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THE EMPLACEMENT OF ACID MAGMA IN THE EPIZONE, AND THE RELATIONSHIP WITH IGNIMBRITES, NORTH QUEENSLAND, AUSTRALIA.

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(read by D.A. White at the International Association of Vulcanology Symposium, Catania Meeting, Sicily 15th - 24th September, 1961.)

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ABSTRACT

There is an aggregate outcrop of 12,000 square miles of Permian-Triassic acid igneous rocks inland from Cairns and Townsville, North Queensland. The rocks consist of ignimbrite and rhyolite, which are structurally and magmatically related to three high-level intrusions - the Herbert River, Esmeralda, and Elizabeth Creek Granites. Most of the igneous rocks intrude the Precambrian Georgetown Inlier, but some of them intrude along a fractured zone on the junction of the Inlier and the shelf zone of the adjacent Palaeozoic Tasman Geosyncline.

The Upper Palaeozoic - Triassic igneous period consists of two main epochs, both consisting of granite, ignimbrite, and rhyolite. In both epochs granite intrudes the comagmatic and coeval ignimbrite and rhyolite.

Rapid horizontal movement and granitic magma through the epizone and major fracturing of the crust are postulated to explain the widespread intrusion of the granite. The granitic magma was probably initially generated 5 miles below the surface of the crust by partial melting of the sediments at the base of the Tasman Geosyncline. Epeirogenic movement in the Precambrian Inlier area formed sheet-like fractures, which provided channels for rapid horizontal movement of the granitic magma. This magma was emplaced along the fractured marginal zone of the Inlier to form a thick sill-like body of granite - the Herbert River Granite - in the first epoch. Magma for the second epoch was derived from melting of the lower part of the granite of the first epoch. Renewed fracturing of the Inlier area formed cauldron subsidence areas and rifts, which were quickly filled with rhyolite and ignimbrite. In these collapsed areas the granitic magma crystallized as the Elizabeth Creek and Esmeralda Granites under an insulating cover of about 1,000 feet of rhyolite and ignimbrite.

INTRODUCTION

The region described in this paper lies inland from the coastal towns of Cairns and Townsville in North Queensland, and extends west 250 miles to Croydon; it is rectangular, and has an area of about 35,000 square miles (Figure 1). It was mapped jointly by the Commonwealth Bureau of Mineral Resources and the Queensland Geological Survey, between 1956 and 1961. From 1957 to 1961 I was a member of this joint survey and I mainly mapped Upper Palaeozoic and Triassic igneous rocks.

The work was designed to produce geological maps at 1:250,000 scale, but in more complex areas maps were produced at a scale of 1:63,360. Air photographs were used both for controlling traverses, and for photo-interpretation of inaccessible areas.

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** Bureau of Mineral Resources, Geology and Geophysics, Canberra, A.C.T., Australia.

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GEOLOGY OF THE AREA

The following notes are mainly taken from a report by White (1961), who was field party leader in North Queensland from 1956 to 1958.

The area consists of a broad Precambrian Inlier - the Georgetown Inlier - 200 miles long and 150 miles wide, and is flanked to the east by a Palaeozoic geosynclinal zone 50 to 150 miles wide, containing 40,000 feet of sediments. The geosynclinal zone is the northern part of the Tasman Geosynclinal Zone, which occupies most of the eastern coast of Australia. (The regional setting of the area is best seen on the Tectonic Map of Australia, 1960.)

Early Precambrian (Archaean?) rocks exposed in the centre of the Inlier are granulite, amphibolite, and migmatite. During the Middle Precambrian (Lower Proterozoic?) these rocks were uplifted to form a geanticline. On the western edge of the geanticline, during the Proterozoic, 30,000 feet of sediments, mostly pelagic, were deposited. Also during this uplift 15,000 feet of quartz and calcareous detritus were deposited on its eastern flank. The Precambrian history of the Inlier terminated with the intrusion of the Forsayth Batholith into the core of the geanticline, and of ultrabasic rocks along its fractured eastern edge. Steep-angled thrusting of the Archaean metamorphics over the Lower Proterozoic sediments may have accompanied both these intrusions. After the Precambrian the Inlier was uplifted and fractured extensively during the deformation of the Tasman Geosyncline.

The Tasman Geosynclinal Zone in North Queensland contains a maximum thickness of 40,000 feet of sediments ranging from Upper Ordovician? to Permian. The deformation of the geosyncline began in the late Silurian, and serpentine and gabbro were intruded along the south-eastern fractured edge of the Inlier. Both sedimentation and uplift continued in the Devonian and Carboniferous; depositional areas were forced to contract and migrate, resulting in the replacement of the early widespread marine sedimentation by restricted freshwater sedimentation. The geosyncline was further deformed by fracturing along the south-eastern edge of the Inlier, which gave rise to a rift.

Minor amounts of sediments were deposited in the area during the late Carboniferous and Permian; immediately after this period the whole of the Tasman Geosyncline and the Georgetown Inlier was land, and the Inlier continued to arch upwards. Two major epochs of acid volcanic activity and granite intrusion occurred in the late Permian and Triassic, and are described in more detail in the next section.

During the Cretaceous, sediments were deposited in the Great Artesian Basin area flanking the Inlier to the west. The extrusion of continental olivine basalt in the Cainozoic near the eastern fractured Inlier edges was the final igneous episode of the history of the area.

GEOLOGY OF THE UPPER PALAEOZOIC & TRIASSIC IGNEOUS ROCKS

The Upper Palaeozoic to Triassic period consists of two epochs, each containing acid volcanics and granites (Fig.1).

First Volcanic Epoch

Three small areas of volcanic activity of different ages are grouped in this epoch (Figure 1). They aggregate 250 square miles and have three properties in common.

(1). The areas appear to be situated at the intersection of major Precambrian faults: two areas are near the edge of the Inlier and one is near its centre.

(2). These are the only volcanics of the igneous period which can be dated: plant-bearing sediments are interbedded with the volcanics and have been dated as Carboniferous on the southern area on the Inlier edge, Lower to Middle Permian on the area in the centre of the Inlier (White,1961b), and Upper Permian to Lower Triassic on the northern area of the Inlier edge (White, 1961a).

(3). In each area, rhyolites and thin ignimbrite sheets (10 to 50 feet) are exposed, and in the two younger volcanics basalt containing agate amygdules is interbedded with the acid volcanic rocks.

First Granite Epoch

A granite, named the Herbert River Granite, intrudes the youngest volcanics of the first epoch, and is probably Upper Permian or Triassic (samples of this, and of the volcanics and granites of the second epoch, have been collected by the Bureau of Mineral Resources for K/A and Rb/Sr age determination, The granite intruded the north-eastern edge of the Inlier and the adjacent Shelf area of the Tasman Geosyncline and crops out as a long and narrow batholith, trending north-west. It has been mapped for 120 miles, with an average width of 25 miles (Figure 1), and probably continues 100 miles to the south-east. The intrusion has been partly controlled by roof block foundering and ring fracturing.

At the north-eastern and northern parts of the batholith, the magma assimilated Upper Silurian/Lower Devonian limestone (Branch,1960) and W.B. Dallwitz (pers.comm.) reports that the batholith contains a hornblende - biotite granodiorite with some unusually calcic plagioclase cores ranging from An60 to An92. Elsewhere, the batholith contains a biotite adamellite or granodiorite, with an average of 74 percent silica. Metamorphism associated with the batholith is slight and consists of silicification and some recrystallization of country rocks.

Copper and silver-lead are the main economic minerals introduced by the batholith, and they appear to be associated with the hornblende granodiorite phase.

Second Volcanic Epoch

The volcanics of the second epoch are widespread over the Inlier and along the shelf edge of the Tasman Geosyncline. They crop out with granite in two Provinces - Elizabeth Creek and Esmeralda. The outcrop of the volcanics in the two

Provinces aggregates 5,000 square miles, and the thickness of volcanics averages 1200 feet. There is no fossil evidence for the age of the volcanics, but they unconformably overlie the Herbert River Granite, and are unconformably overlain by Lower Cretaceous sediments: they are probably Triassic.

The volcanics occupy large cauldron subsidence areas (the largest exposed is 35 miles by 65 miles) and blocks in ring complexes. The margins of the cauldron subsidence areas are controlled by major faults in the Inlier. Multiple injections of igneous rocks along some of the faults suggest that the Precambrian faults were rejuvenated in the late Palaeozoic, and, in some places, again in the Tertiary.

In the cauldron subsidence areas the sequence of events began with the building of groups of puys of viscous rhyolite along the marginal faults and on major faults in the cauldron subsidence area. In some areas the development of small freshwater lakes preceded this first vulcanism. After the initial viscous stage, the magma was enriched gradually with volatiles, as shown by the formation of amygdules in the rhyolite flows. Then generally two or three grey acid ignimbrites were cataclysmically poured out, each about 700 feet thick: in one area seven ignimbrite sheets have been mapped, ranging from 100 feet to 300 feet thick.

Each ignimbrite sheet has a distinctive colour and mineralogy and may be mapped over the whole cauldron subsidence area, and occasionally from one such area to another. The thick ignimbrite sheets consist of phenocrysts of quartz and feldspar in a groundmass of recrystallised and devitrified glass Preliminary universal stage work on the plagioclase to determine high-or low-temperature optics has yielded inconclusive results. The only structure within the sheets is a faint foliation of the feldspar phenocrysts, probably induced during the compaction of the sheet. A few thin ignimbrite sheets, about ten feet thick, contain flattened glass shards. Interbedded pyroclastics are rare. The ignimbrites in the Esmeralda Granite Province contain small pellets of graphite (see next section).

Eight volcanic necks have been mapped: four were contemporaneous with the second volcanic epochs; two are older; and two are younger than the granite of the second epoch. Some are breccia pipes; but others are dykes and ring dykes of rhyolite with vertical flow banding, in which agglomerate-filled necks can be recognised.

Towards the end of the second volcanic epoch, six ring complexes formed, probably from the enlarging of volcanic necks to an unstable size (Reynolds,1956). The complexes have an average diameter of seven miles and consist of crescent-shaped blocks of volcanics and Palaeozoic sediments let down along ring fractures, and intruded off-centre by a granite stock.

Second Granite Epoch

Granite intrudes the volcanics of the second epoch and like them is restricted to the Precambrian Inlier area and the shelf edge of the Palaeozoic geosyncline. The Elizabeth Creek Granite Province covers 11,000 square miles, and the granite outcrop aggregates more than 2,000 square miles. The Esmeralda Granite Province covers 3,500 square miles, in which 500 square miles of granite are exposed

(Figure 1). In both Provinces the granite is probably Triassic and only slightly younger than the volcanics it intrudes.

The granite crops out as individual stocks, or as groups of stocks, with an average diameter of eight miles. Ring fracturing and block foundering were the main intrusion mechanisms, and the flat, undisturbed roof of an intrusion can be found in some areas. Evidence of forceful injection of the magma was found at only one locality.

Throughout the Elizabeth Creek Granite Province the granitic rock is a leucocratic pink granite or adamellite. The texture ranges from a porphyritic microgranite to an even-grained granite; there are no pegmatites or flow structures in the granite. The rock is chemically distinctive, with an average silica content of 78 percent. Tin is the main economic mineral introduced by this granite, as contact lodes in adjacent sediments and igneous rocks, and as greisen lodes within the granite.

The main granitic rock of the Esmeralda Granite Province is an even-grained grey biotite granodiorite or adamellite with an average silica content of 73 percent. In places the rock is rich in graphite xenoliths with a maximum diameter of 12 inches, which were probably derived from the assimilation of a country rock of Proterozoic carbonaceous shale. The fact that small graphite xenoliths of $\frac{1}{4}$ to $\frac{1}{2}$ inch diameter are exposed throughout the rhyolite and ignimbrite, which the granite intrudes, suggests that the granite and the volcanics are magmatically related. Gold and tin are the main economic minerals in the Esmeralda Granite Province. Silicification and recrystallization are the only metamorphic effects around the granite stocks.

Near the central-southern part of the Inlier, within the Elizabeth Creek Granite Province, a ring complex crops out in an elliptical area 16 miles long and 9 miles wide (Figure 2). It is thought that the acid magma was contaminated by the assimilation of Proterozoic calcareous sediments, and then differentiated in a near-surface magma chamber. Ten ring dykes have been mapped, ranging from augite andesite to leucocratic granite. Three swarms of cone sheets cut the dykes, and a stock of granite intruded the northern end of the complex (Branch, 1959).

Three microgranite dyke swarms, each about 40 miles long and 4 miles wide, intruded the Elizabeth Creek Granite Province and represent the final phase of the second granite epoch.

Depth of cover over the granites

Field evidence of the intrusions of the second granite epoch suggest that some at least must have crystallized as medium-grained granites under an insulating mantle of hot ignimbrite, about 1,000 feet thick. From the regional geology it is known that the ignimbrite sheets were never covered by sediments before the granite was intruded, and that probably volcanic eruptions and the granite intrusion were contemporaneous.

As seen today, the ignimbrites in the large cauldron subsidence areas are generally 1,200 feet thick: the thickest ignimbrite sequence found was 3,000 feet. In all places there are remnants of one flow - but never two - above those preserved entirely, and granites intrude all the flows, even the remnants. It is envisaged that at the completion of the second volcanic epoch the large cauldron subsidence areas were depressions. In the field it is seen that the volcanics were not greatly eroded before Lower Cretaceous sediments were deposited with a small angular unconformity over the volcanics, because it is rare to find any pebbles of volcanics or granite in the basal sediments. Hence possibly only one ignimbrite sheet was eroded almost entirely in pre-Cretaceous time, and its thickness probably was 1,000 feet.

Today two erosion surfaces are exposed in the area: The upper one is the exhumed pre-Cretaceous surface, i.e., there are remnants of the sandstone resting on top of ranges composed of ignimbrite sheets; and the lower one is level with the floor of the cauldron subsidence area. Therefore probably the major erosion of the cauldron subsidence areas was pre-Cretaceous, and only 1,000 feet or less of ignimbrite were eroded from above some of the granites exposed today. These are truly granites of the epizone.

AN INTRUSION HYPOTHESIS FOR HIGH-LEVEL GRANITES.

The following facts must be taken into account in any theory explaining the mode of intrusion of the high-level, epizone granites into the Precambrian Inlier:

1. The great lateral spread of the granites, especially those of the second epoch, which crop out within the Inlier 200 miles from the nearest Palaeozoic geosyncline.

2. The complete lack of contemporaneous basic igneous rocks in the area (excepting the few square miles of basalt in the first volcanic epoch).

3. The apparent mobility of the acid magma, both at the surface and at depth.

4. The large cauldron subsidence areas, which are generally bounded by a system of straight-lined faults, range from 20 to 60 miles across; ring-fractured blocks range from 4 to 10 miles in diameter.

5. The intrusion of granite into coeval and comagmatic volcanics.

6. The crystallization of medium-grained granite under a cover of only 1,000 feet.

The granite theory of Read (1957) is not applicable to the North Queensland Upper Palaeozoic - Triassic granites because there is no evidence of their being nearly 'dead' at the time they reach their present position, although ?Carboniferous granites of the Mareeba-Mossman area in the adjacent Tasman Geosyncline appear to follow Read's granite cycle. The Upper Palaeozoic - Triassic granites of North Queensland can be classified as epizone granites (Buddington, 1959); and Buddington's review stresses the magmatic relationship between volcanics and the granites of the epizone. Buddington's review covers most of the facts listed, but it does not adequately explain the great lateral spread of the Upper Palaeozoic - Triassic granites in the epizone.

The exposure of Upper Palaeozoic - Triassic igneous rocks in North Queensland is probably equivalent to what one would find a few thousand feet below those exposed in the Basin Range Province and the Yellowstone area in North America, or the ignimbrite area of the North Island of New Zealand. The comparison with these places is complicated, because each area contains a considerable volume of basic volcanics as well as ignimbrites. The ring complex area of Nigeria (Jacobson, MacLeod, & Black, 1958) would represent the North Queensland area after 2,000 feet of erosion, when nearly all the volcanics in the large cauldron subsidence areas have been removed; and the granite area described by Owen (1960) in Northern Portugal would represent a level below this.

The following hypothesis may explain the Upper Palaeozoic - Triassic intracratonic high-level granites of North Queensland. Two special conditions are required; one is the generation of a superheated acid magma very rich in volatiles, and the other is a source of energy to cause epeirogenic uplift to continue over a long period of time. Both conditions are believed to be satisfied, but they will be discussed in another publication.

1. Doming of the Precambrian Inlier area throughout the Palaeozoic caused extensive fracturing of the Inlier and compression of the Tasman Geosyncline on the north-eastern and south-eastern margins of the Inlier but compression was not great. Especially in the north-east, there is no evidence of large-scale thrusting or overturning of the Alpine type. However, Amos (1961) has proved that the geosynclinal sediments have been folded twice to form overturned folds, and in some areas decollement folding has taken place. Probably a crust of continental thickness continued eastwards under the geosyncline, at least as far as the present coast-line.

2. Twenty-five thousand feet of sediments accumulated in the northern part of the geosyncline, and its base was depressed about five miles. By partial melting of the sediments at the base of the geosyncline (Walton,1960), and also of the sialic crust below, a volatile-rich granitic magma was formed. Some of the magma rose vertically through the geosyncline to form the post-kinematic Carboniferous granites in the Mareeba-Mossman area, a few miles to the north of Mareeba (Figure 1). A small amount migrated laterally into the adjacent fractured margin of the Precambrian Inlier and was poured out as thin flows of rhyolite and ignimbrite.

3. Increased epeirogenic movement began in the central southern part of the Precambrian Inlier area during the early Permian, and gradually moved northwards. This caused deep-seated movement along some Precambrian fault-lines and the local melting of sima. Basaltic magma moved into the sialic crust, causing some melting, and the two magmas rose along the faults and poured out at the surface as basic, some intermediate, and acid volcanics of the first epoch.

4. With the increased movement in the Inlier sheet-like fractures developed in the crust at a depth of about five miles. This possibly occurred when the upward movement of the Inlier was interrupted and it momentarily sagged, causing the crust to be compressed. The first fractures were in the edge zone of the Inlier, parallel to the long axis of the Tasman Geosyncline and in a zone about 40 miles wide, and tapped the magma chamber at the base of the northern part of the geosyn-

cline. The sudden release of pressure on the partly solidified, though volatile-rich, magma, caused rapid melting. Because of the great reduction in pressure, the magma behaved as an ignimbrite at the surface, and moved rapidly into the fractured edge zone of the Inlier as a thick sill-like body of granite. Here, the crust was domed because of the increase in volume of the magma, and pre-existing lines of weakness were opened under tension. The fractured crustal blocks were slightly moved, then detached to sink into the magma to be assimilated, and finally the magma rose rapidly to take their place, and solidified as the granite of the first epoch.

5. The solidification of this batholith partly stabilized the area, but pressure increased, and in the Triassic extensive sheet-fracturing of the whole Inlier area occurred at a depth of about five miles or less. Again the magma-source at the base of the Palaeozoic geosyncline was tapped, and acid magma rich in volatiles moved out rapidly, under tension, as a thick sill-like body through the crust (as described in stage 4). (A structural analogy is with a dolerite sill, mapped by New Zealand geologist in Antarctica at least 1,000 miles long, 60 miles wide, and 800 feet thick (Dr. C. Harrington, pers. comm.). This example shows that a smaller sill-like body of granite magma (200 miles by 50 miles) is structurally possible under exceptional crustal and magmatic conditions.) The rarity in the world of high-level granites similar to those in North Queensland indicates that the conditions for their formation were probably unusual.

6. Most of the lower part of the Herbert River Batholith of the first epoch was melted, mainly by a great reduction of pressure rather than any marked increase of temperature, to provide the magma for the second epoch (a total of about 2,000 cubic miles, including rock assimilated in the Inlier). Because of only partial remelting, a magma rich in silica and poor in calcium was formed which was the source of the igneous rocks in the Elizabeth Creek Granite Province. As the magma wedge moved farther west it assimilated more country rock (including carbonaceous siltstone) and formed the graphitic granodiorite magma of the Esmeralda Granite Province.

7. The movement of magma through the crust caused fractured crustal blocks of the Inlier to become unstable; these blocks subsided into the magma and some were assimilated. The magma rose rapidly, and quietly occupied the space of the foundered blocks: this phase became self-propogating. A transfer of relative positions of the magma and the crustal blocks, without assimilation, must have been the most important mechanism in the rise of the magma towards the surface. If all the crustal blocks had been assimilated, the magma would have required an unreasonably high degree of superheat, and there would have been marked local changes in its composition; the pronounced differences which would thus have arisen between areas in the Inlier and those in the geosyncline are not in fact present.

8. Some of the magma was squeezed up along fractures and poured out at the surface as viscous rhyolite flows. As the magma reached the surface pressure was rapidly released in the top of the magma chamber. This allowed complete liquefaction and boiling off of the upper part of the magma over vast areas of the chamber. Once boiling-off was started at one point it would trigger off the same reaction at other places over the whole Inlier area. Ignimbrites poured out

from fissures at the surface (possibly 700 cubic miles of ignimbrites were poured out at the one time).

The number of ignimbrite sheets indicates that stages 7 and 8 were repeated one to seven times.

9. Where the magma was depleted most, the overlying crust sagged, and extension fractures very rapidly outlined large cauldron subsidence areas; (some resembled grabens) along which large crustal blocks sank. This stopped the eruption of ignimbrite, and subsurface block foundering was accelerated. At shallow depths cylindrical or conical fracturing became prominent.

10. The surface of the area was stabilized by consolidated ignimbrite sheets. The magma, which was stoping its way to the surface, finally filled the space remaining after crustal blocks dropped from the base of the ignimbrite sheets. The magma crystallized as a medium-grained granite under an insulating mantle of hot ignimbrite about 1,000 feet thick. Dyke swarms filled any remaining tension fractures.

11. Rapid movement of the magma through the crust is essential to the emplacement mechanism outlined, to prevent freezing at an early stage. The outpouring of 700 cubic miles of magma in the huge ignimbrite sheets of the second volcanic epoch would take one, or several, days. This indicates the speed at which large volumes of magma may be transferred from within the crust to the surface, and comparison of this time with the length of the volcanic and intrusive epoch of the Lake Toba eruption (van Bemmelen, 1939), suggests that the second epoch, from stage five to stage ten, probably occupied one to five million years.

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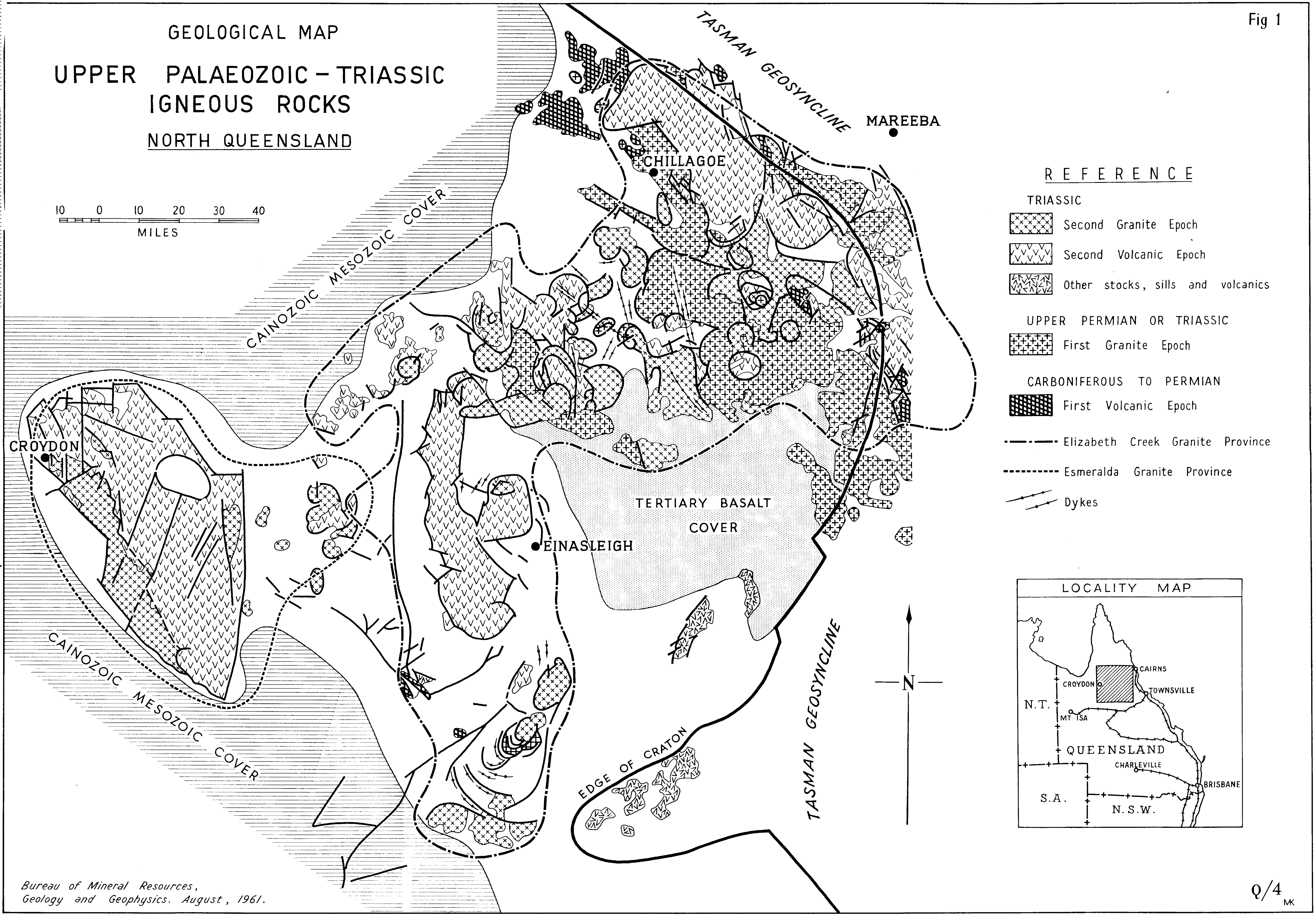
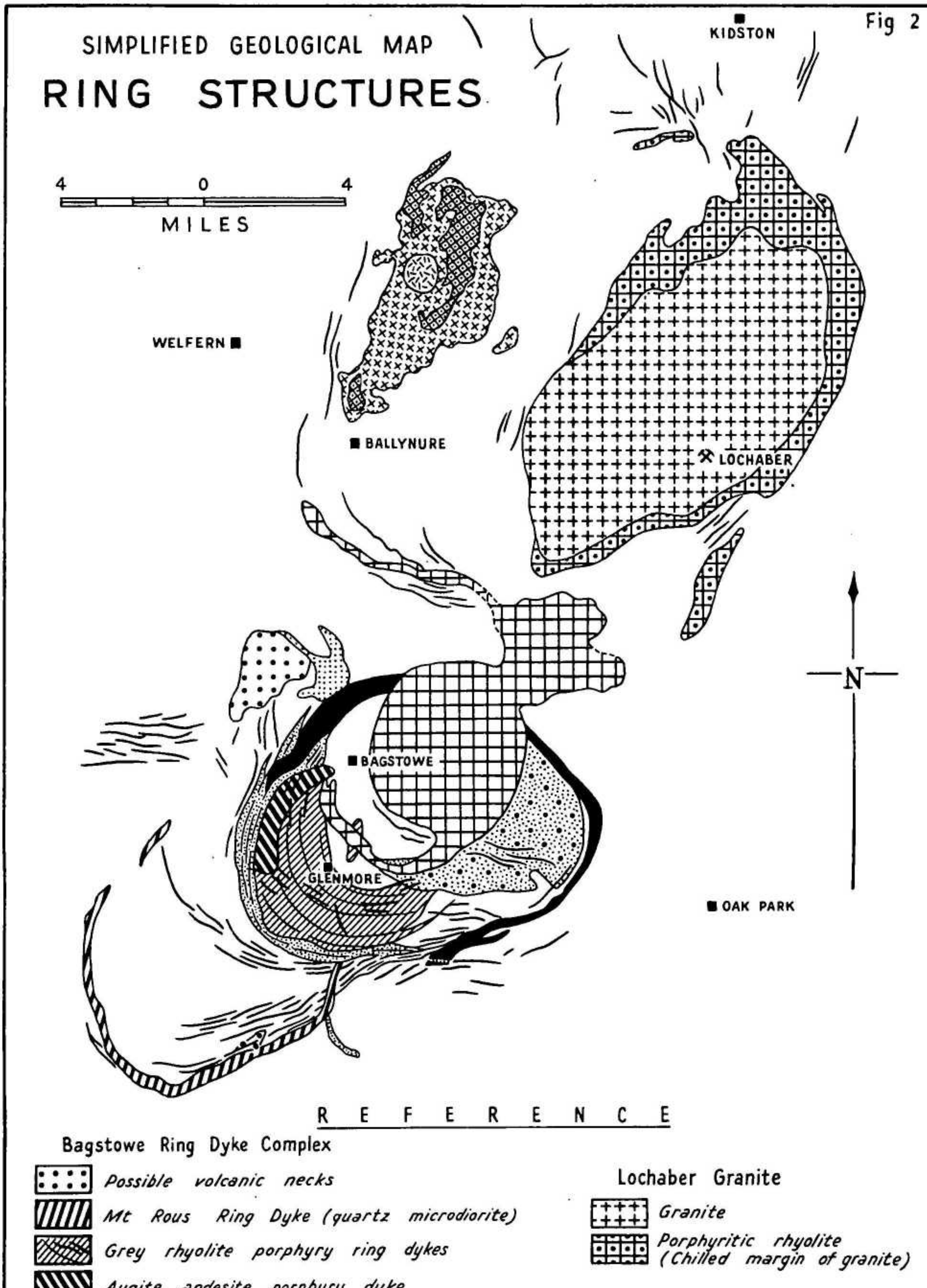


A B C

Reduce A-C (12") to A-B (6")



A B C

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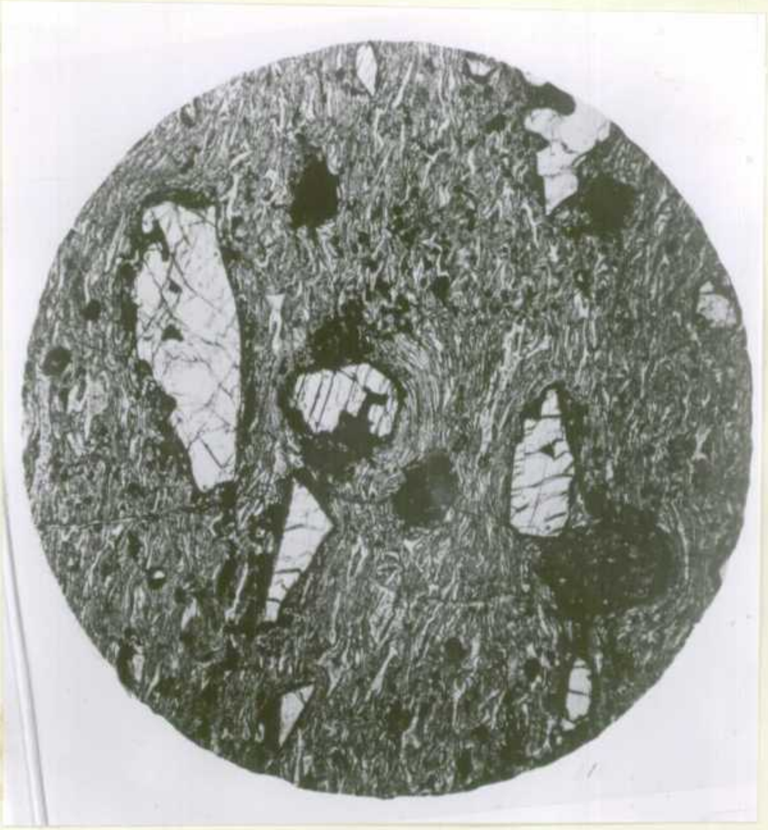

Figure 3. Dacite ignimbrite of the first volcanic epoch. Note compacted and welded glass shards of groundmass. Phenocrysts mainly plagioclase (cleaved), some embayed quartz, some augite and iron ore. X35, ordinary light.

Figure 4.