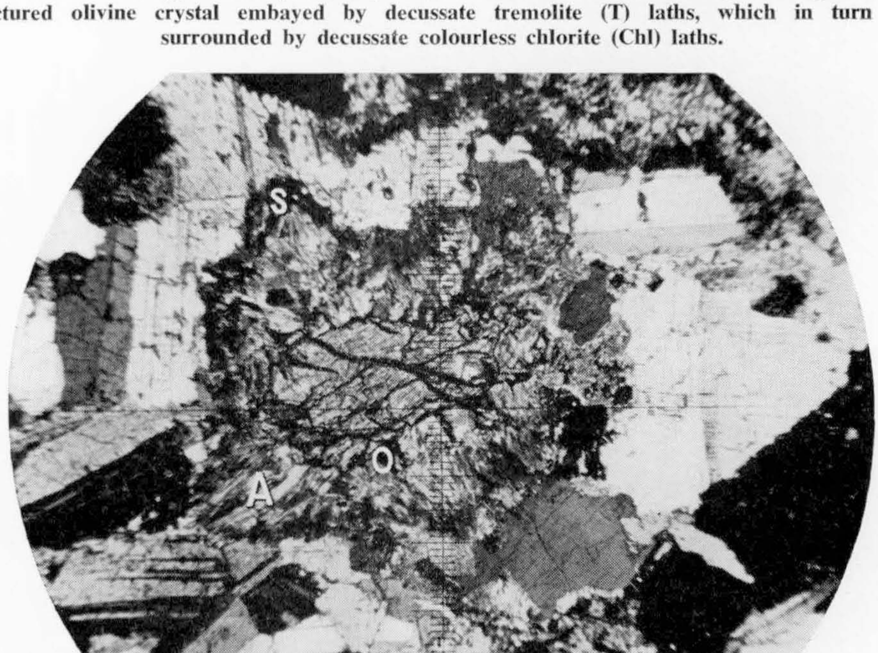
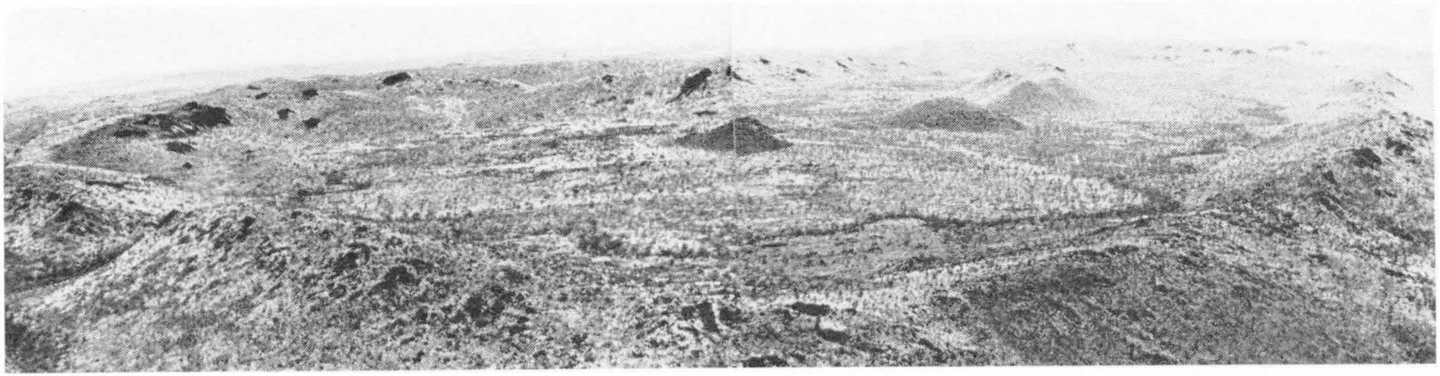


Fig. 2. Gabbro from the centre of the Armanda Sill, showing anhedral fractured olivine crystal surrounded by a symplektite of an opaque mineral (O), a light green amphibole (A), and spinel (S).

PLATE 3



Panorama showing the basinal shape of the McIntosh Sill.

PLATE 4

Fig. 1. Contact between quartz-feldspar porphyry and fine-grained dolerite on the eastern margin of the Armanda Sill. Note the biotite-rich reaction rim at the junction.

Fig. 2. Quartz-muscovite-chloritoid-chlorite schist, Tickalara Metamorphics, with large chloritoid crystals which post-date the crenulation cleavage outlined by muscovite laths.

PLATE 5

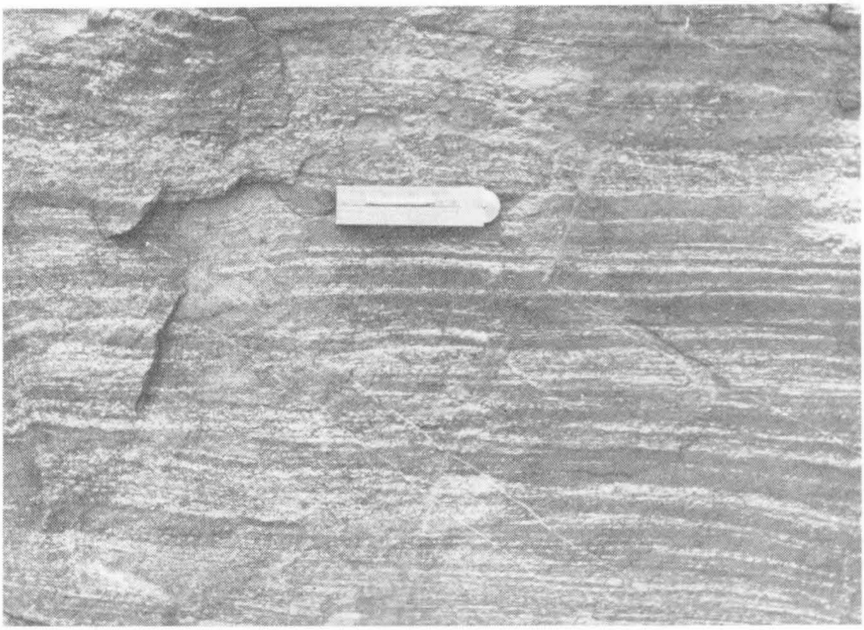


Fig. 1. Banded paragneiss, Tickalara Metamorphics, on the western margin of the Mabel Downs Granodiorite. The dark bands contain biotite and garnet; the white bands are composed mainly of feldspar with subordinate quartz.

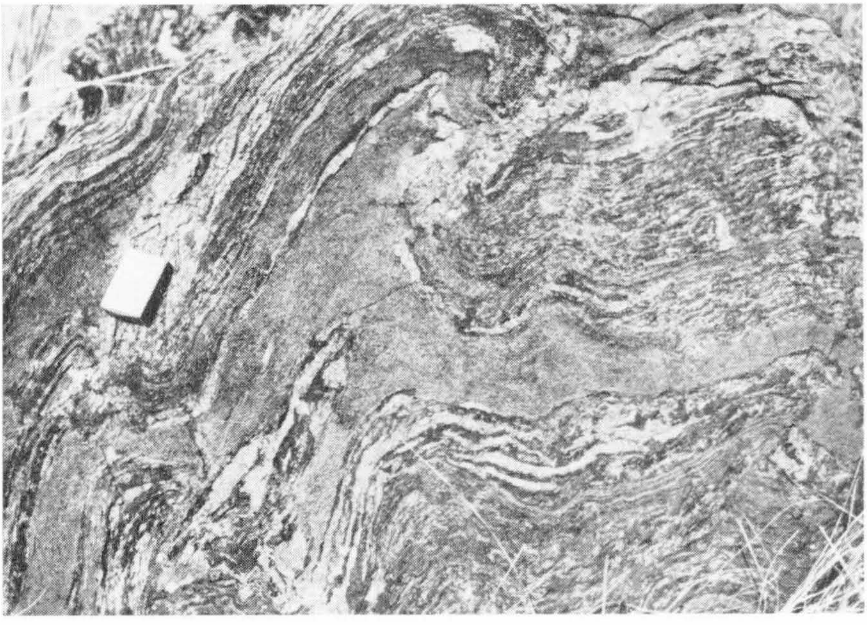


Fig. 2. Migmatite gneiss, Tickalara Metamorphics, 7 miles west of Mabel Downs homestead. The light-coloured bands are composed of quartz and feldspar, and the darker bands contain biotite, sillimanite, cordierite and muscovite.

PLATE 6

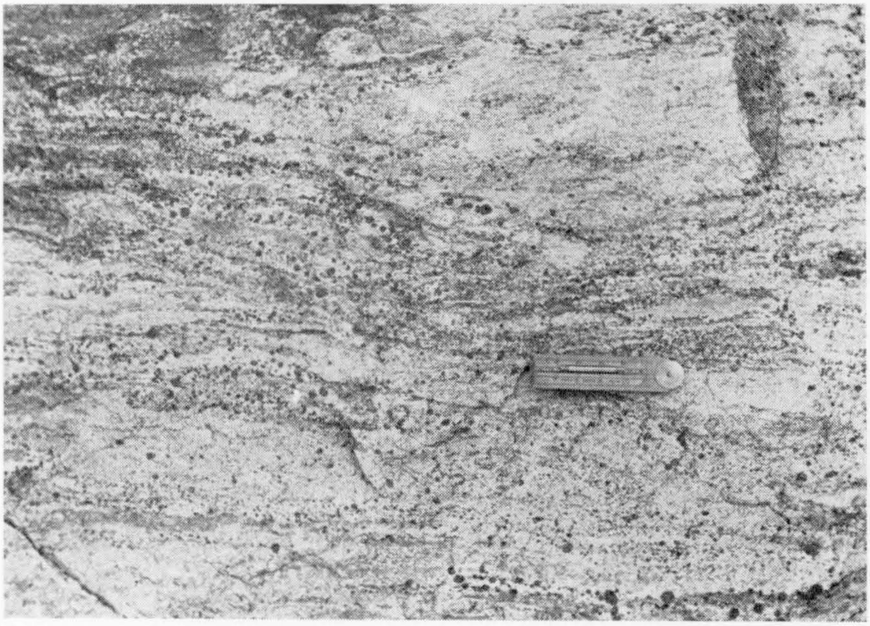


Fig. 1. Leucocratic garnetiferous gneiss, Tickalara Metamorphics, 2 miles west of Turkey Creek Post Office. The mafic portions are biotite-rich schlieren.

Fig. 2. Sillimanite gneiss, Tickalara Metamorphics. Large idioblastic crystals of sillimanite (S) with minor xenoblastic quartz, andesine, and biotite ensheathed by fibrolitic sillimanite (F).

PLATE 7

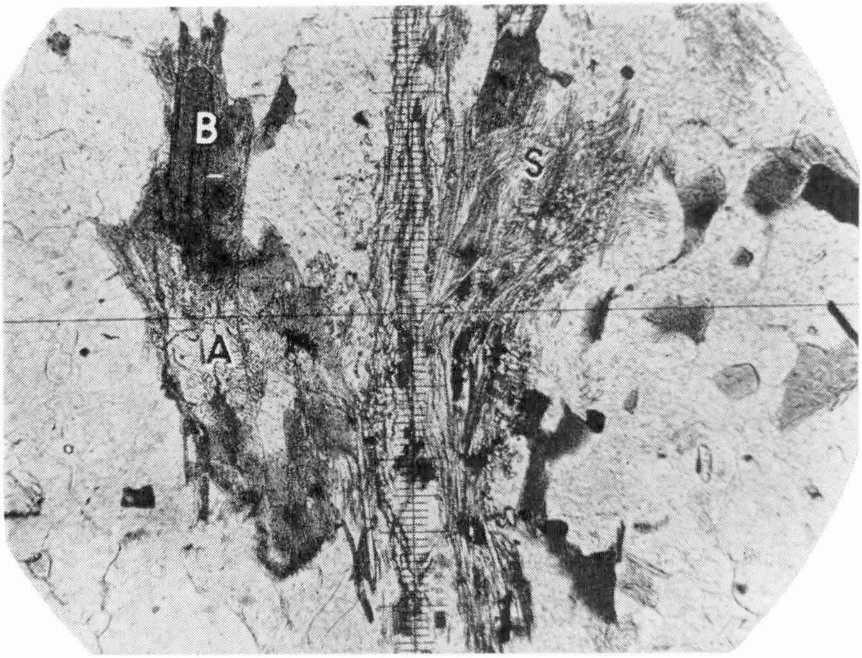


Fig. 1. Myrmekite-like symplektite of andalusite (A) and red-brown biotite (B), Tickalara Metamorphics. Later fibrolitic and acicular sillimanite (S) is intergrown with and possibly replaces the biotite.

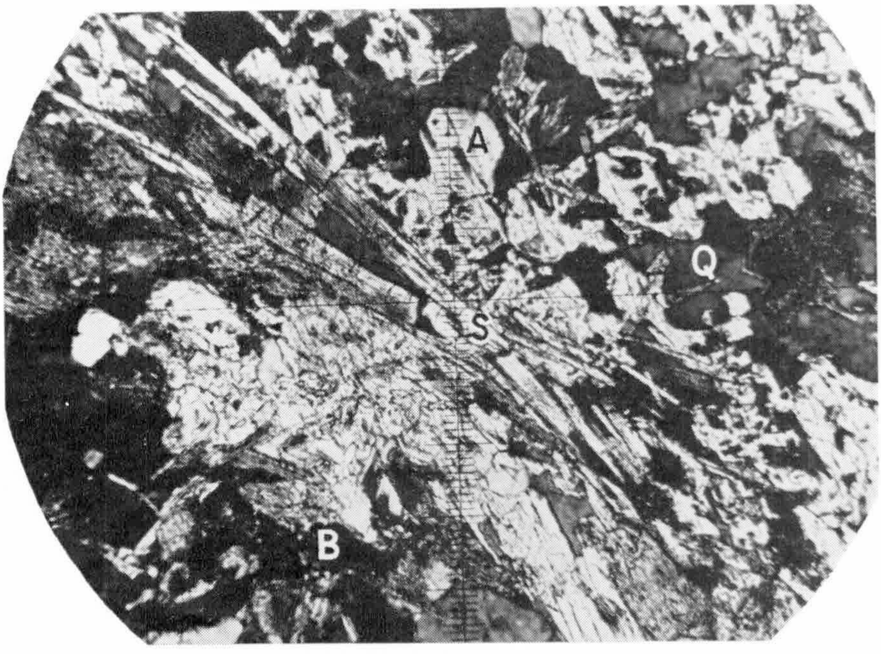


Fig. 2. Xenoblastic andalusite (A), intergrown with quartz (Q) and biotite (B), is replaced by acicular sillimanite (S), Tickalara Metamorphics.

PLATE 8

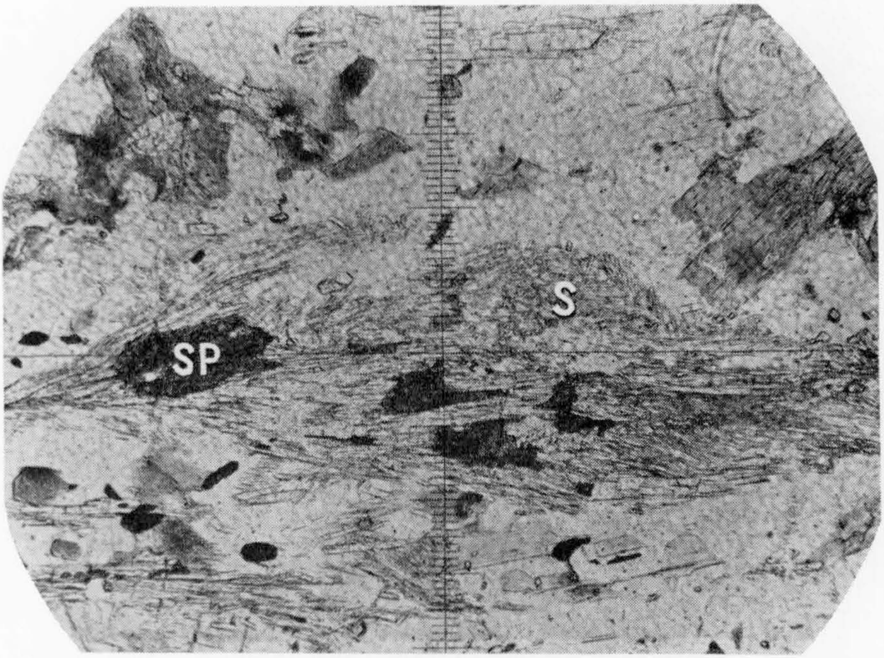


Fig. 1. Decussate acicular sillimanite (S) crystals intergrown with irregularly shaped grains of spinel (SP), Tickalara Metamorphics.

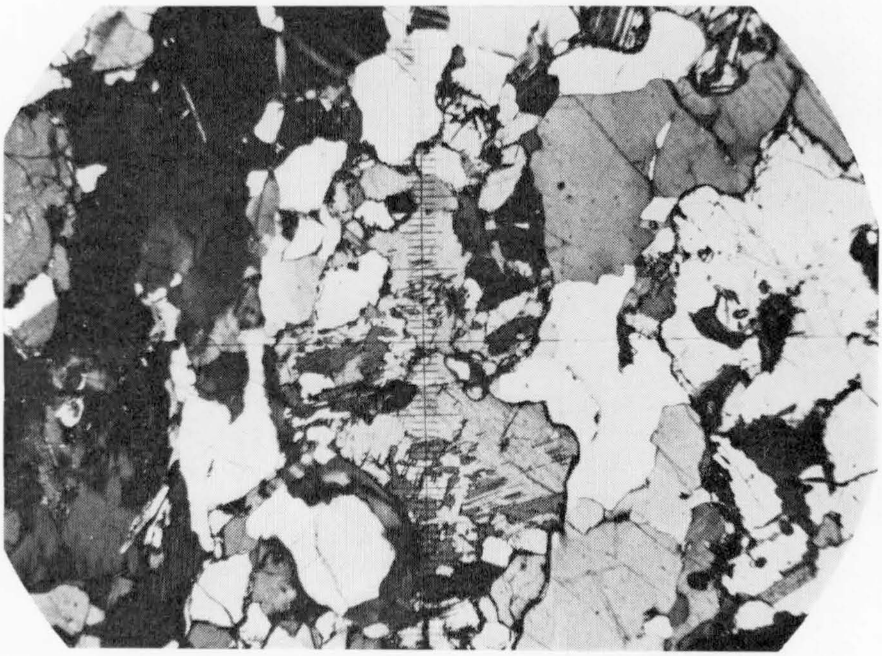


Fig. 2. Xenoblastic cordierite, with concentric twinning, enclosed in a granoblastic mosaic of quartz and plagioclase. Tickalara Metamorphics.

granites, and the contact metamorphic aureoles have obscured the regional metamorphism. (ii) In an area extending from Halls Creek in the south to the Osmond Range in the north; this area includes the Black Rock Anticline and the McIntosh and Panton Sills. (iii) In the Osmond Range inlier.

Entry into Zone B is indicated by the presence of red-brown or brown biotite in the metamorphic derivatives of the pelitic and arenaceous rocks. The sub-greywacke and siltstone of Zone A have been metamorphosed to quartz-biotite-muscovite schist. Quartz has lost its sedimentary form and forms a recrystallized mosaic. A metamorphic foliation has been developed parallel to the bedding, and this in turn is cut by a steep axial-plane cleavage.

Many of the schists in Zone B are garnetiferous, and the spongy garnet has been developed in conjunction with biotite. Some of the schists contain ovoid porphyroblasts of twinned albite, and epidote is marginal to or replaces the feldspars. In places incipient andalusite appears to replace the biotite and muscovite. The presence of large subidioblastic flakes of chlorite, which post-date the axial-plane cleavage, indicates local retrogression.

The small areas of chloritoid schist in Zone B have probably been derived from pelites which were rich in alumina and contained enough iron oxide to form chloritoid.

A little staurolite may be present close to the Zone C isograd. It is always associated with abundant biotite and garnet. The biotite is yellowy brown or green and it probably contains less iron than the red-brown variety in the quartz-biotite-muscovite schists; garnet and staurolite have taken up iron in preference to magnesia (Harker, 1939). The gneisses associated with the staurolite-bearing schists contain quartz, microcline, albite, biotite, and epidote.

The calcareous rocks of Zone B comprise marble and calc-silicate rocks. The marbles are calcite-rich and no dolomitic varieties were found. They consist of a calcite mosaic with less than 5 percent of poorly formed albite laths, granules of epidote and sphene, and laths of tremolite or actinolite. In the calc-silicate rocks, tremolite-rich bands alternate with bands of calcite and recrystallized quartz. Flaky muscovite is distributed randomly through these rocks.

The basic igneous rocks of Zone B comprise foliated amphibolites containing common hornblende. All vestiges of the primary texture have been destroyed and it cannot be established whether they were derived from the dolerites or the basic volcanic rocks found in Zone A. Two types of amphibolite can be distinguished:

(i) Poorly foliated quartz-rich amphibolites with a decussate or roughly nematoblastic texture; decussate sieve-like hornblende laths are randomly oriented, or form rosettes parallel with the foliation. The amphibole is pleochroic from blue-green to dark green. A few grains of albite are present.

(ii) Well foliated amphibolites with a nematoblastic texture. The amphibole is pleochroic from blue-green to dark green. The abundant granular plagioclase ranges from albite to labradorite. It contains needles of hornblende and granules of quartz.

Both types of amphibolite contain abundant sphene and epidote.

Zone C

Zone C contains the highest grade metamorphic rocks in the East Kimberley region. It is confined to two areas (Fig. 6):

(i) A belt to the west of the Halls Creek Fault which extends from the Ord River in the south to the Bow River in the north. Most of the anatectic Mabel Downs Granodiorite masses are surrounded by metamorphic rocks of Zone C.

(ii) A small region in the Halls Creek Fault Zone, just south of the Panton River.

In the metamorphic derivatives of the pelitic and arenaceous rocks, entry into Zone C is indicated by the presence of fibrolitic sillimanite which replaces biotite. The rocks mainly comprise banded gneiss and migmatitic gneiss, but knotted schist occurs in some areas. The banding is probably secondary and it is unlikely that any trace of the primary bedding has been preserved.

The gneiss has a texture ranging from fine-grained to coarse-grained saccharoidal. It contains varying proportions of biotite, andalusite, sillimanite, garnet, cordierite, oligoclase or andesine, and microcline. In Zone B andalusite was incipient, but in Zone C it is well developed; in many cases it is replaced by sillimanite. Cordierite is developed in gneiss derived from chloritic sediments; probably the shale and sub-greywacke of Zone A.

The knotted schist contains a little staurolite and abundant garnet surrounded by fibrolitic sillimanite swirls. Kyanite and sillimanite-rich schists are developed along the Halls Creek Fault.

The calcareous rocks of Zone C comprise marble and calc-silicate rocks. The marble is well foliated and contains mafic-rich bands composed of diopside, hornblende, and a little epidote. The most common calc-silicate rock is massive, and contains grossular garnet, green diopside, and epidote, with subordinate wollastonite and scapolite. Some of the calc-silicate rocks have a saccharoidal equigranular texture. They generally contain bytownite, anorthite, diopside, hornblende, garnet, scapolite, and subordinate epidote. The pleochroism of the amphibole ranges from green to green-brown; colourless varieties are also present.

The metamorphic derivatives of the basic igneous rocks in Zone C are foliated amphibolite and hornblende and pyroxene granulites. The zone is characterized by acicular or granular hornblende ranging from green-brown or brown, and the disappearance of the bluish green tinge marks the transition from Zone B. The hornblende granulite and pyroxene granulite contain clinopyroxene and orthopyroxene, and in some cases a little cummingtonite. The plagioclase ranges from labradorite to bytownite. No epidote is present in any of the rocks, but a few granules of sphene were noted in the amphibolites with greeny brown amphiboles. A little quartz is present in all the rock types.

SCHIST

Zone B contains a variety of schists formed by low-grade regional metamorphism. They are interbedded with calc-silicate rocks and amphibolite on the eastern flank of the Black Rock Anticline and along a narrow belt extending northwards from the Armanda River to Sally Malay Well along the Halls Creek Fault. The main types are quartz-muscovite schist and quartz-biotite schist; garnet, andalusite, chloritoid, and staurolite are present in places.

The crenulated schist of Zone C contains sillimanite and subordinate staurolite. It crops out in the core of the Black Rock Anticline and along a narrow band east of the Mabel Downs Granodiorite between the Ord River and Turkey Creek Post Office. Kyanite-bearing schist crops out in a small region in the Halls Creek Zone to the south of the Panton River.

It is thought that these schists were derived from pelitic and arenaceous rocks in the Olympio and Biscay Formations of the Halls Creek Group.

Micaceous, Garnetiferous, and Chloritoid Schist

On the eastern margin of the Black Rock Anticline and along the Halls Creek Fault, the schists contain the following mineral assemblages: quartz-biotite-muscovite, quartz-muscovite-biotite-albite, quartz-muscovite-garnet, quartz-muscovite-chlorite-garnet, and muscovite-chlorite-chloritoid.

The micaceous schists have a well developed preferred orientation, defined by fine elongate plates of muscovite and red-brown to brown biotite. Quartz has lost its sedimentary form and occurs in polygonal sutured grains. A few ovoid porphyroblasts of twinned albite may be present. In rare cases incipient andalusite appears to replace biotite and muscovite. A little sphene, tourmaline, and apatite may be present.

In the garnetiferous rocks, porphyroblastic garnets are set in a fine-grained brown groundmass of anhedral quartz surrounded by red-brown biotite or muscovite laths. The garnet post-dates, or was contemporaneous with, the formation of the crenulation cleavage. A little tourmaline, zircon, rutile, and opaque minerals may be present.

The chloritoid-rich rocks are dark green, lustrous, and crenulated. They are interlayered with garnetiferous schist and amphibolite. Small black discs (1.5 mm by 2 mm) of chloritoid are distributed randomly through the rock. The crenulation is defined by acicular muscovite and granular quartz. The chloritoid is idioblastic and intensely pleochroic from grass-green to pale amber-yellow; it is usually deformed by the crenulation cleavage, but in rare cases the chloritoid post-dates the cleavage (Pl. 4, fig. 2). In the muscovite-chlorite-chloritoid assemblage the chloritoid is accompanied by irregular flakes of an anomalous blue chlorite. Simpson (1951) has described similar chloritoid-rich rocks from Collier Bay in the West Kimberley region.

Staurolite and Sillimanite Schist

The staurolite and sillimanite schists are found in the core of the Black Rock Anticline and to the east of the Mabel Downs Granite. The rocks are brown and friable and have knots of porphyroblastic garnet or sillimanite wrapped by mica. They are interfoliated with calc-silicate rocks, amphibolite, and epidote-rich quartzite. The following assemblages have been recorded: garnet-quartz-biotite-chlorite-staurolite-sillimanite-andesine, garnet-quartz-staurolite-biotite-muscovite-chlorite, quartz-biotite-muscovite-garnet-staurolite-sillimanite, and quartz-biotite-muscovite-sillimanite-garnet.

The garnet is porphyroblastic and contains many inclusions. Some of the garnets show well developed 'snow-balling' and most are wrapped by muscovite and biotite or sillimanite and biotite. The garnet was probably formed at the same time as the crenulation cleavage. Irregular staurolite is enclosed in garnet or forms individual grains in the foliated mica-rich groundmass. In one specimen a garnet crystal grades along the foliation into staurolite surrounded by muscovite and subordinate chlorite. The sillimanite forms a fibrolite felt and is generally poorly formed. One specimen, however, contains knots of decussate fibrolite wrapped by biotite and muscovite. The fibrolite generally occurs as inclusions in quartz and garnet crystals. In these assemblages a yellowish brown or green biotite occurs in place of the red-brown biotite, which is present in the mica-rich schists. Andesine forms poorly twinned xenoblastic grains enclosed in granular quartz. Opaque minerals and tiny apatite needles may be present.

Kyanite Schist

The kyanite-rich rocks cropping out close to the Halls Creek Fault were probably formed by dynamothermal metamorphism. The large grey rods of kyanite are randomly set in a light grey fine-grained matrix. The kyanite schist is composed of kyanite, sillimanite, and corundum. The large porphyroblasts of kyanite post-date the rudimentary foliation outlined by the oriented sillimanite needles of fibrolite felt and small muscovite and chlorite laths. The corundum forms spongy porphyroblasts and twinned equant granules which may be completely enclosed in the kyanite. A secondary muscovite (paragonite?) replaces kyanite and forms decussate pseudomorphs.

EPIDOTE-RICH QUARTZITE

Lenticular pods and extensive layers of epidote-rich quartzite are interfoliated with the schist, amphibolite, and calc-silicate rocks. The quartzite was probably derived from silica-rich calcareous bands and nodules within the Biscay Formation.

The epidote-rich quartzite is dark green, granular, and generally foliated. The colour is due to the abundance of epidote and some bands are largely composed of this mineral. The quartzite containing numerous opaque minerals has a porous gossanous outcrop. The common assemblages in the quartzite of Zone B are: quartz-epidote-hornblende-lime-garnet-sphene, quartz-epidote-hornblende-lime garnet, epidote-quartz-chlorite-hornblende-sphene, and quartz-zoisite-tremolite-sphene.

All the rocks have a granular fabric and a slight foliation. Xenoblastic epidote or zoisite forms bands parallel to the foliation or occur as individual scattered crystals. Chlorite forms laths around the epidote and accentuates the preferred orientation. The amphibole is a dark green hornblende in the epidote-rich quartzite, or a colourless tremolite in the zoisite-rich rocks. The garnets are small and idioblastic, or large and spongy, and always occur in epidote aggregates. Irregular opaque minerals and spindle sphene may be present.

A higher-grade quartzite of Zone C was observed near Dougalls Bore. It contains quartz, hornblende, diopside, andesine, lime garnet, epidote, and biotite.

The epidote is subordinate and the rock is composed mainly of quartz and hornblende. Dark blue-green amphibole replaces spongy diopside, and forms aggregates in recrystallized and welded quartz. Coronas of epidotes surround the idioblastic andesine; the epidote is probably secondary. Xenoblastic secondary carbonate minerals commonly replace amphibole. A little biotite replaces the hornblende along cleavage traces, and garnet and opaque minerals are also present.

PARAGNEISS

Two types of gneissic rocks are present in the Tickalara Metamorphics; the paragneiss is thought to have been derived by regional metamorphism of sedimentary rocks and the granite gneiss by shearing of intrusive granodiorites and granites. The chemical analyses of the paragneiss indicate that it was derived from a sedimentary terrain.

The paragneiss occurs throughout a belt, 20 miles wide and a hundred miles long, from the Panton River in the south to the Bow River in the north. It is bounded on the east by the Halls Creek Fault, and on the west by late granites which intrude the gneiss. Between Moola Bulla and Springvale homesteads the paragneiss forms large roof pendants in granite.

The paragneiss ranges from quartz-feldspar-biotite gneiss in Zone B to garnetiferous, sillimanite-rich, and cordierite-rich gneisses in Zone C. The texture ranges from well foliated banded rocks in the lower grades to granulitic migmatites in the higher grades.

The paragneiss is thought to have been derived from pelitic and arenaceous rocks of the Halls Creek Group.

Nature of the Paragneiss

In the south, paragneiss is intertongued with amphibolite, and calc-silicate and ultrabasic rocks. The gneiss is composed of dark and light layers less than 5 cm. thick (Pl. 5, fig. 1). The dark bands are composed mainly of biotite and hornblende, or biotite, garnet, and sillimanite. The mafic bands are generally not continuous, but form schlieren parallel to the foliation. The light layers have a granitic composition and a medium to coarse-grained porphyroblastic texture. The structure of the gneiss can be traced by following the amphibolite or calc-silicate bands. In the core of the Black Rock Anticline 'stengel' gneiss is developed by the imposition of two cleavages. Elsewhere, there are constant steeply plunging lineations of aligned biotite flakes or acicular amphibole parallel to the schlieren.

Along the margins of the Mabel Downs Granodiorite, between the Ord River and Turkey Creek, there is a gradual transition from granodiorite to paragneiss. Thin stringers and small pods of basic granulite are interlayered with the migmatite.

The migmatitic paragneiss is rich in garnet, sillimanite, andalusite, and cordierite. The banding is not laminar or continuous, and most of the bands are contorted and swirled in a complex fashion (Pl. 5, fig. 2). The quartzo-feldspathic bands form continuous lenses and streaks and small rootless folds and boudins enclosed in mafic bands. The bands are composed of varying proportions of sillimanite, biotite, garnet, and cordierite. The ptygmatic and isoclinal folds in the migmatites are discontinuous along the strike. The prominent lineations include the alignment of acicular sillimanite and biotite flakes. In places, granitic permeation or the mobilization of the quartzo-feldspathic material is so extensive that the structural trends have been destroyed and large blocks of paragneiss are scattered through the Mabel Downs Granodiorite.

North of Moola Bulla homestead banded sillimanite and cordierite-rich paragneiss forms large roof pendants in the coarse-grained porphyritic Bow River Granite. They invariably have a prominent secondary foliation and compositional banding which ante-dates minerals such as garnet, sillimanite, and cordierite. Thus the formation of these minerals cannot be attributed to contact metamorphism.

Feldspathic Gneiss

Feldspathic gneiss is characteristic of Zone B, but small areas of feldspathic gneiss have also been observed in Zone C; the gneiss is devoid of garnet, sillimanite, and cordierite. It is a coarse to fine-grained rock which is characterized by a regular interlayering of mafic and quartzo-feldspathic minerals. In places the gneiss is interfoliated with granite gneiss and it is difficult to differentiate between the two types in the field. The following assemblages are found in the feldspathic gneiss: quartz-microcline-albite-biotite-epidote, and quartz-microcline-albite-biotite-muscovite.

All the gneisses have a well-developed preferred orientation. Quartzo-feldspathic minerals predominate over the ferromagnesian constituents. Microcline forms eye-shaped porphyroblasts ensheathed by comminuted quartz or biotite folia. Myrmekitic intergrowths are developed at the interface of microcline and plates of xenoblastic albite-oligoclase. The biotite ranges from deep red-brown to brown, and may enclose aggregates of epidote or laths of secondary muscovite. A little zircon, sphene, apatite, and iron oxide are present. The concentrations of epidote and sphene may represent original calcium-rich pods or bands sheared in the foliation.

Garnetiferous Gneiss

Foliated and banded medium to coarse-grained garnetiferous gneiss without sillimanite is distributed sporadically throughout the paragneiss. A little garnetiferous gneiss is present in Zone B, but most of it occurs in Zone C. Extensive areas of garnetiferous gneiss crop out along the western margin of the largest body of Mabel Downs Granodiorite and along the northern margin of a smaller body to the south of the Ord River. The gneiss contains large porphyroblasts of garnet distributed evenly through mafic and leucocratic bands (Pl. 6, fig. 1). In places the foliation is marked by biotite-rich schlieren devoid of garnet.

The following assemblages were noted: andesine-quartz-biotite-garnet-muscovite, quartz-oligoclase-biotite-garnet-muscovite-chlorite, oligoclase-microcline-quartz-biotite-garnet, quartz-microcline-albite-biotite-garnet, and quartz-microcline-andesine-hornblende-biotite-clinopyroxene-garnet.

Quartz forms coarse, xenoblastic, granulated and fractured grains with marked undulose extinction. The plagioclase (albite to andesine) is cloudy and xenoblastic, but is well twinned. In places, the idioblastic plagioclase laths have been exsolved from microcline. Saussuritization is common, and the plagioclase may be completely pseudomorphed by epidote. The potassium feldspar forms porphyroblasts wrapped by biotite laths or xenoblastic grains with vein perthite exsolution lamellae. Myrmekite has been developed at the junction of plagioclase and microcline crystals. Yellow to red-brown lepidoblastic biotite also ensheaths the spongy or fractured garnet porphyroblasts. The garnet usually has inclusions of all the other minerals, and it has probably replaced the biotite. Muscovite and chlorite replace biotite and garnet.

In one of the rocks the dominant mafic constituent is xenoblastic to idioblastic hornblende which is pleochroic from yellow-green to brown-green. The amphibole encloses subordinate xenoblastic clinopyroxene grains and is replaced by red-brown biotite flakes. These minerals define the foliation and ensheath the porphyroblasts of plagioclase and spongy garnet.

The accessories include granular and lenticular opaque minerals, zircon, and apatite.

The biotite-rich schlieren in the garnetiferous gneiss are foliated, fine-grained, and homogeneous. They are composed of quartz, biotite, and oligoclase. The idioblastic quartz mosaic encloses poorly twinned xenoblastic oligoclase. Brown to red-brown biotite forms stubby laths or lepidoblastic aggregates. Irregular opaque grains have been exsolved along the biotite cleavage.

Garnet-Andalusite-Sillimanite-Cordierite Gneiss

Migmatitic gneiss is characteristic of Zone C and assemblages containing garnet, andalusite, sillimanite, and cordierite are concentrated in the Violet Valley region and north of Mabel Downs as far as the Bow River. The sillimanite-rich gneiss is generally devoid of garnet, but fine-grained garnet is present in places. A 2-mile wide belt of garnetiferous gneiss with subordinate sillimanite and cordierite extends from Tickalara Bore to Turkey Creek. The Mabel Downs Granodiorite masses north of the Ord River are surrounded by cordierite-rich rocks with only a little sillimanite and garnet.

North of Moola Bulla homestead banded and foliated andalusite, sillimanite, and cordierite-rich paragneiss forms large roof pendants in the coarse-grained porphyritic Bow River Granite.

The gneisses are composed of biotite, feldspar, garnet, andalusite, sillimanite, and cordierite in varying combinations and proportions. The assemblages noted include: quartz-garnet-biotite-oligoclase-cordierite-sillimanite, quartz-andesine-microcline-biotite-andalusite-cordierite-sillimanite, quartz-microcline-andalusite-cordierite-muscovite-chlorite, quartz-andesine-microcline-biotite-andalusite-cordierite-chlorite-muscovite, quartz-microcline-biotite-sillimanite-cordierite, quartz-microcline-biotite-sillimanite-cordierite-spinel, quartz-microcline-andesine-biotite-sillimanite-cordierite, quartz-cordierite-andesine-biotite, microcline-andesine-cordierite-biotite-andalusite-sillimanite-quartz, quartz-microcline-cordierite-biotite-andalusite-sillimanite-muscovite, quartz-microcline-andesine-cordierite-garnet-biotite-sillimanite, quartz-microcline-cordierite-andesine-biotite-andalusite-spinel, and microcline-quartz-cordierite-biotite-sillimanite.

The gneisses have a saccharoidal texture and range from fine-grained to coarse-grained. They have a banded or clotted appearance. Dark bands and clots of biotite, garnet, and aluminosilicates alternate with leucocratic quartzo-feldspathic material. Cordierite forms irregular black vitreous bands and swirls. The mafic bands probably represent altered pelitic sediments and the leucocratic bands possibly represent granitic lit-par-lit injections.

The ferromagnesian and aluminosilicate minerals were probably formed at the same time, but there is probably more than one generation of biotite and sillimanite. Since microcline and plagioclase include most of the other minerals it is possible that they were the last to develop. The secondary muscovite and chlorite replacing biotite and cordierite is attributed to slight retrogressive metamorphism.

Lepidoblastic biotite defines a rough foliation and individual laths have ragged outlines with opaque minerals exsolved along the cleavage and extremities of the laths. The pleochroism ranges from light yellow to dark brown or from yellow to red-brown. Plates of secondary muscovite or chlorite replace the biotite along the cleavage.

The andalusite is pleochroic from pink to colourless. It ranges from spongy to idioblastic in form and is generally surrounded by biotite laths. The fibrolitic sillimanite forms knots or is disseminated throughout the rock fabric, but the fans and swirls of fibrolite may be confined to individual cordierite crystals. The large sillimanite rods were probably developed out of fibrolite. In places, the porphyroblastic sillimanite crystals are ensheathed by a fibrolite felt (Pl. 6, fig. 2), and it is possible that two generations of sillimanite are present.

Many of the gneisses contain both andalusite and sillimanite, and it is believed that the sillimanite was formed after the andalusite, and that both are the product of the breakdown of biotite. The following mineralogical relationships have been noted:

(i) Spongy andalusite grains are surrounded by, or occur, in a symplektite of red-brown biotite, dark green spinel, and quartz (Pl. 7, fig. 1). In some symplektites the red-brown biotite has been altered to a green variety.

(ii) Where sillimanite and andalusite occur together, the andalusite is xenoblastic and appears to have been replaced by the former (Pl. 7, fig. 2). Acicular sillimanite post-dates the andalusite-biotite symplektites and thin fibres of sillimanite associated with the biotite and spinel pass laterally into andalusite.

(iii) Symplektites of sillimanite, biotite, and spinel are common. In places, biotite is absent, and the fibrolite contains irregular grains of spinel associated with magnetite(?) (Pl. 8, fig. 1).

(iv) Euhedral crystals or long thin fibres of sillimanite are enclosed in biotite.

Quartz forms a granoblastic mosaic of clear strained grains, or is interstitial to feldspar in the quartzo-feldspathic bands. Small sillimanite sprays are frequently enclosed in individual quartz crystals.

Cordierite forms large oval and fractured xenoblastic grains with pinitic or micaceous margins. The cordierite may be completely pseudomorphed by chlorite and muscovite. The proportion of cordierite ranges up to 50 percent. The cordierite displays both star-shaped concentric (Pl. 8, fig. 2) and sector twinning which probably indicate a high-temperature paragenesis (Venkatesh, 1952). Some cordierite grains include helical swirls of sillimanite.

The spongy porphyroblasts of pink garnet are usually enclosed by lepidoblastic biotite folia. They enclose andesine, cordierite, quartz, and opaque minerals.

Microcline forms granoblastic aggregates in the quartzo-feldspathic bands or is randomly distributed as sieve-like xenoblastic crystals. The poikiloblastic crystals include round quartz with sillimanite swirls, biotite laths, and oval cordierite grains. Vein perthite is common and small exsolved plagioclase may be present in the microcline. Where microcline abuts against cordierite or garnet, the feldspar has been replaced by tiny muscovite laths.

The main plagioclase is andesine which forms porphyroblastic augen, wrapped by sillimanite and biotite, or individual xenoblastic grains between the microclines. Twinning is common and incipient zoning has been observed. The porphyroblasts contain poikiloblastic inclusions of quartz, cordierite, and microcline.

Myrmekite is present along the boundaries between microcline, quartz, plagioclase, garnet, and cordierite. The distribution of the myrmekite is sporadic and it is absent in many of the gneisses.

The biotite has been replaced by large laths of muscovite and chlorite, and the cordierite and microcline may be replaced by fine mica along their margins. These alterations are probably due to pneumatolytic solutions.

The accessories in the gneisses include rounded zircon, tourmaline, opaque minerals, brown spinel, rutile, and apatite.

Graphitic Gneiss

Some of the gneiss north of Mabel Downs contains abundant graphite, and has probably been derived from carbonaceous shales in the Halls Creek Group. The lenticular and shredded graphite is oriented parallel to the foliation and wraps around unidentified opaque blebs (chalcedony?), which are the main constituent of the rock. Randomly oriented, decussate, and lath-like muscovite is associated with grains of garnet and quartz. A little rutile is present.

GRANITE GNEISS

Granite gneiss crops out along the western margin of the Tickalara Metamorphics and extends from Moola Bulla in the south to Tickalara Bore in the north. The gneiss was probably derived by shearing of the Mabel Downs Granodiorite and Bow River Granite during the waning stages of metamorphism. The granite gneiss is generally interlayered lit-par-lit with paragneiss, and the two rock types are difficult to differentiate in the field if characteristic metamorphic minerals such as garnet or sillimanite are not visible. The distribution of the granite gneiss is shown in Figure 2.

The gneiss is medium to coarse-grained, foliated, and banded. Undulating narrow biotite-rich bands generally alternate with quartzo-feldspathic bands, but biotite and hornblende-rich schlieren are also abundant. The coarser varieties have a porphyroblastic texture, and augen of quartz or feldspar are wrapped by biotite folia; in the south many of the gneisses contain foliated angular basic xenoliths.

The granite gneisses have a well foliated lepidoblastic or porphyroblastic texture. The fabric is granulated and comminuted along planes roughly parallel with the foliation.

Porphyroblasts of quartz and feldspar, or a comminuted mosaic of strained quartz and feldspar, have been formed in the interstices between the ragged lepidoblastic biotite laths.

The abundance of plagioclase and potassium feldspar reflects the composition of the granite or granodiorite from which they were derived. The plagioclase ranges from albite to andesine. Many of the feldspars still retain traces of their euhedral outline and zoned laths are common. The large porphyroblasts of microcline perthite contain irregular inclusions of quartz and plagioclase. The margins of the potassium feldspar are comminuted and consist of an irregular mosaic of quartz, feldspar, biotite, and convex myrmekite tumours.

A few grains of xenoblastic schillerized light yellow to dark green hornblende are present in the gneisses derived from granodiorite. The amphibole has been replaced and surrounded by decussate biotite laths or enclosed by coronas of epidote. The granitic gneiss contains biotite with granular epidote inclusions and is replaced along the cleavage by secondary chlorite.

The minor minerals include granular iron oxides exsolved from biotite, and euhedral zircon and apatite.

COMPOSITION OF THE SCHISTS AND GNEISSES

Two schists and 8 paragneisses have been analysed to determine if they were comparable with average composition of shale and greywacke. (See Table 4).

Table 4

Chemical analyses of the schists and gneisses.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	36.60	48.30	51.40	53.10	46.50	69.60	66.30	66.50	60.61	75.49	58.10	64.70
Al_2O_3	27.40	18.20	18.20	18.10	31.30	17.50	17.00	17.70	20.14	12.43	15.40	14.80
Fe_2O_3	6.15	7.45	2.30	7.10	2.25	1.09	1.74	0.83	1.53	0.61	4.02	1.50
FeO	8.80	13.90	7.45	9.40	9.70	4.05	5.40	4.55	5.34	2.86	2.45	3.90
MgO	4.95	4.65	2.11	3.33	3.00	1.88	1.92	1.73	2.46	0.96	2.44	2.20
CaO	1.34	1.65	12.10	0.55	0.67	0.26	3.00	0.95	2.05	0.68	3.11	3.10
Na_2O	0.90	1.13	0.74	0.30	0.89	0.11	2.24	1.35	2.08	1.01	1.30	3.10
K_2O	3.90	2.35	2.47	3.66	2.35	2.94	0.55	4.46	3.83	3.88	3.24	1.90
H_2O+	6.17	0.82	0.53	2.95	1.70	1.26	0.52	0.93	0.73	1.00	5.00	2.40
H_2O-	0.24	0.18	0.05	0.32	0.28	0.13	0.11	0.19	0.12	0.18	—	0.70
CO_2	0.55	0.11	1.68	0.02	0.07	0.03	0.03	0.04	—	—	2.63	1.30
TiO_2	2.53	1.49	0.95	1.37	1.02	0.54	1.00	0.56	1.19	0.47	0.65	0.50
P_2O_5	0.15	0.05	0.08	0.12	0.12	0.13	0.05	0.09	0.02	0.08	0.17	0.20
MnO	0.18	0.08	0.24	0.09	0.05	0.04	0.05	0.04	0.04	0.03	—	0.10
FeS_2	—	—	—	—	—	—	—	—	—	0.04	—	—
LiO_2	—	—	—	—	—	—	—	—	—	0.18	—	—
SO_3	—	—	—	—	—	—	—	—	—	—	0.64	0.40
S	—	—	—	—	—	—	—	—	—	—	—	0.20
Total	99.86	100.36	100.30	100.41	99.90	99.56	99.91	99.92	100.14	99.90	99.15	101.00
					*Molecular Proportions**							
SiO_2	36.84	47.21	49.07	53.28	44.68	68.19	63.66	63.75	57.36	73.64	58.57	62.22
Al_2O_3	32.52	20.97	20.48	21.41	33.45	20.21	19.24	20.00	22.47	14.29	18.30	16.78
Fe_2O_3	4.66	5.48	1.65	5.36	1.63	0.80	1.26	0.60	1.09	0.45	3.05	1.09
FeO	7.41	11.36	5.95	7.89	7.79	3.32	4.34	3.65	4.23	2.33	2.07	3.14
MgO	7.43	6.78	3.00	4.98	4.30	2.75	2.75	2.47	3.47	1.40	3.67	3.16
CaO	1.45	1.73	12.38	0.59	0.69	0.27	3.09	0.98	2.08	0.71	3.36	3.20
Na_2O	1.76	2.14	1.37	0.58	1.66	0.21	4.17	2.51	3.82	1.91	2.54	5.78
K_2O	5.01	2.93	3.01	4.69	2.88	3.67	0.67	5.45	4.62	4.83	4.17	2.33
CO_2	0.76	0.15	2.19	0.03	0.09	0.04	0.04	0.05	—	—	3.62	1.71
TiO_2	1.92	1.10	0.68	1.03	0.74	0.40	0.72	0.40	0.85	0.34	0.49	0.36
P_2O_5	1.13	0.04	0.06	0.10	0.10	0.11	0.04	0.07	0.02	0.07	0.15	0.16
MnO	1.15	0.07	0.19	0.08	0.04	0.03	0.04	0.03	0.03	0.02	—	0.08
Total	100.04	99.96	100.03	100.02	100.05	100.00	100.02	99.96	100.04	99.99	99.99	100.00

*Calculated on water-free basis.

1. Quartz-muscovite (paragonite?)-chlorite-chloritoid schist (DR10.25.10. 17°36′30″S; 128°04′40″E). Analysts, L. W. Castanelli and M. R. Hanckel (AMDL).
2. Quartz-biotite-muscovite (paragonite?)-garnet-staurolite-sillimanite schist. (DR6.29.43. 17°21′25″S; 128°09′40″E). Analysts, L. W. Castanelli and M. R. Hanckel.
3. Calcareous gneiss: bands rich in labradorite (bytownite?), quartz, biotite, and garnet alternate with bands rich in bytownite, clinopyroxene, hornblende, and quartz. (DR7.49.39. 17°25′35″S; 128°05′40″E). Analysts, M. R. Hanckel and R. L. Bruce (AMDL).
4. Quartz-andesine-microcline-hornblende-clinopyroxene-garnet-biotite gneiss. (DR7.49.32. 17°27′S; 128°95′50″E). Analysts, L. W. Castanelli and M. R. Hanckel.

5. Microcline-andesine-cordierite-biotite-andalusite-sillimanite-quartz gneiss. (DR2A.11.10. 17°09'15"S; 128°04'50"E). Analysts, M. R. Hanckel and R. L. Bruce.
6. Quartz-biotite-muscovite-sillimanite-garnet gneiss. (DR8. 97.9. 17°30'50"S; 128°05'15"E). Analysts, L. W. Castanelli and M. R. Hanckel.
7. Quartz-cordierite-andesine-biotite gneiss. (DR3.73.6. 17°12'S; 128°07'10"E). Analysts, M. R. Hanckel and R. L. Bruce.
8. Quartz-microcline-cordierite-biotite-andalusite-sillimanite-(muscovite) gneiss. (L13.72.6. 16°52'S; 128°15'E). Analysts, M. R. Hanckel and R. L. Bruce.
9. Quartz-microcline-andesine-cordierite-garnet-biotite-sillimanite gneiss. (DR8.04.9. 17°24' 25"S; 127°52'E). Analyst, R. W. Lindsay (W.A. Chem. Labs).
10. Quartz-microcline-cordierite-andesine-biotite-andalusite-spinel gneiss. (DR15.64.5. 17°55' 30"S; 127°34'10"E). Analyst, J. Gamble (W.A. Chem. Labs).
11. Average of 78 shales (Clarke, 1924, p. 34).
12. Average of 23 greywackes (Pettijohn, 1957, p. 307).

The following general observations can be made:

The schists and gneisses are similar in composition to the average shale and greywacke. The A.C.F. diagram (Fig. 7a) indicates that some of the rocks are derived from pelites and others from more arenaceous rocks tending towards an average greywacke. It is unlikely that the gneisses were derived from granitic rocks.

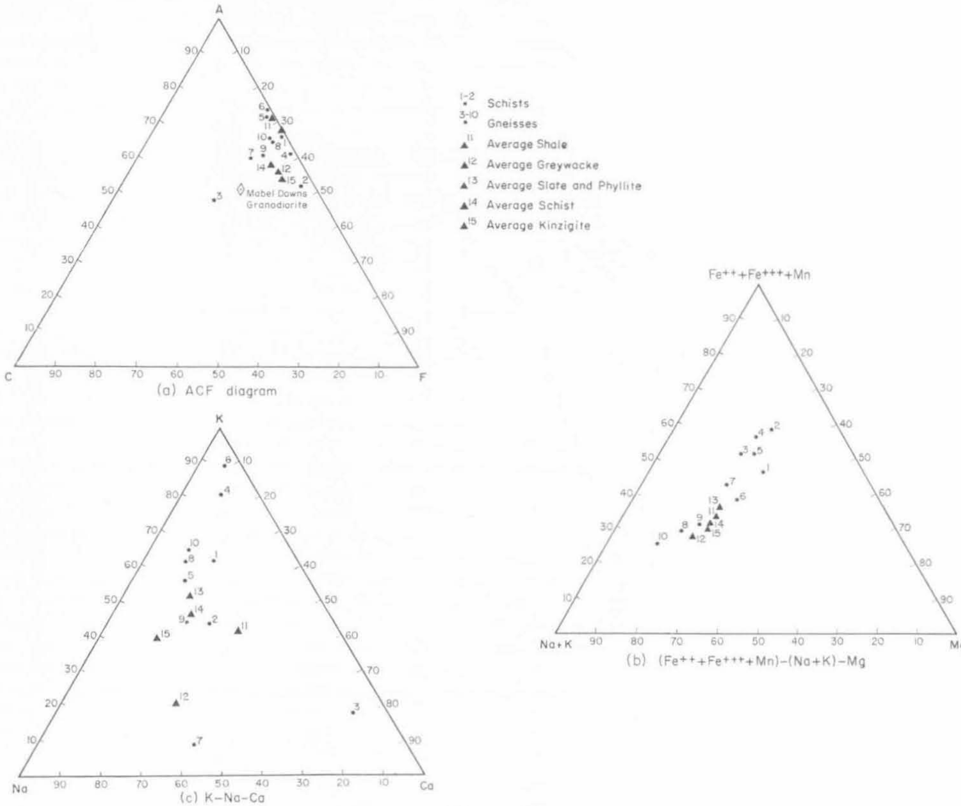


Figure 7

Variation diagrams for the schists and gneisses.

The rocks have a fairly constant magnesium content, but their total alkali and total iron content varies (Fig. 7b). The cordierite-rich gneisses have more total alkali present than the schists. This difference may be related to the original composition of the rocks, but it is also possible that sodium and potassium have been introduced into the cordierite gneisses from the Mabel Downs Granodiorite. The relative amounts of sòdium and potassium (Fig. 7c) is reflected in the mineralogy of the schists and gneisses. For instance, in the sodium-rich gneisses

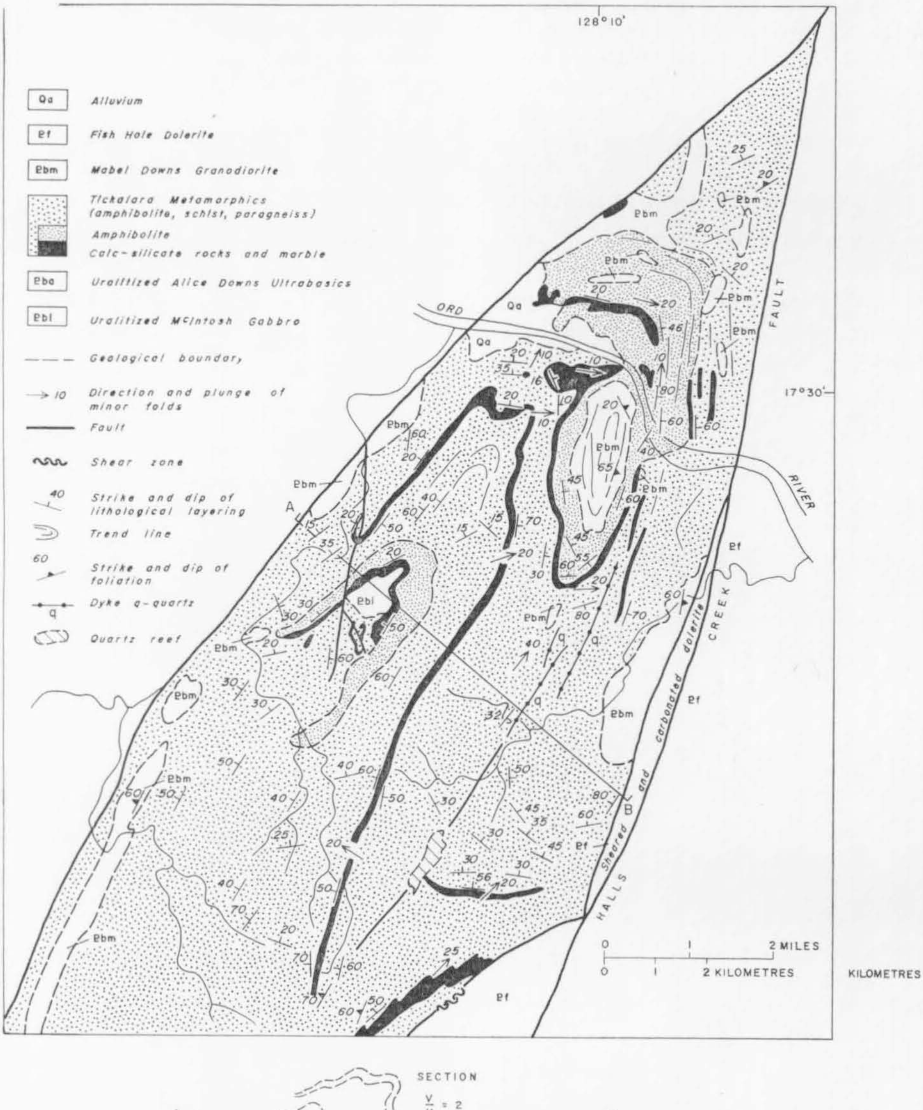


Figure 8
The Black Rock Anticline.

the dominant feldspar is plagioclase. The problem is more complex in the schists, which have a high sodium content but no obvious mineral to accommodate this element. It can be inferred that some of the mica is a sodium-bearing variety such as paragonite. Potassium is mainly present in microcline, but subordinate quantities are taken up by biotite and muscovite.

The calcium and carbon content is fairly constant in all rock types; an exception is the calcareous gneiss shown in analysis (3), which was derived from a calcareous shale or greywacke.

The cordierite-rich gneisses contain less water than the schists. The highest water content is in the rocks which contain hydrated ferromagnesian minerals such as chloritoid and hornblende.

CALC-SILICATE ROCKS

Marble and associated calc-silicate rocks crop out in a belt which extends for 100 miles from Halls Creek to Mount Pitt. In the south, near the Armanda River, deformed roof pendants of calc-silicate rocks crop out within the granitic and basic rocks in the Lamboo Complex. To the north, calcareous rocks of Zones B and C are interfoliated with amphibolite, knotted schist, and gneiss in the following areas: the Black Rock Anticline, on the margins of the McIntosh Hills, and along the Halls Creek Fault. Four continuous calcareous beds and a number of discontinuous beds have been mapped in the Black Rock Anticline (Fig. 8). To the west, on the margins of the Mabel Downs Granodiorite, where the structure is more complex and the metamorphism is higher in grade (Zone C), anorthite-rich calc-silicate bands are truncated by granite and amphibolite.

All the calcareous rocks represent the higher-grade metamorphic equivalents of the dolomites and limestones in the Biscay Formation.

Skarns in the Armanda River Area

Near Armanda River, roof pendants of calc-silicate rocks are interlayered with other metasediments and intruded lit-par-lit by granite. In places, the calc-silicate rocks retain traces of banding (possibly bedding), but they are commonly coarse-grained and massive. The pendants have been migmatized and it is not known how much of the silica has been introduced. The absence of marble is a conspicuous feature, and many of the more massive rocks may have been formed by silicification of marble. Ramifying silica veins are present in all areas, and it is possible that silica has been introduced from the granite masses. The presence of scapolite and microcline in some of the rocks may indicate the introduction of chlorine and potassium while the skarns were being formed.

Although the skarns have been formed by contact metamorphism, the mineralogical assemblages are similar to those found in regionally metamorphosed calcareous rocks of Zone C.

The banded skarns consist of light diopside-rich bands alternating with dark garnetiferous bands. The lighter bands contain diopside, wollastonite, abundant quartz, and plagioclase replaced by epidote; the garnetiferous bands contain poikiloblastic microcline, epidote, and sphene.

In the massive skarns the most common rock type consists of coarse granular green diopside or hedenbergitic pyroxene, pink garnet, light green epidote, and a little scapolite, all of which are intergrown with fibrous white decussate wollastonite. Cavity fillings of xenoblastic carbonate minerals (usually calcite) are distributed randomly through the rock. Some of the skarns have a porphyroblastic texture and contain garnet and hedenbergite up to 2 mm in diameter set in an epidote-rich groundmass. Irregular coronas of garnet surround granular aggregates of hedenbergite, microcline, and xenoblastic calcite with small round scapolite inclusions. Other porphyroblasts consist entirely of pyroxene or a symplektite of garnet and pyroxene. The garnet probably replaces all the calc-silicate minerals. The groundmass consists of epidote, quartz, and potassium feldspar.

Calcareous Rocks in the Black Rock Anticline

Numerous calcareous beds occur in the Black Rock Anticline and near Dougalls Bore. Bands of pure marble are present, but they are generally associated with calc-silicate rocks.

The *marbles* are generally white and coarse-grained, but some contain disseminated silicate minerals and others contain calc-silicate bands and blebs parallel to the regional foliation. The metamorphic grade increases from east to west, with the highest-grade rocks near Dougalls Bore.

The marbles of Zone B are medium to coarse-grained and poorly foliated. The foliation is outlined by tiny grains of epidote and amphibole. The following assemblages were noted: calcite-quartz-plagioclase-epidote-biotite, calcite-quartz-biotite-actinolite-sphene, and calcite-actinolite-chlorite.

The marbles are composed of a granoblastic calcite mosaic, which forms 95 percent of the rock, with interstitial quartz, plagioclase, epidote, sphene, biotite, and actinolitic amphibole. The amphibole contains exsolved tiny opaque grains and is partly replaced by chlorite.

The marbles of Zone C are medium to coarse-grained, well foliated, and slightly banded. The mafic bands range up to 2 cm across and consist mainly of diopside and hornblende.

The following assemblages were noted: calcite-diopside-epidote-quartz-sphene, calcite-diopside-hornblende, and calcite-diopside-hornblende-graphite(?)-spinel.

The marble is composed of a granoblastic mosaic of calcite, which forms 70 percent of the rock, interspersed with calc-silicate minerals. Oval faintly pleochroic grains of green diopside are grouped at the apices of calcite grains, but are not enclosed by the calcite. Hornblende forms discrete oval grains or secondary coronas around the pyroxene. Minor amounts of granular epidote associated with euhedral sphene and pools of sutured quartz may be present. The minor minerals are spinel (pleonaste?) and graphite(?).

Calc-silicate Rocks. Continuous tremolite-rich calc-silicate bands are interfoliated with the marbles of Zone B in the southern part of the Black Rock Anticline. They consist of alternating bands rich in quartz, calcite, and tremolite.

Calcite forms coarse and fine-grained granoblastic bands. Spongy colourless fractured tremolite occurs in rosettes or large idioblastic crystals replacing calcite. Flaky muscovite, intergrown with chlorite, is randomly distributed. Irregularly shaped pools and bands of sutured quartz are aligned roughly parallel to the calcite-rich bands. Opaque material has been exsolved along the cleavage of the tremolite crystals. Massive skarn type calc-silicate rocks form rootless folds, boudins, nodules, lenses, and disseminated grains in the marbles of Zone C (Fig. 9; Pl. 9, fig. 1). Foliated and banded calc-silicate rocks with skarn boudins are interlayered with amphibolite, gabbro, and garnetiferous gneiss.

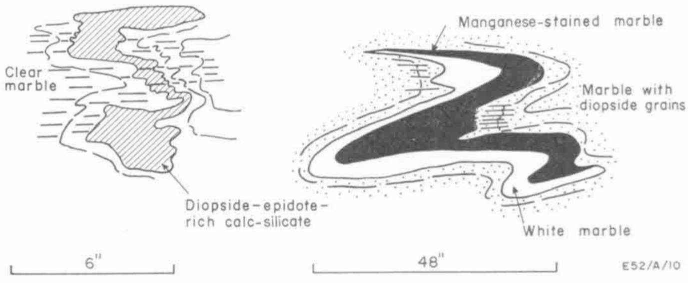


Figure 9

Rootless folds in the Tickalara Metamorphics near Dougalls Bore.

In the massive rocks, scattered crystals of pink grossular garnet are associated with green diopside and epidote. The garnet forms idioblastic crystals or granoblastic aggregates. The rock may consist mainly of granular garnet enclosing xenoblastic epidote and idioblastic diopside. The diopside is dark green and intensely pleochroic. Large patches of xenoblastic carbonate minerals surround the garnet and epidote. A little granular quartz and sphene are also present.

Some of the nodules are composed almost entirely of granular twinned diopside interspersed with ragged blebs of calcite and thin veins of decussate wollastonite laths. Idioblastic sphene is concentrated at the margins of the veins.

In the banded rocks, garnetiferous bands rich in epidote alternate with bands rich in scapolite and diopside. The epidote forms regular to irregular grains which are corroded against the scapolite (Pl. 9, fig. 2). The epidote commonly surrounds, and possibly replaces, the scapolite, and has also replaced garnetiferous aggregates. Idioblastic granules of sphene are also present. White (1959) has also noted that epidote in the Tungkillo Marbles in South Australia is in disequilibrium with scapolite.

An analysis of one of the banded scapolite-rich calc-silicate rocks is given in Table 5. The rock contains much more sodium than the common calc-silicate rock. The sodium is probably restricted to scapolite in the form of the marialite molecule.

Anorthite-rich Calc-silicate Rocks

North of the Ord River, anorthite-rich calc-silicate rocks, interlayered with garnet-cordierite gneiss and amphibolite of Zone C, crop out along the contact of the Mabel Downs Granodiorite. The calc-silicate rocks are commonly coarse-grained, foliated, and banded; the bands consist of red garnet, dark green diopside, and light green amphibole. A little plagioclase is present in all the bands. Some of the massive, fine-grained, and saccharoidal calc-silicate rocks closely resemble the pyroxene granulites.

Table 5
Chemical analyses of the calc-silicate rocks.

			Molecular Proportions	
	1	2	1	2
SiO_2	44.50	48.05	43.06	45.59
Al_2O_3	13.70	10.93	15.63	12.23
Fe_2O_3	4.46	0.80	3.25	0.57
FeO	4.50	2.78	3.64	2.21
MgO	0.67	2.95	0.97	4.17
CaO	27.00	29.24	28.00	29.74
Na_2O	1.20	0.01	2.25	0.02
K_2O	0.19	0.11	0.23	0.13
H_2O+	1.13	1.30	—	—
H_2O-	0.05	—	—	—
CO_2	1.51	4.04	2.00	5.24
TiO_2	1.05	—	0.76	—
P_2O_5	0.07	0.10	0.06	0.08
MnO	0.19	—	0.16	—
Total	100.22	100.31	100.01	99.98

1. Diopside-garnet-scapolite-epidote-sphene calc-silicate rock.
(DR8.02.12. 17°30′30″S; 127°57′00″E). Analyst, M. R. Hanckel (AMDL).
2. Calc-silicate rock, Canberra, ACT. Analyst, NSW Mines Dept, 1911.

The following assemblages were noted: diopside-anorthite-scapolite-sphene, diopside-quartz-anorthite-epidote-scapolite, quartz-diopside-anorthite-lime-garnet-hornblende-sphene, anorthite-quartz-hornblende-lime-garnet-diopside, and hornblende-anorthite-diopside-spinel.

Equidimensional or dendritic grains of dark green clinopyroxene (probably diopside) are set in a granoblastic mosaic of quartz and anorthite. The diopside grains in the plagioclase are rimmed by narrow coronas of epidote. The pyroxene is commonly schillerized and opaque minerals have been exsolved along the cleavage.

The irregular or idioblastic hornblende is pleochroic from yellow to greenish brown, and replaces pyroxene along the cleavage or pseudomorphs it completely. A light green non-pleochroic amphibole (probably hornblende) replaces dendritic diopside and encloses small grains of green spinel.

The well twinned equant xenoblastic laths of plagioclase range from bytownite to anorthite. The feldspar commonly contains tiny inclusions of epidote, or is surrounded by coronas of granular epidote. In the quartz-rich varieties the plagioclase is unstable; it is cloudy or marginally altered where directly in contact with quartz.

Garnet occurs in coarse-grained fractured bands or as irregular spongy fragments partly surrounded by diopside. The bands include equant dark green diopside, granular epidote, pools of quartz, and irregular pools of calcite which are probably secondary. The spongy garnets contain round inclusions of quartz and feldspar.

The equant scapolite grains are stable in the presence of diopside, but the symplektites of scapolite-epidote and scapolite-plagioclase indicate that scapolite is unstable in the presence of these minerals.

PLATE 9

Fig. 1. Diopsidic and garnetiferous calc-silicate boudins and lenses in marble, Ord River, 8 miles south of Tickalara Bore, Tickalara Metamorphics.

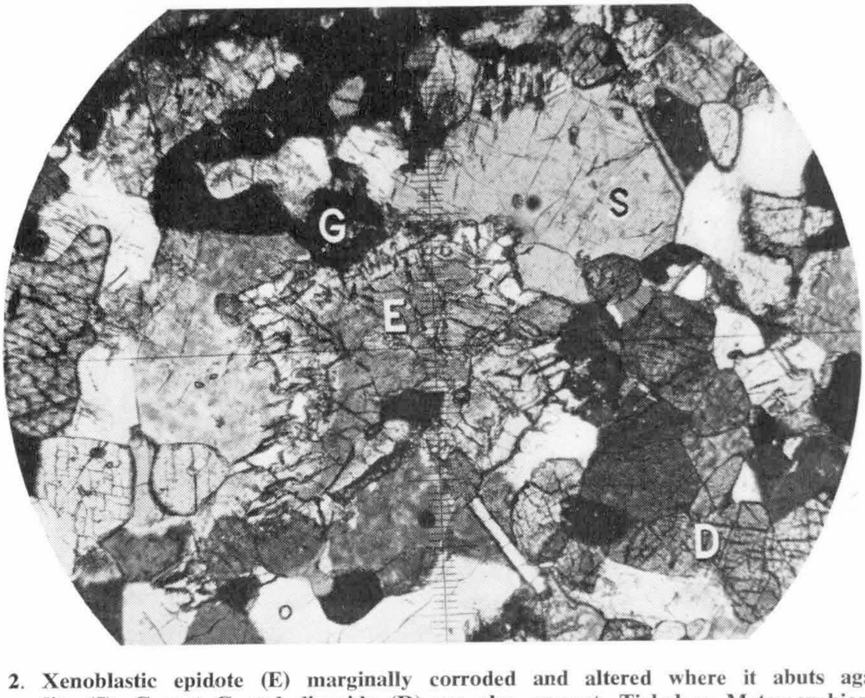


Fig. 2. Xenoblastic epidote (E) marginally corroded and altered where it abuts against scapolite (S). Garnet G and diopside (D) are also present, Tickalara Metamorphics.

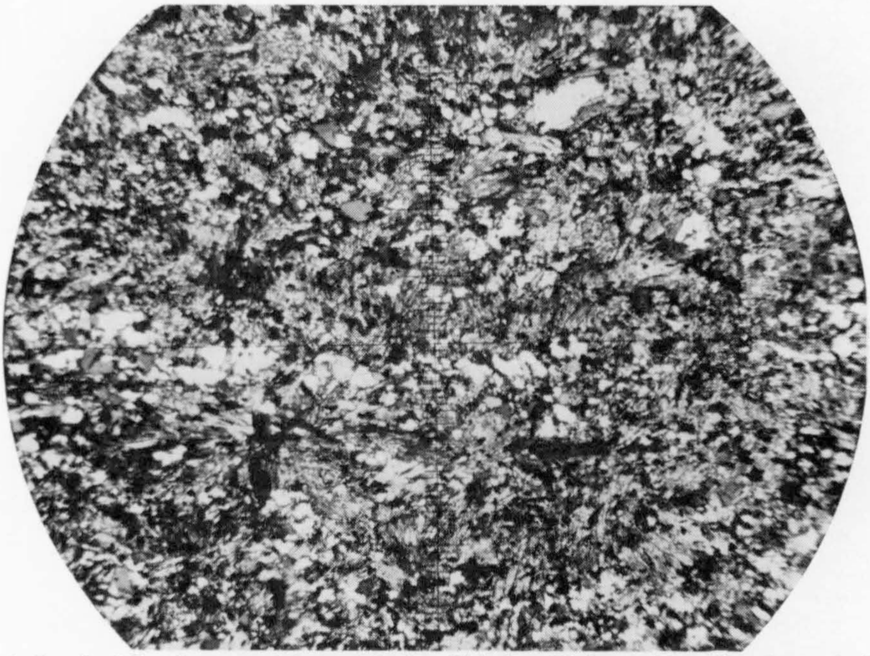


Fig. 1. Poorly foliated quartz-rich amphibolite, Tickalara Metamorphics. The decussate hornblende laths form rosettes interspersed with small irregular quartz grains.

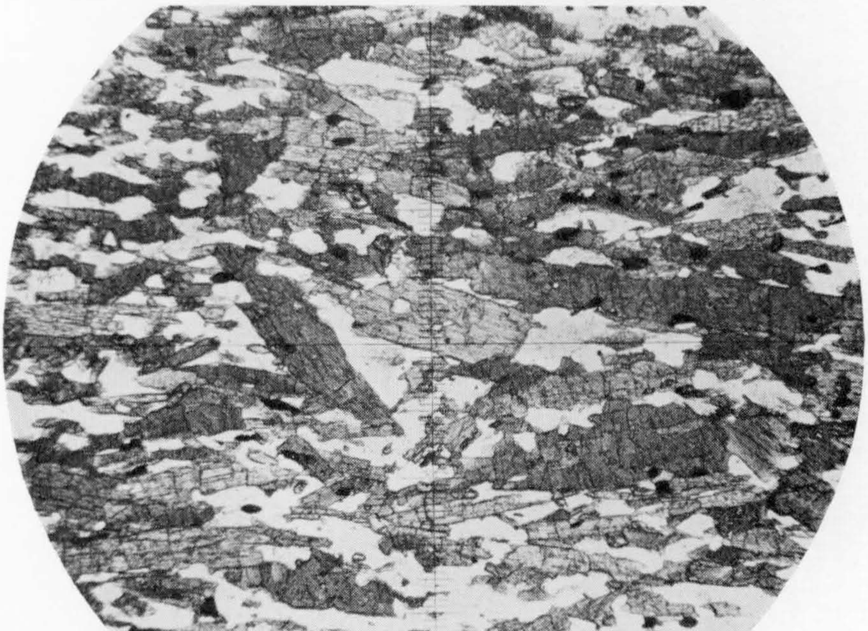


Fig. 2. Well foliated amphibolite, Tickalara Metamorphics. The nematoblastic hornblende laths are aligned roughly parallel to the dominant foliation direction; granular quartz and plagioclase form irregular interstitial pools; small spindles of sphene are randomly distributed through the rock.

PLATE 11

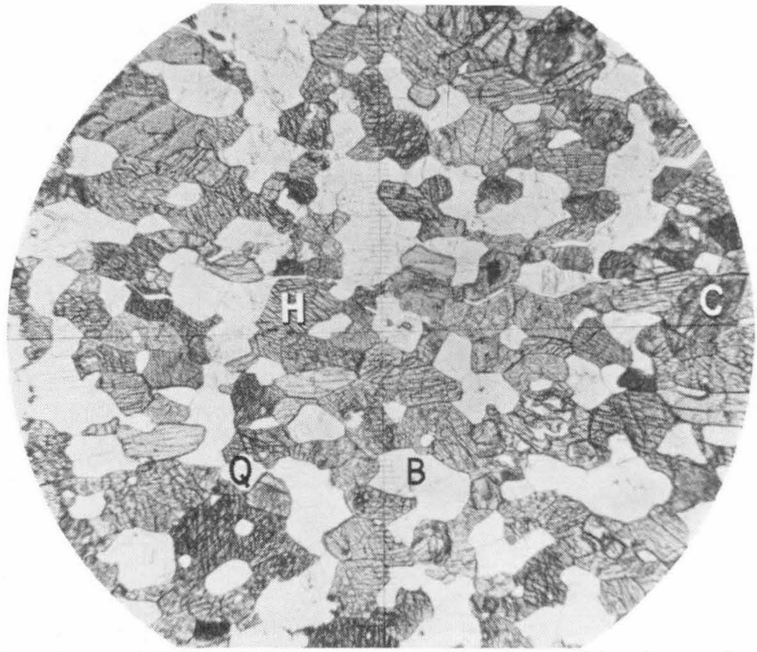


Fig. 1. Granular amphibolite, Tickalara Metamorphics. It consists of equant crystals of hornblende (H), bytownite (B), clinopyroxene (C), and quartz (Q). The hornblende encloses small oval grains of quartz.

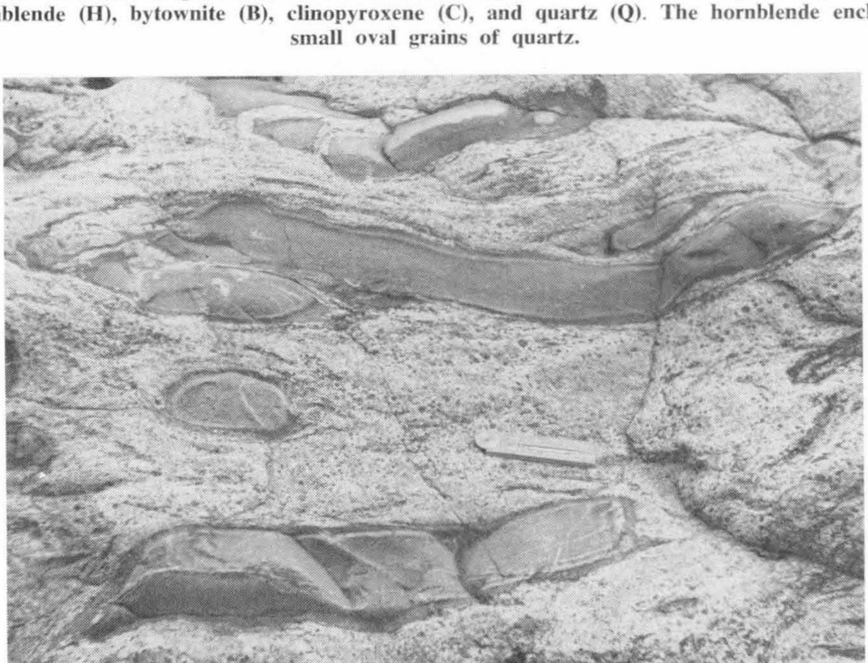


Fig. 2. Irregular bands of pyroxene granulite in a garnetiferous gneiss of the Tickalara Metamorphics, 2 miles west of Turkey Creek Post Office. Note the biotite-rich reaction rim at the margins of the granulite bands.

PLATE 12

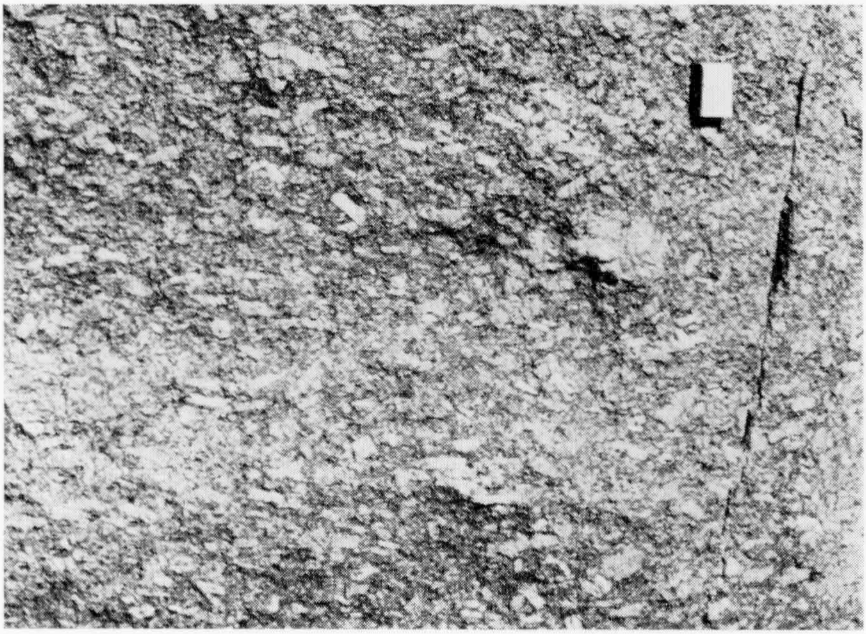


Fig. 1. Primary foliation in the Bow River Granite outlined by euhedral microcline phenocrysts. Near Mount Christine in the Mount Ramsay Sheet area.

Fig. 2. Coarse-grained porphyritic Bow River Granite with oval microcline phenocrysts. Ord River, 30 miles south of Greenvale homestead.

PLATE 13

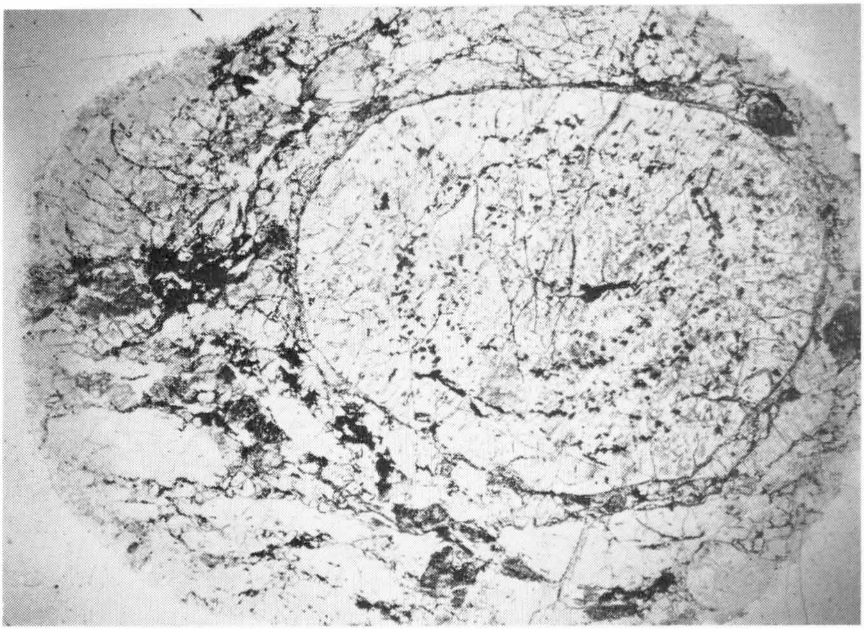


Fig. 1. Oval microcline phenocryst in the Bow River Granite. The phenocryst is surrounded by concentric bands of tiny saussuritized plagioclase laths, and the groundmass is severely granulated.

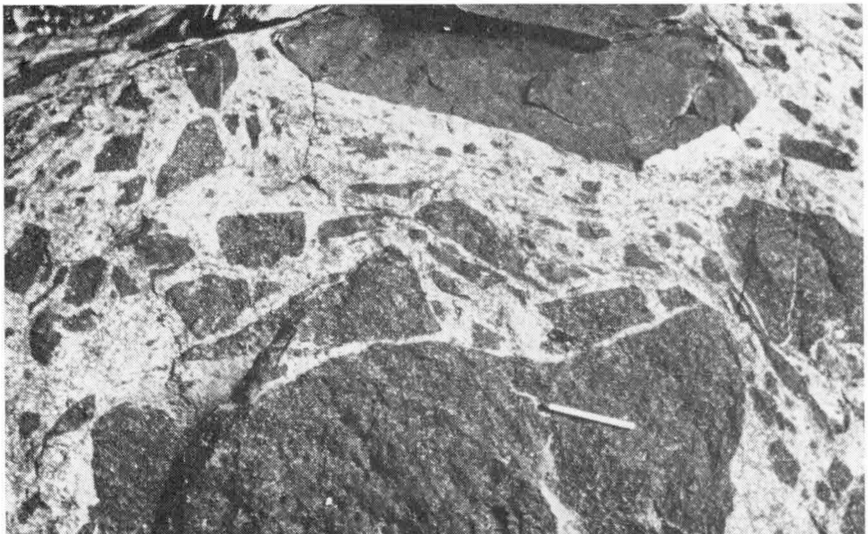


Fig. 2. Granite-gabbro breccia on the eastern margin of Tobys Sill. The breccia is composed of angular and rounded fragments of uralitized gabbro xenoliths in coarse grained Bow River Granite.

Small granules of sphene are concentrated in diopside-rich bands and generally occur at grain interfaces. Sphene also rims irregular ilmenite fragments enclosed in plagioclase and clinopyroxene.

Note on Wollastonite

In the East Kimberley region wollastonite occurs in regionally metamorphosed calc-silicate rocks (p. 39) belonging to the sillimanite-almandine subfacies of the almandine-amphibolite facies. Harker (1939) and Turner & Verhoogen (1960) have suggested that wollastonite is not normally formed by regional metamorphism, presumably because it is unstable at high pressures.

During high-temperature metamorphism quartz and calcite react to form wollastonite and carbon dioxide:

$$\underset{\text{calcite}}{CaCO_3} + \underset{\text{quartz}}{SiO_2} \leftrightarrows \underset{\text{wollastonite}}{CaSiO_3} + \underset{\text{gas}}{CO_2}$$

'When this reaction proceeds to the right, a gas molecule is produced; the temperature of the reaction point will, therefore, increase with increasing pressure' (Barth, 1962, p. 257). If it is assumed that the pressure acting on the carbon dioxide is the same as that acting on the rock, then at high pressures, say 5000 atmospheres, the temperature of reaction would be 900°C; since these temperatures are not normally reached in regional metamorphism wollastonite does not form in these conditions (Barth, 1962). However, if the carbon dioxide is removed as soon as it is formed, the differential pressure will squeeze carbon dioxide out of calcite at a much lower temperature and the development of wollastonite will be aided by increasing pressure.

Thus in regions where the rock cover is permeable to carbon dioxide wollastonite will form in the calc-silicate rocks. In the Tickalara Metamorphics the wollastonite occurs in veins, which suggests the presence of fissures along which the carbon dioxide could escape.

Misch (1964) has described the stable association of wollastonite and anorthite in the amphibolite-facies in the crystalline schists of Nanga Parbat in the north-west Himalayas. He has also suggested that most of the calc-silicate rocks of the region were open systems for carbon dioxide, so that $P_{CO_2} \approx P_{total}$. In local areas, where CO_2 was retained, the wollastonite reaction was arrested or prevented.

Relationship with Amphibolites

The calcareous rocks along the Ord River and near Dougalls Bore are intimately intercalated with amphibolite. Many geologists have suggested that amphibolites can be derived from calcareous rocks, but it is doubtful whether this is the case in the Tickalara Metamorphics. Where there appears to be a gradation between the calc-silicate rocks and amphibolite, it was found that the change was due to tight isoclinal folding. It is possible that some of the granulites associated with the anorthite-rich calc-silicate rocks were derived from calcareous rocks; many of these calc-silicate rocks resemble gabbro, which is commonly associated with basic granulite rich in hornblende.

AMPHIBOLITE

Amphibolite interlayered with metasediments crops out between Dougalls Bore and White Rock Creek Well, in the Black Rock Anticline, on the margins of Mabel Downs Granodiorite, and in the McIntosh Hills. In the Violet Valley region and to the north of Mabel Downs, the amphibolite grades into pyroxene granulite.

Most of the amphibolite was probably formed by the alteration of basic lava flows and basic sills and dykes, and possibly from dolomite of the Biscay Formation. Some were derived by metamorphism and shearing of the McIntosh Gabbro.

The amphibolite can be subdivided on the basis of texture and mineralogical composition into three groups.

Poorly Foliated Quartz-rich Amphibolite

Zone B contains quartz-rich amphibolite which is interbanded with low-grade marble and calc-silicate rocks along the eastern flank of the Black Rock Anticline. The following assemblages were noted: hornblende-quartz-ilmenite, hornblende-quartz-epidote, and hornblende-quartz-chlorite-albite-epidote.

The rocks are fine to medium-grained, and the texture ranges from decussate to roughly nematoblastic. Decussate sieve-like hornblende laths are randomly oriented or form oriented rosettes (Pl. 10, fig. 1). The pleochroisism of the amphibole ranges from blue-green to dark green. Quartz grains are included in amphibole or randomly distributed in pools throughout the rock. A few poorly formed incipient grains of albite are present. Xenoblastic epidote granules impinge on plagioclase boundaries. Some of the rocks contain up to 10 percent of ilmenite which generally forms inclusions in amphibole. The amphibole may be pseudomorphed by large xenoblasts of chlorite which post-date the foliation.

Well Foliated Amphibolite

Well foliated amphibolite is intercalated with gneiss and calc-silicate rocks. It ranges from a foliated dark green homogeneous amphibole-rich type to banded amphibolite containing bands of quartz and feldspar up to 5 cm thick. The banding is generally parallel to the regional cleavage, but in places it appears to be transgressive. The predominant lineation is due to the elongation of amphibole needles on the cleavage planes.

Two suites were noted in this amphibolite. The first is representative of Zone B, and is present in a belt to the west of the Halls Creek Fault, between Sally Malay Well and White Rock Creek Bore. It includes the following assemblages: hornblende-quartz-albite-epidote, hornblende-quartz-andesine-epidote-sphene, and hornblende-labradorite-quartz-epidote.

These amphibolites are fine to coarse-grained and their texture is nematoblastic or granoblastic. Hornblende is usually idioblastic, but ragged acicular laths are also present (Pl. 10, fig. 2). The pleochroism of the amphibole ranges from blue green to dark green. The plagioclase ranges from albite to labradorite and is strained and xenoblastic with shadowy twinning; granular plagioclase with inclusions of hornblende needles and round quartz granules may also be present. Xenoblastic epidote borders the amphibole, and idioblastic spindles of sphene are included in the amphibole, feldspar, and quartz. The minor granular opaque minerals are aligned parallel to the foliation and are generally enclosed in amphibole. Post-foliation carbonate minerals and quartz veins intersect the rocks.

The second suite is present in the higher-grade amphibolites of Zone C which surround the Mabel Downs Granodiorite. It includes the following assemblages: hornblende-labradorite-quartz, hornblende-bytownite-quartz, and hornblende-bytownite-clinopyroxene-quartz.

The texture ranges from slightly nematoblastic to granular, and the hornblende grains are equant and idioblastic (Pl. 11, fig. 1). The amphibole is green-brown in the Z direction. The plagioclase ranges from labradorite to bytownite and is clear, equant, and xenoblastic; some crystals include oval quartz and hornblende grains. Equidimensional grains of light green clinopyroxene may be present; it is enveloped by amphibole but it is not replaced by it. A few equant grains of unstrained quartz are present, and the opaque minerals usually occur at grain interfaces or form schiller textures in amphibole.

The anorthite content generally increases with the increase in the grade of metamorphism, the composition of the plagioclase varies according to the composition of the original rock. Many of the bytownite and labradorite-rich varieties represent metamorphosed McIntosh Gabbro.

Hornblende Granulite

In the Violet Valley region and north of Mabel Downs Station, on the western side of Mabel Downs Granodiorite, the amphibolite of Zone C grades into pyroxene granulite of the same zone. The rocks are dark and massive and have a granular texture. Some of the bands contain pyroxene. The following assemblages were noted: hornblende-labradorite-quartz-(sphene), and hornblende-clinopyroxene-orthopyroxene-bytownite-quartz.

The texture is saccharoidal and equigranular. Subidioblastic hornblende is the predominant ferromagnesian mineral. It is pleochroic from green-brown to brown. The pyroxene grains are xenoblastic and may be surrounded by hornblende, but are not replaced by it. The orthopyroxene crystals are intensely pleochroic from pink to green and contain small opaque inclusions along the cleavage. The plagioclase ranges from labradorite to bytownite and forms xenoblastic to idioblastic simply twinned or untwinned crystals. Quartz is subordinate, and the opaque minerals and granular sphene generally form at grain interfaces. Coronas of amphibole enclose large irregular opaque grains. Some of the rocks are cut by post-metamorphic veins of light green amphibole.

PYROXENE GRANULITE

Pyroxene granulite forms dark lenses and bands in the high-grade paragneiss between Tickalara Bore and Turkey Creek Post Office. The bands range from inches to miles in length and pinch and swell along the strike (Pl. 11, fig. 2). Smaller lenses and pods occur in the migmatites enveloping the Mabel Downs Granodiorite.

The pyroxene granulites are high-grade metamorphic rocks of Zone C. Some of them were derived from amphibolite and calc-silicate rocks; others were derived from gabbros, and to the north of Mabel Downs the pyroxene granulite forms an envelope around the gabbroic stocks.

The pyroxene granulite is dark green to black. It has a fine-grained granular texture and a rudimentary foliation, but no lineation. The foliation is parallel to

Table 6

Chemical analyses of the amphibolites and pyroxene granulites.

	1	2	3	4	5	6	7	8	9	10
SiO_2	50.80	47.10	54.00	50.80	51.50	52.70	48.36	54.20	49.90	50.30
Al_2O_3	14.30	16.50	14.00	15.50	14.50	13.00	16.84	17.17	16.00	15.70
Fe_2O_3	2.25	1.92	2.60	1.07	1.02	2.20	2.55	3.48	5.40	3.60
FeO	10.20	9.20	7.45	9.70	11.40	7.50	7.92	5.49	6.50	7.80
MgO	4.05	6.20	6.90	6.80	7.30	14.20	8.06	4.36	6.30	7.00
CaO	8.55	12.00	10.60	13.00	10.90	7.70	11.07	7.92	9.10	9.50
Na_2O	3.06	2.63	1.29	0.63	0.77	0.84	2.26	3.67	3.20	2.90
K_2O	0.20	0.18	0.54	0.18	0.22	0.46	0.56	1.11	1.50	1.10
H_2O+	1.12	1.47	1.36	1.25	0.75	0.90	0.64	0.86	—	—
H_2O-	0.18	0.09	0.09	0.06	0.07	0.13	—	—	—	—
CO_2	0.08	1.42	0.04	0.07	0.16	0.35	—	—	—	—
TiO_2	4.60	1.06	0.74	0.82	0.92	0.26	1.32	1.31	1.40	1.60
P_2O_5	0.70	0.10	0.09	0.09	0.05	0.04	0.24	0.28	0.40	0.30
MnO	0.17	0.16	0.16	0.17	0.21	0.15	0.18	0.15	0.30	0.20
Total	100.26	100.03	99.86	100.14	99.77	100.43	100.00	100.00	100.04	100.00

*Molecular Proportions**

	1	2	3	4	5	6	7	8	9	10
SiO_2	49.05	44.40	51.75	48.66	49.35	48.61	45.15	50.88	46.58	46.85
Al_2O_3	16.28	18.34	15.81	17.50	16.39	14.14	18.55	19.00	17.61	17.24
Fe_2O_3	1.64	1.36	1.88	0.77	0.74	1.53	1.79	2.46	3.79	2.52
FeO	8.24	7.25	5.97	7.77	9.14	5.79	6.19	4.31	5.08	6.08
MgO	5.83	8.71	9.85	9.71	10.42	19.52	11.20	6.10	8.76	9.72
CaO	8.85	12.13	10.88	13.35	11.19	7.61	11.08	7.97	9.10	9.48
Na_2O	5.73	4.81	2.40	1.17	1.43	1.50	4.09	6.68	5.79	5.24
K_2O	0.25	0.22	0.68	0.22	0.27	0.54	0.67	1.33	1.79	1.31
CO_2	0.10	1.83	0.05	0.09	0.21	0.44	—	—	—	—
TiO_2	3.34	0.75	0.53	0.59	0.66	0.18	0.93	0.92	0.98	1.12
P_2O_5	0.57	0.08	0.07	0.07	0.04	0.03	0.19	0.22	0.32	0.24
MnO	1.14	0.13	0.13	0.14	0.17	0.11	0.14	0.12	0.24	0.16
Total	100.02	100.01	100.00	100.04	100.01	100.00	99.99	99.99	100.04	99.96

*Calculated on water-free basis.

1. Quartz-ilmenite amphibolite near Ilmars prospect. (CD1.32.31. 18°04′S; 127°51′30″E). Analysts, M. R. Hanckel and R. L. Bruce (AMDL).
2. Quartz-albite-(epidote) amphibolite. (DR7.50.25. 17°28′S; 128°07′E). Analysts, M. R. Hanckel and R. L. Bruce.
3. Quartz-andesine-(epidote-sphene) amphibolite. (DR7.49.21. 17°28′15″S; 128°06′E). Analyst, R. L. Bruce.
4. Labradorite-quartz-(sphene) amphibolite. (DR1.00.1. 17°04′45″S; 128°11′45″E). Analyst, R. L. Bruce.
5. Bytownite-clinopyroxene-hornblende-quartz granulite. (DR6.34.21. 17°19′45″S; 127°59′ 10″E). Analyst, M. R. Hanckel.
6. Clinopyroxene-labradorite(?)-cummingtonite-quartz granulite. (DR1.00.9. 17°02′S; 128°10′ 55″E). Analysts, L. W. Castanelli and M. R. Hanckel (AMDL).
7. Average of 160 gabbros (Nockolds, 1954, p. 1020).
8. Average of 49 andesites (Nockolds, 1954, p. 1019).
9. Average of 198 basalts (Daly, 1933, *from* Poldervaart, 1955, p. 134).
10. Average of 200 amphibolites (Poldervaart, 1955, p. 136).

that of the enclosing paragneiss. The following mineral assemblages were noted: bytownite-clinopyroxene-hornblende-quartz, labradorite-clinopyroxene-quartz-hornblende, and clinopyroxene-labradorite(?)-cummingtonite-quartz.

These granulites have an equigranular saccharoidal honeycomb texture and are weakly foliated. Xenoblastic clinopyroxene and plagioclase are the dominant constituents. Some of the granulites contain greenish brown or light brown hornblende; the small xenoblastic hornblende grains impinge against clinopyroxene, but do not replace it. Colourless twinned cummingtonite is concentrated in thin irregular bands. The plagioclase ranges from labradorite to bytownite. A little granular quartz, iron oxides enclosed in clinopyroxene, and pyrrhotite are present.

COMPOSITION OF THE AMPHIBOLITES AND GRANULITES

Four amphibolites and two basic granulites were analysed to determine if there was any marked change in the chemical composition with increased metamorphic grade (Table 6). The specimens were collected from amphibolite or granulite bodies which were probably derived from basic igneous sills (Woodward Dolerite). Nos 1 to 4 are thought to be in order of increasing metamorphic grade: (1) quartz-rich amphibolite — Zone B; (2) and (3) well foliated amphibolites — Zone B; and (4) hornblende granulite — Zone C. The pyroxene granulites Nos 5 and 6 (both in Zone C) have passed through an amphibolite stage or have been directly derived from basic igneous rocks.

The following general observations can be made from the analyses:

(i) The composition of three of the amphibolites (Nos 2-4) corresponds to that of an average basalt or gabbro (Fig. 10), but one of the amphibolites (No. 1) has a composition comparable with that of an average andesite.

(ii) One of the granulites (No. 5) is similar to the amphibolites, but No. 6 has a higher magnesium content, which is reflected by the presence of cummingtonite. Thus the basic granulite was probably derived from a magnesium-rich dolerite or gabbro, possibly a troctolite.

(iii) The total iron and the potassium content is fairly constant in all of the rocks (Fig. 10b, c).

(iv) The low-grade amphibolite contains more sodium and less calcium than the high-grade amphibolite or granulite. Thus albite to andesine is present in Zone B and labradorite to bytownite in Zone C.

(v) The water content decreases from amphibolite to basic granulite and hydrated ferromagnesian minerals are subordinate or absent in the granulite. Eskola's (1939) and Tilley's (1926) analyses of various metamorphic equivalents of basic rocks also show a sharp decrease in the water content from the low-grade to high-grade metamorphic rocks.

METASOMATISM IN THE TICKALARA METAMORPHICS

Although it is believed that the Tickalara Metamorphics were derived from the Halls Creek Group largely by progressive isochemical metamorphism, there are indications that metasomatism has been operative in some cases.

Metasomatism was associated with the late intrusive porphyritic granites. Irregular roof pendants of skarn occur in the coarse-grained granite in the southern part of the Lamboo Complex. The skarns may have been formed by silica replacement of marble. Ramifying silica veins are common, and it is possible that silica was introduced from the granite. Thus the garnet, hedenbergitic pyroxene, scapolite, and microcline in the skarns may be of metasomatic origin.

Solutions and gases of non-magmatic origin played a large part in the lower grades of metamorphism. Water could have been driven off from the high-grade rocks and migrated upwards into zones of lower temperature. Transformation of limestone or dolomite into calc-silicate rocks yields abundant carbon dioxide which

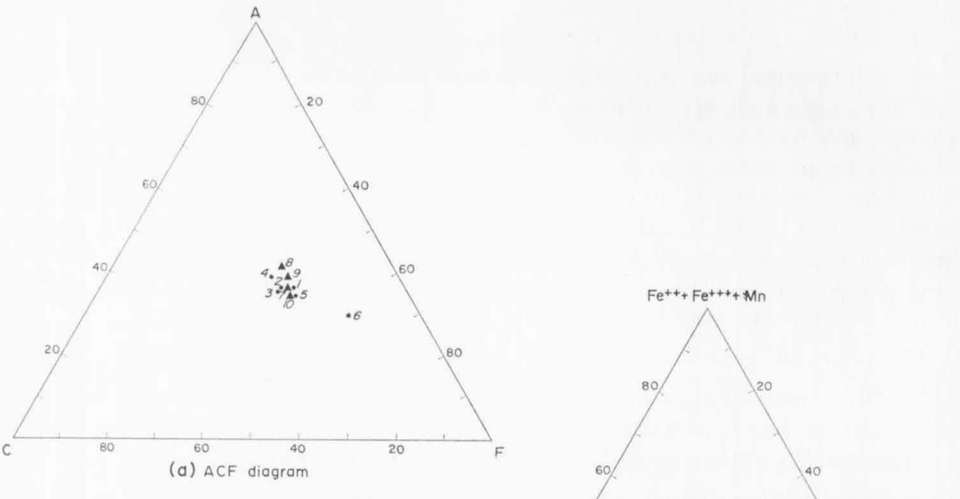


Figure 10

Variation diagrams for the amphibolites and pyroxene granulites.

also migrates upwards into low-grade zones (Turner & Verhoogen, 1960). Water was one of the main agents in uralitizing the dolerite, gabbro, and ultrabasic sills in Zones A and B.

Tourmaline is present in both Zones A and B. In Zone A it is detrital, but in Zone B it is probably allochemical. A metasomatic origin is favoured in this zone because the euhedral tourmaline forms veins and is usually associated with apatite. Binns (1963) has suggested that the tourmaline in the knotted schists at Broken Hill is metasomatic, and Read (1939) states that ubiquitous tourmaline in regionally metamorphosed rocks is an indicator of the action of 'emanation' throughout all grades.

Pitcher (1965) has suggested that there is a close association between the growth of sillimanite and the formation of migmatites, and that the mineral is often a clear indicator of the zone of remelting and metasomatism. This may well be the case in some of the migmatites of Zone C in the Tickalara Metamorphics. Sillimanite generally replaces biotite and andalusite, but in places sillimanite-rich veins are parallel to the dominant foliation, although elsewhere it is closely associated with tourmaline.

METAMORPHIC FACIES IN THE TICKALARA METAMORPHICS

Using the classification of Fyfe et al. (1958), the metamorphic zones in the East Kimberley area can be placed in the following facies:

Zone A: Greenschist facies; quartz-albite-muscovite-chlorite subfacies.

Zone B: Greenschist facies to almandine-amphibolite facies; quartz-albite-epidote-biotite, through quartz-albite-epidote-almandine, to staurolite-quartz subfacies.

Zone C: Almandine-amphibolite to granulite facies; sillimanite-almandine subfacies transitional to hornblende-granulite subfacies.

The slightly metamorphosed rocks of the Halls Creek Group belong to the greenschist facies, whereas the Tickalara Metamorphics range from the greenschist to granulite facies.

Although the metamorphic equivalents of pelitic and arenaceous rocks in Zone C contain cordierite but no orthopyroxene or orthoclase, the basic rocks contain orthopyroxene, which is indicative of the granulite facies. Fyfe et al. (1958) have placed this association in the hornblende-granulite subfacies; the development of this facies may be due to high partial pressure of water which inhibits the breakdown of biotite to form hypersthene and orthoclase in pelitic rocks.

Miyashiro (1961) states that the well known series of greenschist, almandine-amphibolite, and granulite facies represents only one of five possible facies series. The type of series developed depends on the rate of increase in temperature relative to the rate of increase in pressure during metamorphism.

The five types are, in order of increasing pressure/temperature ratio:

(i) Andalusite-sillimanite type
(ii) Low-pressure intermediate group
(iii) Kyanite-sillimanite type
(iv) High-pressure intermediate group
(v) Jadeite-glaucophane type.

The association of different aluminium silicate polymorphs is important in defining the first three facies series.

Applying Miyashiro's classification to the Tickalara Metamorphics, it is apparent that they belong to the low-pressure intermediate group. Andalusite, sillimanite, and cordierite occur in the pelitic rocks, as in the andalusite-sillimanite type on the Abukuma Plateau in Japan (Miyashiro, 1958); staurolite and kyanite also occur as in the kyanite-sillimanite type, which was previously called the Dalradian or Barrovian type (Barrow, 1893, 1912); and finally, the metamorphosed basic igneous rocks in the Tickalara Metamorphics contain no garnet—the same relationship as in the andalusite-sillimanite type.

Miyashiro (1960) thought that the temperatures and rock pressures corresponding to the aluminium silicate-rich facies series could be inferred from the experimentally determined stability relations of the aluminium silicate polymorphs, but this approach may be erroneous. In the high-grade pelitic derivatives of the Tickalara Metamorphics, sillimanite prefers to replace biotite rather than andalusite. Thus, although andalusite and sillimanite occur together, the sillimanite does not always represent the polymorphic inversion of andalusite.

Also, Pitcher (1965, p. 337) states that 'the stability relationships of the naturally occurring aluminium silicates have not yet been closely enough simulated in the laboratory for estimates to be made of the pressure/temperature conditions of metamorphic processes'.

Thus it is impossible to determine the precise physical conditions which were operative during the development of the Tickalara Metamorphics. Suffice to say that the pressures were relatively low and the temperature was high during the development of Zone C.

GENESIS OF THE TICKALARA METAMORPHICS

The genesis of any metamorphic terrain presents complications which cannot be explained by the observed phenomena. Hypotheses can be set up from mineralogical relationships and from the experimentally determined stability relations of characteristic minerals.

High shearing stress and relatively low temperatures were the principal conditions that governed the crystallization of the low-grade metamorphic rocks of Zones A and B.

The Halls Creek Group and part of the Tickalara Metamorphics are highly sheared and tightly folded. Turner (1938, p. 165) has aptly described the progressive steps in low-grade regional metamorphism, which can also be applied to Zone A.

'(i) Mechanical granulation, shearing out, and recrystallization of original clastic grains.

(ii) Simultaneous growth of minute crystals of new minerals with their long axes in subparallel position, and subsequent increase in the size of the reconstituted mineral grains'.

The temperature gradient was slightly higher in Zone B and minerals such as biotite, garnet, chloritoid, staurolite, and andalusite developed. Although it is generally accepted that chloritoid and staurolite are not necessarily restricted to a stress environment, it seems that stress conditions played a large part in the development of these minerals in the Tickalara Metamorphics. They always post-date or are contemporary with the development of a crenulation cleavage.

It is probable that the water content was relatively high in Zones A and B. This facilitated the uralitization of the basic and ultrabasic sills in both zones. The uralitization was not an autometasomatic effect which took place during the intrusion of these bodies, since the small sills are completely altered and the large sills are only altered on the margins. In the larger competent sills the centres were unaffected by metamorphism and water metasomatism.

The development of Zone C was due to a further increase in temperature. This increase may have been related to the intrusion of the syntectonic Mabel Downs Granodiorite in Zone C. However, the field evidence indicates that the Mabel Downs Granodiorite was derived by anatexis of the Tickalara Metamorphics, and the increase in temperature during metamorphism was probably the main factor.

The increase in temperature brought the rocks within the sillimanite field. Sillimanite replaced andalusite in part, but usually preferred to replace biotite or nucleate within biotite. The total pressures during this stage were relatively low since sillimanite occurs with cordierite, which is known from experimental work (Halferdahl, 1956) to break down at high pressures. However, the partial pressure of water was high enough to restrict the formation of the pyroxene granulite facies in the pelitic rocks, and high enough to partially melt the sillimanite and cordierite-rich gneisses to form migmatites and an anatectic granodiorite/tonalite magma. The temperature of formation of cordierite and sillimanite-rich migmatites has been determined experimentally by melting aluminium-rich gneisses at 2000 bars water pressure (Von Platen, 1965). The migmatites formed at temperatures ranging from 690° to 730°C.

Zone C is characterized by low or practically negligible shearing stresses, but along zones of major dislocation, such as the Halls Creek Fault, kyanite and sillimanite-rich assemblages have been noted. Kyanite post-dates and is derived from crenulated sillimanite in these rocks and it is probable that this reaction was accelerated by shearing; in normal temperature and pressure conditions this reaction would proceed very slowly (Verhoogen, 1951).

ANATECTIC IGNEOUS ROCKS

MABEL DOWNS GRANODIORITE

The term Mabel Downs Granodiorite has been used for the gneissic igneous intrusions which extend in a belt from Carrington Springs to the Bow River. The type area is a large lenticular sill-like batholith parallel to the Halls Creek Fault, which extends for 50 miles from the Ord River to the Bow River. The gneissic granodiorite stock, measuring 8 miles by 4 miles, on the southern side of the Ord River is separated from the main mass by a belt of metasediments (Fig. 11). Smaller lenticular bodies, surrounded by high-grade paragneiss and amphibolite of Zone C, occur north and south of the type area, and a number of small discontinuous sill-like bodies intrude the amphibolite and schist of Zone B in the Black Rock Anticline. The distribution of the Mabel Downs Granodiorite is shown in Figure 2.

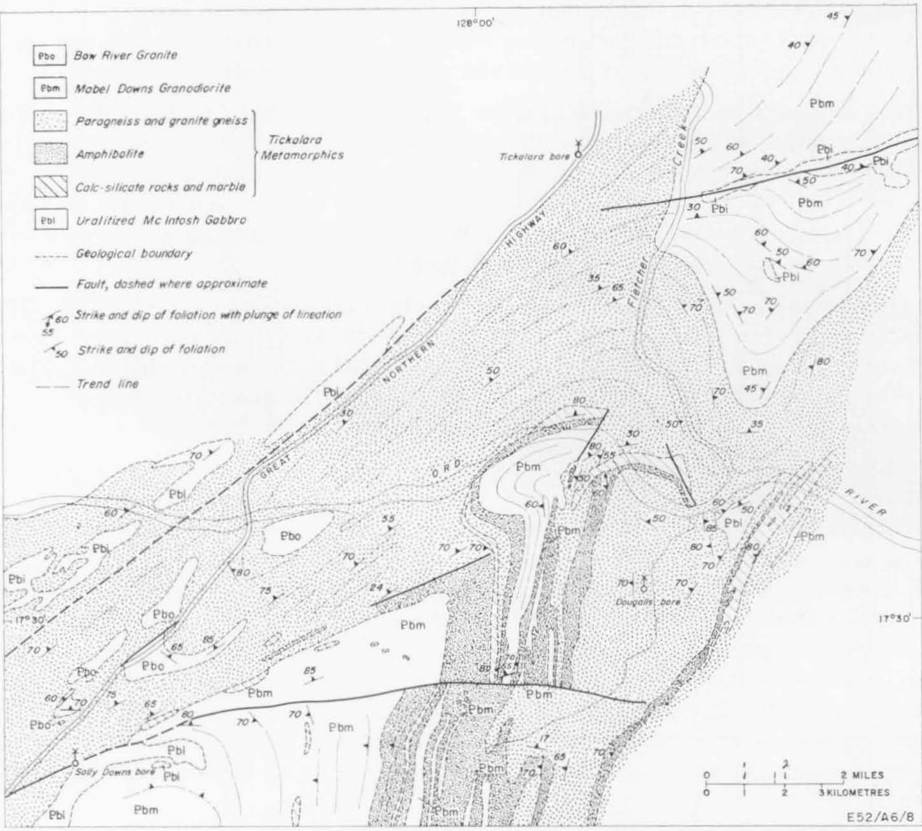


Figure 11

Mabel Downs Granodiorite intrusion in the Ord River/Fletcher Creek area.

The Mabel Downs Granodiorite ranges from tonalite to granite in the Dixon Range Sheet area, but in the Lissadell Sheet area it comprises orthopyroxene-rich granodiorite.

The Mabel Downs Granodiorite intrudes the Alice Downs Ultrabasics and McIntosh Gabbro and incorporates them as xenoliths. The granodiorite also intrudes the Tickalara Metamorphics, but is structurally concordant with them. There is usually a gradual transition from granodiorite to migmatite and paragneiss, and it is generally impossible to delineate an exact boundary. These relationships suggest that the granodiorite was formed by melting of the Tickalara Metamorphics.

Type Area

The Mabel Downs Granodiorite is usually concordant with the Tickalara Metamorphics. Slight discordance has been noted (i) on the eastern margin of the main body, where a wide calc-silicate band is truncated by the granodiorite, and (ii) farther south, where a smaller mass of granodiorite intrudes amphibolite (Fig. 11).

The larger mass is folded into a tight syncline near the Ord River, but the syncline merges into a limb of a drag fold to the north. The smaller body is anticlinal with the eastern limb overturned to the west (Fig. 11). The granodiorite has the same steep westerly dipping foliation as the enclosing rocks. The minor isoclinal folds, schlieren, and lineations have a constant steep northerly plunge ('b' lineation).

The central part of the Mabel Downs Granodiorite consists of foliated coarsely porphyritic hornblende-rich tonalite and granodiorite, which grades outwards into foliated medium-grained biotite-rich granodiorite, which passes in turn into saccharoidal medium-grained gneissic granodiorite or granite, with biotite-rich schlieren, along the margins. The metamorphic rocks around the granodiorite include migmatitic and granitic rocks interfoliated lit-par-lit with coarse-grained metamorphic rocks, containing cordierite, sillimanite, and garnetiferous gneiss, and well foliated medium-grained garnetiferous and sillimanite-rich gneiss interfoliated with amphibolite bands.

The migmatite is well developed in the north between Mabel Downs homestead and Turkey Creek Post Office, but there is little migmatite on the southern margin where the metasediments are slightly lower in metamorphic grade.

The Mabel Downs Granodiorite ranges from tonalite, through granodiorite, to granite. The granitic rocks are mainly restricted to the margins of the batholith.

The tonalites mainly occur in the centre of the intrusion. They are green, medium to coarse-grained, foliated, and porphyritic. The phenocrysts are hornblende with or without feldspar. The tonalite has a porphyritic to granular texture modified by cataclasis. Poorly zoned euhedral oligoclase or andesine is surrounded by granular quartz. The olive-green euhedral and spongy hornblende phenocrysts are replaced by small biotite laths. The foliation is usually outlined by sheaves of dark brown biotite associated with granular epidote. The accessory minerals are apatite, iron oxides, and sphene.

The granodiorite has virtually the same mineralogical composition as the tonalite, but contains subordinate quantities of microcline and vein perthite.

On the southern side of the batholith the tonalite grades into granite. The granite light-coloured, medium to coarse-grained, foliated, and porphyritic. Hornblende has been replaced by biotite. The granite has a cataclastic to granular fabric and the quartz is strained and recrystallized. Anhedral microcline and microperthite form myrmekitic intergrowths with plagioclase and quartz. Zoned albite to oligoclase anhedra are subordinate to the potassium feldspar. Euhedral red-brown biotite interlathed with secondary muscovite and granules of epidote parallel the foliation. The accessories are iron oxides and zircon.

Tonalite Sills in the Black Rock Anticline

Discontinuous sill-like tonalite masses intrude the Tickalara Metamorphics along the margins of the Black Rock Anticline (Fig. 8). The tonalite intrusions are concordant with the enveloping amphibolites and schists. The absence of migmatite is significant. The tonalites have been emplaced in metamorphic rocks of Zone B and it is probable that the sills represent a higher level of intrusion than those in the type area.

The tonalites are green, foliated, and coarsely porphyritic. Phenocrysts of euhedral feldspar and quartz are wrapped by biotite and amphibole laths. A well developed 'b' lineation is defined by acicular amphibole and biotite.

The fabric ranges from hypidiomorphic granular to porphyritic. The subhedral saussuritized and sericitized oligoclase and andesine phenocrysts are wrapped by brown biotite and altered to epidote and chlorite. Pools of intersutured quartz grains define zones of cataclasis; quartz phenocrysts may also be present. Large euhedral spindles of sphene are enclosed in hornblende. A little microcline and vein perthite, which form myrmekitic intergrowths in contact with quartz or feldspar, may be present. The accessory minerals are apatite, zircon, and garnet.

Orthopyroxene-rich Granodiorite

Orthopyroxene-rich granodiorites are present in the northern part of the Lamboo Complex. They are separated from the main granodiorite mass by high-grade migmatitic gneisses. The main body is 5 miles by 5 miles and extends in a northeasterly direction from Bow River homestead to the Bow River. A smaller lenticular mass, 4 miles by 2 miles, crops out 3 miles to the south along the Great Northern Highway. A triangular body, 10 miles by 2 miles, surrounded by migmatites crops out to the northwest of Mabel Downs Station.

The granodiorites are usually concordant with the enclosing gneisses, but transgressive contacts have been noted in places. In the Bow River area, the granodiorites are foliated and have a steep easterly or westerly dip. The rocks have a coarse-grained granitic texture, and are brown to black, with a vitreous lustre. Blue or dull brown feldspar and quartz is interspersed with numerous biotite flakes and clots.

The anhedral oligoclase or andesine crystals are intergrown with subordinate anhedral microcline and large anhedral quartz. Myrmekite is present at quartz-microcline and plagioclase-microcline boundaries. Slightly pleochroic orthopyroxene (probably hypersthene) forms small oval schillerized and fractured grains. Brown biotite replaces the orthopyroxene, but usually occurs in individual laths or decussate clots. In places, secondary green biotite and chlorite aggregates impinge on the pyroxene. Tiny opaque minerals are exsolved along the cleavage of the mica. The accessories are apatite and zircon.

A chemical analysis of a typical orthopyroxene-rich granodiorite from the East Kimberley region is given in Table 7. Analyses of a hypersthene-adamellite from the Musgrave Ranges and a charnockite from St Thomas Mount, Madras, are given for comparison.

The granodiorite is similar in composition to the adamellite, but neither of them resembles the charnockite, which contains much more silica, and less water, alumina, total iron, and lime. The amount of combined water is much higher in the hypersthene granodiorite than in the other two rocks. It corresponds to the amount present in an average granodiorite (Table 9).

GENESIS OF THE MABEL DOWNS GRANODIORITE

It is believed that the Mabel Downs Granodiorite was derived from the Tickalara Metamorphics by anatexis. This conclusion is supported by the following observations: the migmatitic gneisses grade imperceptibly into the foliated Mabel Downs Granodiorite; the granodiorite was formed and probably intruded at the same time as the development of the Tickalara Metamorphics about 1940 million years ago (V. M. Bofinger, pers comm.); and the composition of the Mabel Downs Granodiorite is heterogeneous.

Table 7

Chemical analyses of the Mabel Downs Granodiorite.

				Molecular Proportions		
	1	2	3	1	2	3
SiO_2	66.60	65.92	77.47	63.41	62.24	73.35
Al_2O_3	15.20	14.38	11.00	17.06	16.01	12.28
Fe_2O_3	1.29	1.81	1.04	0.92	1.29	0.74
FeO	3.80	4.16	2.02	3.03	3.29	1.60
MgO	1.96	1.24	0.43	2.78	1.74	0.61
CaO	3.80	3.23	1.02	3.88	3.27	1.04
Na_2O	2.43	3.33	2.86	4.49	6.09	5.25
K_2O	3.18	4.16	4.14	3.86	5.01	5.00
H_2O+	0.64	0.14	0.20	—	—	—
H_2O-	0.20	0.16	0.05	—	—	—
CO_2	0.05	—	—	0.07	—	—
TiO_2	0.58	0.88	0.26	0.42	0.63	0.19
P_2O_5	0.13	0.38	—	0.10	0.30	—
MnO	0.06	0.16	—	0.04	0.13	—
Total	99.92	99.95	100.49	100.06	100.00	100.06

1. Hypersthene granodiorite (Mabel Downs Granodiorite) (L.13.68.6. 16″48′30″S; 128°23′45″E).
2. Hypersthene adamellite (Musgrave Ra., S.A., Wilson, 1959). Analyst, W. H. Herdsman.
3. Charnockite (St Thomas Mt, Madras, Washington, 1917).

Von Platen (1965) has recently demonstrated that anatectic melts can be obtained experimentally by melting gneisses. At 2000 bars water pressure, the melting started between 690°C and 730°C; the variation in the melting point was due to the different initial albite/anorthite ratios and the composition of the gneisses. With increase in temperature, aplitic, granitic, granodioritic, and tonalitic melts were obtained.

Von Platen also produced anatectic melts from greywacke and clay. Melting started between 680°C and 740°C at 2000 bars water pressure. With increasing temperature, the amount and composition of the anatectic melts changed rapidly till the final stage of anatexis was reached between 730°C and 770°C. The composition of the melt in the final stage depends on the chemical composition of the rocks used. Aplitic, granitic, and granodioritic melts were obtained from clays, and granodioritic and tonalitic melts from greywackes.

These experiments show that in regions of high partial pressure of water, anatectic melts can be derived from gneisses and greywackes.

The heterogeneous composition of the Mabel Downs Granodiorite probably reflects the variation in composition of the sedimentary pile. The sediments included greywacke, shale, and calcareous rocks; and basic volcanic and intrusive igneous rocks were also common.

The mode of occurrence of the granodiorite indicates that after its formation by anatexis it was intruded as a mobile magma higher in the crust. In the high-grade areas (Zone C), where the granodiorite is associated with migmatite, there is no evidence of intrusion, but where migmatites are absent, it has intruded calc-silicate rocks and amphibolites. In the Black Rock Anticline the granodiorite has been intruded even higher into the crust and it is surrounded by metamorphic rocks of Zone B.

LATE INTRUSIVE ROCKS

Late-stage discordant igneous rocks with contact aureoles intrude the Tickalara Metamorphics and Halls Creek Group. The Bow River Granite and the comagmatic Castlereagh Hill Porphyry define a large discordant batholith on the western margin of the Lamboo Complex; the Sophie Downs Granite intrudes anticlines and fault zones in the Halls Creek Group; the Violet Valley Tonalite is randomly distributed and intrudes the Halls Creek Group and Bow River Granite; and the McHales Granite, which intrudes the Halls Creek Group in the Osmond Range area, may be related to the Violet Valley Tonalite.

Late-stage dolerite, diorite, aplite, pegmatite, and quartz-feldspar porphyry dykes mark the final phase of igneous activity in the Lamboo Complex.

BOW RIVER GRANITE

The term Bow River Granite embraces a number of related intrusions ranging from coarse-grained porphyritic granite or adamellite to even-grained granite or granodiorite. All these rocks grade into each other and precise boundaries have not been mapped.

The Bow River Granite is confined to a large batholith 200 miles long and 20 miles wide, on the western side of the Lamboo Complex; in the map area it extends from Mount Hawick to Dunham River homestead. Two small inliers of granite crop out south of the Carr Boyd Ranges and another in the Golden Gate area. Small inliers also occur in the Proterozoic rocks south of Mount Amherst homestead. Coarse-grained granite also intrudes the western margin of the Tickalara Metamorphics; a number of lenticular bodies are present in this region (Fig. 2).

The granite crops out as prominent knobbly hills or large smooth exfoliated whalebacks which are common in the Springvale area. In the south, weathered granite mesas are overlain by laterite.

The Bow River Granite intrudes the Halls Creek Group, Tickalara Metamorphics, Alice Downs Ultrabasics, and McIntosh Gabbro. It was introduced during the waning stages of regional metamorphism since the granite and paragneiss are interlayered in the Tickalara Metamorphics.

The Bow River Granite ranges from leucocratic to melanocratic, and from even-grained to porphyritic. The tabular, ovoid, or rhombic feldspars are up to 2 inches across, and are set in a fine-grained groundmass of quartz and feldspar. The potassium feldspars commonly enclose small euhedral plagioclase crystals. In places, the phenocrysts are aligned along a primary foliation (Pl. 12, fig. 1) and lenticular feldspar-rich segregations are common. Biotite granite predominates, but hornblende is developed close to the intruded gabbros.

The margins of the granite are commonly foliated, but the centres remain massive. The foliation was probably developed in the viscous and partly crystallized magma during emplacement. Tectonic foliation and shearing parallel to major faults is evident in places, and mylonites are present in some areas.

Granite

The granite of the Bow River Granite has a coarse-grained porphyritic or coarse hypidiomorphic granular texture. In places, the tabular feldspars are aligned in parallel planes. This is thought to be a primary flow texture (Pl. 12, fig. 1).

The anhedral quartz ranges from minute comminuted grains to large oval phenocrysts. Where an incipient secondary foliation is present, undulose extinction is marked. The feldspars are usually surrounded and lobed by granular quartz.

The euhedral to subhedral plagioclase phenocrysts range from albite to oligoclase. Some crystals are zoned with clear albite rims around a core of oligoclase; saussuritization and sericitization have affected the more calcic core. In the foliated granites the feldspars tend to become oval and marginally corroded.

The potassium feldspar phenocrysts are fresh and clear. The anhedral microcline and microperthite form phenocrysts or interstitial grains. The microcline commonly encloses euhedral laths of plagioclase oriented parallel to the cleavages. Poikilitic inclusions of quartz and epidote pseudomorphs after plagioclase are also present. Myrmekite has been formed at the microcline-quartz and microcline-plagioclase boundaries.

The dominant mafic mineral is dark brown or green-brown biotite. It forms ragged laths or sheaves distributed randomly through the rock. The mica generally contains small exsolved opaque minerals along its cleavage. In the altered granites biotite is partly chloritized and encloses epidote granules.

In the porphyritic rocks the groundmass consists of a fine-grained aggregate of feldspar, quartz, and biotite. The accessories are zircon, tourmaline, sphene, apatite, and opaque minerals.

Cataclastically deformed granite occurs in zones of shearing and faulting; it is fine to coarse-grained and has a porphyroblastic texture. Pink feldspar augen are set in a fine-grained foliated groundmass. The microcline porphyroblasts are wrapped by comminuted and recrystallized bands of quartz and dark brown folia of biotite. Secondary muscovite is interlathed with biotite and both contain inclusions of granular epidote. A little granular albite which has been altered to epidote is also present. The accessories include sphene and opaque minerals.

Cataclastically modified coarse-grained *granites with oval feldspar phenocrysts* set in a groundmass of granular quartz and feldspar (Pl. 12, fig. 2), crop out between Greenvale homestead and the Ord River.

The oval phenocrysts of microcline and perthite are up to 5 cm across. The zoned crystals consist of a series of concentric bands outlined by tiny saussuritized and sericitized albite-oligoclase laths (Pl. 13, fig. 1) set in microcline. The two central bands in Plate 13, Figure 1 are circular, but the outermost band is discontinuous and truncated by microcline (see lower centre). Radially arranged graphic quartz is concentrated in the outer microcline-rich zone. The concentric arrangement of plagioclase is not always present and many of the phenocrysts consist entirely of microcline. The microcline is marginally corroded and bordered by myrmekitic intergrowths associated with granulated quartz. The feldspar retains its angular shape where quartz has protected it from cataclastic effects.

The groundmass consists of angular fragments of microcline, lenticular and fractured quartz, and fine sericitic mica. No plagioclase is present in the groundmass. The cataclastic foliation is defined by ragged plates of green biotite interlathed with chlorite.

Granodiorite

The granodiorite generally has a coarse-grained porphyritic or hypidiomorphic granular texture. Where shearing has been dominant the rocks have a coarse-grained porphyroblastic texture.

Quartz forms large anhedral grains or a granulated mosaic with a marked strain extinction. The euhedral tabular phenocrysts of oligoclase or andesine are twinned and commonly zoned. The cores are replaced by granular epidote and chlorite, or by sphene, epidote, and chlorite. The microcline and microperthite form large irregular phenocrysts or small anhedral interstitial grains. The potassium feldspars are usually clear, but poikilitic inclusions of euhedral plagioclase are common. Coarse flakes of red-brown or dark brown biotite are randomly distributed or define a crude foliation. Secondary muscovite and chlorite are interlathed with biotite, and traces of epidote occur along the cleavage of the micas. A few anhedral spongy dark green hornblende laths are present in some of the rocks. The amphibole is usually replaced by biotite. The accessories are sphene, apatite, zircon, and iron oxide.

Contact Relationships

Three types of contact relationships have been noted.

(i) Faulted contact: the granite is unaltered at the contact and the country rocks are unmetamorphosed.

(ii) Stoped contact: the granite is usually chilled at the contact, but in places no chilling is evident. The country rocks are metamorphosed, and the angular and lenticular xenoliths in the granite are aligned parallel to the contact. Fine granophyric necks intrude the country rocks, and in places a massive closely jointed aplitic phase is developed on the margin of the granite. Aplite apophyses intrude both the coarse-grained granite and the country rock. Pegmatites may also be common in the marginal facies of the granite.

(iii) Migmatitic contact: foliated granite forms lit-par-lit interlayers with sillimanite-rich paragneiss and amphibolite up to 1200 feet wide. The grade of metamorphism falls away from the contact, and the granite becomes more massive and coarse-grained inwards.

Contact Metamorphic Rocks

There is a great variety of metamorphosed rocks in the contact aureoles.

Hornfels. On the Ord Dam Site road, the Halls Creek Group sediments are intruded by porphyritic granite with a metamorphic aureole of hornfels 1000 feet wide. The granite shows no sign of chilling and large microcline phenocrysts persist right to the contact. Large microcline porphyroblasts are present in the first 5 feet of contorted and banded metasediments. The hornfels is composed of fine-grained granular quartz, with relict sedimentary features, and interspersed irregular blebs of mica which represent pseudomorphs after cordierite. They consist of decussate biotite laths and chlorite. A few plagioclase grains were also noted.

Schist. Schist is common where the granite has intruded pelitic rocks of the Halls Creek Group. The main types are brown, fine to medium-grained quartz-biotite-muscovite schists. They are foliated and lineated, and in places have a crenulation cleavage. They are composed of xenoblastic grains of quartz, and biotite and muscovite laths oriented parallel to the foliation. Detrital grains of zircon and tourmaline are present. Assemblages rich in sillimanite and andalusite occur close to the intrusive contacts.

Metasomatized and Uralitized McIntosh Gabbro. To the west of the Springvale Fault, coarse-grained Bow River Granite intrudes the McIntosh Gabbro. The large basic bodies have been uralitized and disrupted, and basic xenoliths are incorporated in the granite. Two types of contact relationship have been observed.

(i) The contact between the fine to medium-grained gabbro and granite is knife-sharp. The granite retains its coarse-grained porphyritic texture right to the contact and there is no chilled margin.

(ii) There is a narrow reaction zone up to 10 feet wide, between the gabbro and granite. The granite retains its coarse-grained porphyritic texture to the edge of the reaction zone. The reaction zone consists of a modified gabbro in which large ovoid crystals of oligoclase or andesine and a little microcline have developed. Some of the plagioclase has normal zoning. Quartz also forms large anhedral phenocrysts with small inclusions of microcline. Dark brown biotite is the predominant mafic mineral; it replaces blue-green spongy amphibole. The groundmass consists of fine-grained microcline, quartz, and plagioclase, and a few epidote crystals.

Close to the porphyritic granite contacts north of the Ord River, the altered gabbroic rocks contain biotite. No reaction zone was noted and all the basic bodies are probably rich in biotite. The altered gabbro consists of andesine, quartz, clinopyroxene, and subsidiary hypersthene. Deep red biotite surrounds and replaces the pyroxene. It is probable that the basic rocks have been transformed by the granite.

Seven of the basic rocks and one of the granites were analysed to investigate the alteration of the McIntosh Gabbro by the Bow River Granite (see Tables 8 and 9). Analyses Nos 1 and 2 in Table 8 are unaltered olivine gabbro and troctolite from the McIntosh Sill, and No. 3 is an unaltered gabbro which is surrounded by cordierite and sillimanite-rich gneisses. Analysis No. 4 is a uralitized gabbro from the core of the Armanda Sill and No. 5 is a uralitized gabbro from the margin of the Toby Sill. The uralitization was due to regional metamorphism or the intrusion of the post-tectonic Bow River Granite. Analysis No. 6 is a biotite-rich gabbro close to the intrusive contact with the Bow River Granite, and No. 7 is a gabbroic rock from the contact aureole of the granite intruding the McIntosh Gabbro. The Bow River Granite (No. 1, Table 9) is a coarse-grained porphyritic variety with slightly oval potassium feldspars.

The following general observations can be made after the examination of $Fe^{++}+Fe^{+++}/K+Na/Mg$, and K/Na/Ca variation diagrams (Fig. 12).

(i) The uralitized gabbros have virtually the same composition as the unaltered gabbros and troctolites, but the total water content is higher in the uralitized rocks.

Table 8

Chemical analyses of the McIntosh Gabbro.

	1	2	3	4	5	6	7	8	9	10
SiO_2	44.16	47.42	53.90	48.38	45.44	56.94	67.60	48.36	43.84	51.86
Al_2O_3	12.43	19.22	13.80	18.47	21.03	15.31	13.90	16.84	13.46	16.40
Fe_2O_3	1.50	0.99	1.48	1.18	1.22	1.27	1.19	2.55	2.20	2.73
FeO	12.58	4.07	13.00	6.00	6.55	7.29	4.20	7.92	9.24	6.97
MgO	17.55	10.92	6.15	7.97	8.87	5.28	1.61	8.06	19.71	6.12
CaO	9.18	15.10	8.95	13.14	12.56	7.86	3.26	11.07	8.16	8.40
Na_2O	1.20	1.11	0.38	1.81	1.64	2.09	2.16	2.26	1.33	3.36
K_2O	0.08	0.05	0.07	0.28	0.24	1.82	3.76	0.56	0.58	1.33
H_2O+	0.63	0.95	0.49	2.26	1.56	0.78	0.81	0.64	0.50	0.80
H_2O-	0.02	1.17	0.09	0.09	0.17	0.14	0.12	—	—	—
CO_2	—	—	0.06	—	—	—	0.03	—	—	—
TiO_2	0.38	0.18	1.29	0.45	0.44	0.86	0.67	1.32	0.67	1.50
P_2O_5	0.03	0.01	0.14	0.08	0.05	0.14	0.17	0.24	0.18	0.33
FeS_2	0.09	0.05	—	tr.	0.09	0.02	—	—	—	—
MnO	0.18	0.07	0.18	0.12	0.13	0.12	0.06	0.18	0.13	0.18
Total	100.01	100.31	99.98	100.23	99.99	99.92	99.54	100.00	100.00	100.00

*Molecular Proportions**

	1	2	3	4	5	6	7	8	9	10
SiO_2	40.41	43.47	52.31	45.28	42.36	53.94	64.95	45.15	39.40	48.46
Al_2O_3	13.41	20.77	15.79	20.38	23.11	17.10	15.75	18.55	14.26	18.07
Fe_2O_3	1.03	0.68	1.08	1.27	0.86	0.91	0.86	1.79	1.49	1.92
FeO	9.63	3.12	10.55	4.69	5.11	5.78	3.38	6.19	6.94	5.45
MgO	23.93	14.89	8.90	11.12	13.32	7.46	2.31	11.21	26.39	8.53
CaO	9.00	14.84	9.31	13.17	12.54	7.98	3.36	11.08	7.86	8.41
Na_2O	2.13	1.97	0.72	3.29	2.96	3.84	4.03	4.09	2.31	6.09
K_2O	0.12	0.06	0.09	0.33	0.29	2.20	4.61	0.67	0.66	1.59
CO_2	—	—	0.08	—	—	—	0.04	—	—	—
TiO_2	0.26	0.12	0.94	0.32	0.31	0.61	0.48	0.93	0.45	1.05
P_2O_5	0.02	0.01	0.12	0.06	0.04	0.11	0.14	0.19	0.14	0.28
FeS_2	—	—	—	—	—	—	—	—	—	—
MnO	0.14	0.05	0.15	0.09	0.10	0.10	0.05	0.14	0.10	0.14
Total	100.08	99.98	100.04	100.00	100.00	100.03	99.96	99.99	100.00	99.99

*Calculated on water-free basis.

1. Olivine gabbro, McIntosh Sill. (DR12.22.32. 17°44′10″S; 127°52′50″E). Analyst, P. Hewson (W.A. Gov. Chem. Lab.).
2. Troctolite, McIntosh Sill. (DR12.22.60B. 17°45′20″S; 127°53′40″E). Analyst, J. Gamble (W.A. Gov. Chem. Lab.).
3. Gabbro, at location surrounded by pyroxene granulite. (DR1.00.7. 17°04′S; 128°09′55″E). Analyst, M. R. Hanckel (AMDL).
4. Uralitized gabbro, Armanda Sill. (DR15A.06.39. 17°59′45″S; 127°48′30″E). Analyst, R. S. Pepper (W.A. Gov. Chem. Lab.).
5. Uralitized gabbro, Tobys Sill. (DR11.65.3. 17°37′15″E; 127°42′E). Analyst, A. J. Sims (W.A. Gov. Chem. Lab.).
6. Metasomatized gabbro. (DR6.34.8. 17°20′55″S; 127°56′55″E). Analyst, R. S. Pepper.
7. Metasomatized gabbro. (DR15A.11.1. 17°56′40″S; 127°39′25″E). Analysts, L. W. Castanelli and M. R. Hanckel (AMDL).
8. Average of 160 gabbros (Nockolds, 1954, p. 1020).
9. Average of 9 troctolites (Nockolds, 1954, p. 1020).
10. Average of 50 diorites (Nockolds, 1954, p. 1019).

Table 9

Chemical analyses of the Bow River Granite.

	1	2	3	Molecular Proportions 1	2	3
SiO_2	71.90	66.88	70.80	69.18	62.66	66.25
Al_2O_3	13.40	15.66	14.60	15.20	17.30	16.11
Fe_2O_3	0.74	1.33	1.60	0.54	0.94	1.13
FeO	2.29	2.59	1.80	1.84	2.03	1.41
MgO	0.50	1.57	0.90	0.72	2.19	1.26
CaO	1.82	3.56	2.00	1.88	3.57	2.01
Na_2O	2.02	3.84	3.50	3.77	6.98	6.35
K_2O	5.18	3.07	4.10	6.36	3.67	4.90
H_2O+	1.17	0.65	—	—	—	—
H_2O-	0.04	—	—	—	—	—
CO_2	0.11	—	—	0.14	—	—
TiO_2	0.40	0.57	0.40	0.29	0.40	0.28
P_2O_5	0.13	0.21	0.20	0.11	0.16	0.17
MnO	0.04	0.07	0.10	0.03	0.06	0.08
Total	99.74	100.00	100.00	100.06	99.96	99.95

1. Porphyritic Bow River Granite. (DR5.71.5. 17°16′30″S; 127°44′50″E). Analyst, M. R. Hanckel (AMDL).
2. Average of 137 granodiorites (Nockolds, 1954, p. 1014).
3. Average of 546 granites (Daly, 1933, p. 9).

(ii) The gabbros from the contact aureole appear to have been hybridized: No. 6 has the composition of an average diorite and No. 7 of an average granodiorite. Compared with the gabbroic parents the hybrids contain much more sodium, potassium, and silicon, and less calcium. The alkalis and silica have been introduced from the granitic magma.

(iii) The amount of total iron remains virtually the same in all samples.

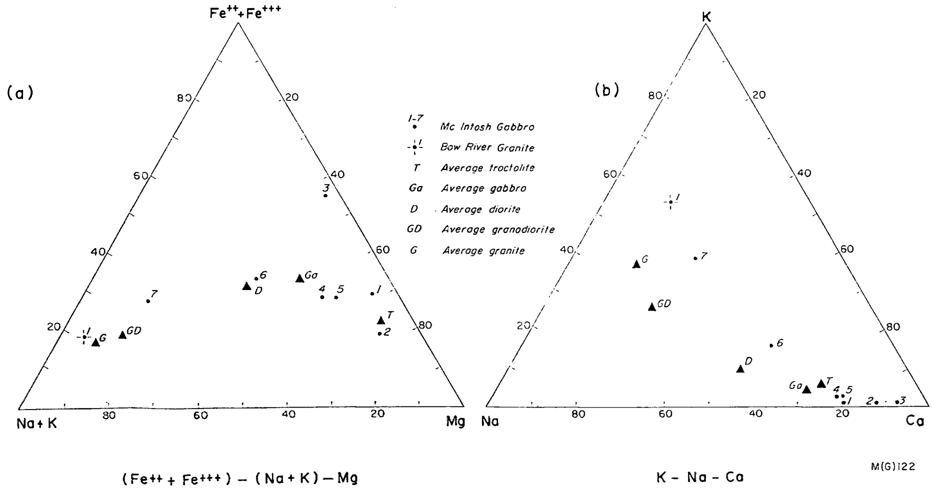


Figure 12

Variation diagrams for the McIntosh Gabbro and Bow River Granite.

These observations indicate that where granite intrudes gabbro, the basic rocks can be altered to rocks which are similar to the normal products of magmatic differentiation (diorite and granodiorite). It is possible that most of the granodiorite in the Bow River Granite was formed by the assimilation of basic rocks by a granitic magma.

Similar reactions between a granitic magma and basic wall rocks have been observed by Turner (1937) at Lake Manapouri in New Zealand.

Granite-Gabbro Breccias. West of the Toby Sill, between Tickalara Bore and the Ord River, and between Robin Soak and Halls Creek, coarse-grained granite has intruded, uralitized, and brecciated the gabbroic rocks (Pl. 13, fig. 2). These breccias, which contain almost equal amounts of basic and granitic rocks, have been denoted by the term 'mixed rocks'.

Skarn. Where coarse-grained granite intrudes calcareous rocks of the Halls Creek Group, banded skarns and marble have been formed. The skarns are granular and coarse-grained, and contain garnet, diopside, and subordinate epidote and carbonate. The rocks are cut by ramifying veins of quartz.

Retrogressed Tickalara Metamorphics. Contact aureoles are present in many areas where the Tickalara Metamorphics have been intruded by coarse-grained granite, but the contacts are generally obscured, and the only evidence of later alteration is the presence of retrogressively formed minerals.

Two miles west of Mabel Downs homestead (field geology by D. B. Dow), coarse even-grained granite intrudes a foliated biotite-garnet gneiss. The contact aureole is up to 20 feet wide, and contains potassium feldspar phenocrysts up to half an inch across. The development of the phenocrysts is similar to those in a large xenolith (50 ft by 20 ft) of Tickalara Metamorphics in the porphyritic granite 1 mile to the southeast. The altered rock is composed of euhedral microcline and rewelded quartz phenocrysts set in a foliated groundmass of quartz and biotite. The foliation wraps around the phenocrysts, which suggests that it was formed at the same time as, or later than, the microcline. The accessories are hornblende, epidote, and sphene.

North of Moola Bulla homestead large roof pendants of banded sillimanite-cordierite-rich paragneiss are present in the coarse-grained porphyritic granite. The small xenoliths of metamorphic rocks in the granite have a prominent secondary foliation and compositional banding which are not post-dated by minerals such as garnet, sillimanite, and cordierite. Though the xenolith-granite contact is knife-sharp, and there are no visible contact effects, the replacement of cordierite by muscovite may be related to the granitic intrusives.

Late Dykes

The final phase of the Bow River Granite intrusion was the development of pegmatite dykes and schlieren and aplite dykes. The thin quartz-feldspar-mica pegmatite dykes and schlieren are generally restricted to the intrusive granites, but the dykes may extend for a short distance into the country rock, in which case tourmaline-rich pegmatites are formed.

The pegmatite dykes are concentrated near Carrington Springs, north of Palm Creek, and near Mabel Downs homestead.

The homogeneous aplite dykes range from inches to hundreds of feet in width and intrude various rock types close to the granite contact. In places, fine-grained gabbro has been intruded by a network of aplite dykes. The dykes are fine-grained and saccharoidal, and consist of microcline, subordinate saussuritized plagioclase, quartz, and interstitial clots of chlorite and epidote.

CASTLEREAGH HILL PORPHYRY (Field geology by D. Dunnet).

Quartz-feldspar porphyry crops out around Greenvale homestead, in the north-western part of the Dixon Range Sheet area, and extends northwards, along the eastern side of the Dunham Fault, to the O'Donnell Brook in the Lissadell Sheet area. Near McPhee Creek a sheet-like body of porphyry crops out along the south-western side of the Carr Boyd Ranges, and extends from the Ivanhoe Fault in the south to near Dunham Hill to the north. Some of the rocks in the Golden Gate area have been included in the Castlereagh Hill Porphyry, and small exposures are also found near Mount Pitt.

The porphyry is commonly dark grey and fine-grained. It is composed of phenocrysts of oligoclase, quartz, and potassium feldspar, set in a groundmass of quartz, potassium feldspar (commonly as granophyric intergrowths), oligoclase(?), biotite, and chlorite after amphibole(?). The accessories are apatite, zircon, and sphene. The quartz phenocrysts are commonly resorbed and may be glomero-porphyritic. Oligoclase is generally more abundant than potassium feldspar. Small inclusions, up to 6 inches long, of sedimentary and fine-grained igneous rocks are common.

The exposure near McPhee Creek appears to be a sheet-like body dipping gently to the east. It grades over a thickness of about 500 feet from a medium-grained hornblende-biotite porphyry at the base, through a fine-grained biotite porphyry to a massive fine-grained black porphyry at the top.

In places, the Castlereagh Hill porphyry is intruded by the Bow River Granite, but elsewhere it intrudes the granite. In the Golden Gate area the porphyry intrudes the Whitewater Volcanics at the base of the Proterozoic sediments.

Dow et al. (1964) have suggested that the Castlereagh Hill Porphyry is co-magmatic with the Whitewater Volcanics and that it represents a late high-level intrusive phase of them, but isotopic ages (V. M. Bofinger, pers. comm.) indicate that the porphyry and granite are contemporaneous.

SOPHIE DOWNS GRANITE

The Sophie Downs Granite is restricted to anticlines and fault zones in the Halls Creek Group. The copper and tin mineralization, and possibly also the gold mineralization, was probably associated with the intrusion of this granite. The age of the intrusion is unknown, and it may be older or younger than the Bow River Granite.

Type Area

The Sophie Downs Granite (Ruker, 1961) is a small granite pluton 10 miles by 4 miles, which intrudes an elongated dome east of the Halls Creek Fault. It was emplaced after the folding of the Halls Creek Group. The granite is unfoliated but is concordant with the enveloping country rocks, and has a marked contact aureole. It encloses two lenticular xenoliths of the country rock along its eastern margin. It may be genetically related to the Bow River Granite to the west.

The pluton is composed of fine to coarse-grained granophyric granite with fine-grained microgranite on its northern margin.

The granophyric granite is composed of irregular grains of microperthite, and quartz, which commonly form graphic intergrowths. The microcline encloses a few laths of sodic plagioclase. Green biotite occurs in clusters of decussate flakes. The accessories include fine-grained iron oxides and zircon.

Contact Metamorphic Rocks. Schist and amphibolite crop out close to the margins of the Sophie Downs Granite. On the southern margin, grey to dark brown well foliated and crenulated schist is intercalated with amphibolite. The following mineral assemblages were found in the schist: quartz-muscovite-biotite, quartz-muscovite-biotite-chlorite-garnet, quartz-biotite-muscovite-garnet, and quartz-biotite-muscovite-andalusite. The dominant foliation (cleavage?) is defined by lepidoblastic red-brown biotite, chlorite, or muscovite. The crenulation cleavage post-dates this foliation, and the tiny porphyroblastic garnets have inclusion trails which are not crenulated. Quartz is commonly fine-grained and forms an intersutured mosaic. A little spongy andalusite may be present. The large subidioblastic flakes of chlorite post-date the crenulation cleavage.

The amphibolite on the northern margin of the Sophie Downs Granite was probably formed by contact metamorphism of basic volcanic rocks or dolerite. It is composed of rosettes of decussate dark green hornblende associated with tiny grains of plagioclase (albite?), augen of epidote, and fine granular quartz. Dendritic iron oxides define the foliation.

Mineralization. Limonitic gossans with secondary copper minerals crop out 6 miles north of the Sophie Downs Granite (Gemuts, 1963). The gossans are localized on shear zones in regionally metamorphosed and intensely folded calcareous rocks. The source of the mineralization was possibly the Sophie Downs Granite.

Cummins/McClintock Range Area

Five elongate granite plutons crop out in the Cummins and McClintock Ranges. Three of them occur in the cores of anticlines and the other two were intruded parallel to the Woodward Fault. All the plutons were emplaced in folded rocks of the Halls Creek Group, and all are associated with tin-bearing pegmatites.

The plutons consist of white, massive, equigranular, medium to coarse-grained granite. There is no change in grainsize at their margins.

The granites consist of microcline, quartz, subordinate oligoclase to andesine, and irregular clots of interlathed biotite and muscovite. The microcline contains poikilitic inclusions of plagioclase, which are replaced by aggregates of sericite, epidote, and chlorite. The accessories are iron oxides and tourmaline.

Contact Relationships. The contacts between the granites and country rock are irregular, and the intrusions are usually discordant. In the thermal contact aureoles the biotite schists pass into hornfels towards the granite contacts. The hornfels is fine-grained and banded around the granites intruding the anticlines in the McClintock Ranges; the mafic bands contain fine granular epidote, ragged biotite, sphene, and opaque minerals. The leucocratic bands are composed of irregular grains of microcline, altered plagioclase, and quartz.

Skarns have been formed in the contact aureole of the granite intruded parallel to the Woodward Fault. They are massive and brown, and contain red granular garnet, white diopside, and light green epidote cut by ramifying veins of quartz. The garnet forms irregular masses and has numerous fractures enclosing diopside and epidote.

Late Dykes

Where the granites intrude the Olympio Formation, pegmatite dykes have been developed in the sediments. They form discontinuous randomly oriented bodies which may be concordant or discordant with the sediments. They range up to 500 feet long and from 10 to 200 feet wide. They are commonly composed of varying proportions of microcline, lamellar albite, quartz, greenish yellow flakes of muscovite, and crystals of black tourmaline up to 2 inches long. The accessories include garnet and ilmenite, and almost all of them contain cossiterite and tantalite. The biotite schists on the margins of the pegmatites contain scattered crystals of andalusite and pyrite.

In addition to the pegmatites, small aplite dykes, up to 20 feet wide, intrude the granite and country rocks close to granite contacts.

Metamorphic Environment of the Pegmatite Dykes. The pegmatite dykes are restricted to a specific zone of metamorphism which is outlined by the appearance of biotite in the Olympio Formation. The biotite isograd shown in Figure 13 is the western limit of the pegmatites, and also encloses the Sophie Downs Granite.

It is believed that the regional development of biotite was related to a cycle of regional metamorphism which antedates the intrusive rocks; all the metamorphic assemblages are similar to those of Zone B in the Tickalara Metamorphics.

The greywacke and siltstone in the Olympio Formation have been metamorphosed to medium-grained foliated and lineated schists. The foliation is parallel to the bedding and is accentuated by alternating bands rich in mica and poor in mica. The bedding is cut by a steep axial-plane cleavage. The following assemblages were noted: quartz-muscovite-biotite, quartz-biotite-muscovite-albite, quartz-biotite-muscovite-garnet, and quartz-biotite-muscovite-epidote-garnet.

Dark brown biotite and muscovite laths, defining pelitic bands or axial-plane cleavage, are interspersed with bands or areas of granular quartz. Most of the schists are garnetiferous; the garnets occur as tiny grains or large spongy porphyroblasts. The garnet both antedates and postdates the axial-plane cleavage. Ovoid twinned albite porphyroblasts postdate the cleavage, and epidote is marginal to or replaces the feldspar. The accessories include zircon, tourmaline, and iron oxide grains. In some of the schists the tourmaline is detrital, but close to the pegmatite dykes the euhedral tourmaline is metasomatic in origin.

Other metamorphic rocks enclosed by the biotite isograd include graphite schist, amphibolite, and calc-silicate rocks. The graphite schists which were derived from carbonaceous siltstone, consist of granular quartz interfoliated with subordinate graphite and ragged muscovite. The amphibolite and associated calc-silicate rocks were derived from metamorphosed dolerite dykes. The amphibolites are dark green, medium-grained, slightly foliated, lineated, and sometimes banded. The ragged to idioblastic blue-green hornblende is interspersed with irregular grains of clear plagioclase (albite to labradorite) and quartz. Epidote is intergrown with the feldspar, and the hornblende is speckled with ilmenite replaced by sphene. Some of the amphibolites are rich in quartz while others contain pods of epidote parallel to the foliation.

The carbonate-rich dolerite dykes are black or dark green and coarse-grained. They are foliated and banded, with alternating bands and pods of light green epidote and white carbonate in a background of dark pyroxene and amphibole. They are composed of needles of light green amphibole and tabular diopside inter-banded with xenoblastic epidote, sphene, and carbonate. The clear xenoblastic checkerboard albite and quartz form porphyroblasts enclosed by carbonate.

VIOLET VALLEY TONALITE

The Violet Valley Tonalite intrudes the Tickalara Metamorphics, Mabel Downs Granodiorite, and Bow River Granite 6 miles to the northwest of Mabel Downs homestead. The tonalite is massive, fine to coarse-grained, non-foliated, and rich in biotite. It is readily distinguished from the surrounding rocks by its characteristic black pattern on the air-photographs.

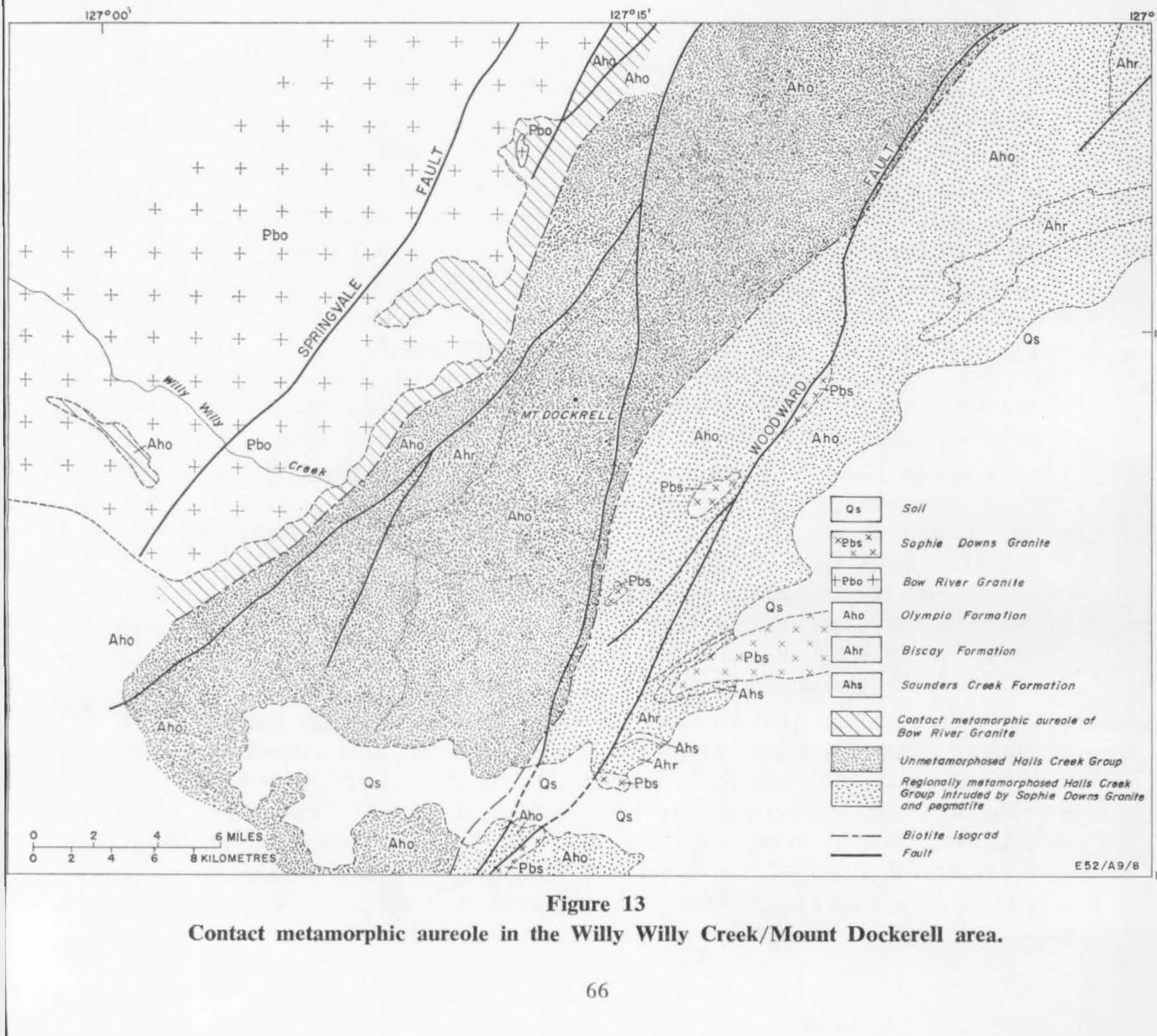


Figure 13
Contact metamorphic aureole in the Willy Willy Creek/Mount Dockerell area.

Large exfoliated bouldery outcrops of equigranular medium to coarse-grained tonalite crop out along the Mueller Range in the Mount Ramsay Sheet area. The tonalite intrudes the Halls Creek Group and Bow River Granite. Where it intrudes the sediments, a narrow zone of banded biotite gneiss and hornfels has been developed near the contact, but where it intrudes the Bow River Granite the contact is sharp and no xenoliths of the country rock occur in the tonalite.

The tonalite consists mainly of oscillatory zoned plagioclase ranging from oligoclase to andesine, associated with interstitial quartz and clots of biotite and chlorite.

McHALE GRANODIORITE

The McHale Granodiorite intrudes the Halls Creek Group in the Osmond Range inlier east of the Halls Creek Fault, and 10 miles farther north along the fault. D. B. Dow (pers. comm.) has suggested that this granodiorite was contemporaneous with the Violet Valley Tonalite.

LATE DYKES

Various late-stage dykes cut the Lamboo Complex. They all post-date the Bow River Granite, and none of them appear to be related to any of the igneous rocks in the Lamboo Complex. They generally crop out as straight resistant ridges.

Dolerite

The dolerite dykes are up to 16 miles long and 200 feet wide. Most of them are confined to the western part of the complex, where they intrude small shear zones and joint planes in the Bow River Granite, but some of the dykes truncate the Tickalara Metamorphics, McIntosh Gabbro, and Mabel Downs Granodiorite. The trend of the dykes ranges from north-northwest to north-northeast. The dykes commonly occur in swarms of up to 10 dykes; they are generally parallel but some of them intersect each other. The contacts with the country rock are sharp, and they are seldom metamorphosed. The dolerites have chilled margins up to 5 feet wide.

The dolerites are commonly fine to medium-grained and black. They have an ophitic texture and are composed of lath-like labradorite and a little granular epidote set in a groundmass of subhedral augite, titanaugite, or pigeonite, and iron oxides. The pyroxene is commonly uralitized and the plagioclase is generally saussuritized. Some of the rocks have interstitial patches with a spherulitic structure which may represent residual devitrified glass.

A dyke with a different texture was noted 12 miles northwest of Moola Bulla homestead. The rock contains coarse zoned phenocrysts of labradorite, up to 2 inches across, set in a fine-grained groundmass containing smaller phenocrysts of amphibole and quartz. The euhedral, oscillatory zoned, and partly saussuritized labradorite, quartz, and altered pyroxene are set in a fine-grained groundmass of amphibole and biotite laths. The pyroxene is altered to pools of biotite, muscovite, and amphibole. The dyke may be a deuterically altered porphyritic quartz dolerite.

Many of the dykes intruding the Castlereagh Hill Porphyry in the Golden Gate area have been uralitized. There is no evidence of metamorphism, and the uralitization may have been an auto-metamorphic effect.

Near McPhee Creek, 1 mile from the Great Northern Highway, a uralitized dyke has been intruded into coarse-grained granite. Autunite and earthy yellow uranium ochre have been deposited as thin linings on shear planes and joint surface in the dyke (de la Hunty, 1957).

Diorite

West of Mabel Hill, in the Springvale homestead area, and to the north of the Armanda Sill area, north-northwesterly trending diorite dykes intrude coarse-grained granite and basic rocks.

The diorite is dark green and consists of coarse olive-green hornblende phenocrysts set in a groundmass of finer granulated hornblende and quartz. The groundmass consists of tiny amphibole crystals, clinopyroxene, andesine, and a little potassium feldspar and quartz. Clinopyroxene is replaced by hornblende and the centres of the amphibole phenocrysts have been replaced by granular aggregates of epidote.

Aplite

Leucocratic medium-grained aplite dykes intrude the Tickalara Metamorphics north of Mabel Downs Station. The dykes are up to 2 miles long and 50 feet wide; they are commonly curved and often intersect each other. No granites are present in the vicinity.

The aplites are white and have small biotite clots set in a quartzo-feldspathic base. They consist of irregular grains of potassium feldspar, oligoclase, and quartz, with a little spongy pink garnet ensheathed by dark brown biotite.

Pegmatite

The numerous pegmatite dykes and schlieren in the Tickalara Metamorphics are not directly related to any granitic intrusions.

Northeast of Turkey Creek, a dyke 6 feet wide and 600 feet long crops out (field geology by D. B. Dow). It consists of graphic intergrowths of quartz and potassium feldspar, muscovite, and a little magnetite, ilmenite, and epidote. Small dykes, from 3 to 6 feet long, occur parallel to the foliation and replace the pyroxene granulite bands. The small dykes were introduced contemporaneously with the faulting which has dislocated the granulite bands. The pegmatites have induced the growth of quartz porphyroblasts in the irregular basic remnants.

Quartz-Feldspar Porphyry

Quartz-feldspar porphyry dykes are confined to the region round Palm Creek and its tributaries. They are up to 2 miles long and 50 feet across, and trend east-west. They intrude coarse-grained porphyritic granite, and have sharp contacts with the country rocks. No chilled margins or contact metamorphism were noted. The dykes may be co-magmatic with the microgranite sills and dykes in the Biscay Formation (Dow & Gemuts, 1965) and with the porphyry intrusion in the Armanda Sill (see p. 19).

The quartz-feldspar porphyries are grey and slightly foliated. They consist of small phenocrysts of greenish feldspar and clear quartz set in cryptocrystalline groundmass. The subhedral orthoclase phenocrysts and acid plagioclase laths are ensheathed by biotite. The groundmass consists of fine-grained orthoclase, quartz, a little plagioclase, and fine irregular flakes of chlorite and biotite. Radial intergrowths of quartz and feldspar, resembling spherulites, occur throughout the groundmass.

'UNDIFFERENTIATED' ROCKS

Near Mount Pitt and 4 miles northeast of Mount Nyulasy a bewildering variety of rock types, ranging from gabbro to hornblende granodiorite, crop out within a radius of 100 feet. They may have been derived from a highly contaminated magma, or from a mixture of basic and acid magmas.

Similar rocks are intermixed with the Tickalara Metamorphics along the Halls Creek Fault to the south. All these rocks are designated as 'undifferentiated' Lamboo Complex on the map.

REFERENCES

BARROW, G., 1893 — On an intrusion of muscovite-biotite gneiss in the south-east Highlands of Scotland. *Quart. J. geol. Soc. Lond.*, 49, 330.

BARROW, G., 1912 — On the geology of lower Deeside and the southern Highland border. *Proc. geol. Assoc. (Lond.)*, 23, 268.

BARTH, T. F. W., 1962—THEORETICAL PETROLOGY. *N.Y., Wiley.*

BASTIN, E. S., 1909 — Chemical composition as a criterion in identifying metamorphosed sediments. *J. Geol.*, 17(5), 445.

BINNS, R. A., 1963 — Some observations on metamorphism at Broken Hill, N.S.W. *Proc. Aust. Inst. Min. Metall.*, 207, 239.

BLAKE, D. H., ELWELL, R. W. D., GIBSON, I. L., SKELHORN, R. R., and WALKER, G. P. L., 1965 — Some relationships resulting from the intimate association of acid and basic magmas. *Quart. J. geol. Soc. Lond.*, 121, 31.

CLARKE, F. W., 1924 — Data of geochemistry. *U.S. geol. Surv. Bull.* 770.

DALY, R. A., 1933 — IGNEOUS ROCKS AND THE DEPTHS OF THE EARTH, *N.Y., McGraw-Hill.*

DE LA HUNTY, L. E., 1955 — Report on Kimberley radioactive deposits. *Geol. Surv. W. Aust. Bull.* 112.

DE SITTER, L. V., 1956 — STRUCTURAL GEOLOGY. *N.Y., McGraw-Hill.*

DOW, D. B., and GEMUTS, I., 1967 — Dixon Range, W.A., — 1:250,000 Geological Series. *Bur. Miner. Resour. Aust. explan. Notes* SE/52-6.

DOW, D. B., and GEMUTS, I., 1969 — Geology of the Kimberley region, Western Australia. The East Kimberley. *Bur. Miner. Resour. Aust. Bull.* 106.

DOW, D. B., GEMUTS, I., PLUMB, K. A., and DUNNET, D., 1964 — The geology of the Ord River region, Western Australia. *Bur. Miner. Resour. Aust. Rec.* 1964/104 (unpubl.).

DUNNET, D., and PLUMB, K. A., 1968 — Lissadell, W.A. — 1:250,000 Geological Series. *Bur. Miner. Resour. Aust. explan. Notes* SE/52-2.

ESKOLA, P., 1939 — DIE ENTSTEHUNG DER GESTEINE. *Berlin, Springer.*

FYFE, W. S., TURNER, F. J., and VERHOOGEN, J., 1958 — Metamorphic reactions and metamorphic facies. *Mem. geol. Soc. Amer.*, 73.

GEMUTS, I., 1963 — Preliminary report on copper mineralisation in the Duffers Limestone, near Halls Creek, Kimberley Goldfield. *Geol. Surv. W. Aust. Rec.* 1963/28 (unpubl.).

GUPPY, D. J., LINDNER, A. W., RATTIGAN, J. H., and CASEY, J. N., 1958 — The geology of the Fitzroy Basin, Western Australia. *Bur. Miner. Resour. Aust. Bull.* 36.

HALFERDAHL, L. B., 1956 — Chloritoid. *Carnegie Instn. Washington. Ann. Rep. Dir. geophys. Lab.*, No. 55 (1955-56), 200.

HARDMAN, E. T., 1884 — Report on the geology of the Kimberley district. *W. Aust. parl. Pap.* 31.

HARDMAN, E. T., 1885 — Report on the geology of the Kimberley district, Western Australia. *Ibid.*, 34.

HARKER, A., 1939 — METAMORPHISM. *London, Methuen.*

HILLS, E. S., 1945 — Some aspects of the tectonics of Australia. *J. Roy. Soc. NSW*, 79, 67.

MATHESON, R. S., and GUPPY, D. J., 1949 — Geological reconnaissance in the Mount Ramsay area, Kimberley Division, Western Australia. *Bur. Miner. Resour. Aust. Rec.* 1949/48 (unpubl.).

MISCH, P., 1964 — Stable association wollastonite-anorthite, and other calc-silicate assemblages in amphibolite-facies crystalline schists of Nanga Parbat, northwest Himalayas. *Beitr. Miner. Petrogr.*, 10, 315.

MIYASHIRO, A., 1958 — Regional metamorphism of the Gosaisyo-Takanuki district in the central Abukuma Plateau. *Tokyo Univ. Fac. Sci.,* 11, 219.

MIYASHIRO, A., 1961 — Evolution of metamorphic belts. *J. Petrol.,* 2, 277.

NOAKES, L. C., 1953 — The structure of the Northern Territory with relation to mineralisation; *in* GEOLOGY OF AUSTRALIAN ORE DEPOSITS, *5th Emp. Min. metall. Cong.,* 284.

NOCKOLDS, S. R., 1954 — Average chemical composition of some igneous rocks. *Bull. geol. Soc. Amer.,* 65, 1007.

PETTIJOHN, F. J., 1957 — SEDIMENTARY ROCKS. *New York, Harper.*

PITCHER, W. S., 1965 — The aluminium silicate polymorphs; *in* CONTROLS OF METAMORPHISM. *Edinburgh & London, Oliver & Boyd,* 327.

POLDERVAART, A., 1953 — Metamorphism of basaltic rocks: a review. *Bull. geol. Soc. Amer.,* 64, 259.

POLDERVAART, A., 1955 — Chemistry of the earth's crust; *in* CRUST OF THE EARTH. *Geol. Soc. Amer. spee. Pap.* 62, 119.

READ, H. H., 1939 — Metamorphism and igneous action. *Nature,* 144, 729.

ROBERTS, H. G., HALLIGAN, R., and PLAYFORD, P. E., 1967 — Mount Ramsay, W.A. — 1:250,000. Geological Series. *Bur. Miner. Resour. Aust. explan. Notes* SE/52-9.

RUKER, R. A., 1961 — The Saunders Creek radioactive prospect, Halls Creek district, Western Australia. *Bur. Miner. Resour. Aust. Rec.* 1961/103 (unpubl.).

SHIDO, F., 1958 — Plutonic and metamorphic rocks of the Nakaso and Iritone districts in the central Abukuma Plateau. *J. Tokyo Univ. Fac. Sci.,* 11, 131.

SIMPSON, E. S., 1951 — MINERALS OF WESTERN AUSTRALIA. *By authority, Perth,* 3 vols.

SMITH, C. H., 1958 — Bay of Islands igneous complex, western Newfoundland. *Geol. Surv. Canada Mem.* 290.

SMITH, J. W., and GEMUTS, I., 1967 — Gordon Downs, W. Aust.—1:250,000 Geological Series. *Bur. Miner. Resour. Aust. explan. Notes* SE/52-10.

TILLEY, C. E., 1926 — On some mineralogical transformations in crystalline schists. *Min. Mag.,* 21, 34.

TRAVES, D. M., 1955 — The geology of the Ord-Victoria region, northern Australia. *Bur. Miner. Resour. Aust. Bull.* 27.

TURNER, F. J., 1937 — The metamorphic and plutonic rocks of Lake Manapouri, Fiordland, New Zealand, II. *Trans. Roy. Soc. N.Z.,* 67(2), 227.

TURNER, F. J., 1938 — Progressive regional metamorphism in southern New Zealand. *Geol. Mag.,* 75, 160.

TURNER, F. J., and VERHOOGEN, J., 1960 — IGNEOUS AND METAMORPHIC PETROLOGY. *N.Y., McGraw-Hill.*

VENKATES, H. V., 1952 — Development of growth of cordierite in paralavas. *Amer. Miner.,* 37, 831.

VERHOOGEN, J., 1951 — The chemical potential of a stressed solid. *Trans. Amer. geophys. Un.,* 32, 251.

VON PLATEN, H., 1965 — Experimental anatexis and genesis of migmatites; *in* CONTROLS OF METAMORPHISM. *Edinburgh & London, Oliver & Boyd,* 203.

WASHINGTON, H. S., 1917 — Chemical analyses of igneous rocks. *U.S. geol. Surv. prof. Pap.,* 99.

WHITE, A. J. R., 1959 — Scapolite-bearing marbles and calc-silicate rocks from Tungkillo and Milendella, S.A., *Geol. Mag.,* 96, 285.

WILSON, A. F., 1959 — The charnockitic rocks of Australia. *Sonder-geol. Rdsch.,* 47, 491.