THE GEOLOGY OF THE BLENHEIM AREA
BOWEN BASIN
QUEENSLAND

by

A.R. Jensen
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SUMMARY

The Blenheim area, covering about 200 square miles, and situated near the northern end of the Bowen Basin, Queensland, is underlain by at least 30,000 feet of Permian-Triassic sediments and volcanics. The Permian-Triassic sequence is folded and overlain by thin Tertiary sediments and basalt. This study has enabled the recognition of six formations within the Permian sequence, which was formerly divided into the Lower, Middle, and Upper Bowen. It has also led to a better understanding of the age of the Triassic sequence by the finding of *Dicroidium* above the Redcliffe Sandstone. From the study interpretations have been made concerning the environment of deposition and provenance of the units, and an evaluation has been made of the clastic quartz grains as indicators of provenance.

The oldest unit recognized in the sequence, the 'Lower Bowen' Volcanics, consists of at least 12,000 feet of basic and intermediate volcanic flows and pyroclastics, with some interbedded greywacke and mudstone. The rocks of this unit, probably under the influence of burial metamorphism, have undergone considerable mineralogical change with the production in some cases of a mineral assemblage of the prehnite-pumpellyite metagreywacke facies.
The 'Lower Bowen' Volcanics are conformably overlain by the Back Creek Group, comprising the Lower Permian Tiverton and Hazelwood Formations, and the Upper Permian Blenheim Formation. The Tiverton Formation, 750 feet thick, consisting mainly of carbonate-rich mudstone and impure limestone, is the product of deposition in a cool water near-shore environment. The overlying Hazelwood Formation, consisting of 1150 feet of sublaborable sandstone with minor interbedded carbonaceous mudstone, gives indications of a general shallowing of the basin of deposition. It is overlain by the Upper Permian Blenheim Formation which consists of 2,800 feet of calcareous mudstone and quartz rich labile sandstone. Deposition of conglomeratic sediments at the base of the formation coincide with a widespread marine transgression in the Bowen Basin.

The Theodore Group, overlying the Back Creek Group, comprises the Turrawalla and Exe Creek Formation. The Turrawalla Formation consists of 4,800 feet of non-marine trough cross-stratified clastic sediments with fossil plants of the *Glossopteris* flora interbedded with volcanic flows and fine tuff. It marks the commencement of non-marine deposition which lasted through the Upper Permian into the Triassic. Sediments at the top of the unit have a greater proportion of volcanic detritus,
indicating an increase in vulcanism. The Turrawalla Formation is overlain by the Exe Creek Formation which may be Triassic in part. This formation is composed of conglomeratic lithic sandstone with interbedded mudstone, and it is 4,000 feet thick.

The overlying Triassic Redcliffe Sandstone consists of 4,500 feet of cross-stratified sublabile sandstone with no fossils. It is overlain by the Teviot Formation with Dicroidium, and consists of 400 feet of mudstone and interbedded labile and sublabile sandstone.

The Permian and Triassic sequence was folded in the late Triassic. Thin quartz rich fluvial sands were deposited over parts of the area during the Tertiary. Basalt, extruded some time in the Tertiary overlies the Tertiary sediments in places.
INTRODUCTION

The Blenheim area, sixty miles west of the Queensland coastal town of Mackay, lies near the northern end of the Bowen Basin. The Bowen Basin, the site of extensive deposition in the Permian and Triassic, extends in an elongate synclinal structure from Collinsville in the north, to Arcadia and Cracow in the south, where it disappears under the Surat Basin (Fig. 1). The eastern edge of the Basin, especially in the northern parts is marked by steeply dipping to overturned sediments, and it is for this reason that it is sometimes referred to as the Bowen Syncline (Hill and Denmead, 1960, p.282).

The first aim of the work was to map the area and establish the stratigraphic succession, recognizing valid and significant rock units. The second aim, already inherent in the first, was to deduce the structure and geological history of the area.

The field work was done over a period of three months as part of a survey of the Mount Coolon 1:250,000 Sheet area by the Bureau of Mineral Resources. Two sets of aerial photographs were available. One set at 1:50,000 scale, photographed in 1945, is rather poor by today's standards. The other set, at 1:26,000 scale,
taken in 1957 is very clear and of excellent quality. Because the Division of National Mapping, Canberra, produced a slotted template base for the area in 1959 at 1:50,000 scale, the field work was plotted on the 1:26,000 scale photos and boundaries transferred to the 1:50,000 scale photos. The boundaries and other information were then transferred to the template base to produce the map presented with the thesis (Enclosure 1).

Points on the ground where observations were made were marked on the 1:26,000 photos and a field number allocated. The air photos and the field notebooks (labelled RJ-MC-1 and 2) are stored at the Geological Branch of the Bureau of Mineral Resources, Canberra. Lithological and palaeontological samples taken were allotted the same number as the point from which they were collected. The sample localities are marked on the main geological map of the area. In the thesis, reference to a point is made using a six figure military co-ordinate, and this grid is marked on the map. The usual practice of giving eastings before northings will be followed.
Topography of the Blenheim area

The topography of most of the Blenheim area is shown in the topographic block diagram (Fig. 2). The area mapped extends further to the west, but the diagram shows all the main topographic elements. The Broken River Range is about 2000 feet above sea level in this area, and about 1000 feet above the area around the Bowen River. The Redcliffe Tableland is about 600 feet above the level of the surrounding plains. The total area mapped, herein referred to as the Blenheim area, is 200 square miles.

The topography strongly reflects the underlying geology. The Broken River Range in this area consists of massive volcanic flows and pyroclastics. Long ridges to the east of the Broken River Range are formed by steeply dipping Lower and Upper Permian sedimentary rocks. The Redcliffe Tableland consists mainly of Triassic sandstone. Conical hills on and to the west of the Tableland are of basalt; they are possibly old volcanic pipes. Small mesas appearing in the south-west part of the block diagram are basalt flows. Much of the flat country on either side of the Tableland is underlain by Permian and possibly Triassic sedimentary rocks.
TOPOGRAPHY OF THE BLENHEIM AREA

FIG. 2
Climate

The area experiences a hot summer, and a cool winter in which frosts are common. Most of the annual average rainfall of 20 inches falls in the summer.

Access

Roads on both sides of the Tableland lead north to Collinsville, about 40 miles, and south to Nebo, about 50 miles. Station tracks provide access in flat areas, but the Broken River Range and much of the hilly country between the Range and the Bowen River is inaccessible except on foot. A rough track ascends the eastern side of The Redcliffe Tableland, but the track down the west side was washed away some years ago. This means that there is no direct route from one side of the area to the other.

Nomenclature used in the thesis

Various systems of nomenclature have been adopted in describing sedimentary rocks in the thesis. They include:

Stratification .................McKee and Weir, 1953
Arenites ......................Crook, 1960
Size terms ......................Wentworth, 1922
Limestones ......................Folk, 1959
Stratigraphic nomenclature conforms with the Australian code (1960) except for the use of Supergroup, which is not mentioned in the code. Stratigraphic names used herein have been cleared by the central register of stratigraphic nomenclature, but they have not been submitted to the Queensland Subcommittee of the Committee on Stratigraphic Nomenclature (Geological Society of Australia). The Tiverton and Blenheim Formations proposed in this thesis have been accepted by the Bureau of Mineral Resources for general usage in this area, subject to the approval of the Queensland Subcommittee.

Previous investigations

Although the history of the geological investigation of the northern part of the Bowen Basin goes back over ninety years, nothing has been published concerning the Blenheim area alone, most of the reports covering a much larger area. Reports of this nature include those of Etheridge Senr. (1872), Jack (1879), and Jack and Etheridge Jun. (1892). By 1879 the basic three-fold division of the Palaeozoic Bowen River Series had been recognized.

There is no doubt that the most significant contribution to the geology of the northern part of the Bowen Basin, and to the Blenheim area, was made by
J.H. Reid from 1924 to 1930 (Reid 1924-25, 1928, 1929, 1930). Without the use of modern transport and without aerial photos or even reliable maps, Reid gave an account of the lithology, structure and palaeontology of the area, much of which is still accepted today.

Isbell (1955) combined previous work with a field reconnaissance and produced a report of the geology of the northern section of the Basin. As well as describing the geology of this large area, Isbell presented useful petrographic descriptions of samples from most of the units.

In 1960, the Bureau of Mineral Resources in conjunction with the Geological Survey of Queensland commenced a programme of regional mapping in the Bowen Basin. A party of four geologists, including the author, was assigned to map the Mount Coolon 1:250,000 Sheet area of which the Blenheim area is a part. The author had sole responsibility for the mapping of the Blenheim area as part of this programme. An unpublished report, completed in 1961, gave the preliminary results of this survey (Malone, Corbett, and Jensen, 1961). This report is soon to be published (Malone et al. 1964).
Acknowledgements

I am indebted to Dr. J.M. Dickins for supplying the specific identifications of Permian marine fossils. I also wish to thank Mr. I. Feeken for his preparation of the topographic block diagram. Members of the staff of the Geology Department of the National University have aided with discussions on various aspects of the work, and this was most welcome. I am especially grateful to Mr. B.W. Chappell for his advice in the field and in the early stages of the work. Chiefly, however, I wish to thank Dr. K.A.W. Crook for his guidance and help both in the field and in my studies in Canberra.
STRATIGRAPHY

Permian

STRATIGRAPHIC NOMENCLATURE

The Permian System was named by Sir Roderick Murchison in 1841 for a sequence of rocks in the Russian province of Perm, west of the Ural mountains. Murchison originally used the term for rocks now placed in the Kungurian, Kazanian and Tartarian series. The underlying Artinskian Limestone was equated with rocks of Carboniferous age in western Europe, but later work showed the Artinskian and even the underlying Sakmarian to be younger than the Carboniferous of western Europe, and they are now included in the Permian.

The divisions of the Permian used in this thesis are those adopted by Glenister and Furnish (1961); they are shown in Table 1. The base of the Permian is now generally accepted as at the base of the Sakmarian Stage (Neaverson, 1955, p.382) but not without some opposition (Sherlock, 1950) and modification (Ruzhentsev, 1954; Glenister and Furnish 1961). The modification involves the introduction at the base of the Sakmarian of a new unit of substage or stage rank. Ruzhentsev
(1950) defined an Asselian substage at the base of the Sakmarian Stage, and he later (1951 and 1954) altered it to full stage status. This usage was followed by Glenister and Furnish (1961) who note 'The stratigraphers attending the Ural Conference of 1956 were unwilling to credit the Asselian with full stage standing and resolved to use the division as the lower substage of the Sakmarian Stage.' Glenister and Furnish argue that it would be confusing to have a Sakmarian Stage divided into a basal Asselian Substage and an upper 'Sakmarian Substage'.

<table>
<thead>
<tr>
<th>Table</th>
<th>Subdivision of the Permian</th>
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<tbody>
<tr>
<td>Series</td>
<td>Stage</td>
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<tr>
<td>Upper Permian</td>
<td>Dzhulfian</td>
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<td> </td>
<td>Guadalupian</td>
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<td>Lower Permian</td>
<td>Artinskian</td>
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<td> </td>
<td>Sakmarian</td>
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<td> </td>
<td>Asselian</td>
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The Sakmarian is followed by the Artinskian Stage, which Ruzhentsev (1956) divides into a basal Aktastinian Substage followed by the Baigendzhinian Substage. The Permian is generally divided into Upper and Lower Permian, and the boundary is taken as the
top of the Baigendzhinian Substage. This convention will be followed herein.

The Russian Upper Permian sequence, in contrast to the richly fossiliferous marine lower Permian, is largely non-marine, and many authors prefer to use the succession in the Guadalupe Mountains of western Texas as a standard. The Upper Permian as used by Glenister and Furnish (1961) comprises the basal Guadalupian Stage followed by the Dzhulfian Stage, named from the uppermost beds of Dzhulfa on the Armenian-Iranian border.

The Bowen Basin Sequence

Although the age of the rocks of the Bowen Basin is regarded as ranging from Permian to Triassic, it may well be that deposition commenced in the Carboniferous. This problem is not confined to the Bowen Basin, for it is difficult to correlate Upper Carboniferous and Permian sequences of the Southern Hemisphere with those of the type areas in the Northern Hemisphere. This is caused by the restriction of the Glossopteris flora and the cold water 'Eurydesma' fauna to the Southern Hemisphere. It appears that the best hope of reliable direct correlation with the type Russian and American Permian is with nektonic rather than benthonic fauna, such as the ammonoids. Although ammonoids are present in large numbers and although they have been described from the
### TABLE 2

Permian stratigraphic nomenclature of northern Bowen Basin

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<td><strong>BOwen River</strong></td>
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<tr>
<td>(Plant fossils)</td>
<td>Upper Bowen</td>
<td>Upper Bowen Coal Measures or Formation</td>
<td>Upper Bowen</td>
<td>Proposed Nomenclature</td>
<td></td>
</tr>
<tr>
<td>(fossils)</td>
<td>Formation</td>
<td></td>
<td>Coal Measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bowen Series</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Carboniferous Series)</td>
<td>Middle Bowen Formation</td>
<td>Middle Bowen Marine Series</td>
<td>Middle Bowen Group</td>
<td>(Exe Creek (Formation</td>
<td>(Turrawalla (Formation</td>
</tr>
<tr>
<td>(marine fossils)</td>
<td>Lower Bowen</td>
<td>Lower Bowen Volcanics</td>
<td>Lower Bowen</td>
<td>(Blenheim (Formation</td>
<td>(Tiverton (Formation</td>
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<td></td>
<td>Formation</td>
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<td>Coal Volcanics</td>
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type Permian areas, they are rare in Australia, particularly in Eastern Australia, and correlation is therefore difficult. The common practice in Australia is to regard Glossopteris as exclusive to the Permian, and this will be followed herein although it is realized that it is for the moment a convention rather than an established fact.

Since 1872, when Etheridge (Senr.) used the term 'Bowen River Series' for sediments in the Bowen River area, numerous authors have proposed different nomenclatural schemes for the same sequence. Some of the previous nomenclature is summarized in Table 2. The tripartite division introduced by R.L. Jack (1879) has been adopted by most authors, and since 1892 the terms 'Upper Bowen', 'Middle Bowen', and 'Lower Bowen' have been combined with various stratigraphic and lithological terms. Over the years a concept of the 'Bowen System' has developed; Isbell (1955) uses 'Upper Bowen Series', and Hill (1955) mentions 'Upper Bowen times'. On the other hand, the subdivisions are regarded by many authors strictly as rock units (Qld. Dept. Mines 1953).

There is a natural tendency to avoid the introduction of new terms when old ones are well established, because of the resulting multiplicity of
names. Despite this, a new system of nomenclature is required to avoid the clash of rock and time-rock connotations of the existing terms and to conform with the requirements of the Australian Code of Stratigraphic Nomenclature (1960) with regard to the naming of rock units (i.e., a geographical name coupled with a lithological term). The time is now right for a revision of nomenclature in the stratigraphy of the Bowen Basin because of the rapid increase in our knowledge of the stratigraphy following work done by government organizations and private enterprise in the search for petroleum and coal, in the last five years.

The introduction of a new system of nomenclature raises two problems immediately—the names to be used, and the rank of the units. The long established term 'Bowen' should be retained if possible in the new system because old terms die slowly and new ones are difficult to introduce into common usage. Also, it is an apt term for the largest rock unit of the Bowen Basin Permian sequence. However, confusion would result if the term 'Bowen' were applied to a unit smaller than the original Bowen River Series as used by Jack (1879). It is therefore proposed that the term Bowen Supergroup be used to include formations previously included in the Lower Bowen Volcanics, the Middle Bowen Group, and the
Upper Bowen Coal Measures.

The mapping in the Blenheim area has made it possible to recognize six formations in the Supergroup, and these are shown in Table 2. Five of these formations it is suggested, can be placed in two natural Groups, corresponding to the Middle Bowen Group and the Upper Bowen Coal Measures, but as already intimated these group names are unsatisfactory.

The term 'Lower Bowen' Volcanics is retained in this thesis, because it is felt that the unit, which is not well exposed in the Blenheim area, should be renamed in another area where a type section can be given.

The term 'Middle Bowen' Group is replaced by 'Back Creek' Group, because like the terms 'Lower' and 'Upper Bowen' it does not conform with present requirements as the name of a formation (there being no place called 'Middle Bowen' etc.). The name 'Back Creek Group' was proposed by Derrington, Glover and Morgan (1959) for a marine Permian sequence in the Cracow area, and this sequence has strong lithogenetic affinities with the three marine formations of the Blenheim area, being deposited at about the same time and under similar conditions. A disconformity between
the lower and upper parts of the unit in the type area of the Back Creek Group is not present in the Blenheim area (Jensen, Gregory and Forbes, 1964). The Back Creek Group in the Blenheim area is composed of the Tiverton, Hazelwood, and Blenheim Formations, these formation names being proposed herein.

Two formations are recognized in the Blenheim area in the group formerly known as the Upper Bowen Coal Measures. They are the Turrawalla Formation and the Exe Creek Formation, and they are considered to constitute a group on lithogenetic grounds. The Group is overlain by the Redcliffe Sandstone which can be correlated with the Clematis Sandstone of the Cracow area. The interval between the Back Creek Group and the Clematis Sandstone in the Cracow area is occupied by the Theodore Group, the Cracow area being the type area (Hill and Denmead 1960; Jensen et al. 1964). The term Theodore Group is used in the Blenheim area to replace the Upper Bowen Group, and it therefore consists in that area of the Turrawalla and Exe Creek Formations.

A summary of the regional correlations on which the nomenclature for group names is based is shown in Table 3.
### TABLE 3

Correlation of Rock units between the Cracow and Blenheim areas

<table>
<thead>
<tr>
<th>Cracow area</th>
<th>Blenheim area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clematis Sandstone</td>
<td>Redcliffe Sandstone</td>
</tr>
<tr>
<td>Rewan Formation</td>
<td>Theodoren Group</td>
</tr>
<tr>
<td>Baralaba Coal Measures</td>
<td>Exe Creek Formation</td>
</tr>
<tr>
<td>Gyranda Formation</td>
<td>Turrawalla Formation</td>
</tr>
<tr>
<td>Mt Steel Formation</td>
<td>Back Ck. Group</td>
</tr>
<tr>
<td>Orange Creek Formation</td>
<td>Blenheim Formation</td>
</tr>
<tr>
<td>Oxtrack Formation</td>
<td>Hazelwood Formation</td>
</tr>
</tbody>
</table>

...
The dominantly volcanic sequence stratigraphically below the Bowen River Series of Etheridge Senr. (1872) was termed the Lower Bowen Formation by Jack and Etheridge (Jun.) in 1879, and the Lower Bowen Volcanics by Reid in 1924 (Reid 1924-25). Reid divided the unit into three formations in the Collinsville area, namely:

- Mount Devlin Volcanics
- Mount Devlin Coal Measures
- Mount Toussaint Volcanics

Continuous outcrop of the unit extends from the Collinsville area through the Blenheim area, and from there to the south for over a hundred miles. However, Reid's three-fold division is not apparent in the Blenheim area, nor has it been recorded elsewhere. Because of insufficient knowledge of the sequence no new name for the unit will be proposed herein, although, as already explained, the term 'Lower Bowen' is not suitable and should be changed to a geographic name.

In the Blenheim area, the unit consists of a thick sequence of basic and intermediate volcanic flows and pyroclastics with interbedded greywacke and mudstone. It crops out only in the eastern side of the area and is overlain by a sequence of marine sediments devoid of volcanics. Close to the eastern boundary of the area, the
unit produces rough hilly country, but further to the west it has produced, with the aid of Blenheim Creek, a relatively flat plain.

**Lithology**

Volcanic flows constitute by far the greatest proportion of the unit and these are interbedded most commonly with pyroclastics. Mudstone is common towards the top of the unit, and feldspatho-lithic greywacke (Crook, 1960) is found in thin beds throughout the unit. Very minor occurrences of concretionary limestone and sublabile feldspathic arenite were noted.

The volcanic flow rocks, and the other main rock types, are characterized by sodic plagioclase, and by the replacement of primary constituents by secondary mineral assemblages some of which include prehnite and pumpellyite. The primary assemblages of the flow rocks included plagioclase, clinopyroxene, glass and, in some cases minor quartz. It is probable that much of the plagioclase was calcic and that albite, like prehnite and pumpellyite is a replacement mineral. Evidence for this lies in the replacement of the other primary phases by albite, manifest in most of the rocks. Most of the flow rocks examined are spilites and there appears to be a development of keratophyre at the top of the unit.
Primary pyroclastics in the unit vary in grainsize from fine tuff to agglomerate with bombs up to one foot across; stratification varies from laminated to very thick bedded. (Fig. 3). Lamination where present is commonly contorted. (Fig. 4). Primary volcanic breccia is rare, but angular shale clasts are common (Fig. 5) in the tuff.

Sedimentary rocks, rich in volcanic debris, comprise mudstone and greywacke. The mudstone is invariably grey-black, and it varies from thin to thick bedded. Slump structures are common, ranging in size from slumped laminae to structures involving beds two feet thick. Graded bedding and slump breccia are commonly associated with the slump structures. Normally hard and dense, in places the mudstone breaks easily into long splinters under the influence of closely spaced reticulate fracture cleavage (Crook 1964). (Fig. 6).

Feldspatho-lithic greywacke is not common in the unit, occurring as thin beds associated with mudstone. It is cross-bedded on a small scale in places (Fig. 7). In at least two places the surface is puckered into a type of 'flame' structure in the overlying mudstone. (Fig. 8).
Primary volcanic pyroclastic with bombs of vesicular lava. 'Lower Bowen' Volcanics.

Contorted laminae in a tuff in 'Lower Bowen' Volcanics.
Intraformational conglomerate of shale clasts in a thickly bedded primary volcanic tuff. 'Lower Bowen' Volcanics.

Closely spaced reticulate fracture cleavage in hard mudstone. 'Lower Bowen' Volcanics.
Small scale cross-stratification in greywacke in 'Lower Bowen' Volcanics.

Overturned interbedded greywacke and mudstone, showing 'flame' structure in greywacke. 'Lower Bowen' Volcanics.
(a) Primary phases

Spilites examined in thin section (1419c, 1419a, 644b, 1418a, 1047, 653, 662, 649) have retained their original fabric, some being porphyritic, others aphyric; some holocrystalline, others hyalocrystalline. Five of the nine are vesicular. The original constituents included plagioclase, clinopyroxene, glass, and possibly magnetite.

Flow rocks (658b, 680a, 658a) from a conspicuous line of hills at the top of the unit, are possibly keratophyres. The original constituents albite (and quartz in 658b & 658a) form euhedral phenocrysts in a fine groundmass of albite microlites (658a & 680a) or replaced glass (658b).

Primary tuffs examined in thin section (644, 644c, 1420b, 666a, 666b, 1420a, 652, 642) contain a high proportion of devitrified volcanic glass, either as shards or as a groundmass, together with angular crystals and lithic fragments. The lithic fragments consist exclusively of volcanic rocks, mainly hyalocrystalline flows which are commonly vesicular.

The one greywacke examined in thin section (1418b) consists of angular to subround quartz and feldspar grains and volcanic lithic fragments, in a
reconstituted fine matrix of quartz, albite and chlorite. It also contains subangular grains of devitrified volcanic glass, the product of contemporaneous vulcanism. The original fabric, that of a poorly sorted arenite, persists even though there has been considerable mineralogical modification, including the complete reconstitution of the matrix. The rock is a litho-feldspathic greywacke, (terminology of Crook, 1960), because of the mineralogical composition, and because the associated sedimentary structures in sediments of the unit indicate that the sediments can be assigned to the greywacke suite (Packham, 1954).

(b) Secondary phases

Secondary phases occur in three ways: (i) as replacements of the original minerals, (ii) as newgrowths, filling cavities within the original framework, and (iii) as veins, disrupting the framework. The replacement pattern is summarized in Appendix B, and Table 4.

The secondary phases comprise albite, various phyllosilicates, prehnite, pumpellyite, epidote, calcite, and quartz.

**Albite:** On rapid examination of twenty-two thin sections it appears that albite wholly replaces feldspar in all cases. Albite has been identified by twinning (Michel Levy method) and comparing its relief with that

*quartz 5.1%, rock frags. 28.9%, feldspar 32.4%, matrix 28.7% opaques 3.9%. Grain count of 515.*
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Group</th>
<th>ab</th>
<th>cal</th>
<th>ch</th>
<th>qu</th>
<th>psil</th>
<th>ser</th>
<th>epi</th>
<th>preh</th>
<th>pump</th>
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<td></td>
<td>R</td>
<td>RNV</td>
<td>RV</td>
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<tr>
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<td>R</td>
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<td></td>
<td></td>
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<td>V</td>
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<tr>
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<td></td>
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<td>R</td>
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<td>R</td>
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</tr>
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<td>1418a</td>
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<td>RNV</td>
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<td>RNV</td>
<td>R</td>
<td>RV</td>
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</tr>
<tr>
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<td>RN</td>
<td>R</td>
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<td>RN</td>
<td>R</td>
<td></td>
<td>R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1419b</td>
<td>VI</td>
<td>RN</td>
<td>N</td>
<td>RV</td>
<td>RV</td>
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<td>RN</td>
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<td>RN</td>
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</tr>
<tr>
<td>1420a</td>
<td>VII</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>RV</td>
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<td>R</td>
<td></td>
<td>R</td>
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<td></td>
</tr>
</tbody>
</table>

**Legend:**
- ab - albite
- cal - calcite
- ch - chlorite
- qu - quartz
- psil - phyllosilicate
- ser - sericite
- epi - epidote
- preh - prehnite
- pump - pumpellyite
- R - Replacement
- N - Newgrowth
- V - Vein
of balsam. In some cases, together with quartz, it completely replaces volcanic glass. It has been observed replacing clinopyroxene and forming newgrowths in vesicles (sample 1419c).

**Sericite:** Sericite occurs most commonly as small flecks within feldspar grains.

**Chlorite:** Chlorite replaces feldspar, clinopyroxene, and glass. It fills vesicles and occurs as newgrowths. Both colourless and light green varieties occur, and in some cases it is pleochroic. Anomalous Berlin Blue birefringence is seen in many samples of chlorite, particularly in sample 1419c.

**White mica:** White mica occurs in a quartz-prehnite-pumpellyite vein (sample 1419b), in long sheath-like structures.

**Other phyllosilicates:** Colourless, light green, and light brown unidentified phyllosilicates were observed in some of the samples, their small size not permitting identification by normal optical methods. They appear to replace volcanic glass and feldspar.

**Prehnite:** Prehnite occurs as a replacement of primary phases, as newgrowths in vesicles and pores, and as a vein mineral. It partially replaces feldspar in sample 1047, and it occurs as newgrowths in the original pore space of sample 1418b (greywacke).
Sample 1419b is a quartz-prehnite-pumpellyite vein (Fig. 9), and the prehnite there occurs in large plates having a fibrous habit, and showing a 'bow tie' structure (Rogers and Kerr 1942, p. 332). Perhaps the finest development of the mineral is in the spectacular vesicles of sample 1419c, where, as in 1419b, it is closely associated with pumpellyite.

Pumpellyite: Pumpellyite occurs in four of the samples examined. The best development is in sample 1419c where it forms large platy newgrowths inside vesicles. The plates, up to 1.5 mm across, consist of elongate radiating fibres, with a prominent cleavage developed at right angles to the length of the fibre, and this association of radiating habit and well developed cleavage forms a spider web pattern. To add to the distinctiveness of this habit, the plates terminate in straight edges against other plates of pumpellyite, calcite, or prehnite. (Fig. 10). Small vermicular growths of green chlorite wind their way through the pumpellyite in this sample. The most striking feature of the mineral in this sample in plain polarized light is the pleochroic change from apple green to grey brown.

Pumpellyite occurring in a vein (sample 1419b) is in the form of aggregates of tiny prismatic needles
A quartz-prehnite-pumpellyite vein in 'Lower Bowen' Volcanics.  (Sample 1419b)
Photomicrograph of a vesicle in sample 1419c surrounded by albite laths and filled with calcite and pumpellyite. (Crossed nicols, x24)
about 0.15 mm long. It is mainly colourless, but small transient pleochroic green patches are seen on rotation of the thin section, in plain polarized light.

In sample 1047 both low iron (colourless to pale green) and high iron (pale yellow to yellow brown) varieties of pumpellyite replace feldspar. Where the two varieties are in contact they are in the same optical orientation but the boundary between the two is sharp and straight, with no sign of transition.

Epidote: Epidote was found in one specimen only (1420b) where it definitely replaces feldspar. Some of the epidote in this sample however, appears detrital.

Calcite: Calcite is found in most of the samples, occurring as a replacement phase, as newgrowths, and as veins.

Quartz: Quartz is also very common either as replacement, newgrowth or vein.

**Secondary assemblages and facies**

The samples examined are divided in Table 4 into seven groups. The groups are an indication of relative depth below the top of the unit, Group I being the highest in the sequence. Any one group comprises samples collected from approximately the same stratigraphic level.
Group I has the assemblage albite-chlorite-calcite-quartz, to which may be added any two of quartz, phyllosilicate or sericite. The same mineral assemblage is found in Groups II to VI with the addition of prehnite and pumpellyite. Group VII does not have prehnite or pumpellyite but epidote has been identified. The appearance of prehnite and pumpellyite and the subsequent appearance of epidote possibly at the expense of prehnite and pumpellyite, may be an indication of increasing grade of metamorphism with depth of burial.

Assemblages of albite-quartz-chlorite with prehnite and pumpellyite have been reported from various thick eugeosynclinal sequences (Coombs 1960; Packham and Crook, 1960; Brown, 1960; Crook, 1963). These assemblages are characteristic of the prehnite-pumpellyite metagreywacke facies of Coombs (1960). The production of this mineral facies is commonly attributed to burial metamorphism of Coombs (1961) or epigenetic diagenesis of Packham and Crook (1960). Metamorphism of this type is caused by an increase of pressure and temperature due to burial, rather than to regional metamorphism which commonly produces schistosity. The prehnite-pumpellyite metagreywacke facies is envisaged as being intermediate in grade between the zeolite facies of Fyfe, Turner and Verhoogen (1958) and the greenschist facies in which
epidote occurs to the exclusion of other Ca-Al silicates. It is for this reason that the appearance of epidote at the base of the sequence is possibly significant.

It is by no means certain however, that the secondary mineral assemblages in the Lower Bowen Volcanics have been produced by burial metamorphism alone; but the evidence would seem to support this conclusion. The sequence has been tightly folded, but as no schistosity has been produced it is improbable that the folding produced the secondary phases. The unit is intruded by a few sills (Malone et al., 1961) but these are rare, and any metamorphic effects would be localized.

**Structure and thickness**

The structure of the unit in the Blenheim area is complex. On a regional scale the unit dips to the west under the Tiverton Formation. For the purposes of description the area of outcrop may be considered as comprising three structural units (i) in the area up to one and a half miles east of Tiverton homestead; (ii) in an area extending east of area (i); and, (iii) in the area extending southwards from the headwaters of Blenheim Creek.

In area (i) the unit generally dips steeply to the west, but in places it appears to be overturned and dips to the east at a high angle (abt. 65°). Evidence
for the overturning lies in the facing of beds determined from graded bedding. A similar structural pattern is seen in a creek one and a half miles north of Tiverton, where the overlying Tiverton Formation is overturned also.

In area (ii) the dip is relatively low, being in the order of from $15^\circ$ to $40^\circ$ and consistently towards the west. The two areas are probably separated by a fault but this could not be substantiated in the field. The change in gross attitude of the beds is however, reflected in the topography, the lower dips being in rough hilly country and the high dips in a relatively flat plain.

Further to the south, in area (iii), the top of the unit dips very steeply to the west under the Tiverton Formation. The dip decreases to the east, until at point 642 (589608) the dip is approximately $40^\circ$.

The 'Lower Bowen' Volcanics are structurally conformable with the overlying Tiverton Formation. The base of the unit is not exposed in the Blenheim area, but Malone et al. (1961) reported it to be intruded by the Urannah Complex.

As the base of the unit is not seen in this area, and because of the structural complexity, estimates of the thickness or partial thickness of the unit are made with great reserve. On the information gathered it is possible that the unit is at least 12,000 feet thick.
Estimation of the depth below the top of the unit for the groups already mentioned is also very difficult. Rough estimates are:

<table>
<thead>
<tr>
<th>Group</th>
<th>Depth below top of unit - feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0 - 200</td>
</tr>
<tr>
<td>II</td>
<td>2,000</td>
</tr>
<tr>
<td>III</td>
<td>6,000</td>
</tr>
<tr>
<td>IV</td>
<td>9,000</td>
</tr>
<tr>
<td>V</td>
<td>10,000</td>
</tr>
<tr>
<td>VI</td>
<td>11,000</td>
</tr>
<tr>
<td>VII</td>
<td>12,000</td>
</tr>
</tbody>
</table>

Assuming the total thickness of younger Permian and Mesozoic sediments to be 15,000 feet, samples in Group VII were possibly buried to a depth of 29,000 feet.

**Age**

One specimen of *Glossopteris indica* Sch. was found at the top of the unit, at point 1066 (521675). Further to the south, off the Blenheim area but near Hazelwood Creek, a number of Lower Permian gastropods, pelecypods, and brachiopods were found in 1960 (Malone, Corbett, and Jensen 1961) in a tuff at the top of the unit. There can be little doubt therefore, that the top of the unit is Lower Permian in this area. However, it is possible that deposition of the unit commenced in the Carboniferous.
Origin

As most of the unit is composed of unfossiliferous volcanic rocks there is no palaeontological evidence for the environment of deposition of much of the unit. Lithological evidence points to a deep water marine environment.

The deep water is indicated by the occurrence of the greywacke suite of sediments with its associated slumping and graded bedding. Bailey (1936) postulated that the graded bedding association of sediments is attributable to relatively deep water deposition and this has since been demonstrated by many authors (eg. Carrozzi, 1957; Ksiaziewicz, 1958) in their descriptions of the turbidity current lithofacies.

The source for the Na$^+$ ions in rocks of the spilite-keratophyre association has long been a bone of contention among petrologists. It has been shown in this thesis that many of the primary phases of the rocks of the 'Lower Bowen' Volcanics have been replaced by albite. This seems to rule out the possibility of a primary sodic magma in this area, but it presents a problem - the source of the soda. It is therefore suggested that the flows were extruded under the sea. This is supported by the presence of volcanic glass in many of the samples, probably caused by rapid chilling. A marine environment is certain for rocks at the top of the unit, just south of the Blenheim area, where marine fossils have been found.
TIVERTON FORMATION

The Tiverton Formation, a new name introduced herein, is the lowest formation of the three constituting the Back Creek Group. The name is derived from Tiverton homestead, and the type section, the basal 750 feet of section 15 (Fig. 11), was measured in a creek one and a half miles north-north-west of Tiverton homestead (Long. 148°12'30" E, Lat. 21°04'30" S). In general the unit crops out very poorly, forming flat country, in marked contrast to the overlying Hazelwood Formation. It can be traced from the type section to Hazelwood Creek but reasonable exposures are found only near Tiverton homestead.

The unit is characterized by calcareous mudstone, siltstone, and sandy biosparite with some interbedded feldspathic sandstone. For the most part, the mudstone and siltstone are richly fossiliferous and the fossils, mainly brachiopods and pelecypods, are well preserved - calcite shells with mud infilling. The unit is distinguished from the 'Lower Bowen' Volcanics by the lack of volcanics, and from the overlying Hazelwood Formation by the lack of thick-bedded sublabile sandstone. In the type area the contact with the 'Lower Bowen' Volcanics is not exposed, there being about 60 feet of section covered by sand. However, the contact
### Fig. 11

#### SECTION 15

Measured one and a half miles north of Tiverton

<table>
<thead>
<tr>
<th>Feet</th>
<th>Bedding</th>
<th>Lithology</th>
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</thead>
<tbody>
<tr>
<td>4700</td>
<td>4600</td>
<td>Brown quartz-rich lithic sandstone</td>
</tr>
<tr>
<td>4500</td>
<td>4400</td>
<td>Black maistone with blue calcareous concretions. Poorly preserved brachiopods (not collected).</td>
</tr>
<tr>
<td>4300</td>
<td>4200</td>
<td>Soft grey quartz-rich lithic sandstone; minor pebble beds. Cross-stratified.</td>
</tr>
<tr>
<td>4100</td>
<td>4000</td>
<td>Thin Blue calcareous siltstone</td>
</tr>
<tr>
<td>3900</td>
<td>3800</td>
<td>Thin Cross-stratified sublubile sandstone</td>
</tr>
<tr>
<td>3700</td>
<td>3600</td>
<td>Thin Sublubile sandstone</td>
</tr>
<tr>
<td>3500</td>
<td>3400</td>
<td>Acid silt</td>
</tr>
<tr>
<td>3300</td>
<td>3200</td>
<td>Thick Sublubile sandstone with some pebbles Red mudstone</td>
</tr>
<tr>
<td>3100</td>
<td>3000</td>
<td>Massive Blue micaceous mudstone, sandy in places, with some round pebbles</td>
</tr>
<tr>
<td>2900</td>
<td>2800</td>
<td>Thin Brown calcilutite</td>
</tr>
<tr>
<td>2700</td>
<td>2600</td>
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</tr>
<tr>
<td>2500</td>
<td>2400</td>
<td></td>
</tr>
<tr>
<td>2300</td>
<td>2200</td>
<td></td>
</tr>
</tbody>
</table>
massive Blue micaceous mudstone, sandy in places, with some round pebbles

thin Brown calcilutite

Brown siltstone
Blue calcareous siltstone with some angular cleats up to 2" in diameter
Blue micaceous, calcareous mudstone

thick Sublithic lithic sandstone, in places pebbly and grading into quartz pebble conglomerate
Quartz pebble conglomerate

thick Brown sublithic calcareous sandstone, calcareous in part

lamin. Poor outcrop of calcareous mudstone with minor silt bands

WELL SABRETOOTH MEMBER
thick Bone-strewn sublithic calcareous sandstone

BASE OF WATERTOWN FORMATION
thin Brown calcareous foraminiferous siltstone, minor sandstone
thin Blue micaceous calcareous siltstone; scattered forams

Calcareous mudstone with interbedded white micaceous siltstone

thin Richly foraminiferous brown calcareous mudstone and sandy biomicrite. Some interbedded fine, cross-stratified sublithic sandstone.

BASE OF TIVERTON FORMATION

REFERENCE
f. . . . . . . . . . . . fine arenite
m. . . . . . . . . . . medium arenite
c. . . . . . . . . . . coarse arenite
s. . . . . . . . . . . marine macro-fossils
is exposed about two miles south-south-east of Tiverton homestead (543618), where thinly bedded impure limestone and blue calcareous mudstone with angular volcanic pebbles overlie a massive volcanic flow.

**Petrology**

Modal analyses of sediments from the formation examined in thin section are given in Table 5.

**Table 5**

Modal analyses of sediments from the Tiverton Formation

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<th>Sample</th>
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<th>T4</th>
<th>T6</th>
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<td>19.2</td>
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<td>matrix</td>
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<td>7.4</td>
<td>7.0</td>
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<td>calcite bioclasts</td>
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<td>2.2</td>
<td>1.8</td>
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<td>10.0</td>
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<tr>
<td>QRF Ratio quartz</td>
<td>4</td>
<td>6</td>
<td>60</td>
<td>51</td>
<td></td>
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<tr>
<td>Q+R+F=100% rock frg.</td>
<td>84</td>
<td>91</td>
<td>26</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>Q+R+F=100% feldspar</td>
<td>12</td>
<td>3</td>
<td>14</td>
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</table>
Samples 657c and T5 are poorly washed sandy biosparite. The carbonate fraction is composed of bioclasts, and a mixture of sparry and microcrystalline calcite; sparry calcite being the more common. The bioclasts are mainly hollow curved spines up to 3mm. long and 0.5mm. in diameter, but there are some angular and subangular brachiopod shell and bryozoa fragments. The terrigenous fraction consists mainly of volcanic rock fragments and devitrified volcanic glass; feldspar phenocrysts are replaced by epidote, chlorite, and calcite. Angular to subangular quartz and feldspar grains form less than 5% of each rock. Non-opaque heavy minerals were not observed in either sample, but a little pyrites is present in 657c.

Samples T4 and T6 are examples of another common lithology in the Tiverton Formation - feldspatho-lithic sandstone. This is a moderately well sorted rock with about 40% quartz, 10% feldspar, and 20-30% rock fragments. The quartz is subangular to angular, and the feldspar, mainly plagioclase, is subangular. Rock fragments are dominantly volcanic. Devitrified volcanic glass is present in both samples. Sample T4 contains green-brown glauconite, and both samples have some colourless phyllosilicate cement. Zircon is present in
minor amounts in both samples, and apatite in T6. The zircon grains are colourless and subhedral, showing some signs of rounding. The apatite is in the form of small, colourless, subhedral grains.

Structure and thickness

The unit dips steeply to the east in the northern area of outcrop, vertically in the central part, and steeply to the west in the southern area. It is overturned and dipping about 50° east, north of
Tiverton homestead; confirmatory evidence for the overturning is the overturned cross-bedding in the thin beds of quartz sandstone at the base of the unit. Two miles south of Tiverton the dip of the formation increases to 80° east, and then to vertical three miles south of that point. It possibly dips about 70° west in the vicinity of Hazelwood Creek, as it is elsewhere conformable with the overlying Hazelwood Formation.

The unit is at least 750 feet thick in the type section, about 60 feet of the sequence being concealed between the base of the formation and the 'Lower Bowen' Volcanics.

**Age and Correlation**

Three fossil collections were made from the unit, two from measured section 15, and the other from a point two miles south-south-west of Tiverton homestead (543618). The following identifications were made by Dr. J.M. Dickins.

**Sample 1414** - in a creek about 1½ miles north-north-west Tiverton homestead.

**Brachiopods**

- *Anidanthus springsurensis* (Booker) 1932
- *Strophalosia preovalis* Maxwell 1954
- *Lissochonetes* sp.
- *Trigonotreta* sp. A (close to *T. stokesi* of Brown 1953)
- *Ingelarella profunda* Campbell 1961
Sample 1062 - in a creek about 1½ miles north-north-west
Tiverton homestead, about 500 feet
downstream from 1414.

Pelecypods

Megadesmus ? cf. nobilissimus (de Koninck)
1877 (may be a variant of Astartila
  gryphoides (de Koninck 1877)

Brachiopods

Terrakea sp. inc.
Anidanthus springsurensis (Booker) 1932
Strophalosia preovalis Maxwell 1954
Taeniothaerus sp.
Lissochonetes sp.
Neospirifera (Grantonia) cf. hobartense
  (Brown) 1953
Trigonotreta sp. A
Dielasmatids
Ingelarella ovata Campbell 1961
Ingelarella profunda
Cancrinella cf. farleyensis (Etheridge
  and Dun) 1909

Sample 657 - About two miles south-south-east of
Tiverton homestead

Pelecypods

Paralleloendon sp. ind.
Eurydesma hobartense (Johnston) 1877
**Brachiopods**

*Deltopecten limaeformis* (Morris) 1845  
*Aviculopecten* sp. ind.  
*Cypricardinia?* sp.

**Terrakea pollux** Hill 1950  
*Cancrinella cf. farleyensis* (Etheridge and Dun) 1909  
*Strophalosia cf. jukesii*  
*Taeniothaerus* sp.  
*Neospirifera (Grantonia) cf. hobartense* (Brown) 1953  
*Trigonotreta* sp. A  
*Terrakea* sp.  
*Strophalosia preovalis* Maxwell 1954

**Crinoid ossicles**

**Bryozoans**

**Cylindrical branching forms**

The most comprehensive study of Permian brachiopods and pelecypods from the northern part of the Bowen Basin (Bowen, Mount Coolon, Mackay 1:250,000 Sheet areas) was made by Dickins in 1960 and 1961 (Dickins J.M. in Malone, Corbett, and Jensen, 1961; Malone, Jensen, Gregory, and Forbes, 1962; and Jensen, Gregory, and Forbes, 1963). From this study it became apparent that the Middle Bowen Beds contained three faunal 'zones' (Fig. 12). The faunas related to the
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<tr>
<td>Nuculana sp.</td>
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<td></td>
</tr>
<tr>
<td>Nuculana sp.</td>
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</tbody>
</table>
'zones' were labelled II, III, and IV, Fauna II being the oldest.

From the species distribution chart (Fig. 12) it can be seen that many species found in the Tiverton Formation belong exclusively to Fauna II. The relevant species are: Anidanthus springsurensis, Strophalosia preovalis, Trigonotreta sp. A, Megadesmus cf. nobilissmus, Neospirifer (Grantonia) cf. hobartense, Ingelarella ovata, Cancrinella farleyensis, and Terrakea pollux.

Within the Bowen Basin, Fauna II has been correlated with the fauna of the base of the marine sequence near Cracow, and that of the Cattle Creek Formation of the Springsure area (Dickins 1961a).

Correlation of Fauna II with the Russian Permian can be made in two ways. Firstly, one might correlate by way of the Cattle Creek Formation, which has been correlated with the Sakmarian (Hill, D. 1955), and with the Lower Artinskian or Upper Sakmarian (Maxwell, 1954). Maxwell's correlation took into consideration a previous comparison (Reed, 1944) of Strophalosia sublamellata of the Indian Productus limestone with Strophalosia preovalis. Dickins (1961a) correlated the Cattle Creek Formation with the Byro Group in the Carnarvon Basin of Western Australia, using Pseudomyalinia mingenewensis.
The Byro Group, on the basis of ammonoids, is regarded as Artinskian (Glenister and Furnish 1961).

The second method involves direct correlation of faunas common to both Fauna II and the Russian succession, but this is not possible with brachiopods or pelecypods. Although there are no ammonites in the formation in the Blenheim area, one was found just to the north, and this permits a more direct correlation with Russian forms. It has been identified by Professor B.F. Glenister (in a letter to Dr. J.M. Dickins) as Neocrimites cf. frederickei, which he considers is not of early Artinskian age but probably Baigendzhinian, although a Guadalupian age is almost equally plausible. (Table 1). Taking into account the various correlation the Tiverton Formation is therefore regarded as Lower Permian.

The Tiverton Formation can be lithologically correlated with coeval formations of the Bowen Basin, such as the Yatton Limestone (Malone et al. 1963) and the Buffle Beds of the Cracow area (Wass 1962). Such correlatives are characterized by carbonate rich sediments with some volcanic detritus.

**Origin**

The unit was deposited in a near-shore neritic environment. Ecology of the fauna throws some light on the environment of deposition. The brachiopods and
pelecypods attest to the marine origin of the unit and Eurydesma in large numbers is taken to indicate cool shallow water conditions (Dickins 1957). The cross-stratified interbedded sandstone indicates the operation of traction currents and this supports the idea of shallow water environment. It is not known if all the volcanic detritus in the unit is from an older volcanic terrain or from penecontemporaneous vulcanism; both may have contributed.
THE HAZELWOOD FORMATION

The Hazelwood Formation, overlying the Tiverton Formation and overlain by the Blenheim Formation, is the middle formation of the Back Creek Group. The name is derived from Hazelwood Creek in the southern part of the Blenheim area where the unit crops out in a number of ridges (Long. 148° 18' E, Lat. 21° 10' S.). The type section was measured in a creek one and a half miles north of Tiverton homestead (Long. 148° 12' E, Lat. 21° 03' S.) and it is presented graphically in Section 15 (Fig. 11) between 750 feet and 1920 feet.

The unit is characterized by lithic sublabile sandstone, but it also contains thin beds of white to grey micaceous quartz rich siltstone and some carbonaceous mudstone. The thickness and age are discussed below under those headings. It is distinguished from the overlying Blenheim Formation by the presence of the thick beds of sublabile sandstone. The Blenheim Formation, while containing thin beds of the same lithology, is characterized by micaceous blue grey calcareous mudstone.

The base of the formation in the northern part of the area, is placed at the base of a strongly outcropping, cross-stratified, sublabile sandstone, called by Reid (1924-25) the Wall Sandstone. No formal type area or section has been published for this rock unit,
but the name is well established in the literature. It is recognized by the fact that it stands up as a long high ridge, contrasting with most of the poorly outcropping beds of the Back Creek Group which form relatively flat country. Reid (1924-25) showed a number of photos of typical outcrops of the Wall Sandstone, one of which, taken in Blenheim Creek, is almost the same as shown in Fig. 13. The Wall Sandstone is regarded herein as a member of the Hazelwood Formation, and in the type section of the formation it occupies the basal 200 feet. Further to the south near Turrawalla, the Wall Sandstone Member dies out, and the base of the formation is marked by the appearance of thick bedded quartz-rich labile sandstone with interbedded hard white siltstone.

The Wall Sandstone Member in the Blenheim area is overlain by thin bedded black micaceous carbonaceous mudstone. This can be correlated, north of the Blenheim area and on the eastern limb of the Bowen Syncline, with beds of siltstone and carbonaceous mudstone with minor coal (Malone et al. 1962). These beds pass laterally into the coal measures at Collinsville, occurring above and below the Glendoo Sandstone Member (Webb and Crapp, 1960), the Wall Sandstone Member not being present.
Outcrop of the Wall Sandstone Member in Blenheim Creek, where it is overturned and dipping steeply to the east (to the left on the photo).
Much of the next 500 feet of section above the carbonaceous mudstone is concealed in the type section, but partly exposed in Blenheim Creek. It is followed by thin to thick bedded labile and sublabile sandstone interbedded with white micaceous siltstone. This part of the sequence contains scattered marine fossils - brachiopods and gastropods. This sequence passes up into sublabile sandstone characterized by round pebbles and cobbles of quartzite up to three inches in diameter. This sandstone, which marks the top of the unit, is shown in section 5 (Fig. 14) and section 15 (Fig.11).

**Petrology**

Samples examined in thin section include: number 645 from the Wall Sandstone Member; 646 from the mudstone above the Wall Sandstone; H1, H2, H3, H4, and 1427f, collected over an interval of 300 to 600 feet above the base of the unit in Blenheim Creek. Modal analyses of the sediments are presented in Table 6.

Sample 645 from the Wall Sandstone is a well sorted lithic sublabile, medium grain sandstone. The quartz grains are mainly subangular with low sphericity; many show signs of overgrowth, and the sandstone in places approaches an orthoquartzite (Pettijohn 1957, p.296). Rock fragments, mainly angular to subangular are chiefly of quartzite or mudstone.
Table 6
Modal analyses of sediments from the Hazelwood Formation

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Sample 645</th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
<th>H4</th>
<th>1427f</th>
<th>H5</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartz</td>
<td>71.8</td>
<td>78.2</td>
<td>35.6</td>
<td>57.4</td>
<td>49.8</td>
<td>41.7</td>
<td>72.6</td>
</tr>
<tr>
<td>rock fragments</td>
<td>10.6</td>
<td>13.8</td>
<td>22.4</td>
<td>4.6</td>
<td>26.0</td>
<td>12.0</td>
<td>3.6</td>
</tr>
<tr>
<td>feldspar</td>
<td>7.8</td>
<td>3.6</td>
<td>6.0</td>
<td>7.6</td>
<td>9.2</td>
<td>2.9</td>
<td>12.6</td>
</tr>
<tr>
<td>matrix</td>
<td>6.8</td>
<td>3.4</td>
<td>9.2</td>
<td>10.2</td>
<td>6.2</td>
<td>3.3</td>
<td>8.4</td>
</tr>
<tr>
<td>colourless phyllosilicate</td>
<td>1.6</td>
<td>0.8</td>
<td>15.8</td>
<td>3.0</td>
<td>2.2</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>muscovite</td>
<td>0.4</td>
<td>0.2</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>carbonate</td>
<td></td>
<td>8.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>opaques + heavies</td>
<td>1.0</td>
<td>0.2</td>
<td>0.4</td>
<td>3.4</td>
<td>1.2</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>chlorite</td>
<td></td>
<td>1.0</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>brown sideritic cement</td>
<td></td>
<td>17.4</td>
<td>3.8</td>
<td>35.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glauconite</td>
<td></td>
<td>0.2</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grains counted</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>498</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>QRF Ratio Q</td>
<td>60</td>
<td>81</td>
<td>56</td>
<td>82</td>
<td>59</td>
<td>74</td>
<td>82</td>
</tr>
<tr>
<td>Quartz+rock frgs + feldspar = 100% F</td>
<td>11</td>
<td>15</td>
<td>35</td>
<td>7</td>
<td>30</td>
<td>21</td>
<td>4</td>
</tr>
</tbody>
</table>

Much of the carbonaceous mudstone (sample 646) is too fine to be identified in thin section. In general, it consists of angular silt-sized quartz grains in a matrix of muscovite, colourless phyllosilicate and clay minerals. The section shows abundant fine shreds of black carbonaceous material, probably plant debris.
SECTION 5
Measured two miles north-north-east of Turrawalla

FEET          BEDDING          LITHOLOGY

-600  thin  Ill sorted sublabile sandstone, fine to coarse grained: contains pebbles and cobbles. Micaceous and fossiliferous

-500  thin  Fossiliferous siltstone with lenses of quartz sandstone: some fossil wood

-400  thick  White sublabile sandstone  Interbedded siltstone  Cross bedded quartz sandstone

-300  thin  Coarse white micaceous siltstone

-200  thick  Well sorted, laminated sublabile sandstone

-100  thin  Grey-white micaceous quartz siltstone

0     thin

m ........ Medium arenite grain size
f ........ Fine arenite grain size
@ ........ Fossil collection (marine)
Sandstones higher in the sequence (samples H1, H2, H3, H4, and 1427f), are composed of: quartz 35-78%; feldspar, 3-9%; rock fragments, 5-26%; matrix, 3-10%; cement 0-35%; opaque and heavy minerals, 1-3%; and chlorite, muscovite, glauconite, less than 1%. Variation in the relative proportion of quartz, rock fragments, and feldspar, gives rise to sublabile sandstone (H1 & H3), and labile sandstone (H2, H4, & 1427f). Quartz and rock fragments are generally subround to subangular, but round grains are not uncommon. The rock fragments commonly consist of a fine mosaic of interlocking quartz grains. They could be devitrified volcanic glass, or low grade metamorphic fragments. Samples H2 and 1427f have a brown, possibly sideritic, cement.

Sample H5, collected near the top of the unit, is a litho-feldspathic sandstone, with more quartz than samples from the 300 to 600 feet interval. Most of the lithic fragments are acid plutonics.

Zircon, garnet, apatite, sphene, and tourmaline, are apparent in thin sections of sandstone from the Hazelwood Formation, zircon being the most common (Table 7). The zircon is generally colourless although dark brown to black grains were noticed in sample H4. The grains are mainly subhedral, showing signs of abrasion. Euhedral zircon grains were noted in an acid
volcanic fragment in H2.

Of the remaining non-opaque heavy minerals, apatite is the most common, and it also was observed in an acid volcanic fragment (sample H3). The apatite is generally in the form of euhedral equant grains with low birefringence. Basal sections are common.

A grain of tourmaline was noted in H3. It is dark green, with a euhedral overgrowth.

**Table 7**

Non-opaque heavy minerals observed in samples from the Hazelwood Formation

<table>
<thead>
<tr>
<th>Mineral</th>
<th>646</th>
<th>645</th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
<th>H4</th>
<th>H5</th>
<th>1427f</th>
</tr>
</thead>
<tbody>
<tr>
<td>zircon</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>apatite</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>sphene</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>garnet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>tourmaline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>rutile</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

Structure and thickness

The dip of the Hazelwood Formation, like that of the Tiverton Formation, changes from steeply overturned and dipping easterly in the north, to steep to the west.
in the southern part of the area. North of Tiverton, the beds are overturned and dipping at $65^\circ$ easterly. In Blenheim Creek, the Wall Sandstone Member is overturned dipping $80^\circ$ to the east, although prominent jointing evident in the outcrop gives the impression of a low dip to the west (Fig. 13). South of Tiverton, the dip gradually changes to vertical, and then to $85^\circ$ west in the creek where section 5 was measured. At Hazelwood Creek the dip is about $70^\circ$ west.

In measured section 15, in the northern part of the area, the thickness of the unit is approximately 1150 feet. The Wall Sandstone Member is about 200 feet thick and the top sandstone member, above the carbonaceous mudstone, at least 500 feet thick.

**Age and correlation**

Reid (1924-25, p. 461) noted *Dielasma hastata* (var.) and *Productus brachythaerus* in 'a sandstone crossing Hazelwood Creek about 2$\frac{1}{4}$ miles above Mr. Turners house'. This location although roughly defined is almost undoubtedly in sandstone of the Hazelwood Formation.

The following fossils, identified by Dr. J.M. Dickins were collected from the formation in measured section 5:
Sample 669

**Gastropods**

*Platyteichum* ? sp. ind.

**Brachiopods**

*Ingelarella undulosa* Campbell 1961

The position of section 5 with respect to the type section is shown in fig. 18. The fossil collection was made near the top of the formation. *Ingelarella undulosa* is restricted to Fauna III of the species distribution chart (Fig. 12).

Dickins (in Malone et al. 1962) indicated that the change from Fauna II to Fauna III is coeval with the *Fenestella* Shale in the Branxton Subgroup of New South Wales. Glenister and Furnish (1961) correlate the Branxton on the presence of the ammonite *Neoocrinoides meridionalis* with the Baigendzhinian, although it possibly ranges into the Guadalupian. The Hazelwood Formation is therefore regarded as Lower Permian although it may possibly range into the Upper Permian.

**Origin** The unit was deposited in a shallow water marine environment. The change from the carbonate rich fine sediments and interbedded sandstone of the Tiverton Formation, to the relatively well sorted, cross-bedded, quartz sandstone of the Hazelwood Formation probably
represents a general shallowing of the sea at this time. The withdrawal of the sea in the Collinsville area with the formation of coal, is reflected in the Blenheim area in the carbonaceous mudstone above the Wall Sandstone. A complete withdrawal of the sea in the Blenheim area is not postulated, however.
BLENHEIM FORMATION

The Blenheim Formation, the uppermost formation of the Back Creek Group in the Blenheim area, is a new unit proposed herein. It crops out on the eastern side of the area mapped, extending from the northern to the southern boundaries. The name is derived from Blenheim Creek (Lat. 21° 04' S. Long. 148° 13' E), where much of the top of the unit is well exposed. The type section however, was measured in a creek one and a half miles to the north (Lat. 21° 03' S. Long. 148° 12' E) and it is shown in measured section 15 (Fig. 11) from 1920 feet to the top of the section.

The unit consists of micaceous blue-grey or brown calcareous mudstone and siltstone with minor thick bedded quartz-rich labile sandstone. The unit is distinguished from the underlying Hazelwood Formation on the abundance of mudstone, the base of the sequence being marked by a conglomeratic mudstone. The top of the unit, exposed in two places only, is a quartz-rich labile sandstone. The formation is distinguished from the overlying Turrawalla Formation by: (a) the abundance of blue-grey non-carbonaceous mudstone with more obvious mica in hand specimen; (b) the presence of more quartz-rich labile sandstone. A supplementary but by no means diagnostic
criterion to distinguish the two formations is the presence of marine fossils in the Blenheim Formation and their general absence from the Turrawalla Formation. A more detailed account of the lithological changes taking place at the boundary of the two formations is given in the section on the Turrawalla Formation.

The general stratigraphic sequence within the unit is shown in measured section 15 (Fig. 11). Mudstone at the base of the formation is poorly sorted, containing large angular fragments up to six inches across of fine sediments and low grade metamorphics. Pebbles in the overlying blue mudstone, between 2,300 and 2,900 feet in section 15, are of volcanic rocks and schist. This basal part of the sequence is fossiliferous, but the preservation of the fossils, mainly brachiopods, crinoid ossicles, and bryozoa, is very poor in this area.

Quartz-rich labile sandstone beds become more apparent from the middle to the top of the formation. They are thick to thin bedded and in places lenticular cross-beds are weakly developed. The top 800 feet of the section is exposed well in Blenheim Creek and shown in section 4. At the base of this section richly fossiliferous blue micaceous siltstone is poorly sorted, and contains clasts up to 12 inches across. The fossils,
SECTION 4

Measured in Blenheim Creek, 1/2 mile west of Tiverton

<table>
<thead>
<tr>
<th>Feet</th>
<th>Bedding</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>thick</td>
<td>Grey-white sublumible sandstone</td>
</tr>
<tr>
<td>700</td>
<td>thin</td>
<td>Grey to black micaceous siltstone and mudstone. Reworked by molluscs</td>
</tr>
<tr>
<td>600</td>
<td>thick</td>
<td>Poorly sorted grey-green micaceous quartz-rich lobile: arenite</td>
</tr>
<tr>
<td>500</td>
<td>thin</td>
<td>Brown and grey micaceous mudstone</td>
</tr>
<tr>
<td>400</td>
<td>thin</td>
<td>Micaceous siltstone and mudstone</td>
</tr>
<tr>
<td>300</td>
<td>thin</td>
<td>Grey micaceous mudstone</td>
</tr>
<tr>
<td>200</td>
<td>thick</td>
<td>Blue calcareous richly fossiliferous micaceous mudstone, becoming poorly sorted at the base and containing scattered angular pebbles and boulders up to 12&quot; across</td>
</tr>
</tbody>
</table>
brachiopods, bryozoa and small corals, are worn and broken, suggesting transportation. On faunal content Dickins (pers. comm.) would correlate this horizon with the Big Strophalosia Zone (Reid 1924-25). The two developments of sandstone at the top of the unit are seen in both section 4 and 15.

Mudstone near the top of the unit (sample 292) is dark, blue-grey with light blue patches scattered throughout, either as small ovoid shapes or elongate swirls (Fig. 16). This is regarded as an indication of the reworking of the original mud by organisms, possibly molluscs. As it occurs near the change from marine to non-marine conditions it may also indicate a relatively shallow water, perhaps littoral, environment. Similar structures are apparent in the Falt Top Formation in the Cracow area, again at the change from marine to non-marine conditions.

**Petrology**

Sandstone of the unit is fine to medium grained, poorly sorted, quartz rich, feldspato-lithic sandstone. Modal analyses of arenites from the formation are presented in Table 8. Approximately 500 grains were counted in each sample.
### Table 8

Modal analyses of samples from the Blenheim Formation

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>293a</td>
</tr>
<tr>
<td>quartz</td>
<td>45.2</td>
</tr>
<tr>
<td>rock fragments</td>
<td>11.8</td>
</tr>
<tr>
<td>feldspar</td>
<td>4.3</td>
</tr>
<tr>
<td>matrix</td>
<td>29.4</td>
</tr>
<tr>
<td>colourless phyllosilicate</td>
<td>0.2</td>
</tr>
<tr>
<td>muscovite</td>
<td>3.8</td>
</tr>
<tr>
<td>carbonate</td>
<td>4.8</td>
</tr>
<tr>
<td>opaques + heavies</td>
<td>2.5</td>
</tr>
<tr>
<td>brown phyllosilicate</td>
<td>27.6</td>
</tr>
<tr>
<td>bioclasts</td>
<td>3.2</td>
</tr>
<tr>
<td>haematite</td>
<td>6.8</td>
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<tr>
<td>chlorite</td>
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</tr>
<tr>
<td>QRF Ratio</td>
<td>Q 74</td>
</tr>
<tr>
<td>quartz+rock frag+R</td>
<td>19</td>
</tr>
<tr>
<td>feld.=100%</td>
<td>F 7</td>
</tr>
</tbody>
</table>
Fig. 16

Indications of an abundant infauna in a mudstone at the top of the Blenheim Formation.
The quartz is generally angular to subangular and the sphericity is low to moderate. However, there is a significant amount of round quartz with high sphericity indicating at least two cycles of transport.

The rock fragments vary from subround to angular. They consist of volcanic glass, volcanic rocks, quartzite, quartz muscovite schist, diorite, and carbonaceous mudstone, but by far the greatest number are of volcanic origin. The glass is subangular to subround and does not appear to have an angular shard form. It is either anisotropic brown showing anomalous birefringence, with no cleavage but some perlitic cracking, or it is completely replaced by fine brown phylllosilicate. In some cases it is dark brown and isotropic. The volcanic rock fragments consist of fine grained groundmass of quartz and feldspar with scattered phenocrysts, usually of albite. Some of these fragments are replaced by iron oxide, probably now limonite, as if they were subjected to weathering before transportation. Coarse grained diorite fragments are extensively replaced by calcite.

Cement when present consists of sparry calcite, brown or colourless phylllosilicate, or grey brown cryptocrystalline siderite. The fine sandstone has a matrix consisting of quartz and fine shreds of muscovite.
Samples from the Blenheim Formation contain a variety of heavy minerals, as shown in Table 9. Colourless zircon is the most common heavy mineral, being present in every sample. Most of the zircon grains are subhedral, showing some degree of rounding. Euhedral grains are rare.

Of the other heavy minerals, colourless apatite is the most common, the grains also showing signs of abrasion.

The sphene observed is brown with dark exsolution laminae. In samples B4 and B2 the grains are subhedral, and a small patch of euhedral grains is present in B3. Euhedral sphene is enclosed in a fragment of mica schist in sample B4.

Yellow green and yellow tourmaline is common in sample B3; varieties in B4 and 293a include brown, blue-grey and green grains. Colourless overgrowths are present on tourmaline of 293a.

Table 9

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Sample</th>
<th>B4</th>
<th>B3</th>
<th>B2</th>
<th>B1</th>
<th>292c</th>
<th>293a</th>
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<tbody>
<tr>
<td>Sphene</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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</tr>
<tr>
<td>Zircon</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Apatite</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tourmaline</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>Rutile</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Garnet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Epidote</td>
<td></td>
<td></td>
<td>x</td>
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</table>
Feldspar, both plagioclase and potassic feldspar, is angular to subrounded. The plagioclase appears to be a mixture of albite and oligoclase. The potassic feldspar shows cloudy brown alteration, and both plagioclase and potassic feldspar are partially replaced by calcite.

**Structure and thickness**

Beds in the unit cropping out in this area are invariably steep-dipping. The unit is overturned and dipping steeply to the east in Blenheim Creek. Further south, in the Hazelwood Creek area, the dip may be as low as 70° to the west.

On the basis of measured section 15 the unit in this area is 2,800 feet thick. The increase in thickness of outcrop measured across the strike in the Hazelwood Creek area, compared with the Blenheim Creek area, is almost certainly due in part to the decrease in dip of the unit.

**Age and correlation**

Two fossil collections were made from the unit, one from the top (292) and the other about 700 feet lower (293). The following identifications are by Dr. J.M. Dickins:
Sample 292  At the Collinsville road crossing of Blenheim Creek

Brachiopods

*Ingelarella ingelarensis* Campbell 1960

Sample 293  About 400 yards downstream from Tiverton homestead

Brachiopods

*Terrakea solida* (Etheridge and Dun 1909)
*Neospirifer* sp. A
*Trigonotreta* sp. B
*Ingelarella* cf. *angulata* Campbell 1961

Pelecypods

*Myonia* cf. *carinata* Morris 1845

The species *Terrakea solida*, *Myonia* cf. *carinata*, *Ingelarella angulata*, *Trigonotreta* sp. B, and also *Cancellospirifer*, are confined to Fauna IV in the species distribution chart. Fig. 12). The interesting feature of the fauna compared with that of Fauna III is the advent of new species rather than new genera.

The Blenheim Formation because it contains Fauna IV, is regarded as Upper Permian. The Mantuan Productus Bed, whose fauna can be referred to Fauna IV, is regarded as Kazanian (upper part of Guadalupian) in age (Dickins 1961b). Support for the Upper Permian age for the
Blenheim Formation comes also from Campbell (1959) who reached the same conclusion, regarding the uppermost marine beds of the Bowen Basin as Kazanian.

**Origin**

Although a change from a dominantly sandy unit to a muddy unit cannot automatically be equated with a change to deeper water conditions, in this case the change is accompanied by features which support the contention. Firstly, as previously mentioned there is a change in the fauna on the specific level, and one would imagine that this could be brought about by a climatic or eustatic change. Secondly, the base of the unit is marked by a conglomerate, possibly indicative of uplift in the source area and corresponding deepening of the basin of deposition. Thirdly, the incoming of Fauna IV is associated all over the basin with a major marine transgression which exceeded the limits of previous marine Permian deposition. (Malone and Dickins 1964).

Cross-bedded sands coming in at the top of the unit may indicate a shallowing of the sea, to give the possible littoral conditions previously suggested. However, the fauna of brachiopods, polyzoa, and small corals suggest a neritic rather than a bathyal environment for most of the unit.
The Turrawalla Formation, a new name introduced herein, forms the basal unit of the Theodore Group in the Blenheim area. The name is derived from Turrawalla homestead (148° 14' 40" E, 21° 10' 00" S) and the type section was measured in a small tributary of the Bowen River which crosses the Turrawalla Collinsville road about three miles north-north-west of Turrawalla homestead, (Measured section 7 and part of 6, Figs. 18, 17). The base of the sequence, concealed in the type section, consists of lithic sandstone, and mudstone which is carbonaceous in places; this is in contrast to the sub-labile sandstone and blue micaceous mudstone of the underlying Blenheim Formation. The top of the formation consists of lithic sandstone and this is overlain by pebble conglomerate of the overlying Exe Creek Formation. The dominant lithology of the unit is lithic sandstone and this is interbedded with volcanic flows, siliceous tuff, minor conglomerate, coal, and sandy limestone.

The Turrawalla Formation crops out both east and west of the Redcliffe Tableland. On the eastern side it occupies a thin strip of land, mainly east of the Bowen River, from about five miles wide in the north to two miles wide in the south. On the western side of the Tableland it crops out over a large area north, west, and
**SECTION 6**

Measured four miles south of Tiverton

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<th>FEET</th>
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<td>Brown lithic sandstone</td>
</tr>
<tr>
<td>1800</td>
<td>Thin</td>
<td>Brown mudstone</td>
</tr>
<tr>
<td>1700</td>
<td>Thick</td>
<td>Brown lithic sandstone, cone pebbles</td>
</tr>
<tr>
<td>1600</td>
<td>Thin</td>
<td>Rhyolite</td>
</tr>
<tr>
<td>1400</td>
<td>Thick</td>
<td>Rhyolite</td>
</tr>
<tr>
<td>1300</td>
<td>Thick</td>
<td>Poorly sorted conglomeratic lithic sandstone. Pebbles up to 6 ins. subangular</td>
</tr>
<tr>
<td>1200</td>
<td>Thin</td>
<td>Intermediate sill</td>
</tr>
<tr>
<td>1100</td>
<td>Thin</td>
<td>Lithic sandstone</td>
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<tr>
<td>1000</td>
<td>Thin</td>
<td>Lapilli tuff</td>
</tr>
<tr>
<td>900</td>
<td>Thin</td>
<td>Silicified fine tuff - leaf impressions</td>
</tr>
<tr>
<td>800</td>
<td>Thin</td>
<td>Tuffaceous lithic sandstone</td>
</tr>
<tr>
<td>700</td>
<td>Thin</td>
<td>Lapilli tuff</td>
</tr>
<tr>
<td>600</td>
<td>Thin</td>
<td>Tuffaceous lithic sandstone - calcareous</td>
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<td>Thin</td>
<td>Coarse grained basic sill</td>
</tr>
<tr>
<td>400</td>
<td>Thin</td>
<td>Silicified fine tuff - leaf impressions</td>
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<tr>
<td>300</td>
<td>Thin</td>
<td>Tuffaceous lithic sandstone</td>
</tr>
<tr>
<td>200</td>
<td>Thin</td>
<td>Lapilli tuff</td>
</tr>
<tr>
<td>100</td>
<td>Thick</td>
<td>Silicified fine tuff - leaf impressions</td>
</tr>
<tr>
<td>0</td>
<td>Thick</td>
<td>Tuffaceous silicic sandstone - fossil wood</td>
</tr>
</tbody>
</table>

**REFERENCE**

- Fossil plants
- Fossil wood
- Coarse grains
- Medium grains
- Fine grains

**NOTES**

- Grey and blue mudstone with fossil wood
- Brown lithic sandstone
- Silicified fine tuff - leaf impressions
- Tuffaceous silicic sandstone - fossil wood
- Rhyolite
- Interbedded lithic sandstone - mudstone
- Quartz lithic sandstone with interbedded acid flows or sills

- Bedding and lithology chart shows various rock types and sedimentary structures.
- The chart includes detailed descriptions of the sedimentary layers and their characteristics.
- The measurements are given in feet, with some notes on the thickness and type of sediments.
south of Byerwen homestead, and also in a wedge shaped area south-west of Poli water bore.

The unit produces relatively flat to gently undulating country with long low strike ridges common east of the Redcliffe Tableland. In the western area of outcrop, the topography is flat except for small rounded hills near the outcrop of Tertiary basalt. Strike ridges are not common in the western area, and the trend lines shown on the map (Enclosure 1) are picked out on the ground by preferential growth of brigalow scrub. East of the Tableland, low strike ridges are common, and small creeks with moderately good outcrop drain the ridges and flow into the Bowen River.

Lithology

The unit is composed of: labile sandstone, which is calcareous in places; mudstone and laminated shale; volcanic flows and primary tuff; conglomerate, coal, and impure limestone.

The sandstone includes lithic sandstone, lithofeldspathic sandstone, and feldspatholithic sandstone. In some cases, especially towards the top of the unit more than 90% of the lithic fragments are derived from a volcanic source, and the sandstone is termed a volcanic lithic sandstone. Sandstone with a carbonate cement is termed calcareous, and this is also common in the unit.
TURRAWALLA FORMATION

TIVERTON FORMATION

HAZELWOOD FORMATION

Well Sandstone Member

TIVERTON FORMATION

LOWER BOWEN VOLCANICS

LOCALITY MAP

REFERENCE

- Fine siliciclastic clays
- Argillaceous sediments
- Calcareous sediments
- Sandstone
- Conglomerate
- Volcanic lithics, conglomerate or sandstone
- Inclusions or extensive igneous rock
Sandstone of the unit is almost invariably thinly to thickly trough cross-stratified; the cross-strata are arranged in lenticular curved sets forming troughs generally one to four feet thick, and from one to twenty feet in length. Measurements indicate that about half the maximum dips of the cross-strata are less than 20° and half are greater. McKee and Weir (1953) put the boundary between high and low angle cross-stratification at 20°. Fifteen measurements of direction along the axis of troughs over 2,000 feet of section showed a standard deviation of 35° from an azimuth of 220° (approx. south-west).

Another feature of the sandstone of the unit is the lenticularity of the beds, and because of this individual beds cannot be traced along strike for any distance (Figs. 19 & 20). The lenses are up to forty feet thick and about ten to one hundred feet long. Small lenses cut through underlying fine sediments in cut and fill structures.

Mudstone in the unit is generally massive but in places dark laminae of carbonaceous material are apparent; the general colour is dark grey, black or brown, depending to some degree on the amount of carbonaceous material present. Mica is commonly present but only in small amounts, in contrast to the micaceous mudstone of the
Sandstone lenses in Turrawalla Formation. Trough cross-stratified sandstone in foreground.

Closer view of lenses in Turrawalla Formation.
Teviot Formation and the Hazelwood Formation. Black carbonaceous plant debris is common and in places fossil leaves are well preserved. The mudstone is generally soft and in outcrop it is massive with miriads of small closely spaced random joints, making the collection of large fossil leaves difficult. Shale in the unit is similar to the mudstone but it has a weak fissility.

The Turrawalla Formation contains interbedded acid flows of rhyolite and dacite. It is not always possible to distinguish between these flows and sills intruded into the sequence. In some cases the sills are slightly transgressive with respect to the underlying beds, and an intrusive relationship can be established. In other cases, where the igneous bodies are completely conformable with the sedimentary sequence, and where a trachytic texture is apparent, the rocks are considered to be extrusive.

Primary siliceous tuff beds are common in the upper half of the sequence, associated with flow rocks and volcanic lithic sandstone. The tuff is aphanitic, blue-grey to grey-white, hard and dense. Fine undulose blue lamination is common. In places it contains extremely well preserved fossil plant impressions.

Pebble conglomerate is common in the middle part of the formation. It consists of pebbles exclusively of
volcanic origin, in most cases very round and with high sphericity. Beds are massive and up to ten feet thick. A volcanic lithic sandstone matrix is common.

In some rocks in the formation, especially towards the base, the amount of carbonate exceeds that of terrigenous detritus, to form impure limestones - lithic sandy micrite, sublabile lithic sandy pseudosparite, and sublabile lithic sandy pseudosparite. These rocks are distinctive in the field, generally having an even brown colour and a smooth surface texture.

**Petrology**

Samples of volcanic conglomerate examined in thin section include 615, 631, 609b, and 620a. Volcanic detritus, both lithic and vitric fragments, form the bulk of these rocks, with minor amounts of quartz, feldspar, and carbonate. Grainsize ranges from fine pebble down into sand sized fragments. The lithic fragments are mainly porphyritic holocrystalline or hyalocrystalline acid and intermediate flows, and tuff. The vitric fragments are brown and generally isotropic, with some small phenocrysts of feldspar and quartz, and rare vesicles; perlitic cracking is common. Both the lithic and vitric fragments are round to subround and sphericity is high. A little sedimentary detritus is evident; one grain in sample 615 is a quartz pebble conglomerate with
Table 10
Modal analyses of samples from the Turrawalla Formation

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<td>292f</td>
<td>292g</td>
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<td>49</td>
<td>11</td>
<td>1</td>
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<td>620b</td>
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<tr>
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<td>20.0</td>
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<td>12</td>
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extremely round quartz grains. Secondary phases in the volcanic conglomerate include: calcite replacement of feldspar fragments, and calcite cement; chlorite filling vesicles in lithic fragments and filling intergranular spaces.

The framework of samples 620b, 298, and 1401 is essentially the same as that of the volcanic conglomerate, but the grains are of arenite size. They are termed volcanic lithic arenite, a modification of Crook’s lithic arenite (Crook, 1960).

One of the most distinctive rocks in hand specimen in the formation is a thick bedded brown calcareous feldspatholithic sandstone (sample 297). It consists of 27% feldspar and 62% lithic and vitric fragments; quartz and a calcite cement constitute the remainder of the rock. Most of the feldspar has a volcanic origin as similar laths are to be seen in the lithic and vitric fragments, and because much of it is plagioclase. An abundance of plagioclase in a sediment is held to be an indication of a volcanic provenance (Folk 1961). At least some of the feldspar is albite.

Sandstone near the base of the formation is moderately well sorted and contains less volcanic detritus than the volcanic lithic sandstone already discussed. The sandstone examined in thin section includes lithic
sandstone (292e, 292g) and lithofeldspathic sandstone (292f). The main constituents are quartz, rock fragments, devitrified glass, feldspar, and secondary calcite. The quartz does not exceed 40% of the rock and it is generally about 30%. The quartz grains are angular to subangular and sphericity is moderate, with the exception of those in sample 292e, which contains subround grains with a moderately high sphericity. The lithic fragments include porphyritic andesite, rhyolite, banded crystal tuff, coarse and fine grained quartzite, and granite. Subround and subangular volcanic glass fragments are not uncommon. The feldspar in contrast to the feldspar of the volcanic lithic sandstone is mainly untwinned; the grains are angular to subangular. Sparry calcite is a common cement.

Sandy carbonate rocks, cropping out mainly near the base of the formation, include lithic sandy micrite (225a), labile lithic sandy pseudosparite (1427a and 608). These terms are the result of a combination of the classification of the terrigenous arenite fraction based on the scheme by Crook (1960), and the classification of the carbonate fraction based on the scheme by Folk (1959). Much of the carbonate is secondary, filling pores and replacing the terrigenous minerals. In 608 and 1427a it is sparry, but this may represent recrystallization of a
primary carbonate mud. In all cases it has grey brown colour, and the composition is unknown. The terrigenous fraction consists of quartz, volcanic glass, volcanic rock fragments, and feldspar. It forms about 30% of the rock.

By far the most common detrital heavy mineral in the Turrawalla Formation is apatite. As shown in Table 11, apatite is present in every sediment examined; it is accompanied by some sphene, zircon and garnet. The apatite is mainly euhedral and shows little sign of abrasion. In many cases euhedral apatite is present in acid volcanic fragments within the sediments; commonly accompanied by quartz exhibiting straight extinction. There can be little doubt that the relative abundance of apatite in this formation is a reflection of the large volcanic component in the sediments.

Flows examined in thin section (601b, 294b, and 292d) are all acid, being rhyolite or dacite in which quartz forms 20% to 30% of the rock, occurring as small anhedral grains. The flows are porphyritic, the phenocrysts consisting of potash feldspar and oligoclase. The groundmass consists of small laths of plagioclase or brown devitrified glass. The small amount of hornblende present in some samples is replaced partially by chlorite. Apatite and magnetite are common accessory minerals.
### Table 11

Non-opaque heavy minerals present in sediments of the Turrawalla Formation

<table>
<thead>
<tr>
<th>Sample</th>
<th>Apatite</th>
<th>Zircon</th>
<th>Colourless garnet</th>
<th>Sphene</th>
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<tbody>
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<td>1401</td>
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</tr>
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<td>620a</td>
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<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>609b</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>620b</td>
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<td></td>
<td>x</td>
</tr>
<tr>
<td>615</td>
<td></td>
<td></td>
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<td>x</td>
</tr>
<tr>
<td>1427a</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>292e</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>292f</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>292g</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

#### Succession east of the Redcliffe Tableland

The broad lithological succession of the Turrawalla Formation east of the Redcliffe Tableland is shown in Fig. 18, by means of graphic sections, established by two methods: integration of individual observations at points on the ground using air photo control, to produce a composite section; and by the correlation of measured sections, measured with tape compass, and abney level.
**NUMBER 14**

Measured in a creek one mile north of Turrawalla Collinsville road-crossing of Blenheim Creek

- Blue and brown calcareous lithic sandstone, interbedded brown mudstone and brown calcilitte

<table>
<thead>
<tr>
<th>Height (ft)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Calciteous lithic sandstone</td>
</tr>
<tr>
<td>10</td>
<td>Very weathered silt or clay</td>
</tr>
<tr>
<td>20</td>
<td>Brown lithic sandstone</td>
</tr>
<tr>
<td>30</td>
<td>Light blue mudstone with interbeds of calcilitte, some calcareous concretions</td>
</tr>
<tr>
<td>40</td>
<td>Brown quartz-rich lithic sandstone</td>
</tr>
<tr>
<td>50</td>
<td>Black mudstone and blue calcilitte concretions</td>
</tr>
</tbody>
</table>

**NUMBER 3**

Measured west along Blenheim Creek from Turrawalla-Collinsville road-crossing

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>197.4</td>
<td>Sample: dark grey micaceous mudstone</td>
</tr>
<tr>
<td>200</td>
<td>Lithic sandstone</td>
</tr>
<tr>
<td>210</td>
<td>Brown mudstone with patches of blue grey calcilitte</td>
</tr>
<tr>
<td>215</td>
<td>Grey-brown micaceous siltstone</td>
</tr>
<tr>
<td>220</td>
<td>Grey-brown lithic sandstone</td>
</tr>
<tr>
<td>225</td>
<td>Grey-brown mudstone</td>
</tr>
<tr>
<td>230</td>
<td>Intermediate sill: black indurated shale with plant fragments</td>
</tr>
<tr>
<td>235</td>
<td>Green-grey lithic sandstone, minor silt bands</td>
</tr>
<tr>
<td>240</td>
<td>Brown and black carbonaceous mudstone</td>
</tr>
<tr>
<td>245</td>
<td>BASE OF TURRAWALLA FORMATION</td>
</tr>
<tr>
<td>250</td>
<td>Grey-white quartz-rich lithic sandstone</td>
</tr>
<tr>
<td>255</td>
<td>Grey to black thinly laminated micaceous siltstone, showing indications of abundant influx</td>
</tr>
</tbody>
</table>

- medium arenaceous silt
- fine
- plant fossils
- marine macro fossils
- thin bedded
- thick bedded
- very thick bedded
The boundary between the Blenheim Formation beneath, and the Turrawalla Formation above, is placed at an abrupt change from a unit composed of micaceous siltstone, mudstone, and sublabile sandstone, to one in which carbonaceous mudstone, shale, and lithic sandstone dominate. The change is well exposed in Blenheim Creek at the Turrawalla-Collinsville Road crossing, and it is shown in measured sections 3 and 14 (Fig. 21). In measured section 3, grey to blue micaceous siltstone with marine fossils is overlain by grey to white sublabile sandstone; both these lithologies are characteristic for the Blenheim Formation. The overlying carbonaceous mudstone with abundant plant debris is taken to be the basal bed of the formation. The same sequence of beds cannot be seen at the same stratigraphic position one mile to the north, in measured section 14; but once again there is a similar change in lithology and fossil content.

The shale and lithic sandstone so characteristic of the basal part of the formation continues throughout the unit but, at 1,800 feet above the base thick beds of pebble conglomerate and a few thin beds of tuff appear. Above 3,000 feet from the base volcanic lithic sandstone and fine tuff are dominant with beds of volcanic conglomerate. In this part of the sequence large logs of silicified fossil wood, some in their growth position,
Fossil wood replaced by silica.
Turrawalla Formation.
are common (Fig. 22). The top of the formation just off the area mapped, west of Turrawalla homestead, is marked by a thin development of coal, and in the area mapped it is marked by the change to a sequence without primary volcanics.

**Succession west of the Redcliffe Tableland**

The general succession of lithic sandstone and carbonaceous shale at the base of the formation, overlain by a volcanic lithic sandstone and conglomeratic sequence with coal at the top, is also present in the area west of the Tableland. Outcrop is very poor however, and only one short section was measured (number 1, Fig. 23). The lowest beds in the sequence, exposed in the north-west corner of the area consist of brown sandy limestone similar to beds in about the same position on the other side of the Tableland, in measured section 14. Fossil leaf impressions are common in this lithology (sample 225). These beds are overlain by 2,500 feet of carbonaceous mudstone and shale with fossil wood, lithic sandstone, and calcareous lithic sandstone. This is followed by about 1,500 feet of section dominated by volcanic lithic sandstone, conglomerate, and coal (measured section 1).

Only the top of the section crops out to the south of Poli bore, consisting of volcanic lithic sandstone
FIG 23

MEASURED SECTION 1

Measured in Kongaroo Ch one mile north Byerwen

Cross-stratified lenticular lithic sandstone
with some pebble conglomerate

? EXE CREEK FORMATION

Very little outcrop. Some weathered carbonaceous
shale and siltstone

TURRAWALLA FORMATION

Trough cross-stratified volcanic lithic sandstone

Transgressive sill

Thinly interbedded carbonaceous shale,
siltstone, and minor quartz-rich labile
sandstone and coal
interbedded with lithic sandstone and calcareous lithic sandstone. Outcrop in this area is extremely poor.

Structure and thickness

The Turrawalla Formation conformably overlies the Blenheim Formation and is conformably overlain by the Exe Creek Formation. The unit east of the Redcliffe Tableland dips slightly south of west. The dip at the base of the unit is steep, varying from 78° east (overturned) in Blenheim Creek, to vertical three miles south, and 55° west near Hazelwood Creek. The steep dips at the base of the unit decrease westward to about 70° west, where in a synclinal bend the dip rapidly changes to 30° west. This is a marked structure, being observed over a distance of seven miles, from a point about three miles north of Turrawalla homestead to the northern edge of the area. West of the structure the dip gradually decreases to about 20°.

The unit west of the Redcliffe Tableland is folded into a broad syncline, here termed the Weetalabah Syncline. The eastern limb of the syncline is cut by a major north trending fault, here named the Commissioner Fault. The hade of the fault is not known definitely, but the lack of overturned beds and the presence of small patches of slickensides dipping steeply to the east parallel to the bedding, probably indicates a normal
fault. Evidence for the presence of the fault elsewhere is: (a) the rupture of trend lines on the air photos, north of Eastern Creek, and (b) beds on the west side of the fault in Eastern Creek dip to the west at 20°; dips in the fault zone are irregular but mainly steep and to the east.

On the western side of the Weetalabah Syncline, north-west of Byerwen homestead, the beds dip to the east at about ten degrees in the extreme north-west to twenty-five near the top of the unit. The basal beds form the eastern side of a domal structure most of which is outside the area of the map. South-west of Byerwen homestead the structure is more complicated, and a regional dip to the east is not apparent. The air photos of this area, south-west of Byerwen, show no trend lines but a number of small anticlines and synclines were observed in one creek, together with small scale thrust faulting.

The thickness of the unit on the eastern side of the Tableland is 4,800 feet. This figure has been derived from the integration of dip information at numerous places, measured sections and trend lines on air photos. Minimum thickness for the unit on the western side of the Tableland is 4,000 feet; the base of the unit is not present. It is therefore probable
that there is little difference in thickness of the unit in the two areas.

**Age and correlation**

Fossil plants collected from the unit in the course of mapping the area were identified by Mrs. Mary White (M. White 1960). Identifications and localities are listed in Table 15.

Many of the genera range into the Triassic from the Permian, but the following species have been found only in the Permian (Hill and Woods 1963):

- **Glossopteris indica**
- **Sphenopteris lobifolia** Morr.
- **Vertebraria indica** Royle

The ovate seed **Samaropsis dawsoni** (Shirley) found near the top of the unit, is reported to be exclusively Upper Permian (Hill and Woods 1963). The Turrawalla Formation is therefore regarded as Upper Permian.

It seems reasonable to equate the tuffaceous upper part of the Turrawalla Formation with similar coal bearing tuffaceous sequences cropping out in the southern part of the Bowen Basin. In particular, the Upper Permian Gyranda Formation contains thin beds of siliceous tuff with well preserved leaves, similar to beds in the
<table>
<thead>
<tr>
<th>No.</th>
<th>grid ref.</th>
<th>Location</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>165724</td>
<td>3½ mls NW Weetalabah</td>
<td>Glossopteris indica</td>
</tr>
<tr>
<td>233</td>
<td>182720</td>
<td>3 mls NW Weetalabah</td>
<td>Phyllotheca australis, Glossopteris indica, Numulospernum bowenense, Sphenopteris lobifolia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Glossopteris indica, Sch. Numulospernum bowenense, Sphenopteris lobifolia</td>
</tr>
<tr>
<td>1017</td>
<td>451672</td>
<td>1¾ mls N junction of Blenheim Creek and Bowen River</td>
<td>Phyllotheca australis, Glossopteris indica, Sphenopteris lobifolia, Cladophlebis roylei, Samaropsis dawsoni</td>
</tr>
<tr>
<td>292</td>
<td>512670</td>
<td>In Blenheim Creek near Turrawalla-Collinsville road crossing</td>
<td>Glossopteris indica</td>
</tr>
<tr>
<td>289</td>
<td>524628</td>
<td>1 mile S Tiverton</td>
<td>Vertebraria indica, Royle</td>
</tr>
<tr>
<td>608</td>
<td>504636</td>
<td>1½ mls WSW Tiverton</td>
<td>Phyllotheca sp., Cladophlebis roylei, Sphenopteris sp., Glossopteris indica</td>
</tr>
</tbody>
</table>

TABLE 15

Fossil plants from the Turrawalla Formation identified by Mrs. M.E. White (White, 1960)
Turrawalla Formation. (Jensen et al. 1964).

**Origin**

The Turrawalla Formation, being devoid of marine fossils and so enriched in plant fossils, is almost certain to mark a change from marine deposition of the Blenheim Group, to freshwater or terrestrial deposition. The basal part of the sequence is characterized by carbonaceous mudstone and shale, interbedded with trough cross-bedded lithic sandstone with small pieces of fossil wood. The full significance of trough cross-stratification of the interbedded sandstone is not known in terms of environment, but formation of such a structure requires strong traction currents in relatively shallow water (Sutton and Watson, 1960). The intercalation of carbonaceous mudstone and lenticular sandstone bodies, together with the other features mentioned, suggests a deltaic or fluviatile depositional environment. More detailed mapping in areas of good outcrop might reveal deltaic facies similar to those reported from the Mississippi delta.

The volcanic upper part of the sequence was deposited in a terrestrial environment. Fossil stumps in their growth position attest to the rapidity of their burial by tuff and lapilli tuff. The consistent
association of well preserved fossil leaves with silicified fine tuff suggests rapid burial of the leaves in volcanic ash. A fluvial or possibly lacustrine environment probably existed from time to time with the deposition of the volcanic conglomerate, volcanic lithic sandstone and mudstone interbedded with the upper part of the sequence. Coal at the top of the unit suggests some swampy areas.
The upper formation of the Theodore Group, the
Exe Creek Formation, occupies three areas: (a) between
the outcrop of the Turrawalla Formation and the eastern
edge of the Redcliffe Tableland, (b) along the western
edge of the Tableland, and (c) the centre of the
Weetalabah Syncline, north and south of Weetalabah
homestead. In all three areas it crops out poorly
because of the softness of the formation and because of
the extensive spread of sand derived from the Tableland.
In some areas it forms low rounded discontinuous strike
ridges, but it commonly produces very flat to gently
undulating country.

The new name 'Exe Creek' Formation, introduced
herein, is derived from Exe Creek, west of Turrawalla
homestead. Because of the lack of outcrop no one
section will be named as the type section. Rather, it
is proposed that the area between the Bowen River and
the Redcliffe Tableland for seven miles north of
Stockton Creek be referred to as the type area. This
includes sections 6, 8 and 9 (Figs. 17, 18) which show
the outcropping lithology. The top 1,600 feet of the
formation in the type area is obscured by sand derived
from the Redcliffe Formation, but some idea of the
lithology of this part of the section was derived from outcrop west of the Redcliffe Tableland.

The unit is composed of conglomeratic lithic sandstone interbedded with fine brown mudstone and minor beds of pebble conglomerate; it is intruded by sills and dykes. The most common lithology is lithic sandstone, which in places becomes a calcareous lithic sandstone with as much as 45% carbonate. The sandstone, although relatively well sorted in that it has little or no matrix, is characterized by pebbles up to two inches in diameter.

The sandstone, almost invariably trough cross-stratified, contains from 10-50% quartz, from 20 to 40% rock fragments, and up to 10% feldspar. The quartz grains are angular to subangular with moderate to low sphericity, except in sandstone at the base of the unit (sample 294e) where it is subround with moderate to high sphericity. All three types of extinction, straight, undulose, and composite are present, no one type being dominant throughout the unit. Rock fragments are of both sedimentary and igneous origin, mudstone and quartzite being common at the base of the formation and granite towards the top. Volcanic rock fragments are present but they never exceed 10% of the rock; some are porphyritic with a glassy groundmass and others consist
of small laths of feldspar. Many very fine-grained rock fragments are indeterminate. Plagioclase and potash feldspar form up to 10% of the sandstone at the top of the formation, where muscovite finds its only development. Biotite is common throughout the sequence. Calcite, when present in significant amounts, is sparry, occurring as interlocking anhedra with indistinct outlines. In some cases the anhedra have spherulitic extinction.

**Table 12**

Modal analyses of samples from the Exe Creek Formation

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>294a</td>
</tr>
<tr>
<td>quartz</td>
<td>13.8</td>
</tr>
<tr>
<td>rock fragments</td>
<td>40.8</td>
</tr>
<tr>
<td>feldspar</td>
<td>0.2</td>
</tr>
<tr>
<td>matrix</td>
<td>0.8</td>
</tr>
<tr>
<td>calcite</td>
<td>40.8</td>
</tr>
<tr>
<td>opaques + heavies</td>
<td>6.8</td>
</tr>
<tr>
<td>colourless</td>
<td></td>
</tr>
<tr>
<td>phyllosilicate</td>
<td>12.0</td>
</tr>
<tr>
<td>muscovite</td>
<td></td>
</tr>
<tr>
<td>silica cement</td>
<td>0.8</td>
</tr>
<tr>
<td>biotite</td>
<td>2.8</td>
</tr>
<tr>
<td>grains counted</td>
<td>500</td>
</tr>
<tr>
<td>QRF Ratio</td>
<td>Q</td>
</tr>
<tr>
<td>Qtz+R.frgs+</td>
<td>R</td>
</tr>
<tr>
<td>fel.=100%</td>
<td>F</td>
</tr>
</tbody>
</table>
No one non-opaque heavy mineral is common in the Exe Creek Formation, as shown in Table 13. The most noteworthy feature is the abundance of apparently detrital yellow epidote in samples 676 and 1405. Apatite, so common in the Turrawalla Formation, is present in minor amount in some samples.

**Table 13 - Non-opaque heavy minerals, Exe Creek Formation**

<table>
<thead>
<tr>
<th>Sample</th>
<th>epidote</th>
<th>apatite</th>
<th>spinel</th>
<th>zircon</th>
<th>tourmaline</th>
<th>garnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>294e</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
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</tr>
<tr>
<td>294a</td>
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<td>x</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Outcrop of argillaceous sediment in the sequence is rare, but considering the amount of hidden section the total amount is probably great. Where seen it consists of brown, slightly micaceous mudstone.

Sandstone at the top of the sequence becomes more quartz rich, evidence for this resting on field observation on the western side of the Redcliffe Tableland. It is possible that there is a lithological gradation into the sandstone of the overlying Redcliffe Tableland, but this is by no means established.

Fossil wood is common at the base of the formation on both sides of the Tableland. It is preserved as large fossil logs up to two feet in diameter completely
replaced by haematite. (Fig. 24), in contrast to the silicified logs of the Tarrawilla Formation. The surrounding sediment is unaffected by the haematite replacement.

Structure and thickness

The unit overlies the Tarrawilla Formation and underlies the Tableland Sandstone. It is conformable with the overlying Tableland Sandstone. If there is an angular discordance it is slight.

The unit is 6,000 feet thick on the eastern side of the Tableland, an estimate based on measured sections and by ascribing a constant dip of 25° from the least western outcrop to the eastern edge of the Tableland.

Fossil wood replaced by haematite. Exe Creek Formation.
replaced by haematite (Fig. 24), in contrast to the silicified logs of the Turrawalla Formation. The surrounding sediment is unaffected by the haematite replacement.

**Structure and thickness**

The unit overlies the Turrawalla Formation with structural conformity. On the eastern side of the Redcliffe Tableland it dips consistently to the west-south-west, the dip ranging from about 20° at the base of the unit to 15° at the most western outcrop. Some lower dips were recorded but these could reflect the influence of undetected primary dips. On the western side of the Tableland the unit occupies the core of the Weetalabah Syncline and the area east of the Commissioner Fault. The dip is steep (60°) immediately east of the fault, horizontal one mile to the east, and increasing to 30° near the base of the Tableland, where the contact with the Redcliffe Sandstone is faulted. On field evidence therefore, the unit appears structurally conformable with the overlying Redcliffe Sandstone. If there is an angular discordance it is slight.

The unit is 4,000 feet thick on the eastern side of the Tableland, an estimate based on measured sections and by assuming a constant dip of 15° from the most western outcrop to the eastern edge of the Tableland.
Structural complexity and lack of outcrop does not permit a reliable estimate of thickness of the formation on the western side.

**Origin**

The fact that much of the unit is not seen because of lack of outcrop does not aid in reliable determination of the depositional environment. In the absence of marine fossils and because the structures in the sandstone of the Turrawalla Formation are much the same as those of the Exe Creek Formation, it is possible that the depositional agent was much the same. The trough cross-stratified sandstone and conglomerate of the unit probably reflect deposition from strong traction currents, acting in relatively shallow water. An oxidizing environment accounts for the absence of carbonaceous fossil plant debris, and for the fossil logs replaced by haematite. From petrographic evidence it would seem that the carbonate in some of the sandstone was deposited with the sediment. If much of the unit is mudstone, quiet waters, possibly lacustrine might be indicated.

**Age**

No fossils were found in the Exe Creek Formation in the Blenheim area, and there is no direct evidence of its age. As it overlies the Upper Permian Turrawalla
Formation, and as Middle to Upper Triassic plants are found above it in the Teviot Formation, the possible range is Upper Permian to Middle Triassic. However, Triassic spores have been recorded from the Upper Bowen Coal Measures about 20 miles to the south of the Blenheim area (Evans 1963b). It is therefore, not unlikely that the Permian-Triassic boundary is within the Exe Creek Formation or at the base of the unit.
**REDCLIFFE SANDSTONE**

Redcliffe Sandstone forms the Redcliffe Tableland, a distinctive topographic feature in the Blenheim area with steep almost vertical sides rising 600 feet above the level of the surrounding plain. (Fig. 2). The Tableland occupies the central portion of the area, extending from the northern to southern boundaries and being about eight miles wide. It slopes gently from both eastern and western edges towards the centre, except in the south-east where the sandstone is covered by lateritized Tertiary sediments which form horizontal plains. The terrain is relatively rugged where the sandstone crops out, differential weathering producing benches and short dip slopes.

Reid (1924-25) placed his the Redcliffe Series above the Upper Bowen Coal Measures in a stratigraphic table of the Bowen River Coalfield. Later (Reid 1928) he correlated the sandstone of the Redcliffe Tableland with that of the Carborough Range, south of the Blenheim area, using the terms 'Carborough Sandstones' 'Carborough Range Sandstone' and 'Carborough Series'. Isbell (1955) restricted the Redcliffe Formation to the Redcliffe Tableland, and Carborough Formation to the Carborough Range. Malone (Malone et al. 1961) favoured the use of Carborough Sandstone in both areas, but the name 'Redcliffe' has priority, and thus it will be used here.
The base of the unit is taken as the beds at the base of the eastern side of Redcliffe Tableland; these differ from the beds of the underlying Exe Creek Formation being quartzose sandstone and sublabile sandstone rather than labile sandstone and mudstone. The top of the unit is marked by a similar lithological change, in this instance from sublabile to labile sandstone and mudstone.

Lithology

The most common and dominant lithology of the formation, sublabile sandstone, is interbedded with fine white siltstone and soft white to buff claystone. In outcrop the sandstone is white to buff, medium to thick bedded (Fig. 25), coarse grained and poorly sorted (Fig. 26), grading in places to quartz pebble conglomerate.

The unit is generally very thickly cross-bedded with sets 7 to 8 feet thick and individual planar cross-strata commonly being about 20 feet long. Cosets of smaller scale lenticular cross-beds are also common, the sets being about 4 inches thick. The maximum inclination of the cross-stratification observed was 34 degrees (after correcting for secondary tilt). Trough cross-stratification is not common.

Small scale slumping has been observed in two places and graded bedding is apparent in the laminae of the slump. (Figs. 27, 28). The graded units are
Thick beds of cross-stratified Redcliffe Sandstone.

Quartz pebble conglomerate in Redcliffe Sandstone.
Small scale slump structure in Redcliffe Sandstone.
Closer view of slump structure showing graded bedding.
**Table 14**

Modal analyses of samples from the Redcliffe Formation

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Sample</th>
<th>215a</th>
<th>215b</th>
<th>685</th>
<th>37/62</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartz</td>
<td></td>
<td>51.9</td>
<td>78.3</td>
<td>80.6</td>
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<td>9.9</td>
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<tr>
<td>matrix</td>
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<td>11.7</td>
<td>3.6</td>
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<td>1.6</td>
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<td>biotite</td>
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<td>10.1</td>
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<td>1.6</td>
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<td>muscovite</td>
<td></td>
<td>1.2</td>
<td>1.1</td>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td>phyllosilicate</td>
<td></td>
<td>2.3</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>silica cement</td>
<td></td>
<td>1.5</td>
<td></td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>X opaque + heavies</td>
<td></td>
<td>1.5</td>
<td>0.3</td>
<td>0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>grains counted</td>
<td></td>
<td>561</td>
<td>493</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>QRF Ratio</td>
<td></td>
<td>Q 72</td>
<td>87</td>
<td>85</td>
<td>79</td>
</tr>
<tr>
<td>Qtz+R.frgs.+</td>
<td></td>
<td>R 14</td>
<td>7</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>feld.=100%</td>
<td></td>
<td>F 14</td>
<td>6</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>

A few zircon grains in samples 215a & 37/62, and a little detrital yellow epidote in 685.
roughly four inches thick. The grainsize of the basal two inches grades upwards from very coarse sand to coarse sand, and thereafter a sudden change to a finer sand, with some coarse admixture decreasing towards the top. This produces a poorly sorted medium to fine sandstone, and the pattern is repeated to form a bed about four feet thick.

Graded bedding is a common feature of the greywacke suite where it is often associated with slump structures (Packham 1954). In that environment it is produced by differential settling from a turbidity current. The lack of fine material in the basal part of the graded units described may indicate deposition from a waning current, rather than a turbidity flow (Pettijohn 1957). Why then is the grading associated with a slump structure? It is possible that the fine sand at the top of each unit is not stable at the angle of repose already assumed by the coarser sand at the base, and slumping has resulted.

**Petrology**

The sandstone consists mainly of quartz with relatively small amounts of chert, feldspar, mica, lithic fragments, and kaolinitic cement. The amount of quartz normally exceeds 75% and in some cases it is estimated to be as much as 90%. Quartz grains are angular to subangular and show some signs of solution and authigenic
quartz overgrowth. Inclusions are common in the quartz, some of them being colourless phyllosilicates. Grains showing straight extinction are uncommon, and strained and composite grains are in roughly equal proportions. Potassic feldspar is uncommon, never exceeding 11% of the rock. Simple twinning is often evident but many of the grains are not twinned. Chess board albite was observed in one specimen. Feldspar grains are angular to subangular and sphericity is low. Rock fragments form up to 13% of the rock, chert being the most common; quartzite, granite and siltstone have been observed. The chert grains are noticeably more rounded and have a greater sphericity than quartz and feldspar grains. Cement when present is normally kaolinitic. There is some chalcedonic cement but no carbonate.

Structure

The structure of the Redcliffe Sandstone is best described by a consideration of the structure of the Redcliffe Tableland, based on photo-interpretation (Fig. 31). The main structure, the axis of which trends north-north-west, is herein termed the Redcliffe Syncline. The Stockton Syncline, inferred from dip measurements and photo-interpretation, plunges to the north and merges into the Redcliffe Syncline which in the northern part of the Blenheim area, plunges to the south. The limbs of the Redcliffe Syncline dip at 10 to 15 degrees. The
western limb is down faulted against the Exe Creek Formation.

Structurally conformable with the underlying unit, the Redcliffe Sandstone is overlain conformably by the Teviot Formation. The contact is exposed in many places along Sandy Creek. Quartz sandstone of the Redcliffe Sandstone grades into the more lithic sandstone of the Teviot Formation within twenty feet without change in attitude of the beds, nor with any sign of a disconformity.

Thickness

The unit is calculated to be about 1,500 feet thick, the calculations being based on the following evidence:
(a) the dip is 12 degrees to the west on the eastern margin of the Tableland,
(b) the dip is 7 degrees to the west at the top of the unit, east of Redcliffe Vale homestead,
(c) the eastern edge of the Tableland is higher than the outcrop of the top of the unit (barometric measurement in the field), by 150 feet. The distance between the two points, as measured on the map, is 8,000 feet. Thus the slope is about one degree west. The thickness of the bed from this information is

\[ \sin \left( \frac{12^\circ + 7^\circ + 1^\circ}{2} \right) \times 8,000 \text{ feet} \]

which is 1460 feet, or about 1500 feet.
The figure of 1,500 feet differs from that given by Isbell (1955) who gave 700 feet as the maximum thickness; he gave no supporting evidence. It does agree with a later report (Malone et al. 1960), where 1,181 feet were measured in Carborough Sandstone in the Carborough Range, and where the total thickness was estimated to be 1,500 feet.

**Age**

The Redcliffe Sandstone contains no fossils and there is no direct method of determining the age. As it lies above Upper Permian units it must be Upper Permian or younger; and as the overlying unit has Triassic plant fossils an upper limit is established. The unit can be correlated lithologically with the Clematis Sandstone which crops out in the southern part of the Bowen Basin, and the Clematis is Triassic as it overlies the Lower Triassic Rewan Formation (Evans 1963a). Even though the Redcliffe and Clematis can be correlated they are not necessarily coeval. Thus the age of the Redcliffe Sandstone on present evidence is certainly somewhere in the range of Upper Permian to Triassic, and it is probably Triassic.

**Origin**

The unit was deposited under fluvial conditions. Evidence for this rests on:
(a) the large scale cross bedding indicating the presence of strong depositional currents, (b) the complete absence of marine fossils making non-marine conditions likely, (c) the absence of thick beds of silt and clay and the relatively well washed but conglomeratic nature of the sands probably indicating shallow water deposition - not lacustrine, (d) the complete absence of plant debris probably indicating a strongly oxidizing environment, such as would be found in a fluvial environment.

The source of the sediments is thought to be from the north-west but conclusive proof of this is lacking. One would expect a greater proportion of volcanic material in the sediments if it had come from the east, where the Lower Bowen Volcanics had their greatest development. Sediment is also unlikely to have come very far from the southern part of the Bowen Basin, at that time an area of deposition. Fifty measurements of cross bedding taken in the vicinity of Stockton Creek, when corrected for tilt indicate currents from the north-north-west. (Appendix A and Fig. 29). One would not place too much importance on measurements from only one area, but the results do not contradict the possibility of a provenance area to the north-west.
Cross-bedding azimutal distribution
Redcliffe Sandstone-50 readings.
TEVIOT FORMATION

The Teviot Formation crops out in the central part of the Redcliffe Tableland, surrounded by the Redcliffe Sandstone. It forms slightly hilly to flat country with red brown soil, contrasting with the strongly outcropping Redcliffe Sandstone with its associated white sandy soil; the photo patterns are also very distinctive.

The formation was discovered on the Redcliffe Tableland in the course of mapping the thesis area, in 1960. It was subsequently recognized further south in what is now the type area - Teviot Creek, which flows between the Carborough and Kerlong Ranges (Lat. 21° 42' S., Long. 148° 16' E.) and the name 'Teviot' was first used in an unpublished report in 1961 (Malone et al., 1961).

Lithology

The unit crops out poorly, consisting mainly of massive, soft, brown, micaceous mudstone and thin to medium beds of brown sandstone. The sandstone being harder crops out well in places, especially in Sandy Creek.

The mudstone forming most of the unit is massive, showing no bedding or current structures. It is light brown when weathered, and darker in fresh specimens. It is micaceous and in places very micaceous; the mica having a brass yellow colour. Plants are moderately well preserved in the more sandy mudstone, either as
impressions or impressions filled with dark carbonaceous matter. Shred of black plant debris are common throughout the mudstone and in some sandstone.

Sandstone in the unit is thickly cross-bedded, and small slump structures are common. The cross-bedding is evident as inclined curved sets up to ten feet long concave upwards. Two varieties of sandstone, both having quartz, lithic fragments, feldspar and mica, have been recognized. One type a biotitic labile sandstone is characterized by the abundance (40% of the rock) of dark pleochroic biotite, as separate grains and forming the matrix. In this variety (samples 1000 and 1009) quartz forms about 40% of the rock and the remaining 20% is made up of muscovite, chert, rock fragments and feldspar. The other variety, a calcareous lithic sublabile sandstone (samples 697 and 1097a) is moderately well sorted and is characterized by calcite cement, often in optically continuous plates, forming as much as 30% of the rock; lustre mottling is evident in hand specimen. The other constituents are quartz 50%, rock fragments and chert up to 13% and minor feldspar and matrix.

Quartz grains in both varieties of sandstone show little sign of rounding (average 0.3) but sphericity varies from 0.1 to 0.6. One sample has a high proportion of quartz grains with a very low sphericity (1009). All
Table 16

Modal analyses of samples from the Teviot Formation

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Sample</th>
<th>697</th>
<th>1000</th>
<th>1009</th>
<th>1097a</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartz</td>
<td>39.6</td>
<td>39.6</td>
<td>36.4</td>
<td>51.2</td>
<td></td>
</tr>
<tr>
<td>rock fragments</td>
<td>13.6</td>
<td>4.5</td>
<td>4.8</td>
<td>13.8</td>
<td></td>
</tr>
<tr>
<td>feldspar</td>
<td>6.8</td>
<td>8.7</td>
<td>1.6</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>matrix</td>
<td></td>
<td></td>
<td>11.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calcite</td>
<td>32.8</td>
<td></td>
<td>0.4</td>
<td>25.6</td>
<td></td>
</tr>
<tr>
<td>biotite</td>
<td>5.2</td>
<td>46.8</td>
<td>41.6</td>
<td>3.4</td>
<td></td>
</tr>
<tr>
<td>muscovite</td>
<td></td>
<td></td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>opaque + heavies</td>
<td>2.0</td>
<td>0.4</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>grains counted</td>
<td>500</td>
<td>553</td>
<td>500</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>QRF Ratio</td>
<td>Q</td>
<td>63</td>
<td>75</td>
<td>85</td>
<td>72</td>
</tr>
<tr>
<td>Quartz+R.Frgs+</td>
<td>R</td>
<td>22</td>
<td>9</td>
<td>11</td>
<td>20</td>
</tr>
<tr>
<td>Feld. X 100%</td>
<td>F</td>
<td>15</td>
<td>16</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

Heavy mineral are uncommon in the formation. Colourless garnet is present in 1097a, and zircon in 1000.
three major quartz extinction types are present, there
being roughly equal proportions of unstrained and strained
grains, and a slightly higher proportion of compound
grains. Quartz overgrowths are not uncommon. (Sample
1097).

Rock fragments and feldspar are present in all
the sandstone examined from the unit. The rock fragments
are mainly of chert and granite, the chert consisting of a
fine mosaic of interlocking anhedral quartz grains.
Exceedingly fine grained brown lithic fragments with rare
feldspar laths probably have a volcanic origin. Granite
fragments, particularly common in sample 1097a, consist of
quartz-feldspar intergrowths. It is possible that most
of the feldspar is derived from such fragments as about
50% of all feldspar grains are untwinned, like the feldspar
of the granite fragments. The remainder show poly-
synthetic and multiple twinning. Chess board albite was
observed in two samples (1000 & 1009). The feldspar
grains are generally angular but subangular and rounded
grains are present.

Structure and Thickness

The unit, like the Redcliffe Sandstone, has been
gently folded to form the Redcliffe and Stockton
Synclines, maximum dip observed being 11 degrees. The unit
is unconformably overlain by Tertiary basalt and
lateritized sediments.
The unit is estimated to be about 400 feet thick. Beds at the base of the formation dip at seven degrees and those at the centre of the Redcliffe Syncline, 8,000 feet to the west, are horizontal. The rate of decrease from seven degrees to horizontal is not known, but assuming an average dip of three degrees for the entire distance the thickness would be in the order of 400 feet.

**Age**

Plant fossils were collected in a brown sandy mudstone at point 697 on the track one mile east of Redcliffe Vale, and in a friable mudstone at point 1425 four miles north-west of the homestead. The plants, identified by Mary E. White as *Dicroidium feistmanteli* (Johns.) Gothan and *D. odontopteroides* (Morr.) Gothan. The age of the *Dicroidium* floras has been discussed by Townrow (1957, p.29) who comes to the conclusion that they range from the Middle Triassic to the lower part of the Upper Triassic. The age of the Teviot Formation therefore is somewhere in that range.

**Origin**

Lack of marine fossils and abundance of carbonaceous plant debris indicates a non-marine environment of deposition. Carbonaceous mudstone being the most common lithology, slow depositional currents were operative.
for most of the time, with possibly periods of quiescence and subsequent settling of plant debris in stagnant reducing lacustrine environment.
SUTTOR FORMATION

In the Blenheim area sedimentary rocks of Tertiary age crop out only on the Redcliffe Tableland. They form low steep sided rises with flat tops, although the top of the formation is generally covered with basalt. The unit is restricted mainly to the central part of the Tableland but there are isolated outcrops towards the margin.

Nomenclature and Lithology

Quartz rich sandstones and siltstone with dicotyledonous leaves were noted by Reid (1924-1925) west of the Blenheim area, about six miles west of Byerwen homestead. Isbell (1955) mentioned these sediments and noted that they seldom exceed 200 feet in thickness. Malone (Malone et al., 1964) proposed the name Suttor Formation for this sequence, making the type area ten miles south west of Byerwen homestead (Lat. 21° 10' S, Long. 147° 50' E). The sequence which was said to contain quartz sandstone and claystone, was reported to overlie basalt. However, another examination of the type area indicated the basalt to be younger. The basalt is topographically lower than the Suttor Formation because it fills old valleys.
The Suttor Formation on the Tableland consists of silicified quartzose sandstone and minor white siltstone. Outcrop is poor and no structures were seen. The sandstone appears to be massive but this may be due to silicification. The unit in the south-western part of the Tableland is covered by an extensive red clay. This is probably derived from lateritized sediments. A few outcrops of lateritized sandstone were noted in the south-western area. The silicification of the sandstone is probably part of the lateritization process.

**Petrology**

The one sample examined (695) is a moderately well sorted silicified quartzose sandstone. It consists of quartz (70.6%), rock fragments (9.2%), feldspar (4.6%), silica cement (11.4%), matrix (3.2%), opaques (0.4%), kaolin (0.4%), and zircon (0.2%).

The quartz is subangular to subround and the average sphericity is moderate. The grains generally contain microlites and vacuoles arranged in straight lines. About 10% of the quartz grains are composite, and the remainder are equally divided into those with straight extinction and those with undulose extinction.

The pore space is filled with silica in the form of quartz overgrowths. The overgrowths are banded and in some cases coloured brown.
The feldspar shows grey-brown cloudy alteration, as if weathered, and it is only recognized by cleavage. The grains are subangular to subround and sphericity is moderate.

Structure and Thickness

The unit is in the order of 50 to 70 feet thick, in the northern area of outcrop. The thickness of the lateritized sequence is unknown, but it is unlikely to exceed 100 feet.

The unit is horizontal, unconformably overlying the Teviot Formation and the Redcliffe Sandstone. It is disconformably overlain by basalt, the two units being separated in outcrop by lateritized Suttor Formation. The basalt is not lateritized.

Age

A Tertiary age was established for the formation by Reid (1924-25) who found it to contain dicotyledenous leaves. Malone et al. (1964) came to the same conclusion on the basis of plant remains.

The age of the lateritization and associated silicification is not known, except that it is Cainozoic. As basalt of probable Tertiary age overlies the laterite a similar age must tentatively be assigned to the laterite. Laterite is widespread in Queensland and more than one age of lateritization has been suggested (Hill
and Denmead 1960, p.276-377).

**Origin**

Little evidence can be put forward to support a theory of the origin of this unit, because of the poor outcrop. It is known (Malone et al. 1964) that the unit is strongly cross-bedded west of the Blenheim area. Taking into consideration the cross-bedding, the plant fossils, and the absence of marine fossils, it is not unlikely that the unit is fluvial or possibly lacustrine.
Basalt, probably of Tertiary age, produces two distinctive topographic forms in the Blenheim area: conical hills up to 200 feet high with rounded tops; plateaux areas with moderately flat top 100 feet above the level of the plain.

Round top, conical hills are common west of the Redcliffe Tableland in the northern part of the area. Reid (1929) in describing similar isolated hills of basalt north of the Blenheim area near Collinsville, was of the opinion that they represent volcanic pipes. Isbell (1955) suggested that they represent residuals of small basalt flows, and not pipes. No evidence for or against Reid's theory can be advanced for the hills in the Blenheim area, but their shape and relative isolation from one another suggests that they are not residuals of flows.

Residual plateaux found west of the Redcliffe Tableland in the southern part of the area, and also on top of the Tableland, are formed by basalt flows, the plateaux top probably being close to the original surface. One high rounded hill of basalt is joined to the western edge of the Redcliffe Tableland, possibly representing a flow of basalt down an existing water-cut gorge.

It is possible that basalt forms a small plain south-west of Tiverton homestead. Scattered basalt float
was observed in this area only in a few places, most of the plain being covered with black soil. The plain, actually the floor of a small valley, appears to be tilted slightly to the west. It has a poorly developed drainage system, which is central and not lateral.

Petrology

Three thin sections of basalt were examined from this unit, samples 222a and 222c which come from a basalt plateaux in the western part of the area, and sample 1454 which comes from a small conical hill (232637).

Samples from point 222 are fine grained, aphyric, and one of them (222c) is vesicular. The rock consists mainly of plagioclase and clinopyroxene, with some haematite after magnetite. Fifteen measurements of the extinction of albite twins (Michel Levy method) in sample 222c, averaged 29° with a standard deviation of 6° and a maximum of 43°. This suggests the feldspar is labradorite.

Sample 1454 is relatively coarse and contains olivine in addition to clinopyroxene, plagioclase, and magnetite. The olivine, which in this sample is optically positive, is partially replaced by a brown fibrous mineral, probably iddingsite.
Structure and thickness

The basalt on the Redcliffe Tableland and west of it is horizontal, lying disconformably above the Suttor Formation. On the Redcliffe Tableland, small hills of Suttor Formation rise above the basalt surface, the result of basalt filling old valleys.

The total thickness of the flows is in the order of 100 to 200 feet. Malone et al. (1961) reported 400 feet of basalt near Exeval homestead, south of the Blenheim area. Reid (1929) reported 1,000 feet of basalt near Nebo, at Mount Fort Cooper; but it is possible that Mount Fort Cooper is a plug, not a residual plateaux built of many flows, and that the thickness of basalt in that area is much less than 1,000 feet (Jensen et al. 1963).

Age

Unconformably overlying the Teviot Formation, the basalt on the Redcliffe Tableland and west of it was certainly extruded after the orogeny which folded the Triassic sedimentary sequence, and after considerable erosion of the mountains thereby produced. The basalt is therefore regarded as Tertiary by analogy with similar basalt of that age found throughout the Bowen Basin. Basalt in other parts of the Basin is associated with more acid extrusives and in the Clermont area it has been dated by radioactive methods as Tertiary (R.G. Mollan pers. comm.).
There are four types of undifferentiated Cainozoic deposits in the Blenheim area: (a) sand on the eastern side of the Redcliffe Tableland, (b) black soil east of Tiverton homestead, (c) red clayey soil on the Redcliffe Tableland, and (d) cemented gravel in the Blenheim area.

Although sand derived from the Redcliffe Tableland covers areas on either side of the Tableland, it appears to be more extensive on the eastern side. On that side the brown to white quartz rich sand forms an extensive cover about one and a half miles wide, from the northern to the southern boundaries of the area. The sand is washed into the Bowen River by small creeks which start near the base of the Tableland.

Black soil (Czb on the map) is essentially an alluvial deposit derived from basalt near Tiverton. It occupies much of the Blenheim Creek valley upstream from Tiverton.

Red clayey soil (Cz1 on the map) has developed over lateritized Tertiary sediments on the Redcliffe Tableland. It forms exceedingly flat plains, with few outcrops of ferruginous laterite.

Blenheim Creek, below Tiverton homestead, contains a cemented gravel of round volcanic and
sedimentary pebbles, cobbles and boulders. (Fig. 30 ).
The deposit, which is cemented with a white calcareous
material, does not occur in any other stream in the area.
It is about three feet thick in most places in the creek,
reaching a maximum of five feet. Unlike most streams in
the area Blenheim Creek is perennial.
Dykes, sills, and small streams, mainly of intermediate to basic composition, intrude the Permian sequence, and one dyke was observed cutting Triassic sedimentary rocks. Many separate intrusions have been outlined on the map of the area. The above are but a few of the dykes that have been observed. Much attention was given to the migmatitic and leucocratic gneisses which make up the bulk of the rock, together with green hornblende, biotite, quartz, and magnetite. Hornblende is found in both samples, but biotite only in one. Quartz is minor in both samples and is estimated not to exceed 10% of the rock. Chlorite and epidote replace the hornblende of Pale.
IGNEOUS INTRUSIONS AND ASSOCIATED METAMORPHICS

Dykes, sills, and small stocks, mainly of intermediate to basic composition, intrude the Permian sequence, and one dyke was observed cutting Triassic sedimentary rocks. Three separate intrusions have been outlined on the map of the area, the other smaller intrusions are not shown; their position is, however, noted in many cases on the appropriate stratigraphic section.

The intrusion north-west of Tiverton

The Turrawalla Formation is intruded by a small discordant stock of leucocratic tonalite, about two miles north-west of Tiverton homestead (495660). About one and a half miles long and half a mile wide, the stock forms a topographic low, surrounded by ridges of metamorphosed sediments.

Two thin sections of the intrusion were examined (1413 and 1415a). Andesine and some potassic feldspar make up the bulk of the rock, together with green hornblende, biotite, quartz, and magnetite. Hornblende is found in both samples, but biotite only in 1415a. Quartz is minor in both samples and is estimated not to exceed 15% of the rock. Chlorite and epidote replace the hornblende of 1413.
The intrusion is surrounded by an aureole of hornfels which, being harder than the intrusion, stands up as a roughly circular ridge. No detailed study was made of the rocks of the aureole, a few samples being taken as close as possible to the intrusion and from more than one bed. The size of the aureole based on the first appearance of a new mineral phase is unknown. Induration of the surrounding sediments has taken place some 400 feet from the contact.

Four samples from the aureole examined in thin section (1410a, 1415b, 1415c, 1415d) all proved to be hornfels, three of them being quartz-muscovite hornfels. The other sample (1415b) is a calc-silicate hornfels consisting of porphyroblasts of diopside and recrystallized original grains of quartz in a fine groundmass of quartz, feldspar and rutile. Of the three quartz-muscovite hornfels, sample 1415c proved to be of most interest having a brown pleochroic biotite and some graphite. This sample shows poeciloblasts of a colourless mineral, possibly quartz or cordierite, in the large grains of quartz. Although recrystallization has gone far enough in this rock to warrant the term hornfels, the relic fabric of an arenite still persists.
The intrusion south of Tiverton

About one mile south of Tiverton homestead (522628) the same topographic pattern, of low hills surrounding a roughly circular depression, is almost the only surface manifestation of an intrusion similar to the one west of Tiverton. Outcrop of hornfels surrounding the intrusion is plentiful, but outcrop of the intrusion itself, a biotite hornblende diorite, is scarce.

A thin section of the intrusion (289) shows that it consists mainly of andesine, with very little potassic feldspar, together with brown hornblende and biotite. Anhedral quartz makes up less than 10% of the total rock.

The metamorphic aureole, which appears to be about the same size as the one surrounding the tonalite west of Tiverton judging on the width of the zone of induration, consists of quartz-muscovite hornfels (288b).

The intrusion in south-east Blenheim area

A gabbro sill, intruded into the 'Lower Bowen' Volcanics, forms a cuesta 400 feet high in the south-east part of the Blenheim area (595580). Dense vegetation makes the intrusion rather inaccessible, and although one sample of the sill was obtained nothing is known of possible metamorphic effects in the surrounding Permian volcanics.
The rock is a medium grained melanocratic gabbro. In thin section (1429) it is seen to consist of labradorite and clinopyroxene with accessory magnetite. The feldspar and clinopyroxene are partially replaced by chlorite and there is a little secondary quartz.

**Miscellaneous small intrusions**

Small sills and dykes intrude much of the Permian and the Mesozoic sequence. The intrusions examined in thin section are of intermediate and basic composition but some of the sills observed intruding the Turrawalla Formation in the field were thought to be acid, unfortunately these were not sampled. The samples examined in thin section include intrusions into the 'Lower Bowen' Volcanics (648), the Turrawalla Formation (619, 613a, 613b, 601c) and the Teviot Formation (1015a).

A small sill intruding the 'Lower Bowen' Volcanics near the top of the unit (563577) is a porphyritic dolerite. Holocrystalline hiatal porphyritic, it consists of pyroxene and feldspar phenocrysts in a fine groundmass of feldspar. Two pyroxenes are present, one pale brown and pleochroic with straight extinction and the other colourless with oblique; these are probably hypersthene and augite. The feldspar is labradorite.

* Sample 648
Sills and dykes are common in the Turrawalla Formation especially east of the Redcliffe Tableland. Many of these are probably comagmatic with the tonalite-quartz diorite intrusions west and south of Tiverton as they are quartz microdiorite (eg. sample 619); however, some are of a more basic composition being gabbros. One of these (613a) is intruded by a microdiorite dyke (613b). The gabbro, in the field a sill about 20 feet thick, has a little serpentinized olivine and epidotized hornblende. Deuteric alteration is apparent in another gabbro sill, (sample 601c) with an abundance of chlorite, epidote, and iddingsite.

One dyke was observed intruding the Teviot Formation, and the very weathered sample collected is a porphyritic microdiorite (1015a). A gabbro stock intrudes the northern end of the Redcliffe Tableland and dykes, radially disposed about the stock, intrude the Redcliffe Sandstone and Teviot Formation. This dyke is part of that system.

**Age of intrusion**

The small stocks west and south of Tiverton are discordant and therefore it is most likely that they were intruded during or after the main folding movement which effected the Permian-Triassic sequence. Many of the sills and dykes intruding the sequence are of the same composition, and were probably intruded at the same time. Gabbro intrusions are possibly earlier.
GEOLOGICAL STRUCTURE

The structure of the Blenheim area (Fig. 31) is best described in terms of three subdivisions:

(a) an eastern area bounded by a synclinal bend and the eastern edge of the map, (b) a central area, bounded by the synclinal bend and the Tableland Fault, and (c) a western area, extending from the Tableland Fault to the western edge of the map.

The eastern area is structurally complex. Beds immediately to the east of the synclinal bend dip steeply westwards. As one travels eastwards the dip increases until the beds are overturned and dip to the east. A zone of overturned beds extends eastwards for one and a half miles, but the dip then changes abruptly to values of from 15° to 45° to the west. The cause of this rapid change is not known but it is suggested that the two blocks are separated by a thrust fault. The zone of overturned beds dies out towards the south.

The central area has a relatively simple synclinal structure. The limbs dip at about 15° on either side of a south plunging axis. The structure is terminated on the western side by the Tableland Fault, a normal fault with the east block downthrown. The throw is not great and the fault is most evident in
aerial photos where it finds expression in a particularly straight edge of the Redcliffe Tableland. The relatively simple structure of the central area is slightly complicated by the north plunging Stockton Syncline, a small structure on the eastern side of the Redcliffe Syncline.

The structure of the western area is intermediate in complexity between the central and eastern areas. Details of the main structures, the Weetalabah Syncline and the Commissioner Fault have been discussed in sections on the Turrawalla Formation and Exe Creek Formation. Briefly, the Weetalabah Syncline, a relatively gentle structure, is cut by the Commissioner Fault which is thought to be a normal fault with the east block downthrown.

The age of the folding

As there is a gap in the sedimentary sequence in the area from the Middle or Upper Triassic to the Tertiary, one must look to other areas for an indication of the age of the folding. The oldest unit overlying the Bowen Basin sequence and not affected by folding of any magnitude is the Lower Jurassic Precipice Sandstone cropping out west of Cracow (Jensen et al. 1964). In the Cracow area, the Permian and Triassic sequence was
folded and eroded to form a peneplain, which was sub-
sequently silicified (Jensen et al. 1964). The almost
horizontal Precipice Sandstone was deposited on this
surface in the Lower Jurassic. As no evidence is
available, it is suggested that the Permian and Triassic
sequence of the Blenheim area was folded at the same
time.

Normal faulting west of the Redcliffe Tableland
probably took place after the main compressional folding
but there is no evidence as to how soon after.
PROVENANCE STUDIES

It is most probable that a number of source areas have contributed to the 15,000 feet of sediment deposited between the top of the Lower Bowen Volcanics and the top of the Teviot Formation in the Blenheim area. Determinations of provenance in other areas have involved the study of mineral groups and minerals, such as clays, heavy minerals, feldspar, and quartz. No one method is certain of success and where possible more than one method should be employed; this seldom happens because of the length of time involved. In the study of the Blenheim area it was decided to rely mainly on the type of rock fragments in the clastic sediments to give some idea of provenance, and the results are summarized in Table 17.

Each formation as shown in Table 17 is assigned to one of three provenance classes depending on the provenance indicated by the rock fragments. The significance of each class is:

<table>
<thead>
<tr>
<th>Class</th>
<th>Provenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>mainly a plutonic source</td>
</tr>
<tr>
<td>B</td>
<td>a mixture of types</td>
</tr>
<tr>
<td>C</td>
<td>mainly volcanic source</td>
</tr>
</tbody>
</table>
### TABLE 17

Provenance of rock fragments in Permian and Triassic rocks

<table>
<thead>
<tr>
<th>Formation</th>
<th>Provenance Class</th>
<th>Rock Fragments</th>
<th>Average %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teviot</td>
<td>A</td>
<td>x</td>
<td>xxx</td>
</tr>
<tr>
<td>Redcliffe</td>
<td>A</td>
<td>x</td>
<td>xxx</td>
</tr>
<tr>
<td>Exe Creek</td>
<td>B</td>
<td>x</td>
<td>xx</td>
</tr>
<tr>
<td>Turrawalla</td>
<td>G</td>
<td>xxx</td>
<td>xxx</td>
</tr>
<tr>
<td>Blenheim</td>
<td>B</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Hazelwood</td>
<td>B</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Tiverton</td>
<td>B</td>
<td>x</td>
<td>xx</td>
</tr>
</tbody>
</table>

xxx very common  
xx present  
x very minor

The study of clastic quartz grains

The study of the sedimentary sequence in the Blenheim area afforded an opportunity to check the significance of different types of quartz grains with respect to provenance. As long ago as 1896 quartz grains in sediments were reported to have differences depending on provenance. Early workers (Mackie 1896; Tyler, 1936;
Keller and Littlefield (1950) were concerned with the inclusions in quartz grains. There was general agreement as to the type of inclusions common, but none as to the significance of each type. Preliminary results in the study of inclusions in quartz of sediments in the Blenheim area by the author were inconclusive and this study was not continued.

A second study attempted in the past was the examination of the types of extinction of quartz grains. Krynine (1940) combined a study of extinction with that of inclusions and morphology, and this method is recommended by Folk (1961). Folk distinguishes six types of quartz grain extinction:

1. Single grain, straight extinction
2. Single grain slightly undulose extinction
3. Single grain strongly undulose extinction
4. Semi-composite grain, straight to slightly undulose extinction
5. Composite grain, straight to slightly undulose extinction
6. Composite grain, strongly undulose extinction.

Greensmith (1963) in his work on Carboniferous and Cretaceous sandstone, utilized three extinction types:

a. Single grain, straight extinction
b. Single grain, undulose extinction - no matter how feeble
c. Polycrystalline or compound extinction.

Greensmith used three types for ease of presentation in graphical form, but it was later proved (Christie and Blatt, 1963) that the degree of 'Undulation' is dependant on orientation. Consequently the six types defined by Folk can be reduced to three types as defined by Greensmith. Greensmith's study (1963) showed that points representing USC ratios (undulose, straight, and composite) of sandstones from the one formation occupied a restricted field peculiar to that formation.

It was therefore decided to examine the extinction of quartz grains from formations of the Blenheim area to determine (a) if samples from the same formation or provenance class have approximately the same USC ratio, and (b) if the USC ratio has any significance in terms of provenance.

The results of counting the extinction types present in thirty-seven samples from Lower Permian-Triassic is shown in Table18. Where possible one hundred grains were examined in each specimen in non-duplicatory traverses, using a mechanical stage. The results are presented graphically in terms of three components in Figs. 32 &33, to illustrate the differences in the fields occupied by the three provenance classes.
**TABLE 7**

Summary of quartz extinction types in Permian Triassic sequence of Blenheim area

<table>
<thead>
<tr>
<th>Field No.</th>
<th>Total No. of grains counted</th>
<th>Unit</th>
<th>%Straight</th>
<th>%Undulose</th>
<th>%Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>697</td>
<td>100</td>
<td>Teviot Fm.</td>
<td>24</td>
<td>58</td>
<td>18</td>
</tr>
<tr>
<td>1000</td>
<td>100</td>
<td>&quot;</td>
<td>6</td>
<td>34</td>
<td>60</td>
</tr>
<tr>
<td>1009</td>
<td>100</td>
<td>&quot;</td>
<td>18</td>
<td>57</td>
<td>25</td>
</tr>
<tr>
<td>1097a</td>
<td>100</td>
<td>&quot;</td>
<td>6</td>
<td>54</td>
<td>40</td>
</tr>
<tr>
<td>215b</td>
<td>100</td>
<td>Redcliffe Ss.</td>
<td>12</td>
<td>38</td>
<td>50</td>
</tr>
<tr>
<td>685</td>
<td>100</td>
<td>&quot;</td>
<td>4</td>
<td>52</td>
<td>38</td>
</tr>
<tr>
<td>215a</td>
<td>100</td>
<td>&quot;</td>
<td>5</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>37/62</td>
<td>100</td>
<td>&quot;</td>
<td>10</td>
<td>48</td>
<td>42</td>
</tr>
<tr>
<td>676</td>
<td>100</td>
<td>Exe Creek Fm.</td>
<td>24</td>
<td>24</td>
<td>52</td>
</tr>
<tr>
<td>1409</td>
<td>100</td>
<td>&quot;</td>
<td>36</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>1405</td>
<td>100</td>
<td>&quot;</td>
<td>10</td>
<td>62</td>
<td>28</td>
</tr>
<tr>
<td>1403</td>
<td>100</td>
<td>&quot;</td>
<td>59</td>
<td>28</td>
<td>13</td>
</tr>
<tr>
<td>294e</td>
<td>100</td>
<td>&quot;</td>
<td>33</td>
<td>45</td>
<td>16</td>
</tr>
<tr>
<td>294a</td>
<td>200</td>
<td>&quot;</td>
<td>24</td>
<td>45</td>
<td>31</td>
</tr>
<tr>
<td>290</td>
<td>100</td>
<td>Turrawalla Fm.</td>
<td>62</td>
<td>23</td>
<td>15</td>
</tr>
<tr>
<td>608</td>
<td>100</td>
<td>&quot;</td>
<td>60</td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td>634</td>
<td>100</td>
<td>&quot;</td>
<td>28</td>
<td>33</td>
<td>39</td>
</tr>
<tr>
<td>1427a</td>
<td>70</td>
<td>&quot;</td>
<td>39</td>
<td>43</td>
<td>18</td>
</tr>
<tr>
<td>292e</td>
<td>100</td>
<td>&quot;</td>
<td>33</td>
<td>33</td>
<td>34</td>
</tr>
<tr>
<td>292f</td>
<td>100</td>
<td>&quot;</td>
<td>44</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>292g</td>
<td>100</td>
<td>&quot;</td>
<td>28</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>292c</td>
<td>100</td>
<td>Blenheim Fm.</td>
<td>20</td>
<td>59</td>
<td>21</td>
</tr>
<tr>
<td>293a</td>
<td>100</td>
<td>&quot;</td>
<td>16</td>
<td>20</td>
<td>64</td>
</tr>
<tr>
<td>645</td>
<td>100</td>
<td>Hazelwood Fm.</td>
<td>48</td>
<td>42</td>
<td>10</td>
</tr>
<tr>
<td>1427f</td>
<td>100</td>
<td>&quot;</td>
<td>40</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>657c</td>
<td>40</td>
<td>Tiverton Fm.</td>
<td>45</td>
<td>33</td>
<td>22</td>
</tr>
<tr>
<td>Field No.</td>
<td>Total No. of grains counted</td>
<td>Unit</td>
<td>% Straight</td>
<td>% Undulose</td>
<td>% Composite</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------</td>
<td>-----------------------</td>
<td>------------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td>H1</td>
<td>100</td>
<td>Hazelwood Fm.</td>
<td>20</td>
<td>48</td>
<td>32</td>
</tr>
<tr>
<td>H2</td>
<td>100</td>
<td>&quot;</td>
<td>48</td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td>H3</td>
<td>100</td>
<td>&quot;</td>
<td>12</td>
<td>47</td>
<td>41</td>
</tr>
<tr>
<td>H5</td>
<td>100</td>
<td>&quot;</td>
<td>12</td>
<td>52</td>
<td>36</td>
</tr>
<tr>
<td>T4</td>
<td>100</td>
<td>Tiverton Fm.</td>
<td>26</td>
<td>47</td>
<td>27</td>
</tr>
<tr>
<td>T5</td>
<td>100</td>
<td>&quot;</td>
<td>34</td>
<td>50</td>
<td>16</td>
</tr>
<tr>
<td>T6</td>
<td>100</td>
<td>&quot;</td>
<td>20</td>
<td>56</td>
<td>24</td>
</tr>
<tr>
<td>B1</td>
<td>100</td>
<td>Blenheim Fm.</td>
<td>11</td>
<td>73</td>
<td>16</td>
</tr>
<tr>
<td>B2</td>
<td>100</td>
<td>&quot;</td>
<td>19</td>
<td>56</td>
<td>25</td>
</tr>
<tr>
<td>B3</td>
<td>100</td>
<td>&quot;</td>
<td>21</td>
<td>54</td>
<td>25</td>
</tr>
<tr>
<td>B4</td>
<td>100</td>
<td>&quot;</td>
<td>13</td>
<td>62</td>
<td>25</td>
</tr>
</tbody>
</table>
Fig. 32

USC diagram (undulose, straight, composite) showing fields of Provenance Classes A and C.

Δ Turrawalla (Provenance Class C)
+
Redcliffe/Teviot (Provenance Class A)
Provenance Close

Turrowalla

Redcliffe/Teviot (Class A)

Fig 33

USC diagram (undulose, straight, composite) showing fields of
Provenance Classes A, B, and C.
Fig. 32 shows that Provenance Classes A and C occupy two distinct fields of the USC triangle. Provenance Class B is seen in Fig. 33 not to be restricted to either of the fields of A or B.

Some conclusions can be drawn from these results although the number of samples is small. Firstly, it is evident from the results that the fields of point distribution of two of the classes are restricted. Secondly, it is evident in Fig. 32 that Classes A and C occupy different fields. Because the fields are restricted and because Class A is characterized by lithic fragments of plutonic origin, and Class C by fragments of volcanic origin, it is concluded in this case that the relative abundance of straight extinction quartz grains is indicative of a volcanic provenance.

This conclusion, if correct, explains why Class B occupies a large field, as it is the product of a mixture of sediments from different provenance areas - volcanic and non-volcanic.

It appears from Fig 33 that none of the Classes has a significantly high or low proportion of grains with either undulose or composite extinction.
The conclusions derived from this study are supported by the recent findings of Blatt and Christie (1963) who examined thin sections of 119 igneous and metamorphic rocks and 44 clastic rocks in an attempt to evaluate the significance of undulose and composite extinction of quartz grains. Blatt and Christie found that while straight extinction quartz is uncommon in plutonic and metamorphic rocks, it is abundant (91%) in extrusive igneous rocks. They are of the opinion that very little quartz in sediments is derived from extrusive igneous sources, and they add:

'...undulatory grains appear to be destroyed selectively by mechanical and chemical agencies during successive sedimentary cycles. Consequently, an abundance of non-undulatory quartz grains in a sedimentary rock possibly indicates the assemblage of grains has passed through several sedimentary cycles, rather than derivation from other plutonic igneous or metamorphic source rocks.'

It is felt that in the case of Class C, the high proportion of straight extinction (or non-undulatory) quartz grains is due to the volcanic provenance already indicated by the high proportion of volcanic glass, and volcanic lithic fragments.
The preferential destruction of undulose and composite grains because of their high internal strain energy, suggested by Blatt and Christie, is not apparent in the mature sandstone of the Redcliffe Sandstone.

Summary of conclusions regarding quartz extinction

1. Sandstone of the Turrawalla Formation has a relatively high proportion of non-undulatory quartz grains, and this is probably due to the influence of a volcanic provenance.

2. Sandstone of the Redcliffe Sandstone and the Teviot Formation consistently has a relatively low proportion of non-undulatory quartz, and this reflects a plutonic or metamorphic provenance.

3. Sandstone of the Exe Creek Formation and the Back Creek Group has a mixture of quartz extinction types none of which is dominant; this probably reflects the influence of more than one provenance area.

Heavy mineral assemblages

Non-opaque heavy minerals noted in thin section during the course of this study, confirm in part the conclusions concerning provenance based on rock fragments. The heavy mineral assemblages are summarized in Table 16.
### TABLE 19

Heavy minerals in Permian-Triassic sequence

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redcliffe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teviot</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tiverton</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>VC</td>
<td>C</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>C</td>
<td>P</td>
</tr>
<tr>
<td>Hazelwood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P</td>
<td>P</td>
<td>C</td>
<td>P</td>
</tr>
<tr>
<td>Blenheim</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exe Ck</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>P</td>
<td>VC</td>
<td>P</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turrawalla</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zrn.</th>
<th>zircon</th>
<th>Epi.</th>
<th>epidote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apt.</td>
<td>apatite</td>
<td>Spl.</td>
<td>spinel</td>
</tr>
<tr>
<td>Trml.</td>
<td>tourmaline</td>
<td>P.</td>
<td>present</td>
</tr>
<tr>
<td>Grnt.</td>
<td>garnet</td>
<td>C.</td>
<td>common</td>
</tr>
<tr>
<td>Sph.</td>
<td>sphene</td>
<td>VC.</td>
<td>very common</td>
</tr>
<tr>
<td>Rutl.</td>
<td>rutille</td>
<td>Hzlwd.</td>
<td>Hazelwood</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turrawalla</td>
<td></td>
</tr>
</tbody>
</table>

Heavy minerals do not appear to be common in samples from Provenance Class A. One would expect zircon and rutile to be common if the sediments were derived from a granitic provenance. The lack of these minerals may be related to the environment of deposition, or to the difficulty in seeing the minerals in thin section, if the grains are small.

Class B, as might be expected, has a great variety of heavy minerals, probably reflecting many source areas,
as demonstrated in the studies of rock fragments and quartz. This is further exemplified by the numerous varieties of tourmaline present in sediments of this class, particularly in the Blenheim Formation.

Class C is characterized by the abundance of euhedral apatite grains. The apatite was derived from acid volcanic rocks, and the abundance of this mineral in the heavy mineral assemblage of the formation is an indication of the importance of the volcanic source in the formation of the unit. The common source for both the apatite and the quartz grains with straight extinction is demonstrated by the many volcanic rock fragments in the sediments which contain both as phenocrysts.
GEOLOGICAL HISTORY

The geological history of the Blenheim area since the Upper Carboniferous or lowermost Permian has been (a) subsidence, and the filling of the depression with volcanic and terrigenous deposits, (b) relatively strong folding of the sequence and intrusion of intermediate and basic magma, (c) a long period of erosion, (d) thin terrestrial sedimentation and extrusion of basalt, (e) slight tilting movement and extensive erosion.

It is not impossible that the area received its first geosynclinal sedimentation in the Devonian, as geosynclinal deposits of this age crop out to the east and west of the Blenheim area (Reid, 1930; Jensen et al. 1963). However, the history of the Bowen Basin sequence in this area commenced in the late Carboniferous or early Permian when much of what is now the eastern edge of the Bowen Basin, from Collinsville to Cracow, was the site for the accumulation of a thick pile of intermediate and basic flows and associated pyroclastics. These deposits possibly had their origin in a volcanic island arc structure as evidenced by the thickness of the deposit and its extent; and they accumulated in a rapidly sinking deep depression on the western side of the structure. The water was too deep and probably too toxic for marine life to flourish. The depression was rapidly filled
with these deposits and the sea shallowed considerably, and in places benthonic marine was able to subsist.

With the almost complete cessation of volcanic activity in the area marine life flourished (Fauna II). Terrigenous clastic sediments were mixed with calcareous organic detritus to produce the sediments of the Tiverton Formation. The small amount of primary or secondary volcanic detritus in these sediments represents a minor continuation of volcanic activity.

The distinct change of lithology and fauna commencing at the base of the Hazelwood Formation reflects a basin-wide shallowing of the Permian sea. This is recorded in the Collinsville area by the development of coal measures. In the Cracow area units equivalent to the Hazelwood Formation are missing from the sequence (Jensen et al., 1964), although equivalents of the Tiverton and Blenheim Formations are present; this not only suggests a shallowing of the sea but a complete withdrawal in this area. There is no evidence of a complete withdrawal of the sea in the Blenheim area, but the sea must have been quite shallow, producing near-shore marine sands (the Wall Sandstone Member) and lagoons (carbonaceous mudstone above the Wall Sandstone Member).

In contrast to the sharp change in fauna and lithology between the Hazelwood and Tiverton Formations,
the change between the Hazelwood and Blenheim Formations is more transitional. This change is the reflection of a basin-wide deepening of the sea - a major marine transgression, described by Dickins et al. (1964). It was accompanied by uplift in other areas adjacent to the Blenheim area, as indicated by the conglomeratic nature of the topmost beds of the Hazelwood Formation and the basal beds of the Blenheim Formation.

During the deposition of the Blenheim Formation sediments, the sea gradually became shallow, with the eventual production of shallow water marine muds with an abundant infauna. Once the sea had withdrawn the basin continued to sink and the depression was covered by an extensive flood plain or series of small lakes. The formation of this depression was accompanied by a renewed volcanic activity, at first only minor, but reaching its zenith late in the Permian. Terrigenous clastic sediments were deposited in deltaic fans pushed out across the flood plain. This type of deposit, although prominent in the initial stages of the filling of the depression, became subordinate in the late Permian when thick pyroclastic deposits were formed. Scattered swamps became the site for the development of peat deposits, probably in a relatively humid environment as indicated by sporadic coal deposits towards the end of deposition of the Turrawalla Formation.
We now reach the transition time between the deposition of units known to be Permian and those undoubtedly Triassic. At this stage, as an aftermath of the Upper Permian vulcanism, volcanic detritus was reworked and deposited in the area by rivers. At the same time there was a climatic change from the humid conditions conducive to peat development to a different climate which caused oxidation and eventual destruction of plant debris. In the southern parts of the basin this climatic change is evident in the change from coal measures to red beds of the Rewan Formation. The same climatic change is represented in the Sydney Basin in the change from coal measures to the Narrabeen Group. The amount of volcanic detritus reworked by the rivers became less until only mature quartz-rich sediments were deposited. This environment must have been very much like that of the 'channel country' of western Queensland, as pointed out by Whitehouse (1955).

Subsidence followed this period of apparent stability and this was probably coeval with uplift of granitic terrains to the north and west of the area. Rivers and lakes played their part once again in the deposition of the sediment of the Teviot Formation. The presence of carbonaceous debris indicates that the
oxidizing conditions previously operative had been somewhat mollified, probably by a change of climate, or possibly because deposition took place in stagnant lakes.

After deposition of the Teviot Formation, the Permian and Mesozoic sequence was folded in response to a strong orogenic push from the north-east. This was the main folding movement of the Bowen Basin, producing thrust faults to the north of the Blenheim area, near Collinsville. Intrusion of basic and intermediate magmas followed this folding in the Blenheim area. The folding probably took place at the end of the Triassic, as the Jurassic sequence of the Surat Basin, to the south of the Bowen Basin, is relatively flat lying.

There followed a long period of erosion and the next deposition in the area was in the Tertiary when, as in many parts of Queensland, thin sedimentary deposits were formed in freshwater lakes.

Basalt flows were extruded over much of the area west of the Redcliffe Tableland, and on parts of the Tableland itself, during the Tertiary. It is possible that there has been minor tilting to the west since the Tertiary, as indicated by the basalt plain at the headwaters of Blenheim Creek.
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Cross-bedding directions in the Redcliffe Sandstone.

As measured in Stockton Creek - Regional dip 13°W, strike 330°.

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<td>115</td>
<td>195</td>
<td>28</td>
<td>155</td>
</tr>
<tr>
<td>30 S</td>
<td>110</td>
<td>200</td>
<td>22</td>
<td>180</td>
</tr>
</tbody>
</table>
APPENDIX A (Cont.)

<table>
<thead>
<tr>
<th>Dip</th>
<th>Strike</th>
<th>Dip Direction</th>
<th>Corrected Dip</th>
<th>Corrected Dip Direction</th>
</tr>
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<tbody>
<tr>
<td>20 S</td>
<td>110</td>
<td>200</td>
<td>12</td>
<td>160</td>
</tr>
<tr>
<td>30 W</td>
<td>350</td>
<td>260</td>
<td>19</td>
<td>270</td>
</tr>
<tr>
<td>28 S</td>
<td>240</td>
<td>150</td>
<td>30</td>
<td>130</td>
</tr>
<tr>
<td>13 NE</td>
<td>130</td>
<td>040</td>
<td>35</td>
<td>050</td>
</tr>
<tr>
<td>21 E</td>
<td>010</td>
<td>100</td>
<td>30</td>
<td>090</td>
</tr>
<tr>
<td>13 S</td>
<td>060</td>
<td>150</td>
<td>18</td>
<td>110</td>
</tr>
<tr>
<td>20 S</td>
<td>115</td>
<td>205</td>
<td>12</td>
<td>160</td>
</tr>
<tr>
<td>30 S</td>
<td>090</td>
<td>180</td>
<td>28</td>
<td>155</td>
</tr>
<tr>
<td>25 S</td>
<td>100</td>
<td>190</td>
<td>20</td>
<td>160</td>
</tr>
<tr>
<td>15 E</td>
<td>350</td>
<td>080</td>
<td>28</td>
<td>072</td>
</tr>
</tbody>
</table>
APPENDIX B

Assemblage Analyses

The following method of presentation is based on that used by Crook (1963) in his description of low grade metamorphic rocks from Fiji. Lines are used to indicate relationships between primary phases and secondary phases.

Abbreviations:

<table>
<thead>
<tr>
<th>Primary phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>ab - albite</td>
</tr>
<tr>
<td>cal - calcite</td>
</tr>
<tr>
<td>ch - chlorite</td>
</tr>
<tr>
<td>epi - epidote</td>
</tr>
<tr>
<td>fel - feldspar</td>
</tr>
<tr>
<td>gls - glass</td>
</tr>
<tr>
<td>lim - limonite</td>
</tr>
<tr>
<td>wm - white mica</td>
</tr>
<tr>
<td>op - opaques</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Replacing phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>psil - phyllosilicate</td>
</tr>
<tr>
<td>pl - plagioclase</td>
</tr>
<tr>
<td>preh - prehnite</td>
</tr>
<tr>
<td>pump - pumpellyite</td>
</tr>
<tr>
<td>pyt - pyrite</td>
</tr>
<tr>
<td>pyx - clinopyroxene</td>
</tr>
<tr>
<td>qu - quartz</td>
</tr>
<tr>
<td>ser - sericite</td>
</tr>
<tr>
<td>sph - sphene</td>
</tr>
</tbody>
</table>

Primary phases are designated: ab, pl, etc.
Replacing phases are designated: ab, qu, etc.
Newgrowth phases are designated: AB, CH, etc.
Vein phases are designated: QU, CAL.

Samples are arranged in numerical order according to their field number. The second number, shown in brackets, is the coordinates of the sample site.
649 (562582)
flow

```
pl - op
ab    ch    cal    lim

CAL  CH
CAL  CH
```

652 (571600)
tuff

```
pl - gls - op
cal  ab  psil  op  lim

CAL  QU
CAL
```

653 (573602)
flow

```
fel - pyx - op
ab    ser    preh    qu    ch    pump    sphene
```

658a (542618)
flow

```
pl - qu
ab    psil    ch    qu

QU
```

658b (542618)
flow

```
pl - gls - qu
ab    qu    cal

PSIL  CH  CAL
```
662 (591539)
flow
- fel - op - gls (minor)
  ab  ch  cal  op

CH    CAL

666a (593549)
tuff
- fel - gls - op
  ab  qu  psil  cal  ch

CAL  QU  CH

666b (593549)
tuff
- gls - pl - op
  qu  ch  ab  cal

CAL

680a (554603)
flow
- fel - wm - sphene
  ab  ch

CH

1047 (542645)
flow
- pl - pyx - op
  ab  ch  cal  pump  qu  preh  sphene
1418a (547645)
flow 
pl - gls - pyx 
ab - psil - ch - qu - preh - cal 
QU - PREH - CAL - AB 

1418b (572645)
gwke 
pl - matrix - qu 
cal - ab - preh - psil - qu 
CAL - PREH 

1419a (576649)
flow 
gls - fel 
ch - qu - ab 
CAL - AB - CH 

1419b (576649)
vein in flow 
?pl - pyx - op 
preh - epi - ch - qu 
QU - PREH - PUMP - WM 

1419c (576649)
flow 
pl - gls 
cal - ser - ab - qu - preh - ch - op 
PUMP - CH - CAL - PREH - QU
1420a (578660)  
tuff  
gls - pl - op - epi - sph  
psil  op  ab  qu  cal  
QU  

1420b (578660)  
tuff  
gls - pl  
op  
op  epi  ab  cal  ser  ch  
CAL  QU  CH