THE THERMAL METAMORPHISM OF PORTIONS OF THE WOLOMIN GROUP IN THE ARMIDALE DISTRICT, N.S.W.

PART I. THE PUDDLEDOCK AREA.

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With Plate XII and two Text-figures.
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ABSTRACT.

A portion of the intrusive contact between the New England batholith, and the eugeosynclinal Woolomin Group occurs near Puddledock, in northern New South Wales. The igneous complex comprises mainly quartz monzonite with subordinate hypersthene diorite, pyroxene granite, biotite porphyrite and dolerite. The sedimentary group originally consisted of greywacke, quartzite and basic lava, which are now represented by biotite hornfels, saccharoidal quartzite and a group of rocks rich in calc-silicate minerals.

INTRODUCTION.

The great New England batholith is a multiple intrusion of subsequent type which extends for over two hundred miles through the eastern highlands of northern New South Wales and southern Queensland as a meridional belt. It is chiefly acid in character, although there are variations from basic to ultra-acid types.

The intruded rocks around Armidale consist of a thick and broadly folded eugeosynclinal series consisting of greywackes (as defined by Pettijohn, 1949), polymictic breccias, sub-greywackes, quartzites, jaspers and basic lavas which has been named the Woolomin Series by Benson (1918) and Voisey (1942). These rocks are referred to here as the Woolomin Group, rather than the Woolomin Series, in accordance with the Code of Stratigraphic Nomenclature (Raggatt, 1950) because the length of time involved in their deposition is at present unknown, hence the "rock" term group is preferred to the "time-rock" term series. Due to the lack of diagnostic organic remains, the age of these rocks is not known, but they are regarded as probably Silurian-Devonian. Regional metamorphism is lacking unless the silicification which gave rise to the widespread jaspers can be regarded as a low-grade regional metasomatic process. Thermal metamorphism by both the Epi-Silurian (?) and Permian batholiths is rather slight, and restricted to fairly narrow contact aureoles. Metasomatism associated with the intrusions is uncommon, although scapolitization of the basic lavas has been found in two localities. These rocks are well shown in the area described, which is about half a mile north-east of the Puddledock Dam and 10 miles north-east of Armidale. A portion of the intrusive contact is exposed in an area of about two acres, which is entirely surrounded by flat-lying Tertiary basalts. Mapping was done by plane-table on a scale of 200 feet to 1 inch, and the contours shown on Figure 1 are taken from a purely arbitrary 1,000 feet datum level.
THE IGNEOUS ROCKS.

The main body is a quartz monzonite with a chilled margin and a steeply dipping sharp contact with the sediments. The other igneous rocks are found in small bodies and their mutual relations are somewhat obscured by soil cover and consequently the intrusive sequence could not be established definitely. The probable order is as follows:

1. Biotite porphyrite.
2. Hypersthene diorite.
3. Quartz monzonite.
4. Pyroxene granite.
5. Dolerite.

The biotite porphyrite occurs as an elongated, dyke-like body about 30 feet wide and 800 feet long. It appears to be cut off at one end by the hypersthene diorite and consequently is regarded as the earliest intrusive. It is a light grey porphyritic rock with a very fine-grained groundmass rich in poorly twinned albite crystals and contains phenocrysts of biotite, hornblende and andesine (Ab₈₅).

The hypersthene diorite is a coarse-grained brownish rock consisting of almost equal amounts of felspars and ferromagnesian minerals. The relative amounts of orthoclase and plagioclase are variable and the rock might be termed diorite in some specimens and monzonite in others. Plagioclase is most abundant (35%) as subhedral crystals which are often strongly zoned (oligoclase Ab₇₀ to andesine Ab₅₀) and twinned on combinations of the Albite and Carlsbad laws. Orthoclase is present in quantities up to 30% and appears as slightly perthitic crystals which are frequently moulded on plagioclase giving a monzonitic fabric. The dark minerals are augite, hypersthene, hornblende and biotite. The pyroxene is chiefly augite, accompanied by quite abundant hypersthene, and
the two may be intergrown or surrounded by a corona of hornblende or biotite. There is about 5% quartz occurring as tiny intergranular crystals or as blebs and myrmekitic growths in the orthoclase. A striking feature is the presence of about 2% of apatite which occurs as aggregates of rod-like prisms frequently radiating outwards from the pyroxene. As this intrusion is early in the sequence, the coronas of hornblende and biotite and also the growths of apatite could be interpreted as being due to the thermal metamorphism of the rock by later intrusions, but it is thought they are most probably the result of deuteric crystallization.

The quartz monzonite is a light coloured, medium-grained rock becoming dark coloured and fine-grained in the chilled marginal zone. Near the contact the rock is a micro-monzonite, generally even grained, or slightly porphyritic with larger plagioclase phenocrysts set in a slightly finer grained matrix containing felspar with biotite, augite, hornblende and occasional hypersthene. It is usually a mid-andesite, but may be zoned from oligoclase Ab$_{85}$ to andesine Ab$_{50}$. Dusty orthoclase is present in amounts up to about 20% and quartz may be almost absent or up to 15%. The most abundant ferromagnesian mineral is biotite. Green augite and hypersthene are usually fringed with biotite or pale green hornblende.

The normal quartz monzonite differs from the border phase in its coarser grain and lack of pyroxene. It is a medium to coarse grained rock containing plagioclase, orthoclase and biotite with a little hornblende and quartz, and shows a monzonitic fabric. The plagioclase is well formed and is andesine, but shows zoning from Ab$_{70}$ to Ab$_{55}$. Orthoclase is anhedral and dusty and surrounds the plagioclase. Quartz is present up to 20% as grains or vermiculate growths with felspar. Biotite is abundant and often intergrown with pale hornblende.

The pyroxene granite occurs as a few small outcrops located between the monzonite, diorite, porphyrite and hornfels. It does not show any significant relation towards them and there is nothing to indicate whether it was intruded before or after the neighbouring rocks. It is only about 50 feet by 30 feet in area. It is a coarse-grained, leucocratic rock containing perthitic orthoclase (65%), quartz (24%), augite (8%), sphene (3%) and a very little plagioclase (oligoclase Ab$_{50}$). The augite is green and slightly pleochroic while sphene is remarkably abundant as brown prisms and grains.

The dolerite is a fine-grained greenish-grey rock which occurs in a very small outcrop in the east end of the central basic hornfels mass. It occurs only a few feet from the monzonite and intrudes the Group B hornfelses. It has an intergranular texture with laths of albite up to 0.1 mm. long forming an imperfect mesh enclosing the ferromagnesian minerals. These are entirely secondary and consist chiefly of pale green, almost isotropic chlorite, tiny needles of tremolite (?) and a very little brown hornblende. Epidote occurs as scattered small grains, and ilmenite is very abundant with a great deal of finely granular sphene. This dolerite has many affinities with the spilites and was at first considered to have been a pre-granite intrusion associated with the Woolomin volcanism. However, as it occurs within basic rocks which have been strongly metamorphosed and which contain garnet, pyroxene, wollastonite, etc., it is unlikely, in view of its unmetamorphosed character, that it could have been in position prior to the emplacement of the monzonite, and consequently it is placed at the end of the intrusive cycle.

The texture, composition and dyke-form of the biotite porphyrite are more in keeping with the later phases of emplacement of the batholith, and it was at first considered to be part of the widespread system of dykes of porphyry and lamprophyre which are a feature of the last phases of this intrusive cycle. The field evidence appears to preclude this view, and indicates that the dyke invaded
the sediments first, and was followed and partly obliterated by the later hypersthene diorite. The diorite was followed by the major intrusion of quartz monzonite which cuts across all the other rocks. This has a chilled margin and the mineralogical differences from the edge inwards indicate the trend of crystallization. The micro-monzonite has less quartz, less hornblende and a more basic plagioclase and contains augite and hypersthene, which are absent from the quartz monzonite. The position of the rather basic pyroxene granite in the sequence is not known, but from the abundance of quartz and orthoclase it has been tentatively regarded as the last plutonic unit to form. The abundance of such minerals as pyroxene (augite and hypersthene) apatite and sphene in the hypersthene diorite and pyroxene granite suggests that they may have been contaminated by absorbing some spilitic, but no field evidence was found to support this hypothesis.

The Metamorphic Rocks.

The rocks which have been altered by the intrusion were originally fine grained greywacke, quartzite and spilitic. These have been altered to varying degrees, but because of their widely different chemical compositions it was not possible to find zones of decreasing grade of metamorphism away from the intrusion. Both greywackes and spilitic attained the amphibolite facies of Turner (1948), but the latter may have reached the pyroxene hornfels facies in one place.

The Basic Hornfelses.

The most interesting of the thermally altered rocks are those derived from the basic lava flow. It has been observed in several localities around Armidale that basalts have been altered to rocks of spilitic nature prior to the intrusion of the batholith and that the thermal metamorphism operated on the spilitic mineral assemblage. There are two major groups which have different mineralogical and textural characteristics and each of these groups is subdivided into varieties.

A. Those showing original igneous texture.
   (1) Hornblende rich.
   (2) Diopside rich.
   (3) Scapolite or prehnite rich.

B. Those not showing original igneous texture.
   (1) Calcite quartz bearing.
   (2) Wollastonite bearing.

Group A.

The spilitic which occurs as the narrow band shown in the upper central part of Figure I is less altered and still retains some of the original igneous (amygdaloidal and intergranular) texture. The three varieties show differing original composition and degree of alteration with the typical associations hornblende-albite, diopside-andesine and diopside-scapolite (or prehnite).

The hornblende rich variety is a dense green rock which appears to show least alteration. Blasto-intergranular texture is shown by radiating laths of original poorly twinned albite with fresh pale yellowish-brown to dark brown hornblende and colourless diopside crystallizing between the felspar. Secondary plagioclase (andesine Ab₉₀) occurs only in amygdales, where it may be accompanied by diopside and sphene.

The diopside-rich variety is pale greenish grey in the hand specimen and it is common to find the diopside and hornblende rich varieties together, even in one hand specimen. The intergranular texture is not shown so well as in the
previous variety, but the albite laths form radiating growths with diopside granules between. Secondary fresh plagioclase (albite to basic andesine) is sporadic and is usually found in amygdales, although in parts the original basaltic texture is replaced by a granoblastic aggregate of plagioclase and diopside. The amygdales were probably originally filled with calcite, and during metamorphism there has been a migration, chiefly of lime out from the amygdale and alumina, silica, etc., into the amygdale from the surrounding rock. This resulted in a zone of grossular ringing the amygdale, with a central zone containing one or more of the following minerals: calcite, plagioclase, scapolite, prehnite, diopside or apatite, as shown in Figure 2. The texture is often diablastic with growths of calcite and andesine, calcite and grossular, diopside and andesine, etc. Some of the grossular is birefringent. Scapolite and prehnite are restricted to amygdales in this variety but become abundant in the mass of the rock in the third type.

Where scapolite or prehnite become very abundant, they replace original albite laths over large areas. The primary basaltic texture is obliterated as the scapolite envelopes the plagioclase and forms comparatively large crystals with sutured margins. These areas contain unaltered diopside granules whose mutual relations still show the intergranular texture to some extent. Growth of other minerals from the amygdales outward tends to give a coarse granoblastic texture.
The amygdales contain similar assemblages to the diopsidic variety mentioned previously, untwinned or poorly twinned plagioclase being notable. The scapolite and prehnite both form from plagioclase and the scapolite may alter to prehnite. The scapolite is a mizzonite $\text{Ma}_{35}$ with $N_e = 1.546$, $N_p = 1.574$, D.R. = 0.028. These values were measured by immersion methods on fragments of a large crystal from an amygdale, but measurements with a Berek Compensator on the groundmass scapolite in thin sections indicated generally a more sodic dipyre $\text{Ma}_{35}$ with D.R. averaging 0.012. In one specimen where calcite was abundant, a lime-rich scapolite occurred and was greatly altered to wollastonite suggesting that the scapolite and wollastonite may not be stable together, the latter mineral representing a higher grade of metamorphism.

The three varieties probably do not indicate differing grades of metamorphism, but rather differing compositions which may be original or due to metasomatism. The mineral assemblages indicate that equilibrium has not been established, thus enabling a series of metamorphic changes to be recognized.

**Group B.**

The mineral assemblage of this group is quite different from that of the preceding one, both because the original basic rock was much richer in calcite and also because the metamorphic grade is higher. This richness in calcite has been observed in unmetamorphosed spilites which contain closely packed amygdales filled with calcite so that the rock contains at least 50% of that mineral. Calcite also has replaced plagioclase by a premetamorphic process. Rocks of this group occur in a small patch surrounded by quartz monzonite, pyroxene granite and biotite porphyrite and their elevation to at least the cordierite-anthophyllite sub-facies of the amphibolite facies and possibly to the pyroxene hornfels facies is a reflection of the proximity of igneous rock almost completely surrounding the hornfels. Complete recrystallization has taken place and no vestige of the igneous structure remains. The structure is coarse and irregular with diablastic and poikiloblastic textures common. The minerals present include calcite, quartz, wollastonite, diopside-hedenbergite and grossular. Members of this group are divided into two classes, depending on the presence of calcite plus quartz or wollastonite, and thus a division is made between rocks of different metamorphic grade.

The lower grade hornfels is typically light coloured with large bladed crystals of both plagioclase and calcite up to 3 cms. long, containing pyroxene or garnet poikiloblastically. The garnet, which is pale brown and probably grossular, sometimes constitutes up to about 90% of a dark, heavy garnet-rock. The pyroxene is deep greenish-brown in colour with a relief close to that of grossular and a D.R. of 0.027, and thus is an iron-bearing diopside as distinct from the colourless diopside in the group A hornfelses. Calcite and quartz grow diablastically without any tendency to form wollastonite. Sphene and scapolite or prehnite occasionally occur, while a greenish-brown fibrous amphibole replaces the pyroxene as a retrograde product in some rocks. The plagioclase is a basic andesine.

Those hornfelses which contain wollastonite instead of calcite plus quartz usually have a coarse and irregular texture or are granoblastic aggregates of wollastonite, pyroxene, garnet and plagioclase (as basic as labradorite $\text{Ab}_{85}$).

Some hornfelses of this group are indistinguishable from calc-silicate rocks derived from lime-rich sediments. They are presumed to be the products of metamorphism of calcite-rich basic igneous rocks rather than sediments for the following reasons:

(a) No limestones have been found in the Woolomin Group.

(b) They occur in the line of strike of the basic lava.
They are frequently porphyroblastic with large grossular crystals set in a decussate growth of wollastonite with abundant tiny pyroxene crystals. Calcite may occur where there was not sufficient silica to allow the complete change to wollastonite.

**Sedimentary Hornfelses.**

The metamorphosed sediments found here are regarded as having been derived from fine-grained greywackes and quartzite. The most common hornfels is a black, saccharoidal, rather soft rock which is spotted with biotite flakes growing along the bedding. The texture is porphyroblastic with large flakes or aggregates of biotite set in a very fine granoblastic aggregate of quartz, felspar and biotite. Each of the large biotite crystals is surrounded by a zone barren of mica, from which the ferromagnesian material has been derived. Quartz and felspar are usually equally abundant and each constitutes about 40% of the rock. The felspar is quite fresh and is chiefly untwinned plagioclase varying in composition from orthoclase to andesine (Ab10-30). The freshness and range of composition suggest that the plagioclase is metamorphic and has been derived from the cloudy felspar common in the unaltered Woolomin greywackes. A few crystals which have a cloudy core and a fresh peripheral zone represent partially recrystallized felspar. A little chlorite and poorly crystallized muscovite may occur with apatite as accessories. One hornfels contains abundant tiny granules of diopside in groups with quartz and orthoclase.

**The coarse white saccharoidal quartzite is very pure and has a granoblastic to sutured texture. It contains only minute amounts of minerals other than quartz; tiny crystals of muscovite, epidote, apatite, pyrite, magnetite and rutile occur.**

**Degree of Metamorphism.**

The rocks show the impress of a moderate grade of thermal metamorphism with a higher grade where there has been repeated intrusion. Metasomatism appears to have been restricted to a little introduction of halogen and water to the basic rocks where scapolite and prehnite were formed from plagioclase. The spilitite was much more susceptible to both metamorphism and metasomatism than the sediments. There was a distinct period of retrograde metamorphism when pyroxene altered to hornblende. The mineral assemblages of the basic lava are typical of thermal metamorphism of such rocks. The basaltic rocks of group A originally contained the assemblage augite plus labradorite and this was changed to the spilitic assemblage albite plus hornblende, epidote, calcite and actinolite prior to the thermal metamorphism. The original minerals are not found here but the first process was presumably an alteration of actinolite to hornblende, while the albite was unchanged. At a further stage the albite recrystallized. In rocks which were richer in epidote or calcite, diopside appeared with albite and hornblende. At higher temperatures the assemblage diopside plus andesine was accompanied by grossular. The scapolite and prehnite which earlier were restricted to the amygdales then replaced the groundmass plagioclase over large areas. The processes have been arrested at various stages of completion, and the failure to achieve equilibrium between the minerals is typical of these rocks.

The group B rocks probably originally contained calcite, albite, chlorite, actinolite and a little quartz. The first stage was the production of the assemblage andesine-pyroxene-grossular with calcite plus quartz. The second stage was marked by the combination of calcite plus quartz to give wollastonite with garnet, pyroxene and plagioclase. The hornblende rich members of group A contain hornblende-diopside-albite, which is an unstable assemblage arrested in its trend to hornblende-diopside-plagioclase probably representing the cordierite-anthophylite sub-facies of the amphibolite facies. Amphibole...
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Sedimentary Hornfelses.

The metamorphosed sediments found here are regarded as having been derived from fine-grained greywackes and quartzite. The most common hornfels is a black, saecorialoid, rather soft rock which is spotted with biotite flakes growing along the bedding. The texture is porphyroblastic with large flakes or aggregates of biotite set in a very fine granoblastic aggregate of quartz, felspar and biotite. Each of the large biotite crystals is surrounded by a zone barren of mica, from which the ferromagnesian material has been derived. Quartz and felspar are usually equally abundant and each constitutes about 40% of the rock. The felspar is quite fresh and is chiefly untwinned plagioclase varying in composition from oligoclase to andesine (Ab$_{60-70}$). The freshness and range of composition suggest that the plagioclase is metamorphic and has been derived from the cloudy felspar common in the unaltered Woolomin greywackes. A few crystals which have a cloudy core and a fresh peripheral zone represent partially recrystallized felspar. A little chlorite and poorly crystallized muscovite may occur with apatite as accessories. One hornfels contains abundant tiny granules of diopside in groups with quartz and oligoclase.

The coarse white saecorialoid quartzite is very pure and has a granoblastic to sutured texture. It contains only minute amounts of minerals other than quartz; tiny crystals of muscovite, epidote, apatite, pyrite, magnetite and rutile occur.

Degree of Metamorphism.

The rocks show the impress of a moderate grade of thermal metamorphism with a higher grade where there has been repeated intrusion. Metasomatism appears to have been restricted to a little introduction of halogen and water to the basic rocks where scapolite and prehnite were formed from plagioclase. The spilitic was much more susceptible to both metamorphism and metasomatism than the sediments. There was a distinct period of retrograde metamorphism when pyroxene altered to hornblende. The mineral assemblages of the basic lava are typical of thermal metamorphism of such rocks. The basaltic rocks of group A originally contained the assemblage augite plus labradorite and this was changed to the spilitic assemblage albite plus hornblende, epidote, calcite and actinolite prior to the thermal metamorphism. The original minerals are not found here but the first process was presumably an alteration of actinolite to hornblende, while the albite was unchanged. At a further stage the albite recrystallized. In rocks which were richer in epidote or calcite, diopside appeared with albite and hornblende. At higher temperatures the assemblage diopside plus andesine was accompanied by grossular. The scapolite and prehnite which earlier were restricted to the amygdales then replaced the groundmass plagioclase over large areas. The processes have been arrested at various stages of completion, and the failure to achieve equilibrium between the minerals is typical of these rocks.

The group B rocks probably originally contained calcite, albite, chlorite, actinolite and a little quartz. The first stage was the production of the assemblage andesine-pyroxene-grossular with calcite plus quartz. The second stage was marked by the combination of calcite plus quartz to give wollastonite with garnet, pyroxene and plagioclase. The hornblende rich members of group A contain hornblende-diopside-albite, which is an unstable assemblage arrested in its trend to hornblende-diopside-plagioclase probably representing the cordierite-anthophyllite sub-facies of the amphibolite facies. Amphibole
is not found in the other basic hornfelses, which may extend up into the pyroxene-hornfels facies. The assemblages diopside-plagioclase, diopside-plagioclase-scapolite (prehnite)-grossular, diopside-grossular or diopside-grossular-wollastonite are not critical and may indicate the upper part of the amphibolite or the lower part of the pyroxene hornfels facies. The presence of plagioclase as basic as labradorite Ab₄₀ would indicate that some at least of the wollastonite bearing rocks of group B lie in the latter facies. The change from an assemblage in which calcite and quartz occur together to one in which wollastonite is stable marks a definite step in the metamorphic processes and Turner (1948) states that calcite plus quartz is stable on the lower part of the cordierite-anthophyllite sub-facies, while wollastonite is stable over the upper half, thus calcite plus quartz does not extend into the pyroxene-hornfels facies.

In the greywackes, the assemblage quartz plus oligoclase or andesine plus biotite with or without diopside indicates that the sediments reached the same approximate level of metamorphism as the basic rocks in the cordierite-anthophyllite sub-facies. However, some biotite hornfelses contain albite or acid oligoclase with a little muscovite and chlorite, and possibly represent a stage as low as the actinolite-epidote hornfels sub-facies of the albite-epidote-amphibolite facies. The presence of abundant potash which is represented by biotite prevented the appearance of such minerals as cordierite, andalusite or almandine, etc. There is a moderately close relation between the degree of metamorphism of the spilite and the greywackes, but in general the basic rocks contained a mineral assemblage which is susceptible to metamorphism and were permeable, thus suffering considerable alteration, whereas the fine-grained massive greywackes were both structurally and mineralogically more resistant.

Somewhat similar rocks have been found in similar environments at Tilbuster and Durnaresq, some miles to the west, and a description of these other areas will be presented in the second part of this paper.

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REFERENCES.


EXPLANATION OF PLATE.

PLATE XII.

Fig. 1.—Apatite prisms surrounding biotite and pyroxene as radial growths in the hypersthene-diorite. × 60.

Fig. 2.—Hornfels of group A containing diopside and plagioclase with the intergranular texture almost destroyed. × 60.

Fig. 3.—Hornfels of group B showing a decussate aggregate of wollastonite with pyroxene and garnet. × 60.

Fig. 4.—Hornfels of group B showing a granoblastic aggregate of diopside and plagioclase. × 60.
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