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Willaura

Sheet 7422, Victoria

1:100 000 Map Geological Report

by

P.G. Stuart-Smith & L.P. Black

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Australian Geological Survey Organisation, Record 1999/38

Department of Industry, Science and Resources

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Parliamentary Secretary: The Hon. Warren Entsch, MP
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Australian Geological Survey Organisation

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ABSTRACT

The Willaura 1:100 000 sheet area comprises an inlier of early Palaeozoic metasediments, volcanics and intrusives, unconformably overlain by Silurian sandstone and surficial Cainozoic sediments and volcanics. The exposed basement rocks form the easternmost part of the Late Proterozoic-Cambrian Adelaide Fold Belt.

Exposed bedrock comprises Cambrian turbidites and minor tholeiitic mafic rocks of the Glenthompson Sandstone, and a faulted belt of high-K calc-alkaline andesitic lavas and volcaniclastics distinguished as the Mount Stavely Volcanic Complex. U-Pb zircon analyses indicate a crystallisation age of 495±5 Ma for metadacite in the upper part of the complex. A 501±9 Ma age obtained from detrital zircons in a mafic volcaniclastic within the same unit places an older limit on its deposition. Both the sandstone and the complex share similar structural and metamorphic histories with only one phase of upright NNW-trending folding accompanied by very low to low grade burial metamorphism. This deformation, part of the Delamerian deformation that affected the Adelaide Fold Belt, preceded the intrusion of the 489±7 Ma Bushy Creek Granodiorite, and other, probably Cambrian, diorite and granite plutons.

The Silurian Grampians Group forms is a discontinuous belt of mainly fluviatile sediments unconformably overlying the Glenthompson Sandstone and a swarm of undated rhyolite dykes, distinguished as the Wickliffe Rhyolite. U-Pb zircon analyses indicate a crystallisation age of 412±3.5 for minor post-depostional rhyolite intrusions within the lower part of the Grampians Group. The group, up to 3200 m thick, is subdivided into three units that are correlated with the Grampians Range stratigraphy to the north.

A transgressive fluviatile to marine sequence of Tertiary rocks overlies older units in the centre and south of the sheet area. Units distinguished are the White Hills Gravel, undifferentiated sediments, Clifton Formation and undifferentiated ferricrete and sand.

Quaternary units cover most of the sheet area and comprise basalt flows and scoria deposits of the Newer Volcanics, and a range of fluvial and lacustrine sediments including: older alluvial terrace deposits; older alluvial and colluvial deposits; colluvial deposits; swamp and lagoonal deposits; stream alluvial deposits; and lunette deposits. Late Pleistocene aeolian clay, the Windgelli Clay, forms a thin veneer over the most of the Palaeozoic rocks and the Newer Volcanics.

Deposits of clay, sand, gravel, basalt, laterite and sandstone have been worked in the area and several occurrences of copper mineralisation within the Mount Stavely Volcanic Complex have been prospected. No economic metalliferous deposits are known. However, the correlation of the complex with the highly mineralised Mount Read Volcanics in Tasmania, strongly supported by this and other studies, significantly upgrades the potential of the complex and the other parts of the Mount Stavely Belt to host similar significant VMS deposits.

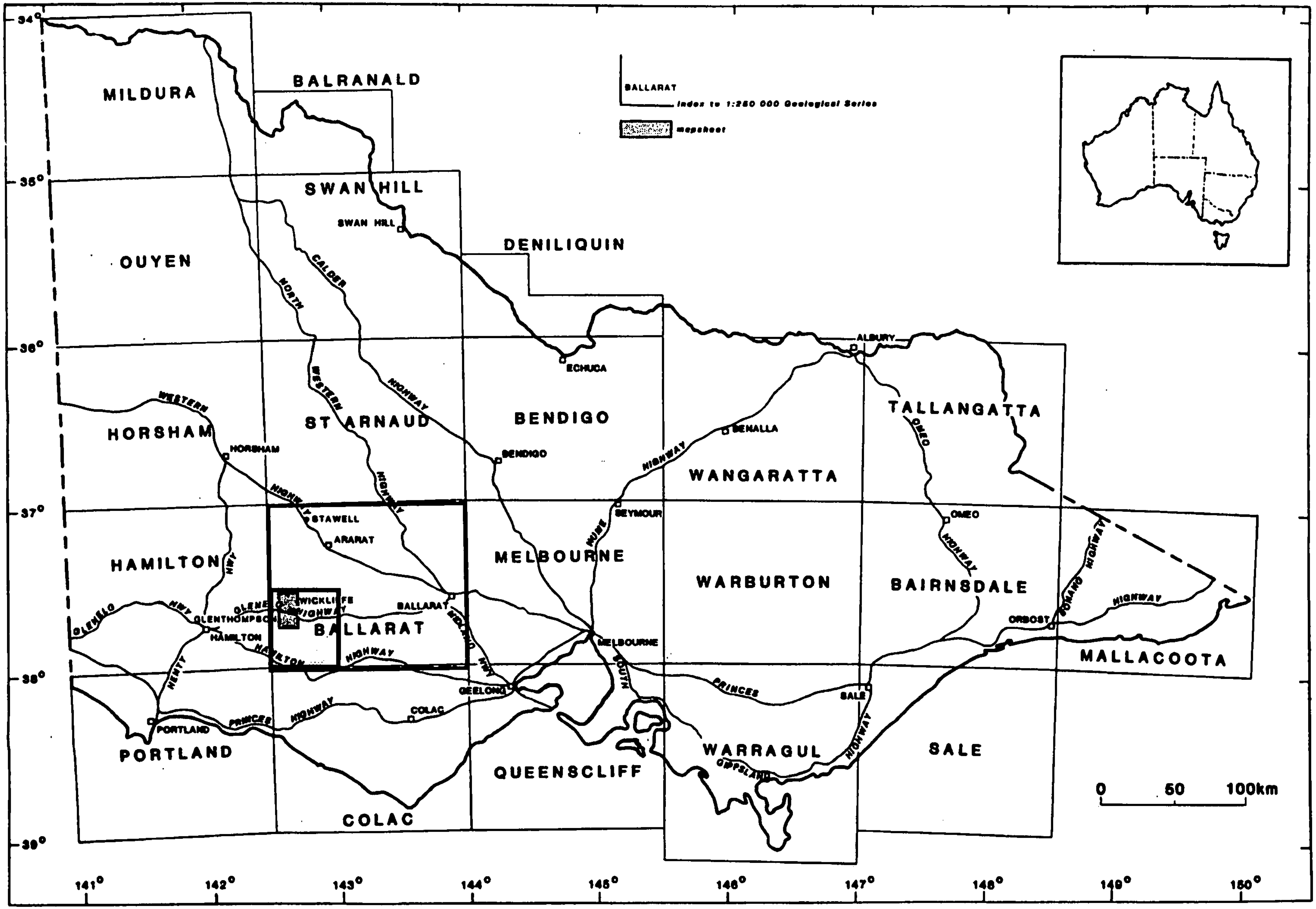

Figure 1. *Location of the Willaura 1:100 000 and Ballarat 1:250 000 sheet areas*

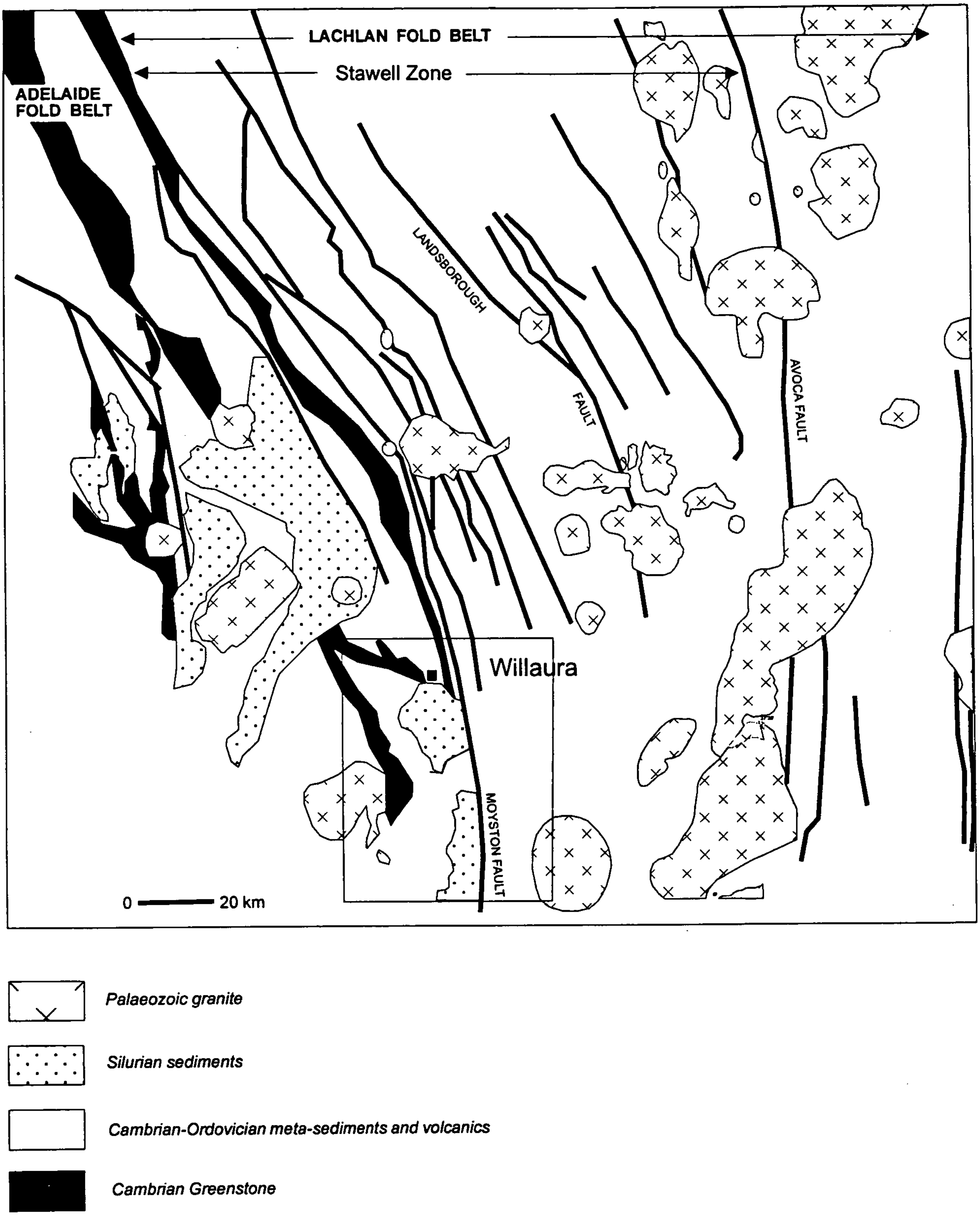

Figure 2. *Regional Palaeozoic geology of western Victoria (modified from Buckland, 1987). Note that all areas west of the Woorndoo Fault shown as Lachlan Fold Belt are now included in the Adelaide Fold Belt.*

1. INTRODUCTION

This map commentary and accompanying 1:100 000 scale geological map present the results of mapping carried out by the Australian Geological Survey Organisation (AGSO) and the Geological Survey of Victoria as part of the National Geoscience Mapping Accord. About eight weeks fieldwork was undertaken in 1993 and 1994 utilising data obtained from a high resolution airborne magnetic and gamma-ray spectrometric survey. Specifications and operational details of this survey are given by Richardson (1993).

The Willaura 1:100 000 Sheet area (WILLAURA[1]), part of the Ballarat 1:250 000 sheet area, lies between latitudes 37° 30'S and 38° 00'S and longtitudes 142° 30'E and 143° 00'E, centred about 95 km west of Ballarat, in central west Victoria (Figure 1). It contains the small rural centres of Willaura, Glenthompson, Wickliffe, Lake Bolac, Westmere, Woorndoo, Chatsworth, Caramut and Hexham. Principal access is provided by the Glenelg Highway that bisects the sheet area running east to west through Lake Bolac and Glenthompson; numerous sealed and unsealed roads link the population centres with surrounding rural properties.

The area was mapped, at a regional scale, as part of the Ballarat 1:250 000 scale map series (Geological Survey of Victoria, 1973; King, 1985) and later detailed mapping (1:50 000 scale) was carried out over exposed areas of the Mount Stavely Volcanic Complex in the centre of WILLAURA. Results of this work were published by the Geological Survey of Victoria as a special geological map (Buckland, 1985) and accompanying report (Buckland, 1987). The stratigraphic nomenclature of Buckland (1987) has been used in this report and much of the detailed mapping of the Mount Stavely Volcanic Complex by Buckland (1985) has been incorporated into the 1:100 000 geological map though with some modification. Preliminary results of geochronological investigations undertaken as part of the mapping program were presented by Stuart-Smith and Black (1995) and Crawford and others (1995, 1996).

2. REGIONAL GEOLOGICAL SETTING

Palaeozoic bedrock in WILLAURA includes a belt of volcanic rocks at Mount Stavely, one of a series of discontinuous, greenstone sequences (collectively referred to as the Mount Stavely Belt), lying within the easternmost part of the Late Proterozoic-Cambrian Adelaide Fold Belt (AFB) in western Victoria (Figure 2). The complex comprises a mildly deformed and low-grade sequence of lavas, volcaniclastics and intrusive rocks that are interbedded, faulted against and surrounded by quartz-rich turbidites of the Glenthompson Sandstone. These rocks are interpreted to terminate in the east, against the east-dipping Moyston Fault which throws higher grade and multiply deformed metavolcanics and sediments of the Stawell Zone over the Glenthompson Sandstone. A similar, but west-dipping, thrust fault (the Escondida Fault) is also interpreted to throw slightly higher grade and multiply deformed meta-turbidites and meta-mafic rocks of the Miga subzone[2] (of the Glenelg Zone) to the west over lower grade Glenthompson Sandstone (Dimboola subzone).

The Moyston Fault is the surface boundary between the AFB and the Lachlan Fold Belt (LFB) to the east (Cayley & Taylor, 1996). Lachlan Fold Belt rocks, exposed in adjoining ARARAT and SKIPTON, do not crop out in WILLAURA, but are interpreted to lie beneath Newer Volcanics basalt in the eastern part of the area. Prior to recent isotopic dating studies of the volcanic complex (Stuart-Smith and Black,

[1] Names of 1:100 000 Sheet areas are printed in capitals

[2] Rocks within this zone in WILLAURA are here loosely correlated with the Glenelg River Complex.

1995; Foster & others, 1996), the age of exposed unfossiliferous bedrock in WILLAURA was not known. They had been interpreted as either part of the LFB (e.g. Gray & others, 1988, Gibson & Nihill, 1992) or as an eastward extension of the AFB (e.g. Wilson & others, 1992). Most earlier workers correlated the Mount Stavely Volcanic Complex (at least in part) with other fossiliferous Middle to Late Cambrian greenstone belts throughout LFB in Victoria (e.g. Gray & others, 1991).

The Cambrian meta-sediments and volcanics are intruded by Cambrian granodiorite, diorite and granite plutons, and locally by a swarm of Silurian rhyolite dykes (Wickliffe Rhyolite). Unexposed Devonian granites are interpreted from magnetic data to intrude LFB rocks in the east. In the centre of the area, flanking the western margin of the Moyston Fault, a down faulted block of folded Silurian Grampians Group rocks unconformably overlies the Glenthompson Sandstone and Wickliffe Rhyolite, forming a discontinuous north-trending belt of mainly fluviatile sediments.

A transgressive fluviatile to marine sequence of Tertiary rocks overlies older units in the centre and south of the sheet area. Units distinguished are the White Hills Gravel, undifferentiated sand and carbonaceous-rich sediments, the Clifton Formation and undifferentiated ferricrete and sand.

Quaternary units cover most of the sheet area. They comprise basalt flows and scoria deposits of the Newer Volcanics, and a range of fluvial and lacustrine sediments, including: older alluvial terrace deposits; older alluvial and colluvial deposits; colluvial deposits; swamp and lagoonal deposits; stream alluvial deposits; and lunette deposits. A late Pleistocene aeolian clay, the Windgelli Clay, forms a thin veneer over the most of the Palaeozoic rocks and the Newer Volcanics.

3. GEOMORPHOLOGY

The geomorphology of the area has been described by King (1985) and Jenkins (1976). Ollier and Joyce (1986) mapped the regolith terrain units. Topographically, WILLAURA is a low-lying region, ranging mostly between 200 m and 300 m ASL. The area consists of two major landform subgroups: the Dundas Surface and the Western District Volcanic Plains (Figure 3).

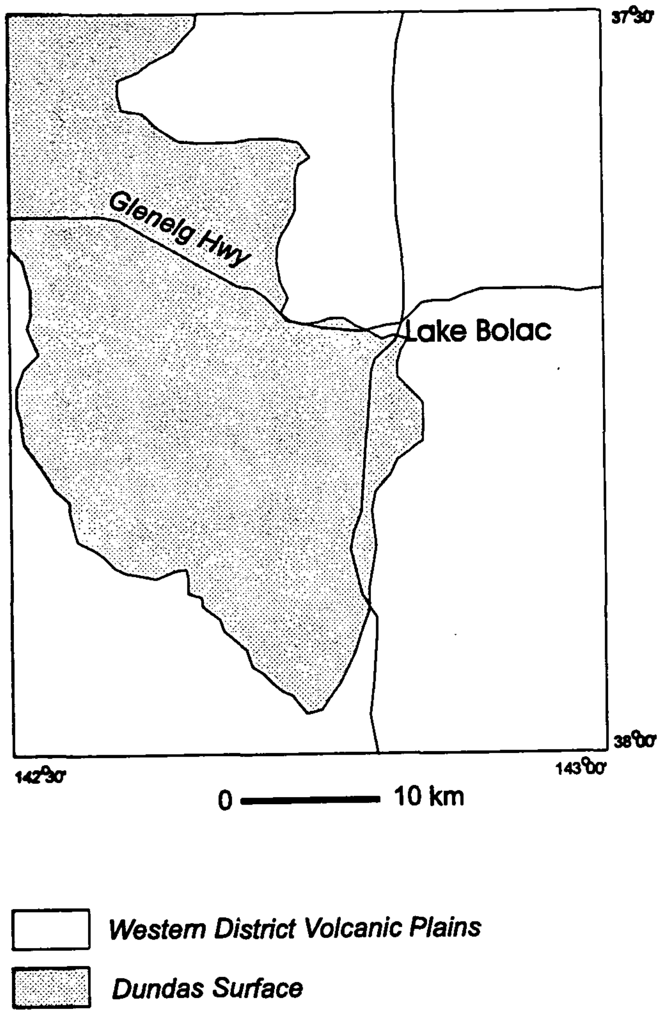

Figure 3. *Geomorphology of the the Willaura 1:100 000 and Ballarat 1:250 000 sheet areas.*

The *Dundas Surface* is typified by low rounded hills, up to 368 m ASL, of deeply weathered Palaeozoic rocks in the northwest around Mount Stavely. The deep weathering profile of the Surface has been developing since the early Tertiary (Cayley & Taylor, 1997) and encorporates extensive areas of ferricrete and sand. This surface is best developed on Lower Palaeozoic rocks and Tertiary sediments southwest of Lake Bolac. The surface also includes: low hills of fresh Mount Stavely Complex rocks around Mount Stavely; minor outliers of ferruginous cemented Tertiary gravels, capping hills south of Willaura township; and extensive alluvial flats, that formed as a result of Newer Volcanics lava flows impounding streams flowing from the north.

The *Western Districts Volcanic Plains* embody the amalgamated basaltic lava sheets and volcanic cone deposits of the Cainozoic Newer Volcanics. Mostly the plains are covered by a thin veneer of loess and scattered lacustrine deposits, with only the youngest flows forming stony rises, such as those around Mount Hamilton and Mount Fyans in the southeast. The plains contain a number of volcanic features, including: lava cones, lava discs, lava domes, scoria cones and lava caves. Lava domes form the majority of eruptive centres in the area, particularly for the older flows such as those near Lake Eyang east of Woorndoo. Mount Hamilton is the best example of a basalt cone (Ollier & Joyce, 1964), standing 80 m high with a central crater 400 m wide and 30 m deep. It also has well-preserved caves formed when lava drained from beneath a partially solidified flow (Ollier, 1963). Lava discs, or small flat topped eruptive centres capped by a collapsed lava sheet, occur at Mondilibi in the south and 3 km northeast of Willaura. Bald Hill in the northeast is the only scoria cone in the sheet area. Minor scoria deposits are also present at the Mount Fyans and Mondilibi eruptive centres; however, they are mostly capped by lava flows.

The main drainage of WILLAURA lies within the Hopkins River catchment, draining to the south. Small areas of internal drainage are common, particularly on the Western District Volcanic Plains. Rainfall averages about 600 mm.

Table1. *Stratigraphy of the Willaura 1:100 000 sheet area*

Unit	*Lithology*	*Relationships*	*Thickness (max. m)*	*Remarks*
QUATERNARY				
Qu	Clay and sand	Cresent-shaped deposits on the southeast margins of Qrm deposits		Lunette deposits
Qra	Clay, silt, sand and minor gravel	Active deposits in main watercourses		Stream alluvium
Qrm	Clay, silt and sand	Occupy depressions in Qvn and Qvh and along margins of Qvh flows		Swamp and lagoonal deposits
Qrc	Sand and silt	Upper parts of most of most drainage catchments		Colluvial deposits
Qpa	Partly consolidated clay, silt and sand	Remnant deposits in major fluvial courses or adjacent to advancing Qu, Qrm and Qrc deposits		Older alluivial and colluvial deposits
Qar	Partly consolidated clay, silt and sand	Eroding deposits adjacent Qra		Older alluvial terrace deposits
Newer Volcanics				
Qvs	Basalt scoria	Cones capping Qvn and Qvh3	50	Volcanic cone deposits
Qvh1	Vesicular basalt	Mt. Hamilton area	80	Younger blocky flows
Qvh2	Vesicular basalt	Mt. Fyans area	75	Younger blocky flows
Qvh3	Vesicular basalt	Mondilibi area	40	Younger blocky flows
Qvn	Olivine basalt	Disconformably overlies Palaeozoic and Tertiary units. Covered by Windgelli Clay	90	Amalgamated lava sheets
Qvn1	Olivine-pyroxene-phyric basalt	Lava cone south of Mt. Hamilton area. Covered by Windgelli Clay	40	Volcanic cone
Qvnm	Negatively magnetised basalt	Magnetic feature at a Qvn volcanic centre		Intrusion at depth

Table 1. *continued*

Unit	*Lithology*	*Relationships*	*Thickness (m)*	*Remarks*
TERTIARY				
Tps	Unconsolidated sand	Outliers unconformably overlying Palaeozoic units	5	Continental deposits
Tpl	Laterite, sand, ironstone	Resistant outliers unconformably overlying Palaeozoic and older Tertiary units	5	Lateritic weathering profile
Clifton Formation Tok	Quartz sand, clay and calcarenite	Overlies Tae. Sand ridges lateritised and magnetic	15	Swamp and strandline deposits
Tae	Consolidated cross-bedded quartz sandstone, gravel, clay, lignite and coal	Unconformably overlies Palaeozoic units. Overlain by Tok	40	Fluvial and swamp deposits
White Hills Gravel Tlw	Consolidated ferruginous quartzose gravel	Resistant outliers unconformably overlying Palaeozoic units	5	Fluvial deposits
DEVONIAN				
Dg	Undifferentiated magnetic granite	Intrudes St. Arnaud Beds. Unconformably overlain by Newer Volcanics		Interpreted from magnetic data
SILURIAN				
Grampians Group Slk	Pebbly cross bedded quartz sandstone, polymictic conglomerate, siltstone and rhyolite	Unconformably overlies Wickliffe Rhyolite and Glenthompson Sandstone	3200	Fluvial to shallow-marine deposits. 412.6± 3.5 Ma (U-Pb zircon)
Wickliffe Rhyolite Svj	Pink flow-banded rhyolite	Forms dykes intruding Glenthompson Sandstone. Unconformably overlain by Willaura Sandstone		Dykes
CAMBRIAN				
Cg	Undifferentiated magnetic granite	Covered by Newer Volcanics. Intrudes Glenthompson Sandstone		Interpreted from magnetic data
Buckeran Diorite ∈ dim	Magnetic diorite	Intrudes Glenthompson Sandstone		Zoned intrusion
∈ di	Diorite			
Bushy Creek Granodiorite ∈ gd	Grey porphyritic biotite hornblende granodiorite	Intrudes Glenthompson Sandstone		Zoned intrusion 489±7 Ma (U-Pb zircon)
∈ gdm	Magnetic granite in subsurface			
∈ d	Magnetic microporphyritic diorite	Intrudes Glenthompson Sandstone		Interpreted from magnetic data

Table 1. *continued*

Unit	*Lithology*	*Relationships*	*Thickness (m)*	*Remarks*
Glenthompson Sandstone ∈gs	Medium-grained meta quartz sandstone and minor siltstone	Interfingers and overlies the Mount Stavely Volcanic Complex. Intruded by Bushy Creek Granodiorite and Wickliffe Rhyolite		Turbidite deposits
∈gm	Meta dolerite, meta-basalt, meta diorite,			Tholeiitic subvolcanic intrusions and minor volcanic flows and volcaniclastics
Mount Stavely Volcanic Complex				
∈sm	Undifferentuiated magnetic mafic/ultramafic rocks	Covered by Tertiary sediments and Newer Volcanics		Interpreted from magnetic data
Lalkaldarno Porphyry ∈sl	Porphyritic hornblende quartz diorite.	Intrudes other units of the complex.		Intrusion coeval with Towanway Tuff volcanism (Buckland, 1987).
Williams Road Serpentinite ∈sw	Serpentinite.	Faulted contacts with other units in the complex.	600	Tectonically emplaced. Altered mafic cumulate (Buckland & Ramsay, 1982)
Towanway Tuff ∈st	Dacitic crystal lithic volcanic sandstone. Minor laminated chert and volcanic siltstone.	Transgressive, conformable contact with underlying Nanapundah Tuff and Fairview Andesite Breccia.	800	Subaqueous epiclastic deposits (Buckland, 1987). 501±9 Ma (U-Pb zircon)
Narrapumelap Road Dacite Member ∈stn	Dacitic to rhyolitic lava.		100	495±5 Ma (U-Pb zircon)
Nanapundah Tuff ∈sn	Andesitic crystal lithic volcanic sandstone.	Conformably overlies and intertongues with the Fairview Andesite Breccia. Faulted against the Williams Road Serpentinite.	800	Subaqueous epiclastic deposits (Buckland, 1987).
Fairview Andesite Breccia ∈sf	Massive andesitic breccia, minor andesite and basalt lava.	Conformably ?overlain by and intertongues with the Nanapundah Tuff. Faulted against the Glenthompson Sandstone	2500	Subaqueous debris flow deposits (Buckland, 1987).
Glenronald Shale Member ∈sfg	Laminated black pyritic shale, volcanic siltstone, minor chert.		13	Subaqueous, lagoonal environment (Buckland, 1987).

4. STRATIGRAPHY

The stratigraphy of WILLAURA is summarised in Table 1. The area contains a bedrock of Cambrian, Silurian and Devonian meta-sediments, meta-volcanics and intrusive rocks, and cover sequences of Tertiary and Quaternary sediments and volcanics.

4.1 CAMBRIAN

4.1.1 Mount Stavely Volcanic Complex

The Mount Stavely Volcanic Complex comprises a mildly deformed and low grade sequence of andesitic to rhyolitic lavas, volcaniclastics and intrusive rocks which are interbedded, faulted against and surrounded by quartz-rich turbidites of the Glenthompson Sandstone. Despite low-grade burial metamorphism, primary igneous textures and mineralogy are commonly preserved in the volcanic rocks. Outcrop of the complex within WILLAURA is confined to two belts: the Mount Stavely and the Mount Dryden Belts (Figure 1).

The geology of the Mount Stavely Belt is described by Buckland and Ramsay (1982), Buckland (1985 & 1987), and Crawford (1988), and stratigraphy is summarised in Table 1. The belt crops out poorly as a series of low, isolated hills, over more than 30 km, in a 2 km wide southeast-trending belt passing through Mount Stavely. Three main volcano-sedimentary stratigraphic units and two intrusive units are defined (Buckland & Ramsay, 1982) and include: the Fairview Andesite Breccia, Nanapundah Tuff, Towanway Tuff and the intrusive Lalkaldarno Porphyry and Williams Road Serpentinite. In addition, a cherty laminated black pyritic shale horizon within the Fairview Andesite Breccia is distinguished as the Glenronald Chert Member; a felsic lava within the Towanway Tuff is defined as the Narrapumelap Road Dacite Member.

The Mount Stavely Belt is overlain by a veneer of Cainozoic sediments, ferricrete and basalt. However, pronounced aeromagnetic anomalies along the belt indicate considerable subsurface continuation of the belt to the south and to the north of the sheet area beneath the Silurian Grampians Group and sediments of the Murray Basin well into NSW.

Small outcrops of very low-grade andesitic lapilli tuff and crystal tuff, south of Lake Bolac (Ramsay, 1981; Buckland, 1981) are the southern continuation of the Mount Dryden Belt. They occur in close proximity to the interpreted Moyston Fault and probably form a tectonic sliver that is thrust over Grampians Group sediments to the west. The rocks are here included within the Fairview Andesite Breccia.

4.1.1.1 Description and relations

4.1.1.1.1 Fairview Andesite Breccia

The Fairview Andesite is the main outcropping unit of the Mount Stavely Volcanic Complex in WILLAURA, forming the base of the volcanic sequence along the western margin of the Mount Stavely Belt. It is inferred to be faulted against the Glenthompson Sandstone to the west and is overlain to the east by the Nanapundah Tuff. In places, the latter contact is either truncated by discordant intrusive bodies of Lalkaldarno Porphyry, or is faulted, with tectonic slivers of Williams Road Serpentinite separating the overlying tuff. The contact with the tuff unit is not exposed but appears to be a regional angular discontinuity that may represent either an originally disconformable contact or a laterally interfingering relationship. The predominance of moderately to highly magnetic (250-1500 x 10^{-5} SI Units) andesitic rocks enables the unit to be traced beneath Tertiary sedimentary cover for least 6 km south of the Hopkins River.

The formation comprises a massive volcanic pile, up to 2500 m thick, of mainly breccias and lavas of porphyritic non-vesicular andesite breccia, with minor clinopyroxene-phyric andesite and rare hornblende andesite lavas. A fine-grained sedimentary unit is distinguished as the Glenronald Shale Member.

The most abundant rock type is a fine-grained, pale to dark green, *porphyritic non-vesicular andesite breccia*. The andesite clasts, up to 30cm across, contain abundant euhedral clinopyroxene, small, stubby, zoned plagioclase and rare orthopyroxene phenocrysts. The groundmass is fine-grained to microcrystalline, with a pilotaxitic to subtrachytic texture, and comprises albitised plagioclase laths and secondary quartz, epidote, prehnite, pumpellyite, carbonate, chlorite and sericite. The matrix between clasts consists of massive to laminated, fine-to medium-grained, volcaniclastic material (Buckland, 1986) with secondary sericite and chlorite. The breccias probably represent autobreccias formed during volcanic flow.

Minor *clinopyroxene-phyric andesite* vesicular lava and rare *hornblende andesite* lava are also present. The clinopyroxene-phyric andesite vesicular lava is dark greenish grey and crops out on the southern bank of the Hopkins River, about 1700 m southwest of 'Noarlunga'. The lava is distinguished from the andesite clasts in the breccia by the presence of prehnite-quartz-chlorite-epidote amygdales. The andesite forms a semi-continuous horizon near the top of the Towanway Tuff that can be traced in aeromagnetic data a further 2 km to the north and 8 km to the south beneath Tertiary sediments. The andesite is moderately magnetic, with magnetic susceptibilities greater than 500 x 10^{-5} SI Units. Contacts with adjacent rocks are not exposed. The andesite is interpreted to be a lava flow, either faulted within, or interdigitating with, the tuffaceous sedimentary sequence.

The *Glenronald Shale Member* (also referred to as the Glenronald Chert Member, Buckland & Ramsay, 1982) forms a narrow sedimentary horizon up to 8 m thick, cropping out discontinuously over 11 km strike length from north of Mount Stavely to the Hopkins River in the south. The member comprises thinly bedded laminated dark grey to black pyritic shale, laminated grey volcaniclastic siltstone and minor black chert. The volcaniclastic sediments are silicified and contain abundant mineral fragments of quartz, sericitic feldspar, biotite and chlorite (Buckland & Ramsay, 1982). Magnetic susceptibilities are low, ranging from 5 to 80 x 10^{-5} SI Units.

4.1.1.1.2 Nanapundah Tuff

Dark greyish green, massive, poorly sorted, medium- to coarse-grained andesitic crystal lithic volcanic sandstone, differentiated as the Nanapundah Tuff, overlies and probably interfingers with the Fairview Andesite Breccia. The sandstone is overlain by more felsic volcaniclastic sediments of the Towanway Tuff, probably with conformable contacts. The boundary is defined by the more dacitic composition of the overlying unit (Buckland, 1987). The lower contact is well-defined by a marked change in magnetic response: the tuff is weakly magnetised (magnetic susceptibilities of about 10 x 10^{-5} SI Units) compared to the more highly magnetic andesite.

The unit is best developed north of Mount Stavely where it has a maximum thickness of 800 m (Buckland, 1987). Its strike extent is limited by faulting to the north and to the south, where it is thrown against the Glenthompson Sandstone, and against tectonic slivers of Williams Road Serpentinite, respectively. In places, the sandstone is intruded by discordant bodies of Lalkaldarno Porphyry.

The sandstone comprises abundant angular to subrounded andesitic clasts with crystal fragments of plagioclase, K-feldspar, hornblende and clinopyroxene in a recrystallised matrix of metamorphic chlorite, titanite, prehnite, epidote and sericite (Buckland & Ramsay, 1982; Buckland, 1987). Pyrite and chalcopyrite are also present (Buckland & Ramsay, 1982). The rock is fine- to coarse-grained and mostly massive, with a weak lamination present in places.

4.1.1.1.3 Towanway Tuff

The Towanway Tuff is the second most extensive unit, occupying the northern part of the belt and pinching out at Hopkins River. Exposure is very poor, with rare in situ exposures confined to creek beds. The extent of the unit has been mostly defined in the subsurface by drilling, magnetic data and areas of surficial 'float'.

Contacts with adjacent units are not exposed. The unit structurally overlies the Nanapundah Tuff and the Fairview Andesite to the west with apparent conformity or paraconformity. The contact is marked by the change to more andesitic compositions in the underlying units (Buckland, 1987). The unit is overlain and faulted against the Glenthompson Sandstone that flanks the unit to the east. An original gradational sedimentary contact can be inferred by the presence of interbedded rhyolitic volcaniclastic sandstone beds within the Glenthompson Sandstone adjacent to the contact and quartz sandstone beds within the upper portion of the tuff (e.g. ~850 m NE of 'Binbook' 647772 5826910). Stratigraphic facing in both units is to the east indicating that the Glenthompson Sandstone overlies the Towanway Tuff. Most contacts with adjacent units are faulted, and are in many places filled by slivers of Williams Road Serpentinite. Irregular bodies of Lalkaldarno Porpyry intrude the unit near Stavely.

The tuff comprises a well-bedded sequence of dacitic volcaniclastic sandstone with a dacitic flow differentiated as the *Narrapumelap Road Dacite*. Maximum thickness is about 2000 m, being the interpreted maximum surface width of the unit in the north.

The Towanway Tuff comprises rhyolitic/dacitic lithic lapilli tuff, crystal tuff and volcaniclastic sandstone. The rocks range from very thinnly bedded, laminated cherty (devitrified) crystal tuff, to fine-grained poorly sorted laminated lithic lapilli tuff and medium-bedded, coarse-grained volcaniclastic sandstone. Beds are commonly graded, with basal small-scale scours present in places. Volcanic clasts are mostly dacitic and less commonly andesitic in composition; crystal fragments comprise plagioclase, quartz, and chloritised mafic minerals (clinopyroxene). The rocks are highly altered, with pervasive secondary carbonate, sericite, chlorite, leucoxene, epidote and quartz. Locally, near the contact with the overlying Glenthompson Sandstone, volcaniclastic breccia forms very thick beds within thinnly bedded laminated tuff. The breccia is composed of angular clasts of rhyolite (identical to the Narrapumelap Road Dacite Member) and cherty laminated crystal tuff in a laminated quartz sandstone matrix. Macroscopic disharmonic folds in the sandstone matrix are probably soft-sediment structures formed by slumping or compaction. The volcaniclastics are weakly magnetic, with magnetic susceptibilities mostly ranging between 20 to 30 x 10^{-5} SI Units.

Minor dark pinkish grey *dacitic to rhyolitic lavas* of the Narrapumelap Road Dacite Member crop out in two areas: south of Stavely railway siding and in the Hopkins River Valley, north of Yarrack Road. In the latter area, which includes the type locality, the member extends discontinuously over 4 km, with an estimated maximum thickness of 100 m (Buckland, 1987). The lavas are mostly porphyritic, with abundant euhedral plagioclase, embayed quartz and rare clinopyroxene and hornblende phenocrysts in a recrystallised microcrystalline groundmass containing K-feldspar, chlorite, hematite and altered iron-titanium oxides. Common alteration minerals include sericite, albite, titanite, pumpellyite and epidote (Buckland & Ramsay, 1982). The lavas are very weakly magnetic with magnetic susceptibilities of about 10 x 10^{-5} SI Units.

4.1.1.1.4 Williams Road Serpentinite

The Williams Road Serpentinite is a highly disrupted unit, forming discontinuous tectonised lenses up to 600 m across, mostly along the faulted margins of the Mount Stavely Belt and within the belt along the faulted contact between the Towanway Tuff and the underlying Nanapundah Tuff and Fairview Andesite Breccia. The serpentinite is intruded by, and also faulted against, the Lalkaldarno Porphyry near Mount Stavely. The serpentinite is the most strongly magnetised (700 - 2000 x 10^{-5} SI Units) unit within the complex, enabling it to be traced in the subsurface from Stavely Railway Siding to the northwest corner of the sheet area, where drilling has confirmed its presence and that it is the source of number of magnetic anomalies.

The serpentinite is a pale to dark greenish grey rock composed almost entirely of platy and fibrous serpentine (?chrysotile) with euhedral chromite (Cr/Cr+Al = 0.89-0.93; Buckland & Ramsay, 1982; Crawford & others, 1996), magnetite, and secondary quartz (Buckland, 1986). The rock is either brecciated or strongly foliated where shearing is more intense: original igneous textures are not preserved. The subvertical foliation parallels the northwest trend of the volcanic complex.

The presence of euhedral chromite suggests that the Williams Road Serpentinite represents an altered olivine-rich mafic cumulate lava or plutonic rock (Buckland & Ramsay, 1982), with the chromium-rich nature of the chromites, indicating an ultramafic boninite protolith (Crawford & others (1996). Although Cambrian and later tectonism have deformed and probably remobilised the serpentinite to some extent, the inferred intrusive relationship by the Lalkaldarno Porphyry indicates that the serpentinite must have been part of the volcanic pile during its formation. A lava flow origin is therefore the most likely. Ovate siliceous nodules (Buckley, 1987, Figure 9 page 20) may be relict pillows.

4.1.1.1.5 Lalkaldarno Porphyry

The Lalkaldarno Porphyry forms a number of irregular-shaped bodies within the Mount Stavely Volcanic Complex, in places enclosing small 'rafts' of volcaniclastics. The largest of the bodies is about 3 km^2 and crops out south of Mount Stavely. Contacts are not exposed. However, the distribution of outcrop crosscuts the volcanic stratigraphy, and the porphyry is interpreted to form small stocks and narrow sill- or dyke-like bodies intruding the volcanic sequence.

The porphyry is a massive light grey rock of tonalitic to trondhjemitic composition. Euhedral zoned plagioclase, prismatic hornblende and augite form phenocrysts up to 5 mm across. Less common microphenocrysts of quartz, zircon, apatite, and iron-titanium oxide are also present. The groundmass is equigranular holocrystalline quartz-feldspar mosaic, titanite, epidote, chlorite, prehnite, carbonate and pyrite. Plagioclase is altered to sericite, chlorite, epidote, titanite, and opaque oxide; augite to chlorite, epidote, titanite and quartz (Buckland & Ramsay, 1982). Magnetisation ranges widely from non-magnetic varieties to highly magnetic bodies (<1500 x 10^{-5} SI Units).

The Lalkaldarno Porphyry is interpreted to represent high-level intrusives that are cogenetic with the volcanic lavas of the Mount Stavely Volcanic Complex.

4.1.1.1.6 Undifferentiated magnetic mafic/ultramafic rock

Magnetic data indicate a strongly magnetic body lies at depth beneath a thick sequence of Tertiary sediments, about 6 km east of Chatsworth. The body lies along strike from the southernmost portion of the Mount Stavely Belt, but cannot be connected with any certainty to outcropping units to the north. The source of the magnetic anomaly is likely to be a body of either mafic rocks of the Fairview Andesitic Breccia or the Williams Road Serpentinite, as these two units are the most magnetic within the volcanic complex.

Other unexposed magnetic mafic/ultramafic rocks, covered by Quaternary basalt flows, form a continuous northerly trending belt (the Mount Dryden Belt), flanked by the Moyston Fault and connecting outcrops of andesitic rocks at Loke Bolac to outcrops of the belt in ARARAT.

4.1.1.2 Geochemistry

Representative analyses[3] of the volcanic and intrusive rocks from the Mount Stavely Belt are given in Table 2. The complex comprises five main compositional groups: (1) pyroxene-plagioclase-phyric andesitic lavas; (2) hornblende-plagioclase andesite lava; (3) dacite lava; (4) tonalitic-trondhjemitic intrusives; and (5) serpentinised ultramafic boninite lavas (Figure 4). Major and trace element data show that the lavas have low levels of compatible elements, with MORB normalised patterns of incompatible elements demonstrating an impoverished trend (<1) for high field strength elements (Buckland & others, 1985). They are LEE enriched with $(La/Sm)_N$ increasing from 2.2 in mafic units to 4.54 in more felsic members (Buckland & others, 1985). Likewise $(La/Yb)_N$ progressively increases with SiO_2.

The geochemistry of the andesites suggests that they have affinities varying from medium-K calc-alkaline, through high-K calc-alkaline to shoshonitic suites (Crawford & others, 1995). The andesitic rocks have unusually high Sr and low Y and Sc contents, also indicating adakitic affinities. Rather than representing fractionates from a basaltic precursor, they were probably derived from a metabasaltic (eclogite) source (Crawford & others, 1996). The Narrapumelap Road Dacite Member was probably derived from a different source, probably a crustal melt, rather than via fractionation of the andesitic rocks (Crawford & others, 1996).

The geochemistry of the lavas reflects an orogenic andesite association, implying that they were erupted in either an island-arc setting or on an active continental margin (Crawford, 1988). However, REE patterns are more comparable to calc-alkaline volcanics developed on continental crust and $^{87}Sr/Sr_{86}$ ratios (0.7040 for andesites and 0.7059 for dacites) suggest continental affinities (Buckland & others, 1985). Interbedded submarine sedimentary rocks - including quartz-rich sandstone - and volcaniclastic sandstone (with continental-sourced detrital zircons) are intercalated with the andesite sequence; suggesting that eruptions were at least in part submarine and proximal to exposed continental crust. These relationships, together with geochemistry, indicate that the complex probably represents either a high K-orogenic andesite suite erupted in a mature arc built on moderately thin continental-margin crust, or a post-collisional high-K calc-alkaline andesite suite.

[3] all published and new geochemical data used in this paper are from AGSO's ROCKCHEM database

Table 2. *Representative analyses from the Mount Stavely Volcanic Complex (calculated volatile free).*

Sample No.	26241	26247	26244	26232	26253	26234
Lithology *	1a	1a	1a	2	1b	3
Si02	59.37	60	60.39	61.02	68.6	65.4
7i02	0.8	0.9	0.67	1.17	0.61	0.52
AI203	13.27	16.65	16.31	17.12	13.98	16.8
FeO	8.49	7.25	6.66	5.4	4.26	3.26
MnO	0.12	0.11	0.08	0.1	0.07	0.05
Mg0	5.34	3.69	4.49	4.19	1.7	3.37
CaO	8.36	6.66	7.09	5.2	5.27	4.48
Na2O	2.67	3.28	3.08	3.87	4.77	5.43
K20	1.25	1.21	1.04	1.47	0.49	0.59
P205	0.33	0.25	0.19	0.46	0.25	0.11
LOl	1.94	2.46	2.44	2.98	2.55	1.52
Rb	30	25	29	34	14	11
Ba	241	152	268	407	111	128
Sr	749	516	631	534	338	425
Zr	122	132	148	215	101	
Y	16	7	14	18	7	15
Ni	42	35	42	45	17	80
V	196	219	166	103	160	79
Sc	24	24	20	12	8	10
Cr	190	12	72	46	14	46
Zr!Sc	5.08	5.5	7.4	17.92	12.63	
ylZr	1.61	1.66	1.12	0.48	1.58	
Ti!Zr	39.31	40.88	27.14	32.62	36.21	
TiJV	24.47	24.64	24.2	68.1	22.86	
	5.34	3.69	4.49	4.2	1.7	
La	24	14.4	17.2	41.5	13	
Ce	62.4	38.1	45.7	88.4	30.1	
Pr	8.05	4.93	5.88	10.31	3.66	
Nd	34.9	21.7	24.1	38	15.7	
Sm	6.73	4.56	4.87	5.95	3.08	
Eu	1.26	1.55		1.84		
Gd	4.78	3.92	4.08	4.55	2.46	
Dy	2.77	2.44	2.67	3.75	1.78	
Er	1.23	1.02	1.53	2.15	1.06	
Yb	1.01	0.81	1.15	1.78	0.83	
(LalYb)n	15.7	11.74	9.88	15.4	10.35	
(La!Sm)n	2.17	1.93	2.15	4.25	2.57	
(Gd!Yb)n	3.8	3.89	2.85	2.05	2.38	

Chondrite-normalised values

Sample No.	26241	26247	26244	26232	26253	26234
Lithology *	1a	1a	1a	2	1b	3
La	76.19	45.71	54.6	131.75	41.27	
Ce	76.75	46.86	56.21	10.8.3	37.02	
Pr	66.53	40.74	48.6	85.21	30.25	
Nd	58.46	36.35	40.37	63.65	26.3	
Sm	35.05	23.75	25.36	30.99	16.04	
Eu	17.45	21.5		25.48		
Gd	18.46	15.14	15.75	17.57	9.5	
Dy	8.52	7.51	8.22	11.54	5.48	
Er	5.77	4.79	7.18	10.09	4.98	
Yb	4.86	3.89	5.53	8.56	3.99	

* 1a = plagioclase-clinopyroxene andesite, 2 = hornblende andesite, 1b = dacite, 3 = tonalite

4.1.1.3 Geochronology of the Mount Stavely Volcanic Complex

Five rocks from the Mount Stavely Volcanic Complex were initially selected for U-Pb zircon dating. Two of the rocks, a diorite (Lalkaldarno Porhyry) and tuff, yielded no zircon. However, zircon was recovered from a metadacite (Narrapumelap Road Dacite Member of the Towanway Tuff), a mafic volcaniclastic sandstone (Towanway Tuff) and a meta-andesite breccia (Fairview Andesite Breccia). The metadacite would be expected to produce a crystallisation age for upper part of the complex, whereas the other two should yield older age limits for their times of deposition. Analytical methods are given in the Appendix and all sample locality information is held in AGSO's OZROX database. In addition to the U-Pb zircon dating undertaken, Ar-Ar dating of selected samples was carried out by M. Bucher (La Trobe University).

4.1.1.3.1 Narrapumelap Road Dacite Member *metadacite (No. 93843111)*

Zircons in the metadacite are mostly euhedral, with prolific second-order prisms and pyramids. Irregular embayments and rounded equant to rod-shaped silicate inclusions are also common. Grains are generally less than 200 μm in length with elongation ratios values of mostly 2 or less, but ranging up to 3. Although most grains are optically homogeneous, faint euhedral zonation is occasionally present. Obvious cores are rare, and none were analysed.

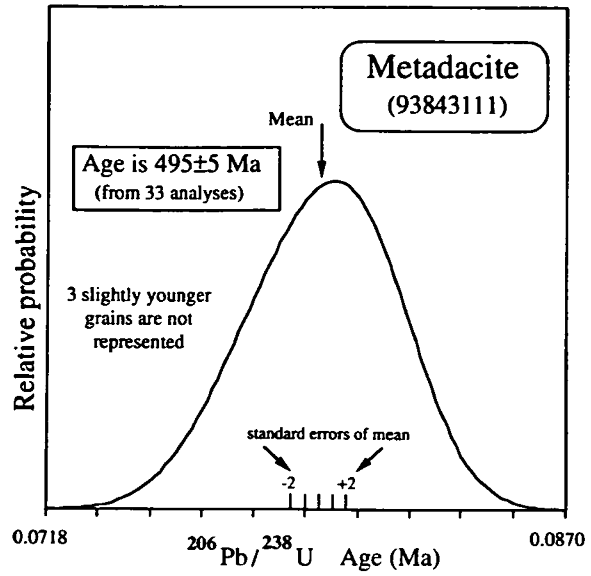

Figure 4. *Cumulative probability diagram (which takes account of individual analytical errors, and allocates equal areas to each analysis) of $^{206}Pb/^{238}U$ for 33 zircons from the metadacite (sample 93843111). Three slightly younger analyses are not plotted. The apparent tailing to younger values (and slight offset of the mean from the mode) is not significant. A preferred age of 495±5 Ma is obtained for the crystallisation of this rock.*

Isotopic data, including the ages of individual grains, are presented in the Appendix. Overall, the ages form a relatively tight grouping (Figs. 4 and 5), although three of the grains (8.1, 14.1 and 26.1) are slightly younger than the main group. The main population of 33 analyses generate a Chi square of 1.05, the symmetry of which is evident from the cumulative probability diagram (Fig. 4). An alternative representation of the isotopic data is given in the Tera & Wasserburg (1972) concordia diagram (Fig. 5), which clearly discriminates the factors (common Pb, inherited radiogenic Pb, and recent Pb loss) most likely to modify radiogenic Pb compositions, and demonstrates the minimal effect of common Pb correction. Based on the goodness of fit to a single isotopic population, and the obvious igneous morphology of the zircon grains, the pooled age of 495±5 Ma (95 % confidence limits) for the main population is taken to temporally define the igneous crystallisation of the metadacite.

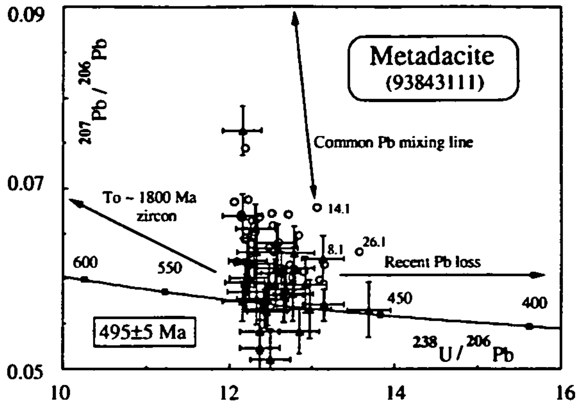

Figure 5. *Tera & Wasserburg (1972) concordia diagram for zircons from the metadacite (sample 93843111). In this and other related diagrams, uncorrected analyses are represented by unfilled circles, and 208-corrected data are shown as triangles with 1 σ error bars. Correction for common Pb should shift the analyses downwards, towards concordia (shown with appropriate age loci). However, in the case of grain 14.1 the analysis has been significantly shifted in the opposite direction, due to open system behaviour of the Th-U-Pb isotopic system. This anomaly is not reflected in the reported Palaeozoic and latest Neoproterozoic ages. These are calculated from 207-corrected data, which minimises such effects.*

The similar morphologies and chemical characteristics of the three slightly younger grains to those in the main population indicate that the three grains did not grow during a later (e.g. metamorphic event). These isotopic compositions therefore reflect a secondary process or processes. They are interpreted to be a consequence of preferential radiogenic Pb loss in recent times. U (78-317 μg/g) and Th (71-465 μg/g) contents of the analysed grains are quite low, and there is also no correlation between these elements (nor with Th/U ratios) and the slightly young ages. Thus, the inferred Pb loss was not primarily governed by the extent of radiation damage to the zircon lattice, but presumably by secondary factors, such as the ease of access of meteoric water to particular grains.

4.1.1.3.2 Towanway Tuff *mafic volcaniclastic sandstone (No. 93843103)*

Zircons from the Towanway Tuff mafic volcaniclastic sandstone have a diverse range of morphologies, from well rounded, through slightly rounded, to euhedral grains. Some of the euhedral grains have simple pyramidal and prismatic faces, whereas others have well developed second order facets. The grains are on average slightly larger than those from the metadacite, most about 200 µm long, with elongation ratios of about 2:1 Rounded equant grains, some of which appear to preserve sedimentary pitting, are also present. Most grains are optically homogeneous, though zoning and rounded cores are occasionally present. Spherical and rod-shaped inclusions are common.

In contrast to the metadacite, zircons from the volcaniclastic sandstone have a considerable range of ages, in keeping with its clastic origin. The age spread is also consistent with the more diverse range of zircon morphologies noted above. The isotopic data can be divided into four broadly defined age groups at about 500 Ma, 580 Ma, 1100 Ma and older than 2000 Ma. None of these age groupings have distinctive U and Th contents, and Th/U ratios are similarly indiscriminatory.

Zircons assigned to the oldest, somewhat arbitrary, grouping are often characterised by mutifaceted, roughly equant grains. Grains with these features yield $^{207}Pb/^{206}Pb$ ages of about 2400 Ma, 2500 Ma, 2800 Ma and 3100 Ma (Appendix). Although none of the pitted grains were analysed in detail, reconnaissance analyses (not shown in the Appendix) indicate that two of them, with ages of about 2500 Ma and 3300 Ma, also belong to this grouping.

Zircons which crystallised at about 1100 Ma are elongated, euhedral, and are characterised by well preserved terminations formed essentially of first order pyramids. In common with the older zircons, the eight grains in this Mesoproterozoic grouping span a significant time interval, from about 1000 Ma to 1200 Ma. A cumulative probability diagram (Fig. 6) depicts the age distribution of all Mesoproterozoic and older zircons.

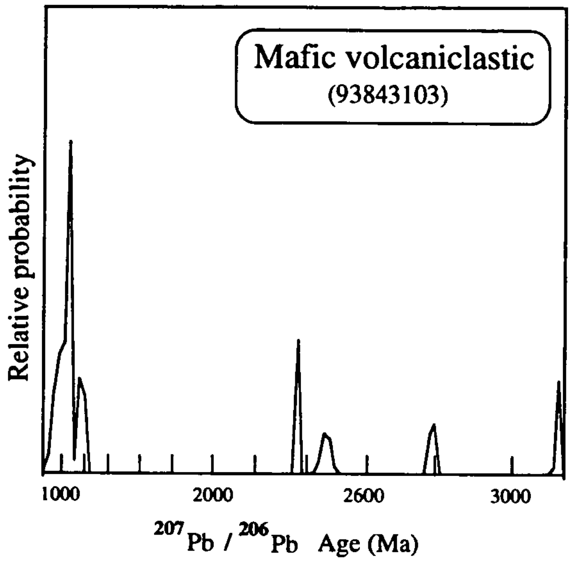

Figure 6. *Cumulative probability diagram for older zircons within the mafic volcaniclastic (93843103). Eight of these grains crystallised at about 1100 Ma; the others range upwards to more than 3000 Ma.*

The two younger groupings have simple age structures. All six of the approximately 580 Ma zircons conform to a single population with a mean age of 579±12 Ma (Figs. 7 & 8). With one exception (an equant, multifaceted grain), these grains are elongated and euhedral, with relatively simple terminations.

Although the youngest zircon grouping is also composed of elongated, euhedral grains, their terminations are characterised by prominent steep pyramids. All of the eight analyses in this grouping define a single, 501±9 Ma, population (Figs. 8 & 9). In view of its clastic origin, this age represents an older limit for the deposition of the Towanway Tuff. However, it probably also approximates the unit's depositional age (at least within the quoted errors), as most detritus within the rock is likely to have been derived from units within the Mount Stavely Volcanic Complex.

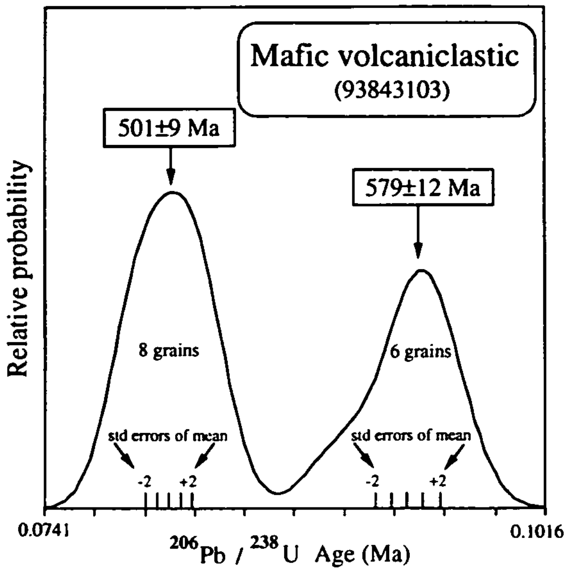

Figure 7. *Cumulative probability diagram for younger zircon populations in the mafic volcaniclastic (93843103), showing the clear separation of the 501±9 Ma and the 579±12 Ma populations.*

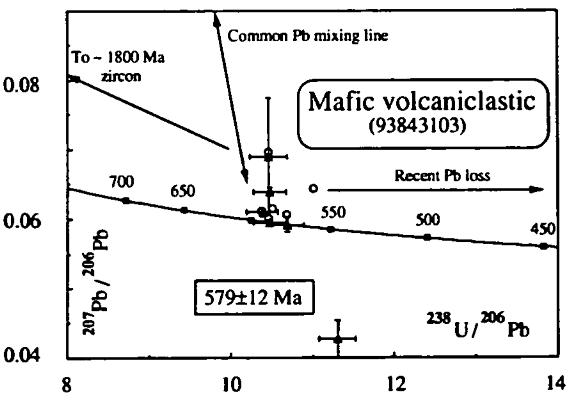

Figure 8. *Tera & Wasserburg (1972) concordia diagram for the 579±12 Ma zircon population in the mafic volcaniclastic (93843105). As common Pb contents are low, 208-correction has not displaced the analyses significantly from their uncorrected compositions. The position of analysis (68.1) at the bottom of the diagram is due to disturbance of the Th-U-Pb isotopic system.*

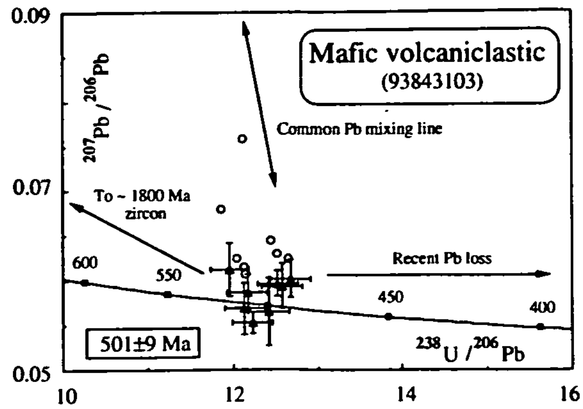

Figure 9. *Tera & Wasserburg (1972) concordia diagram for the 501±9 Ma zircon population in the mafic volcaniclastic (93843103). Common Pb corrections are minor, and 208-corrected data fall close to the concordia.*

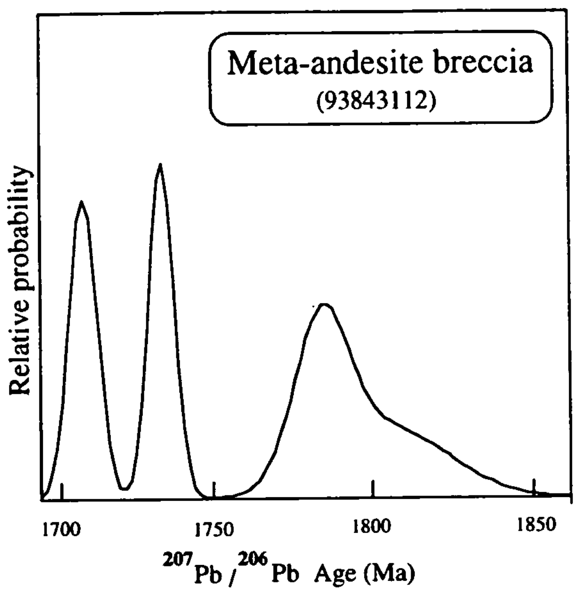

Figure 10. *Cumulative probability diagram showing that the four analysed zircons from the meta-andesite breccia (93843112) crystallised between about 1700 Ma and 1800 Ma ago.*

4.1.1.3.3 Fairview Andesite Breccia (No. 93843112)

Unlike the two samples of Towanway Tuff, zircon is quite rare in the sampled Fairview Andesite Breccia, with only six grains being recovered. The four largest, and best formed of these were analysed. These grains are subhedral, with rounded terminations and elongation ratios ranging from 3 to 1.5. Their widths are about 80 μm. Rounded inclusions are present, and no obvious cores were observed. The grains are unzoned. One of the analysed zircons (120.1) and one that was not analysed appear to preserve the pitting characteristic of detrital grains.

Despite their large range in U content (109-1003 μg/g), the analysed grains have a relatively restricted age range, from about 1700 Ma to 1800 Ma (Fig. 10). There might be a recognisable infrastructure to the isotopic data, with the two grains with low Th/U (about 0.08) yielding younger $^{207}Pb/^{206}Pb$ ages (about 1700 Ma) than those with higher Th/U (about 0.4), which have ages indistinguishable from 1800 Ma. However, the small number of analyses does not allow this claim to be made with confidence, and the data are not necessarily indicative of two separate crystallisation ages. Nevertheless, it is clear that the zircons were not derived from the Mount Stavely Volcanic Complex, but from a considerably older terrain.

4.1.1.3.4. Lalkaldarno Porphyry

No zircons were recovered from the collected Lalkaldarno Porphyry samples. However, amphibole extracted from samples collected by M. Bucher (La Trobe University) from the same outcrop yield ^{40}Ar-^{39}Ar plateau age of 500±3 Ma (personal communication, 1995). The porphyry is interpreted from field relations to intrude the youngest volcanic unit (Towanway Tuff) of the volcanic complex, and as such should be expected to yield a younger age than the tuff. The Ar-Ar age is not significantly older than the U-Pb zircon age of 495±5 Ma for the metadacite within the tuff unit.

4.1.1.4 Regional Correlations

Previous workers (eg. Crawford, 1988 & Crawford & Berry, 1992) have drawn attention to the similarity between the lithology, mineralogy and geochemistry of the Mount Stavely Volcanic Complex and other Victorian greenstones to the Cambrian greenstones of Western Tasmania. Geochemical studies of the Victorian Cambrian greenstones indicate that they include arc andesites, boninites and backarc basin tholeiites (Crawford & others, 1984; Crawford & Cameron, 1985; Crawford & Keays, 1987). Boninites and low-Ti magnesian quartz tholeiites have been described from western Tasmania (Crawford & Berry, 1992). In particular, the Mount Read Volcanics (western Tasmania), characterised by medium to high-K calc-alkaline andesites and more evolved lavas, and strongly LREE-enriched shoshonitic basalts (Crawford & others, 1991) are very similar to the orogenic andesites with medium-K calc-alkaline affinities, which dominate the Mount Stavely Belt.

A correlation between the Mount Read Volcanics and the Mount Stavely Volcanic Complex is further supported by almost identical U-Pb zircon SHRIMP age determinations. The crystallisation age of 495±5 Ma for Towanaway Tuff metadacite places the upper part of the Mount Stavely Volcanic Complex in the Late Cambrian[4] whereas the 501±9 Ma age derived from a mafic volcaniclastic sandstone within the same unit places an older limit on its deposition, but is also likely to directly date an earlier part of the sequence. Perkins and Walshe (1993) and Perkins and others (1993) dated the Mount Read Volcanics using $^{40}Ar/^{39}Ar$ and U-Pb zircon SHRIMP techniques. They produced a pooled age of 503±7 Ma for various parts of the Mount Read Volcanics, and ages of 494±8 Ma and 495±9 Ma for the Comstock Tuff (Tyndall Group) in the upper part of the sequence, and the Mount Black Dacite (Central Volcanic Complex), respectively. Turner and others (in press) and Black and others (1997) have produced a more comprehensive set of U-Pb

[4]assuming the latest estimates of Young & Laurie (in press) which place the Cambrian/Ordovician boundary at about 490 Ma.

SHRIMP ages for the Mount Read Volcanics, that is also similar to the ages reported in this Record for the Mount Stavely Volcanic Complex.

4.1.2 Glenthompson Sandstone

A sandstone-dominated sequence, cropping out in the northwest quarter of WILLAURA, was defined by Buckland (1987) as the Glenthompson Sandstone (variation on Glenthompson beds of Vandenberg and Wilkinson, 1982). The unit forms low hills, with the best exposures along creek beds, such as Back Creek near Mount Stavely and Grays Creek west of Chatsworth. Remnant outliers of Tertiary sand, gravel and ferricete form a thin capping on flat-topped hills, and extensive Quaternary colluvial, fluvial and lacustrine deposits cover the unit in the far northwest. To the east and south, outcrop of the sandstone is limited by Newer Volcanics basalt flows.

The formation is intruded by the Wickliffe Rhyolite and unconformably overlain by the Silurian Grampians Group. Its relationship with the Mount Stavely Volcanic Complex, which forms a faulted belt within the sandstone, is less clear. However, an original gradational sedimentary contact can be inferred by the presence of interbedded rhyolitic and andesitic volcaniclastic arenite beds within the Glenthompson Sandstone (e.g. Drysdale Road) and the occurrence of quartz arenite interbedded with thinly bedded volcaniclastics in the upper portion of the Towanway Tuff (e.g. ~850 m NE of 'Binbook' 647772 5826910). At the latter locality stratigraphic facing in both the complex and adjacent sandstone is to the east, indicating that the Glenthompson Sandstone overlies the Towanway Tuff. The presence of volcanic clasts within the sandstone has been noted by previous workers (Vandenberg & Wilkinson, 1982; Ramsay, 1982, 1983; Buckland, 1983 & 1987). Volcanolithic pebbly arenites occur at two separate localities, both close to the eastern contact of the volcanic complex, and both facing west. At one locality, in a creek bed adjacent to Drysdale Road (644553 58344828), medium-grained graded quartz arenite beds contain angular clasts of laminated black cherty devitrified crystal tuff, identical to that in the Towanway Tuff. About 2 km farther to south, at another locality about 1 km east of the complex (646155 5832470), poorly sorted pebbly arenite, containing intraformational arenite and porphyritic dacitic and andesitic volcanic clasts, forms channel-fill deposits in a sequence of graded, very thickly bedded quartz arenite.

Owing to the lack of continuous outcrop and the presence of faults and tight folding, a consistent stratigraphic relationship between the Glenthompson Sandstone and the Mount Stavely Volcanic Complex cannot be established on the basis of indicated facing directions alone. However, the presence of quartz clastics within the upper part of the Towanway Tuff, and the occurrence of volcanolithic material derived from the volcanic complex in the Glenthompson Sandstone east of the contact, strongly suggest that the sandstone interfingers with and overlies the volcanic complex.

The Glenthompson Sandstone is unfossiliferous and there are no suitable rocks for isotopic age determinations. However, a late Cambrian age is indicated by relationships with other units. The inferred stratigraphic position of the sandstone above the Mount Stavely Volcanic Complex suggests it is slightly younger than 500 Ma. The minimum age of the sandstone is well constrained by the ~489 Ma intrusive Bushy Creek Granodiorite.

The formation comprises a folded low-grade, turbidite sequence of thickly bedded arenite and lesser pelitic rocks, with minor meta-mafic rocks. Three measured sections, shown in Figure 11, illustrate the range of turbidite facies present, from the more proximal graded sand-rich section in the type area (647362 5830624) to a finer, more distal siltstone-rich facies at locality *93843006* (647490 5829050). Owing to poor exposure and tight folding the thickness of the unit is unknown. Rare thin calcareous mudstone beds occur northeast of Mount Stavely (Buckley, 1987) and at Grays Creek west of Chatsworth (Vandenberg & Wilkinson, 1982).

The arenite ranges from very thickly bedded (<2 m thick) and coarse-grained, to medium-bedded finer grained varieties. Mostly it is a thickly-bedded buff to grey medium-grained quartzose arenite with very poorly sorted subangular quartz, minor feldspar, felsic volcanolithic fragments and detrital muscovite. West of Chatsworth, where the regional metamorphic grade is greenschist facies, the arenite is recrystallised and foliated, with visible metamorphic biotite. Beds are commonly graded, with the top 10 to 15 cm forming a laminated fine sandy or silty horizon with ripple cross lamination or convoluted structures locally present. Basal scours are common and rare intraformational rip-up-clasts and volcanolithic clasts are locally present, particularly near the interpreted base of the unit, immediately east of the Mount Stavely Belt.

Pelitic units make up less than 10% of the formation and comprise buff to grey siltstone and shale (or slate and phyllite west of Chatsworth), occurring as minor thin to medium interbeds or rare laminae within more thinly bedded arenite sequences (Figure 12). The siltstone is typically laminated with graded fine- to medium-grained, ripple cross-stratified, sandy laminae.

Moderately magnetic (50 - 600 x 10^{-5} SI units) meta-mafic rocks are intercalated with the sandstone-siltstone sequence, particularly in the west where they crop out in Grays, Back and Bushy Creeks. Overall, they comprise less than 5% of the Glenelg River Complex. In magnetic images the rocks

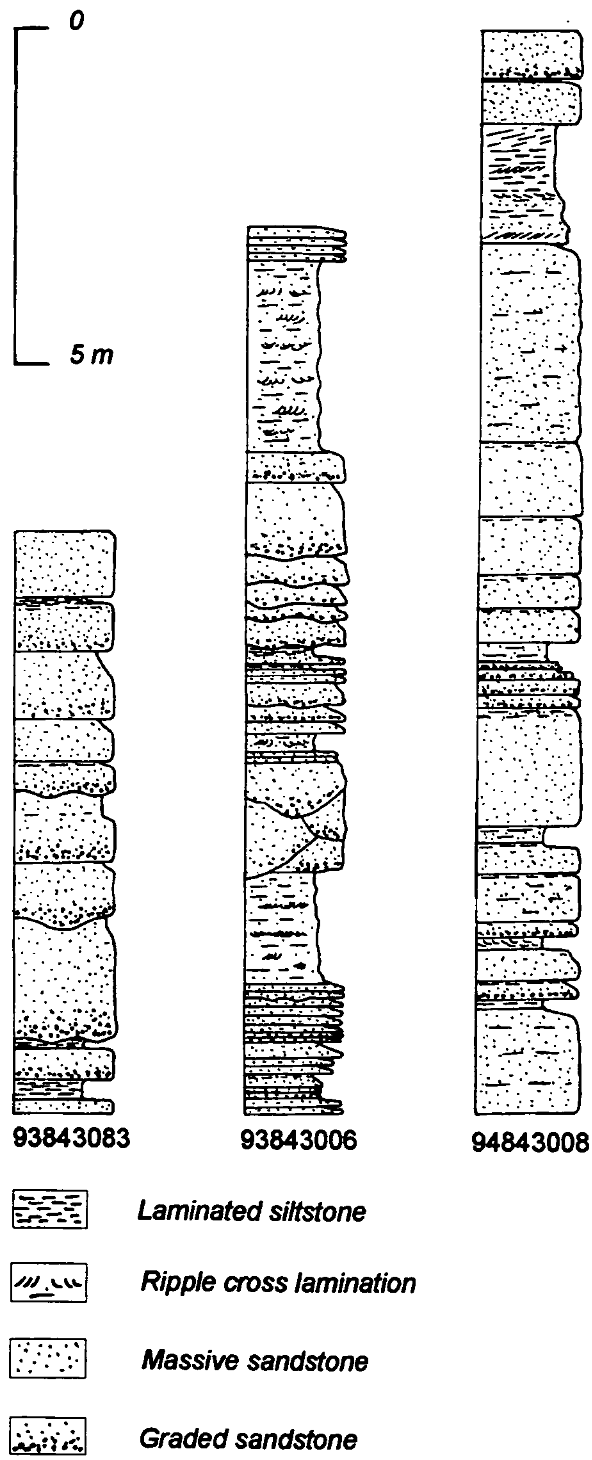

Figure 11. *Measured sections of the Glenthompson Sandstone. Location of sections:* 93843083[5] -- *647362 5830624;* 93843006 – *647490 5829050;* 94843008 – *636709 5810818*

[5] All localities (eight digit sample numbers) referred to in the text are from AGSO's OZROC database. This database contains all field observation data recorded during the fieldwork in 1993 and 1994

form three horizons that can be traced semi-continuously in the subsurface along the western flank of the Escondida Fault from west of Glenthompson in the north to Chatsworth in the south. Although, it is possible that the separate horizons may be repetitions of the same unit, duplicated by either thrusting or folding.

The mafic rocks are typically greyish green in colour, massive, fine- to medium-grained and include: amphibolite, meta-diorite, meta-gabbro, meta-dolerite, meta-basalt and meta-basaltic lapilli tuff. The latter is a very thickly bedded unit comprising clasts of meta-basalt up to 20 cm across, in a schistose matrix of foliated biotite and actinolite. It crops out along Bushy Creek about 1400 m NE of Scrubby Hill (634217 5823206), where it is interbedded with quartz arenite and phyllite.

The meta-mafic rocks are mostly recrystallised, with ubiquitous metamorphic actinolite, chlorite, epidote and sericite. However, primary ophitic clinopyroxene and plagioclase laths are commonly preserved. Compositionally, the mafic rocks are part of a low-K tholeiitic suite, similar to the subalkaline basalts and subvolcanic dolerite and gabbro sills which are the dominant rocks in other Victorian Cambrian greenstone belts, and are interpreted to have formed in a backarc environment (Crawford, 1988). They possibly represent parts of a late-Proterozoic to Cambrian ocean floor and differ from mafic components of the more felsic and volcaniclastic-rich Mount Stavely Volcanic Complex.

The Glenthompson Sandstone represents sand-dominated turbidite deposits mostly typical of the Bouma 'a' division facies, comprising thick to very thick amalgamated massive and graded sandstone beds. Sand to mud ratios range from 20:1 to 2:1. Facies intervals represent fining upward cycles, ranging in thickness from 3.2 m in the siltstone-rich facies to 7.5 m in the sand-dominated facies. The base of the sand beds is generally sharp, and scours are common, particularly in the lower sand beds within any one cycle. The sediments are interpreted to represent mostly mid-fan channel-fill deposits. The occurrence of intercalated tholeiitic mafic volcanics and possible intrusions refects a probable back arc setting.

4.1.3 Bushy Creek Granodiorite

The Bushy Creek Granodiorite (McLaughlin and Tattam, 1976) is a roughly circular pluton about 8 km across, centered north of Bushy Creek in the central western part of WILLAURA. The unit is very poorly exposed and deeply weathered, and is locally overlain by a thin veneer, of Tertiary laterite or windblown friable well-sorted medium-grained quartz sand. The best exposures are along Bushy Creek where several corestones crop out in the valley floor.

The pluton stitches the Escondida Fault and intrudes the Glenthompson Sandstone and Glenelg River Complex, with interpreted smooth discordant contacts. A contact metamorphic aureole, marked by cordierite porphyroblasts in pelitic beds, extends up to 500 m from the granodiorite. In places (e.g. 634632 5822081), narrow fine-grained biotite granite dykes are present within hornfels. Late-stage aplite dykes are common in outcrops of the granodiorite.

Aeromagnetic patterns reveal that the pluton is concentrically zoned, comprising four zones of alternating highly magnetic and moderately magnetic phases. The more magnetic phase forms the outer margin around the northwestern part of the pluton, and the second inner annular zone, with the less magnetic phase occupying the core and the third outer (and most extensive) zone. Relations between the phases are not known, and are interpreted as gradational. The phases probably represent separate magma pulses.

The moderately magnetic phase (magnetic susceptibility 550 x 10^{-5} SI Units) probably corresponds to a coarse-grained, equigranular, hornblende biotite granodiorite, that, where exposed, is deeply weathered. The more magnetic phase is a porphyritic hornblende granodiorite. The latter rock is described by Ramsay (1982) as containing phenocrysts of quartz, plagioclase, alkali feldspar and hornblende in a groundmass of interlocking plagioclase laths and granophyric intergrowths of quartz and alkali feldspar. Mafic minerals show minor chloritic alteration; plagioclase is weakly sericitised. Accessory minerals in both phases include: titanite, apatite and magnetite.

4.1.3.1 Geochronology

The age of the Bushy Creek Granodiorite was previously interpreted as Devonian, based on lithological correlation with nearby intrusives, such as the Mafeking Granodiorite (ARARAT) (Buckland, 1987). White and others (1988) placed the granite in the Mafeking Suite, the most westerly Devonian suite within the Lachlan Fold Belt. However, U-Pb zircon analyses indicate a Cambrian age for the granodiorite.

Despite its low Zirconium content (62 ppm), the Bushy Creek Granodiorite is quite enriched in zircon, which is typically coarse and euhedral, with an average width of about 130 μm. In addition to their commonly squat habit (elongation ratios rarely exceed 2:1), the grains are characterised by a strong development of complex faces, producing multifaceted grains. These features contrast with those of most granitic zircons in the region, where more elongated grains with a restricted development of complex crystal faces are characteristic. Most grains contain a few fluid inclusions. The zircon has low U (see Appendix), a feature mirrored by the granodiorite itself, in which uranium was not detected.

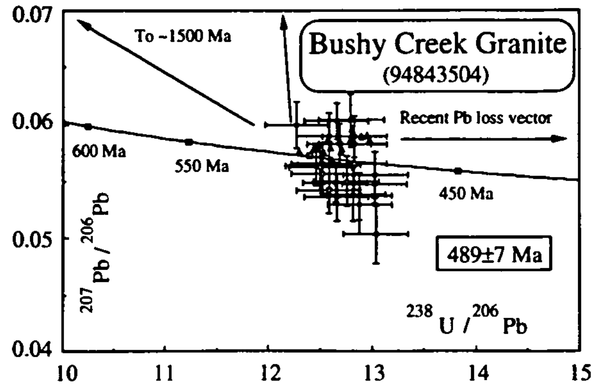

Figure 12. *Tera & Wasserburg (1972) diagram for the Bushy Creek Granodiorite (94843504). It is clear that neither recent Pb loss nor admixture with exotic radiogenic Pb occurred. A small common Pb component, which is easily stripped from the radiogenic Pb, is indicated by the tendency of the uncorrected analyses to group above concordia.*

Cathodoluminescence studies show that a fine-scale igneous zonation is ubiquitous, and almost always continuous throughout any particular zircon grain. However, a small percentage of the grains contain a small, central, anhedral, poorly luminescent region that probably represents a nucleus of inherited zircon.

All analyses were sited on the dominant, continuously zoned phase, which clearly represents the zircon that crystallised from the granodiorite. Both U and Th are low in abundance (Appendix). Common Pb levels are only marginally enhanced, with only one grain (# 15.1) having greater than a 1% proportion of common to total Pb.

All of the 23 analyses yield $^{206}Pb/^{238}U$ ages that are within the limits of analytical error of each other, and combine to yield a weighted mean age of 489±7 Ma (Fig. 12). The overall conformation of the data, when the individual errors are taken into account, is a well-defined normal distribution (Fig. 13).

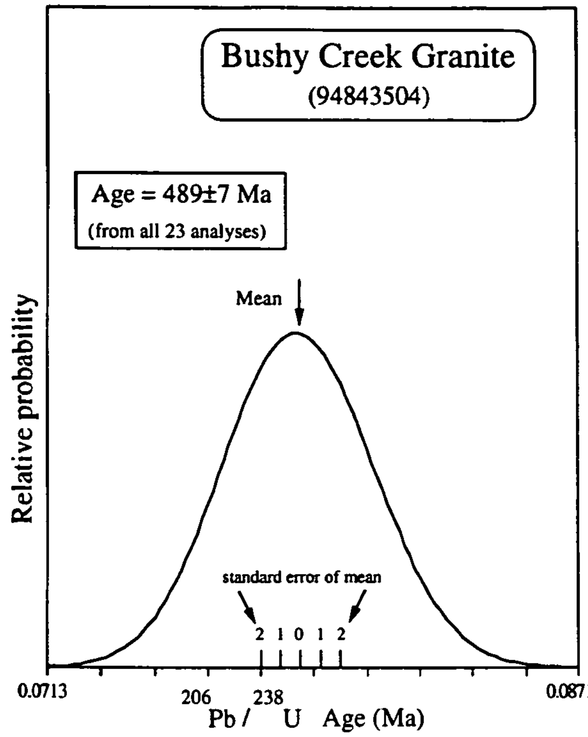

Figure 13. *Cumulative probability diagram of $^{206}Pb/^{238}U$ for all 23 zircons from the Bushy Creek Granite (sample 94843504). The data define a simple bell-shaped curve, which is indicative of a simple population.*

It is possible to assess the assumption of concordance (i.e., that the zircons have remained closed to the migration of U and Pb since their initial crystallisation) of the $^{206}Pb/^{238}U$ system by comparison with the independent, and commonly less robust, $^{208}Pb/^{232}Th$ dating scheme. In this example, the latter also produces a statistically tight data array with an indistinguishable mean age of 491±9 Ma. It is therefore highly probable that the more precise $^{206}Pb/^{238}U$ age is valid, and therefore that the Bushy Creek Granodiorite crystallised at 489±7 Ma. This age is slightly younger than a Ar-Ar biotite age of 499±2 Ma recently obtained from the same sample by M. Bucher (personal communication, 1995).

4.1.4 Buckeran Diorite

The Buckeran Diorite (Buckland, 1987) forms an elongate pluton, about 8 km long and up to 3 km wide, lying to the east of the Bushy Creek Granodiorite, centred about 10 km southwest of Wickliffe. Outcrop of the diorite is poor, owing to extensive Tertiary ferricrete and sand cover, except in the northern extremity around Reedy Creek, where bouldery outcrops are common. In the extreme south, outliers of Newer Volcanics overlie the diorite on the northern bank of the Hopkins River.

The diorite intrudes the Glenthompson Sandstone, with a narrow contact metamorphic aureole present.

The main rock type is a massive dark grey highly magnetic (magnetic susceptibility = 3000 x 10^{-5} SI Units) medium- to coarse-grained equigranular diorite composed of subhedral plagioclase, anhedral hornblende (with relict clinopyroxene cores), biotite, quartz, and accessory apatite, zircon and secondary titanite, chlorite and epidote. Aeromagnetic data show that a small circular less magnetic phase about 1 km across is present in the central southern part of the pluton. This phase is not exposed.

There are no age data for the Buckeran Diorite. However, on the basis of its proximity, chemical affinity (both are part of the same metaluminous suite) and similar field relationships to the Bushy Creek Granodiorite a Cambrian age is assumed.

4.1.5 Undifferentiated magnetic granite

Seven separate granite intrusions, mostly about 3 km across, are interpreted from aeromagnetic data to intrude the Glenthompson Sandstone and Glenelg River Complex south of the Bushy Creek Granodiorite. Only parts of the northern three plutons are present in the subsurface. One is centred on Back Creek, another between Chatsworth House and Chatsworth township, and the other 7 km southwest of Chatsworth township. The remaining bodies lie farther to the south beneath Tertiary sediments and Newer Volcanics basalt flows. Of the three plutons not covered by younger units, exposure is limited to the granite at Back Creek. A thin veneer of colluvial soil and sand, reworked from outlying Tertiary deposits, covers the other two bodies.

In Back Creek (640395 5814251) the western contact of a coarse-grained equigranular biotite granite body that intrudes banded amphibolite hornfels, is exposed. Pegmatite, granite and aplite dykes are common in a contact aureole that extends up to 300 m from the contact. Within the aureole cordierite porphyroblasts, up to 1 cm across, are common in meta-pelites and overprint older foliated fabrics.

There are no isotopic, geochemical or petrographic data for the granites. Their similar magnetic character, spatial association and intrusive relations to the Bushy Creek Granodiorite suggests that they may also be Cambrian in age.

4.1.6 Undifferentiated diorite

An irregular-shaped 3 km long body of magnetic microporphyritic diorite is interpreted from magnetic data to intrude the Glenthompson Sandstone north of Glenthompson. The body is not exposed, but shallow stratigraphic drilling has confirmed its presence beneath a thin soil cover. A residual outlier of Tertiary ferricrete caps a small hill at the body's centre. Most of the body is overlain by Quaternary alluvial, colluvial and lacustrine deposits. The age of the diorite is not known. The similar magnetic character, spatial association and intrusive relations of the diorite to that of the Cambrian Bushy Creek Granodiorite suggests that it may also be Cambrian in age, and part of the same suite.

4.2 SILURIAN

4.2.1 *Wickliffe Rhyolite*

The term Wickliffe Rhyolite, redefined by Buckland (1987), is used to describe narrow rhyolite dykes that intrude the Glenthompson Sandstone. They are concentrated around the margin (within 1000 m) of the Grampians Group in the 'Erin Park' area north of Wickliffe, where they form a swarm over a 5 km^2 area. Here, the high proportion of the dykes is reflected in airborne gamma-ray spectrometric data by higher potassium responses than the Glenthompson Sandstone elsewhere. The dykes range up to a few metres wide and trend mostly 030°. They are massive microcrystalline rocks, pink to buff in colour, with ubiquitous, distinctive, flow-banding and minor plagioclase microphenocrysts. The groundmass is typically spherulitic, comprising microcrystalline quartz and alkali feldspar, with secondary chlorite and sericite.

The Grampians Group unconformably overlies the Glenthompson Sandstone sequence intruded by the dykes. The unconformable contact is exposed in the Hopkins River 350 m southeast of the Willaura-Wickliffe Road - Major Mitchell Road junction (651724 58311718). Pebbles of the rhyolite have also been noted in basal conglomerates of the Grampians Group (Willaura Sandstone: Buckland, 1987).

The Wickliffe Rhyolite was previously correlated with the Rocklands Rhyolite (Spencer-Jones, 1988; Simpson & Woodful, 1994). However, field relations show that the Rocklands Rhyolite is post-deformational to, and overlies the Grampians Group (Simpson & Woodful, 1994) whereas the Wickliffe Rhyolite predates the Grampians Group.

4.2.2 Grampians Group

Grampians Group sediments in WILLAURA were previously mapped as 'Willaura Sandstones' (Spencer-Jones, 1965) a term latter modified by Buckland (1987) to 'Willaura Sandstone'. The latter term has been discontinued here and the stratigraphic nomenclature used for the group in the Grampian Ranges to the northwest has been extended into WILLAURA.

The group crops out in a discontinuous northerly-trending belt extending from Cockajemmy Lakes, near Willaura in the north, to the Hopkins River 5 km north of Hexham in the south. The rocks mostly dip shallowly to moderately to the east, forming the western limb of an overturned regional syncline. The axis of this syncline passes through Lake Bolac and Woorndoo (Figure 14). The outcrops are probably linked at shallow depth beneath a cover of Newer Volcanics north of Lake Bolac and Tertiary sediments to the south. Exposure of the group is poor except along the Hopkins River and in Salt Creek south of Woorndoo. Elsewhere, exposure is limited to blocky rubble on low rises and deeply weathered exposures along lake shores.

The group is more extensive than previously mapped, and a total maximum thickness of 3200 m is estimated. This is considerably more than the 915 m section estimated for the Willaura-Wickliffe area (Spencer-Jones, 1988) which only represents the basal portion of the group. A more complete section is exposed between the Hopkins River west of 'Kia Ora' and Salt Creek south of Woorndoo. Here the group can be subdived into three units: a 1600 m thick basal sandstone unit - the Red Man Bluff Subgroup; a 300 m thick middle siltstone - the Silverband Formation; and an upper 1300 m thick sandstone - the Mount Difficult Subgroup (Figures 14 & 15). These thicknesses are maximum estimates based on limited exposure and assume there is no repetition by faulting. It is quite possible that parts of the sequence may be thrusted, such as is interpreted for the Grampians Group to the north (Cayley & Taylor, 1996). However, the thicknesses and stratigraphy are comparable to that reinterpreted for the Grampians Group by Cayley and Taylor after removal of structural repetition.

4.2.2.1 Description and relations

4.2.2.1.1 Red Man Bluff Subgroup

The Red Man Bluff Subgroup is well exposed in the Hopkins River between Wickliffe and Willaura and in the south, west of 'Kia Ora'. Thickness estimates range from at least 915 m in the north to a maximum of 1600 m in south. The base of the formation and its unconformable contact with underlying steeply dipping Glenthompson Sandstone meta-sediments is exposed on the banks of the Hopkins River 4.5 km north of Wickliffe (651724 5831718). The underlying metasediments are intruded by Wickliffe Rhyolite dykes, and are extensively altered by iron oxides and chlorite. The unconformity surface dips 25° to 052°.

The base comprises massive matrix-supported polymictic boulder conglomerate up to 7 m thick, which grades rapidly up into very thickly bedded, laminated or planar cross-bedded, pebbly quartz sandstone. Boulders and pebbles consist of well-rounded vein quartz, quartz-tourmaline rock, chert, micaceous quartz arenite, fine- to medium-grained biotite granite and rhyolite. The arenite and rhyolite clasts are similar to those in the underlying Glenthompson Sandstone and Wickliffe Rhyolite, respectively. The conglomerate matrix comprises very poorly sorted gritty quartz sandstone.

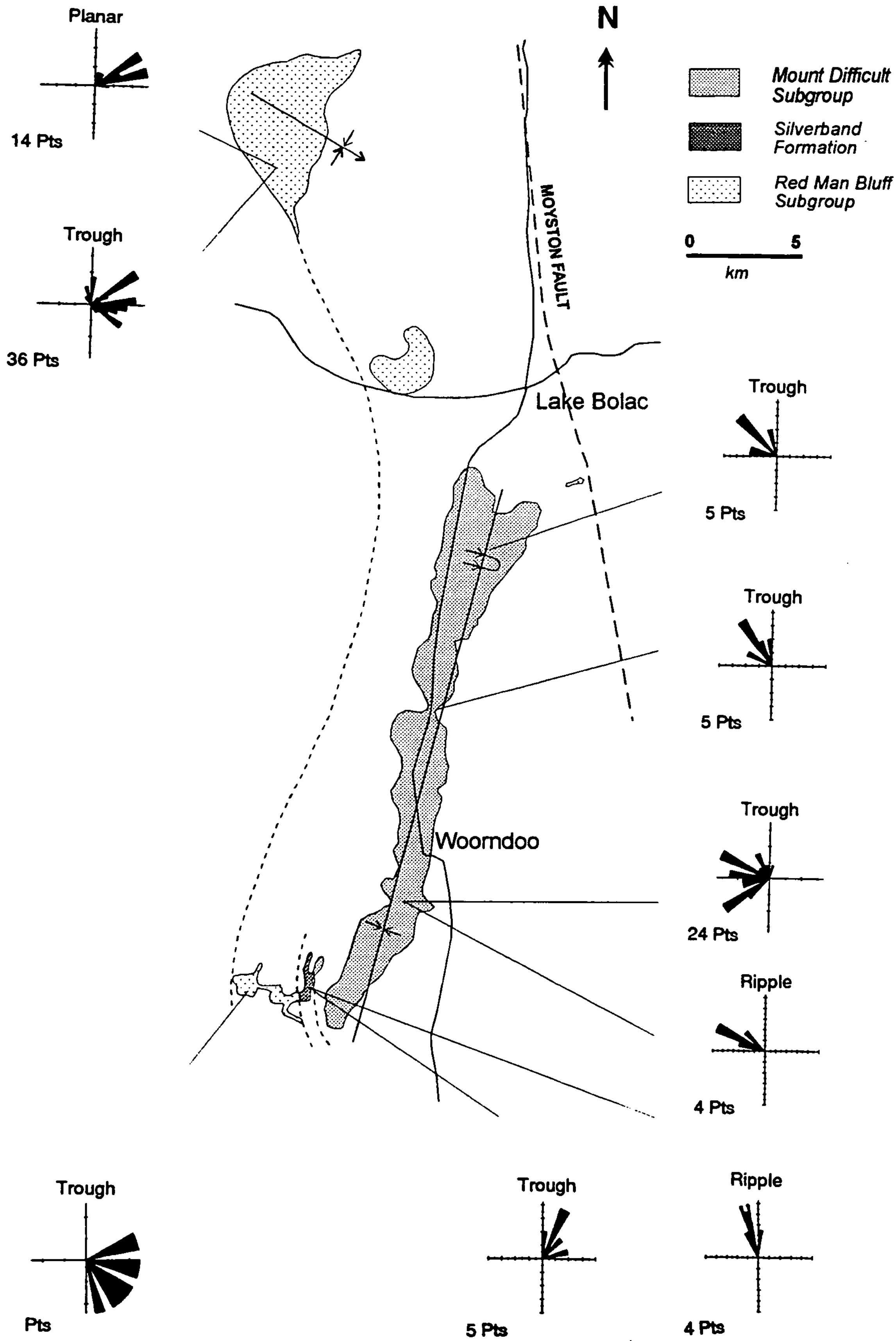

Figure 14. *Distribution of outcropping Grampians Group and interpreted extent in the subsurface. Current direction data were measured from, trough cross beds, planar cross beds and asymmetrical ripples.*

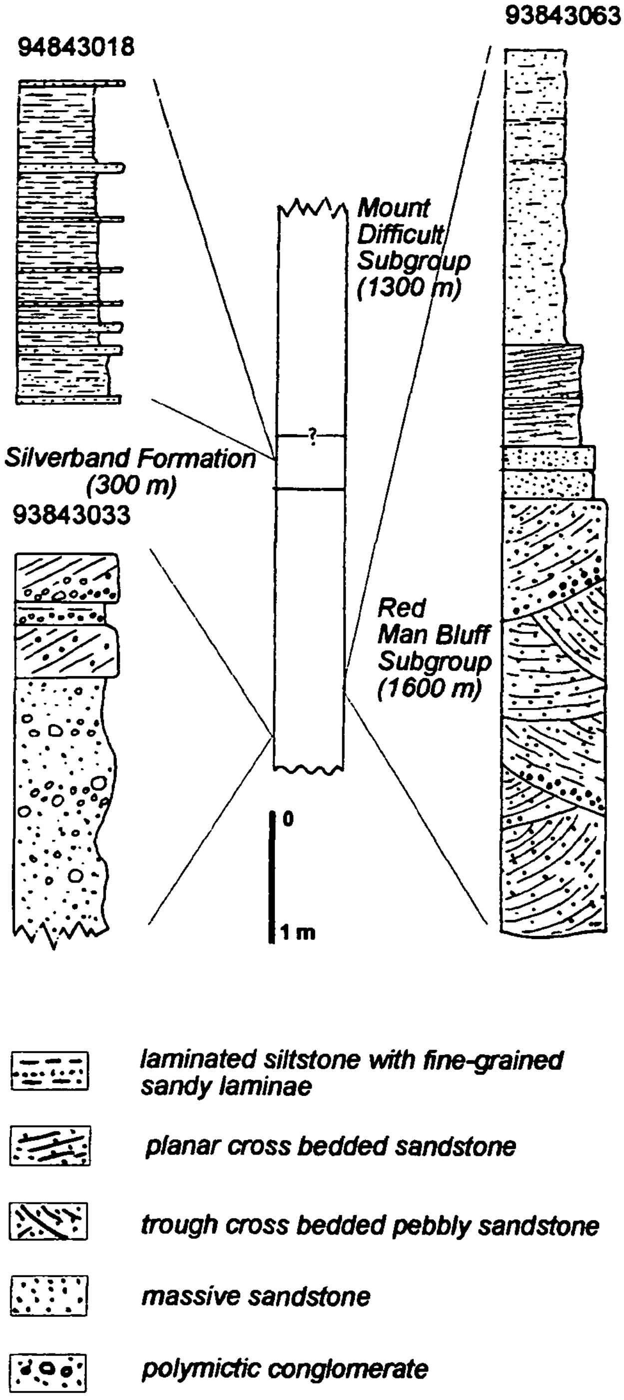

Figure 15. *Measured sections of Grampians Group. The section at 93843063 represents a typical upward-fining cycle. Location of sections:* 94843018 – *652750 5798475;* 93843033 – *651356 5832440;* 93843063 – *652790 5833877.*

The bulk of the subgroup comprises a sequence of buff to white, medium- to thickly bedded, very poorly sorted, coarse- to very coarse-grained feldspathic quartz sandstone, and very minor siltstone (Figure 15). Typically, the sediments form upward fining cycles that are about 5 m thick, and consist of trough cross-bedded pebbly sandstone overlain by more thinly bedded coarse-grained sandstone with low-angle planar tabular cross beds. These are topped by laminated coarse-grained sandstone with very minor greenish grey or red siltstone laminae. The trough cross-bedded sandstone, constituting about 30% of the subunit, is predominant in outcrop. Basal scours are common and individual troughs range up 4 m across and 1m deep. Both the trough beds and low-angle planar tabular cross beds indicate a current direction to the east (Figure 14). This direction remains fairly consistent throughout the section of the Red Man Bluff Subgroup in both the Willaura-Wickliffe and 'Kia Ora' areas. The sedimentary facies of the subgroup is typical of a meandering fluvial environment, with the trough cross-bedded pebbly sandstone representing lag channel deposits overlain by point bar deposits (planar cross bedded sandstone) and bar-top siltstone (deposited in ridges and swales on top of sand bars). There is a lack of preservation of any sediments that may represents overbank fines.

About 150 m above the base of the unit, 5 km south of Willaura, a cream-coloured, moderately weathered rhyolitic body, at least 5 m thick, occurs within the sandstone, and extends for about 2 km along strike. The rhyolite is distinct from the Wickliffe Rhyolite having abundant plagioclase and embayed quartz phenocrysts (<2 mm) and lacking the characteristic flow-banding of the latter. The contact with enclosing sandstone is exposed in a quarry at the junction of the

Wickliffe-Willaura Road and Stapylton Road. At this locality (653954 5838180) the lower contact forms lobes of 3 to 5 m across that meet in an acute apex injected by sandstone. The presence of sand injection structures within the rhyolite, and the contortion of sedimentary structures in the sandstone near the contact with the rhyolite, indicate that the rhyolite was probably emplaced prior to consolidation of the sandstone. The top of the rhyolite is not exposed. The lack of features characteristic of extrusion suggests the rhyolite is a shallow sill-like body that intruded the Red Man Bluff Subgroup sandstone while it was in an unconsolidated state.

4.2.2.1.2 Silverband Formation

The Silverband Formation is only exposed in the south within a creek bed about 500 m north of 'Kia Ora'. Here discontinuous exposures of purple laminated sandy siltstone with minor thin interbeds of buff fine-grained laminated quartz sandstone occur over a ~300 m thick section. Asymmetric ripple marks are common in the silty beds, indicating transport direction was to the north. One to five metre thick sequences of medium-bedded crossbedded medium-grained quartz sandstone probably form about 50% of the formation. Limited observations of trough cross beds in the sandstone indicate a current direction to the northeast (036°). Generally finer grain size, well-sorted nature and reddish colouration of the sediments in the Silverband Formation reflects a much slower rate of sedimentation than the Red Man Bluff Subgroup and a possible transition into shallow marine conditions (Spencer-Jones, 1988).

4.2.2.1.3 Mount Difficult Subgroup

A 1300 m section, of quartz sandstones of the Mount Difficult Subgroup is exposed along Salt Creek south of Woorndoo. The section forms the steeply west-dipping limb of the regional syncline that occurs about 1 km west of Woorndoo township and Lake Alexander. The other limb, poorly exposed as rubbly rises west of the creek, overlies the Silverband Formation farther to the west. Based on the similar estimated thicknesses of the Mount Difficult Subgroup on both the western and eastern limbs, the Silverband Formation should lie directly to the east of Salt Creek beneath Newer Volcanics basalt flows. The Mount Difficult Subgroup comprises buff medium- to thickly bedded coarse- to medium-grained moderately sorted quartz sandstone with common trough cross beds with truncated tops. At the core of the syncline (656100 5800050), pink massive very thickly bedded conglomerate containing rounded quartz and jasper pebbles (<5 cm across) in a very coarse poorly sorted quartz sand matrix overlies sandstone beds.

Although the Mount Difficult Subgroup and the Red Man Bluff Subgroup are generally similar, the former differs markedly by its less feldspathic and lithic composition, by the absence of the planar cross bedded sandstone and siltstone facies, and by the common presence of asymmetrical ripple marks (not observed in the Red Man Bluff Subgroup). Indicated current directions of cross beds are to the west- north west and ripples to the north west (mean 301°): the opposite of that in the Red Man Bluff Subgroup. It would seem that with these differences it is unlikely that the Mount Difficult Subgroup represents a structurally duplicated section of the Red Man Bluff Subgroup. Rather, it indicates a younger sequence characterised by renewed higher energy deposition of quartz-rich clastics in a fluvial to shallow marine environment.

4.2.2.2 Geochronology

Fossil evidence in the Grampians Group is insufficient to establish an age (Spencer-Jones, 1988). However, intrusive relations with Earlier Devonian granitic rocks suggest a Silurian age for the Grampians Group. In order to provide a minimum and more precise age of the group, a rhyolite unit that intruded the lower part of the Red Man Bluff Subgroup, was sampled for U-Pb isotopic zircon analysis.

This rhyolite contains common zircon grains that are mostly euhedral in habit, with prismatic faces dominated by simple 100 and 010 forms and grain terminations characterised by 211 rather than the 101 faces. Grainsize is variable, with diameters ranging from 50 μm to 150 μm. Although most of the zircon is heavily cracked and broken (possibly due to laboratory, rather than geological, processes), it is obvious from unfractured larger portions that many were originally elongated, the maximum preserved aspect ratio being 5:1. Silicate inclusions are relatively uncommon. Fairly broad-scale oscillatory zoning and sector zoning are obvious from cathodoluminescence images. A small proportion of grains contain anhedral cores that are probably inherited from older rocks, but none of these were analysed. Th/U values of about 0.1 are at the low end of typical felsic igneous values.

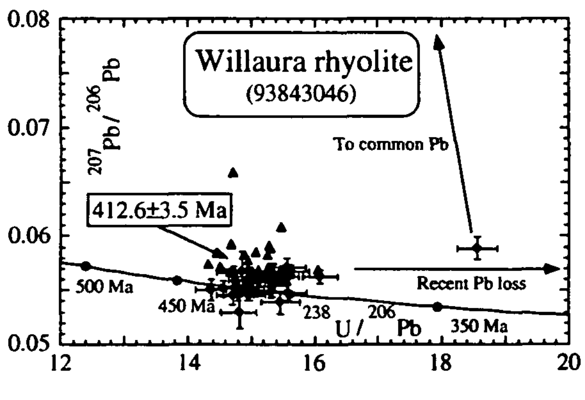

Figure 16. *Tera & Wasserberg (1972) diagram for zircon from the Willaura rhyolite. Data that are uncorrected for common Pb are represented by solid triangles. Corrected data are shown by open diamonds with 1 s error bars.*

Zircons from the rhyolite were dated in two separate analytical sessions. The first of these yielded a calibration of 1.9 %. All 15 zircon ages derived during this session are within error of each other (χ^2 is 0.9), and yield a weighted mean age of 409.1±6.0 Ma.

A further 22 analyses were completed during a second analytical session which yielded a 1.7 % calibration. Two of the interspersed analyses of the unknowns yield significantly younger ages than the other twenty analyses. The most aberrant of these (analysis 66.1) has the highest U content, a feature that should enhance the likelihood of breakdown of the crystallographic lattice, with consequent loss of radiogenic Pb. Although the other young analysis (57.2) is presumably also the result of recent Pb loss, it has no unusual chemical features. The weighted mean age of the remaining twenty analyses is 414.6±4.4 Ma. This value is not significantly different from that obtained during the first analytical session, and the two values can be combined to produce a preferred age of 412.6±3.5 Ma for the crystallisation age of the rhyolite (Fig. 16 & 17). Thus defining a minimum late Silurian age for the Red Mans Bluff Subgroup of the Grampians Group in WILLAURA.

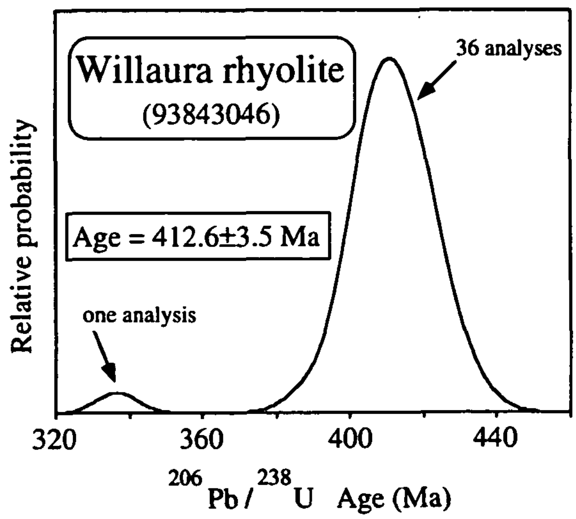

Figure 17. *Cumulative probability diagram for zircon analyses from the Willaura rhyolite. The most discrepent analysis is shown as an obvious outlier. The other analysis that has been discarded from the combined age calculation is located in the young tail of the main population.*

In view of the similarity in age and relationships with the Grampians Group, the rhyolite within the Red Mans Bluff Subgroup probably correlates with the 410±3 Ma (Fanning, 1991; mentioned in Simpson & Woodfull, 1994) Rocklands Rhyolite date. The latter rhyolite comprises a series of high temperature ignimbrites and lavas with minor associated sediments (Simpson, 1993) that disconformably overlie and intrude the Grampians Group northwest of WILLAURA (Simpson & Woodfull, 1994).

4.3 DEVONIAN

4.3.1 *Undifferentiated granite*

Several small magnetic bodies at depth beneath Newer Volcanics basalt in the northeast and a broad anomaly in the southeast of WILLAURA are interpreted as granite plutons. Such plutons are not exposed in the area, but have been intersected in two boreholes beneath over 60 m of basalt and 10 m of Tertiary sediments (Nolan & others, 1990). The northern anomalies are continuous northwards with outcrops of the Devonian Ararat Granodiorite in ARARAT.

4.4 TERTIARY

4.4.1 White Hills Gravel

The oldest Tertiary deposits in the area are consolidated ferruginous quartzose gravel that forms remnant, flat-lying, resistant caps on a number of Palaeozoic hills in the upper reaches of Hopkins River near Willaura. The base of the gravel slopes towards the Hopkins River, from over 40 m above the river at Willaura, to only a few metres above it in outcrops along the river bank 2 km south of the Willaura golf course. At the latter locality the gravel is overlain by basalt flows of the Newer Volcanics.

The gravel is dark brown in colour, very thickly bedded, and contains well- to sub-rounded pebbles to boulders of quartz, quartz sandstone, and rare pegmatite in a very coarse quartz sand matrix cemented by goethite and minor hematite.

The gravel represents fluvial deposits that probably correlate with the early Tertiary White Hills Gravel.

4.4.2 Undifferentiated sediments

Yellowish brown friable to poorly consolidated gritty quartz sandstone is exposed in a bluff along the banks of the Hopkins River 3 km south of Chatsworth (644225 5806100). The sandstone forms a sequence, about 5 m thick, unconformably resting on folded meta-sandstone and meta-dolerite of the Glenthompson Sandstone. Clasts of basement rock form a basal breccia within the sandstone. Planar cross beds indicate a depositional scarp about 5 m high and a current direction to the west (259°). At the top of the exposed profile the sandstone is unconformably overlain by late Tertiary ferruginous quartz pebbly sand and ferricrete.

Farther to the north, along the Chatsworth-Lake Bolac Road, drilling (North Ltd., personal communication, 1994) indicates that gritty quartz sandstone forms part of a 15 m thick sequence of fluviatile quartz sandstone and gravel channel-fill deposits. These sediments grade up into a carbonaceous-rich sedimentary sequence, up to 25 m thick, lying beneath a ~10 m thick capping of Clifton Formation sediments. The quartz sandstone and gravel deposits contain minor diagenetic pyrite, and carbonaceous matter. The main carbonaceous-rich portion of the sequence includes coal, lignite, and dark brown carbonaceous clay intercalated with coarse quartz sand with silt and fine carbonaceous matter and minor gravel (Figure 18). North and east of Lake Bolac, boreholes indicate the fluviatile sands and carbonaceous deposits, together with the overlying Clifton Formation, occupy a 87 m thick trough, running between Tatyoon and Westmere (Nolan & others, 1990).

The pre- Clifton Formation sediments in WILLAURA possibly correlate with either the carbonaceous-rich Wangerrip Group of the Otway Basin (Abele and others, 1988), or the Palaeocene to early Miocene Renmark Group in the Murray Basin. Similar rocks, intersected in water bores in adjoining SKIPTON, have also been interpreted as the late Palaeocene to Early Eocene Dilwyn Formation (Nolan & others, 1990). The sediments in WILLAURA represent a transgressive sequence from high energy fluviatile channel deposits to low energy swamp and lagoonal deposits. These were possibly deposited during the second Tertiary marine transgression in the Otway Basin which culminated in this area with the deposition of the overlying marine to littoral deposits of the Clifton Formation. The full extent of the sediments beneath younger Tertiary deposits is unknown.

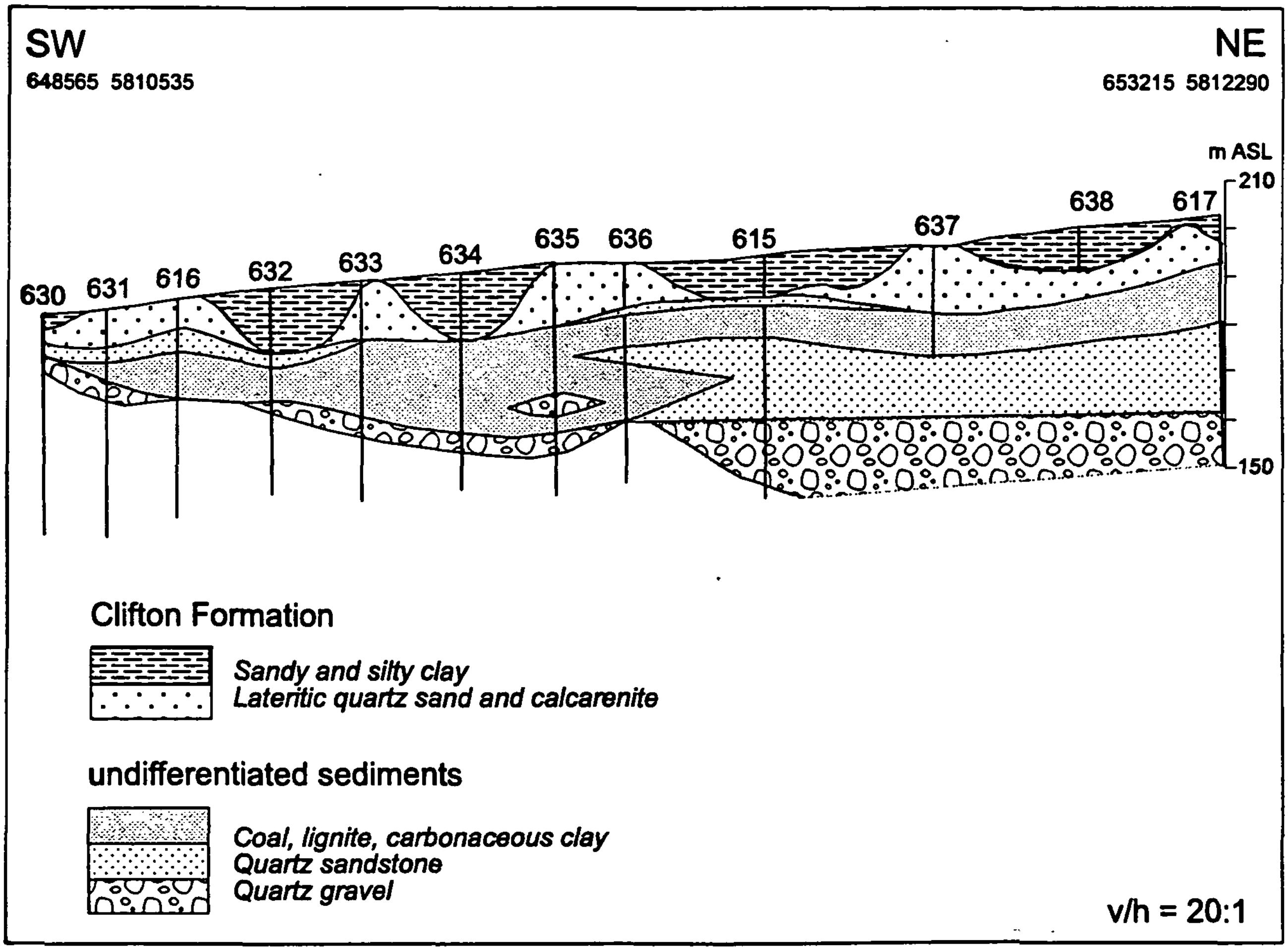

Figure 18. *Interpreted section, approximately 5 km long, of the Eastern View and Clifton Formations along the Chatsworth - Lake Bolac Road. All drilling data are from North Ltd. Exploration. Grid references to the ends of the traverse are given in the top left and right hand corners of the figure. The location of the traverse is shown on Figure 19.*

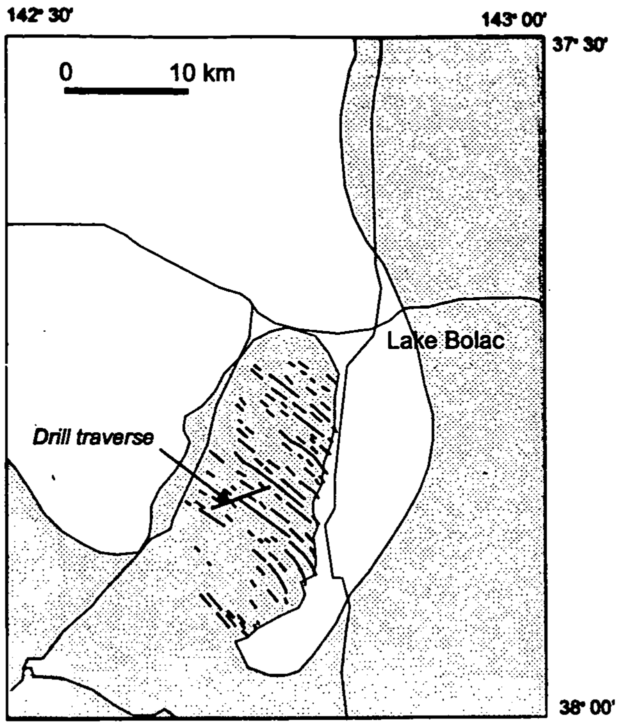

Figure 19. *Interpreted subsurface extent of Tertiary sediments. Strandline deposits (Clifton Formation) are outlined by curvlinear magnetic horizons shown as heavy lines.*

4.4.3 Clifton Formation

Ferruginised quartz sand, fossiliferous calcarenite, and brown sandy and silty clay, here mapped as Clifton Formation, form curvilinear deposits, up to15 m thick, beneath a thin veneer of Tertiary laterite and Quaternary deposits over much of the area between Chatsworth and Lake Bolac. The deposits overlie the undifferentiated fluviatile and lagoonal deposits, and are exposed about 6 km north of Woorndoo (656250 5810720) at about 200 m ASL. However, the formation can be mapped in the subsurface by subdued ridge crests and coincident magnetic anomalies that together outline the distribution of the sand and calcarenite deposits (Figure 19). Shallow drilling (North Ltd., personal communication, 1994) shows that the sands are heavily ferruginised, with reddish brown ironstone and magnetic pisolites present throughout much of the profile (Figure 19).

The quartz sand and calcarenite probably form strand line deposits, with sandy and silty clay swamp deposits occupying the zones between the ridges. The deposits represent the most inland marine/littoral deposits of the Otway Basin and were probably formed during peak Miocene transgression and the following regressive phase. Similar deposits of Late Oligocene to early Miocene sandy bryozoal calcarenite occur in the southeast of the Ballarat 1:250 000 sheet area and have also been mapped as Clifton Formation (Taylor & others, 1996).

4.4.4 Ferricrete, sand, ironstone

Deep weathering lateritic profiles are preserved on Palaeozoic and Tertiary rocks throughout the area, and are typified by a resistant capping of ferricrete and pisolitic ironstone which form the remnant cappings of the Dundas Surface. These ironstones are commonly developed in a surficial transported sandy horizon up to 5 m thick (Figure 20) overlying saprolite. The most widespread development of the deposits is above the Tertiary sand deposits of the Clifton Formation in the area between Chatsworth and Lake Bolac. Here ferricrete persists to 15 m depth, and ironstones are sufficiently massive and magnetic to produce anomalies in airborne magnetic data.

A complete section of the lateritic profile is exposed in a bluff on the Hopkins River about 3.5 km north of Chatsworth (645440 5812400) (Figure 21). Here a thin palaeosol of sandy loam and clay separates overlying Newer Volcanics basalt. At another locality on the river to the south of Chatsworth (644225 5806100), a 2 m thick, horizontally bedded, reddish brown ferruginous gritty quartz sand and ferricrete with a basal quartz pebble conglomerate horizon up to 10 cm thick, overlies undifferentiated Teriary sandstone.

The age of the ferricrete, ironstone and sand deposits is constrained by their development on Miocene strata and unconformable relationship with overlying late Pliocene-Pleistocene Newer Volcanics.

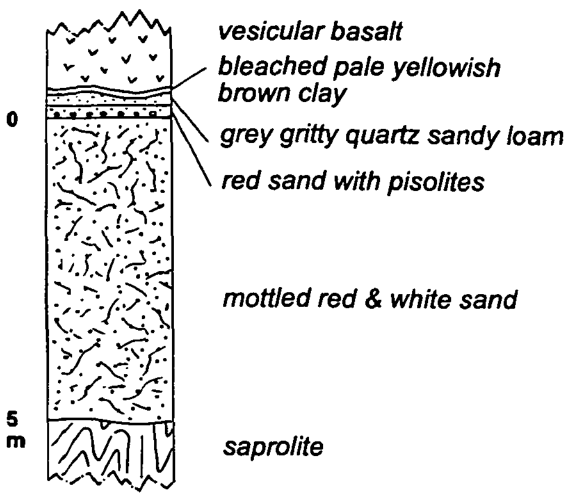

Figure 20. *Measured section of Tertiary lateritic weathering profile at* 93843139 – *645440 5812400.*

4.4.5 Unconsolidated sand

Unconsolidated well-sorted quartz sand deposits, commonly with loose ironstone pisolitic gravels form remnant cappings with ironstone deposits on the Dundas Surface. They are best developed in the west where they overlie the Glenthompson Sandstone and Bushy Creek Granodiorite.

4.5 QUATERNARY

The Newer Volcanics were extruded as extensive basalt sheets during the late Pliocene to Pliestocene, forming the Western Victoria Volcanic Plains. Recognised fluvial and lacustrine sediments include: older alluvial terrace deposits; older alluvial and colluvial deposits; colluvial deposits; swamp and lagoonal deposits; stream alluvial deposits; and lunette deposits. A late Pleistocene aeolian clay, the Windgelli Clay, forms a thin veneer over the most of the Palaeozoic bedrock and the Newer Volcanics. The unit is described here, but has not been mapped, as it cannot readily be distinguished from residual soils.

4.5.1 *Newer Volcanics*

The Newer Volcanics form a continous basaltic lava field covering over half the sheet area in the south and east. This field forms part of the Western Victoria Volcanic Plains, which extend along the southern margin of higher Palaeozoic hills to the north. In the south the basalt flows overlie a sequence of Tertiary sediments, whereas elsewhere in the sheet area they mostly overlie deeply weathered Palaeozoic rocks and minor Tertiary sediments. The present topography has changed little since volcanism, with only minor inversion of relief. Basalt flows, such as one along the Hopkins River valley, still occupy the topographic lows as valley-fill deposits. Present watercourses have mostly shifted to the margins of these flows or followed the palaeo-drainage, cutting through the basalt.

The volcanics are part of an intraplate continental basaltic volcanic province which covers about 15,000 km^2 and contains nearly 400 known eruption points (Joyce, 1975). Nine eruption points have been identified within the Willaura sheet area, which lies within the Western Plains Subprovince of the Newer Volcanics Province. Volcanism began at about 4.6 Ma and ceased about 4,500 years ago (Nicholls & Joyce, 1989). There are no isotopic age determinations on basalt in WILLAURA, however, based on geomorphological evidence, the Newer Volcanic activity in the Ballarat 1:250,000 sheet area took place during the late Miocene to Pleistocene. Isotopic (K-Ar) age determinations for Newer Volcanics basalt near Ballarat and Beaufort yield dates ranging from 6.07 Ma to 2.49 Ma (Cayley & McDonald, 1995; Taylor & others, 1996).

The volcanics in WILLAURA have been subdivided into a number of mappable units.

These include: older basalt flows; blocky basalt flows, and scoria deposits. The relative age of the units cannot be determined, other than that the blocky basalt flows and scoria deposits are younger than the older basalt flows, and that there was a considerable time gap, during which late Pleistocene aeolian soils (Windgelli Clay) developed on the older flows. Nicholls and others (1993) suggest that the younger lava and scoria deposits probably belong to a 250,000 - 5,000 Ma phase of activity.

Regional geochemical studies (Nicholls & others, 1993) throughout the Newer Volcanics province indicate that the basalts range from tholeiiitic to strongly alkaline in composition, with the younger cones composed mainly of the strongly alkalic types (Price & others, 1988). Overall, tholeiitic to transitional types predominate (Nicholls & others,1993). They are interpreted as the products of different degrees of melting of mantle sources, followed by crystal fractionation dominated by olivine removal (Irving & Green, 1976). The basanites are considered to be partial melts from a garnet peridotite source, with the liquids unmodified by crystal fractionation (Nicholls & others,1993)

4.5.1.1 Older basalt flows (Qvn, Qvn1)

Massive dark grey vesicular basalt (Qvn) consitutes the bulk of the Newer Volcanics, forming extensive, largely unbroken, amalgamated lava sheets. Drilling data indicate that at least four separate flows are present in some areas (Harvey, 1985). Based on gentle regional gradients and the presence of collapsed ring structures, four lava domes, rising up to 50 m above the general level of the plain, have been identified as the volcanic centres for the flows in the area. Regional slopes in the southwest indicate a fifth centre is located west of Chatsworth, probably in the adjoining sheet area. One of the lava domes, centred about 6 km northeast of Woorndoo, lies within a strong negative magnetic anomaly, possibly indicating the presence of a larger negatively magnetised intrusive body at depth. The older lava is distinguished from the other units by a thin veneer of windblown soil, the Windgelli Clay. Outcrop of the unit is poor, except in depressions around swamps and lagoons, and in erosional scarps adjacent to river courses. The basalt is also distinguished from other units by lower magnetic susceptibilities and lower gamma-ray spectrometric responses (Table 4.). The overall thickness of the unit ranges from a few metres to possibly up to 90 m in the far southeast (Nolan & others, 1990).

About seven kilometres southwest of Mount Hamilton a lava cone of massive olivine and pyroxene-phyric basalt flows (Qvn1) is distinguished by its different composition, manifested by the abundance of olivine and pyroxene phenocrysts, less vesicular nature and its higher magnetisation and gamma-ray spectrometric response (Table 4). The cone is about 3 km across and rises over 40 m above the plain.

4.5.1.2 Blocky basalt flows (Qvh1, Qvh2, Qvh3)

Three blocky vesicular basalt units, overlying the older basalt flows, are distinguishable in the southeast. The units are associated with volcanic centres at Mount Hamilton (Qvh1), Mount Fyans (Qvh2), and Mondilibi (Qvh3). The basalt flows are well exposed as stony rises, forming a rough topography of hummocks, depressions, ridges and channels with a relief of up to ten metres. These flows were thicker and probably more solidified than the relatively thinner 'sheet flows' typical of the older basalt units. Numerous lakes and swamps lie within the flows, particularly in their outer and lowermost portions.

The volcanic centres are more pronounced topographic features than the lava shields and cones associated with the older basalt units. Mount Hamilton is a 80 m high lava cone, with a central crater exposing a layered sequence of highly vesicular basalt. Farther to the south at Mount Fyans, a small scoria cone, about 300 m across, is capped by vesicular basaltic lavas. At Mondilibi, in the south, a collapsed lava disc caps a small scoria cone. Basalt comprising the blocky flows is more variable in composition than the older basalt units. The basalt at Mount Fyans is distinctly plagioclase-clinopyroxene and olivine-phyric; basalt at Mondilibi is highly magnetic.

4.5.1.3 Scoria deposits (Qvs)

Scoria deposits are associated with two eruptive centres: at Mount Fyans in the east; and at Bald Hill in the northeast. Small amounts of scoria are also present at Mondilibi in the south. The largest scoria deposits are at Bald Hill where they form a single cone 2 km across and 50 m high. The scoria forms an unconsolidated, crudely layered deposit of vesicular basalt ejectamenta ranging from fine ash to bombs. Angular quartzite clasts, up to 60 cm across, are common and were probably derived from the Saint Arnaud Group, that is interpreted to underlie the basalt east of the Moyston Fault. The cone has a 400 m wide central crater partially filled with lacustrine clay deposits.

4.5.2 ***Windgelli Clay***

The Windgelli Clay (Ollier & Joyce, 1986) is a calcareous aeolean clay up to 2 m thick, which covers most of the Palaeozoic bedrock, Tertiary units and all but the youngest basalt flows of the Newer Volcanics in WILLAURA. The character and thickness of the deposit shows no relation to slope or underlying bedrock, indicative of its predominantly aeolian origin. The deposits are possibly a correlative of the Quaternary aeolian Woorinen Formation which formed by deflation of Pliocene quartzose beach ridges and strandplain deposits in western Victoria during the late Pleistocene (Ollier & Joyce, 1986). The deposit is best exposed in road cuttings or in erosional cliffs around lake shores (e.g. southern shore of Lake Bolac). The presence of iron pisolite gravel horizons up to 30 cm thick and basal scours in places is indicative of some sheet wash and fluvial reworking of the deposits. Calcareous nodules present in a number of levels are concentrated in a basal horizon immediately above saprolite. In places, a pisolitic gravel horizon above the ferruginised saprolite is also cemented by carbonate.

4.5.3 Older alluvial terrace deposits (Qar)

Very minor deposits of partly consolidated clay, silt and sand along the Hopkins River, form older alluvial terraces. The deposits are being actively eroded by the current rejuvenated stream.

4.5.4 Older alluvial and colluvial deposits (Qpa)

Older alluvial and colluvial deposits of partly consolidated clay, silt and sand occur either as remnants in the major fluvial courses, such as the Hopkins River, or in zones between lunette and lagoonal deposits and actively advancing colluvial deposits. The deposits are most widely developed in the northwest around the margin of the Heifer and Walker Swamps.

4.5.5 Colluvial deposits (Qrc)

Colluvial deposits of unconsolidated silt and sand are commonly developed in the upper portions of most drainage catchments, particularly in higher relief areas of outcropping Palaeozoic rocks. The most extensive deposits are in the northwest, north of the Glenelg Highway. These deposits are derived in part by the reworking of Tertiary deposits and thin Quaternary loess soils.

4.5.6 Swamp and lagoonal deposits (Qrm)

Lacustrine deposits of clay, silt and sand are widespread, particularly across the Western Victoria Plain, the undulating basalt surface providing numerous depressions and internal drainage catchments. The lakes are saline and most are ephemeral. The most extensive deposits are associated with the Lake Muirhead, Heifer Swamp and Dry Creek floodplain in the far north west.

4.5.7 Stream alluvial deposits (Qra)

Minor deposits of stream alluvium comprising, clay, silt, sand and minor gravel, are found on most watercourses in the area. The most extensive are associated with the Hopkins River, Fiery Creek, and the upper parts of Salt Creek.

4.5.8 Lunette deposits (Qu)

Crescent-shaped lunette deposits of clay and sand are common around the southeastern margins of ancestral and existing lakes. The deposits formed by concentrations of clay, sand, salt and Coxiella shells derived from the adjacent dry lake-bed deposits and transported by the prevailing northwesterly winds. They often contain fossil soils, indicating stable periods between phases of lunette growth (Ollier & Joyce, 1986). The most extensive lunette deposits occur north of Glenthompson, where they are associated with a chain of lagoons which runs eastwards to the Cockajemmy Lakes, south of Willaura.

5. STRUCTURE AND METAMORPHISM

Folded and metamorphosed early Palaeozoic sediments, volcanics and granitoids form bedrock to weakly deformed and unmetamorhosed unconformably overlying Silurian sandstone (Grampians Group), and flat-lying surficial Tertiary and Quaternary sediments and volcanics (Newer Volcanics). The bedrock can be subdivided into three major domains: the unexposed Stawell Zone east of the Moyston Fault; the central Dimboola Subzone; and the more westerly Miga Subzone.

The Mount Stavely Volcanic Complex and the Glenthompson Sandstone comprise the Dimoola Subzone. Both were regionally metamorphosed to very low grade and affected by only one phase of upright NNW-trending folding. Folds within the Cambrian units are open to tight, plunging subhorizontally to either the NNW or SSE. Common grading in sandstones indicates that folds are upright and are inclined to the west about steeply WSW-dipping to subvertical axial planes. A weak axial-planar spaced or slaty S1 cleavage is locally present, typically developed within fold hinges. Quartz veining is mostly absent except for rare thin veins (up to a few mm) filling S1 axial surfaces.

The age of the folding and metamorphism is tightly constrained by crosscutting relations with the intrusive 489 Ma Bushy Creek Granodiorite. Associated contact metamorphic mineral assemblages and textures overprint the S1 fabric and are undeformed. The deformation and metamorphism in the Glenthompson and Mount Stavely Volcanic Complex is therefore Cambrian in age, being younger than the ~495 Ma volcanic complex and older than the ~489 Ma old intrusive. This places the deformation within the Delamerian Orogeny (500±10 Ma; Lui & Fleming, 1991), and indicates that the region lies within the Adelaide Fold Belt rather than the Lachlan Fold Belt. The interpreted deformation age defines a more precise age than the 485 Ma lower limit age of deformation and metamorphism indicated for the Glenelg River Complex (Turner & others, 1993) to the west of WILLAURA.

The Mount Stavely Volcanic Complex forms a subvertical north-northwest-trending paraautochthonous slice (the Mount Stavely Belt) within the enclosing Glenthompson Sandstone. Buckland (1987) interpreted fault contacts along both western and eastern contacts of the Mount Stavely Belt, naming them the Mount Stavely West Fault and Mount Stavely East Fault, respectively. The Mount Stavely West Fault, although not exposed, is evident by apparent truncation of bedding trends and structures in the sandstone and the volcanic complex. Strongly sheared Williams Road Serpentinite within the Mount Stavely Fault East forms the eastern margin of much of the belt separating the Glenthompson Sandstone to the east. However, the tectonised serpentinite body is discontinuous, and does not follow the entire eastern contact. In the north, where the serpentinite is absent, the presence of interbedded sandstone and volcaniclastic sediments along the eastern margin of the complex indicates a probable conformable sedimentary contact, and that the Glenthompson Sandstone overlies the complex.

The Williams Road Serpentinite occurs as allochthonous slices of hydrated olivine-rich protolith (depleted harzburgite) tectonically emplaced as "cold intrusions" (Crawford, 1988) within the subvertical NNW-trending Mount Stavely East Fault. *S-C* fabrics are locally well-developed in the serpentinite and indicate a dextral sense of shear. As the fault parallels the axial surface of the regional folds in the enclosing rocks, it is unlikely these fabrics were the result of the same compressional event that produced the folds. Rather, they may reflect later wrench movement during the Silurian, when significant transcurrent reactivation of bedrock faults affected the Grampians Group and older units (Cayley & Taylor, 1997). The serpentinite may have been emplaced at that time, or earlier during the Delamerian folding and supracrustal emplacement of the volcanic complex, when presumably the Mount Stavely West and East Faults were active thrust faults.

The Escondida Fault forms the boundary bewteen the Dimboola Subzone and the Miga Subzone to the west. The fault is interpreted as a west-dipping thrust with tightly folded upper greenschist facies rocks in the hangingwall. The thrust is stiched by the Bushy Creek Granodiorite, indicating Delamerian movement. Minor east-northeast and southeast-trending faults are interpreted from magnetic data to displace this fault and the faults bordering the Mount Stavely Volcanic Complex. They appear also to displace the Buckeran Diorite, and are therefore post-Delamerian.

The eastern boundary of the Dimboola Subzone is the Moyston Fault (Cayley & Taylor, 1996), a major crustal suture whose southern continuation into WILLAURA lies east of the Mount Dryden Belt occurrence of the Mount Stavely Volcanic Complex cropping out at Lake Bolac (Buckland, 1981). The fault is not exposed, being covered by Newer Volcanics. However, its presence is manifest by: regional gravity gradients and coincident crustal discontinuities interpreted from isotopic compositions of basalts (Mortlake discontinuity: Nicholls & others, 1993); changes in granite compositions (Chappell & others, 1988); and differing Tertiary uplift history (Foster & Gleadow, 1992 & 1993). The Woorndoo Fault, previously inferred to run parallel to Salt Creek on the basis of tilted and overturned Grampians Group strata (Spencer-Jones, 1965), may be the southern continuation of the Moyston Fault. Minor reverse faults, dipping ~60° to the southeast, are also present in overturned sandstone beds exposed on the southern shore of Lake Alexander, about 3 km west of the inferred Moyston Fault. The Moyston Fault is the surface expression of the boundary between the Adelaide and Lachlan Fold Belts (Cayley & Taylor, 1996).

Regional metamorphic assemblages in the Mount Stavely Volcanic Complex and the Glenthompson Sandstone of the Dimboola

Subzone are mostly prehnite-pumpellyite facies. Characteristic alteration assemblages within lavas, volcaniclastics and intrusive rocks of the Mount Stavely Volcanic Complex are albite + pumpellyite + prehnite + iron-rich epidote + chlorite ± actinolite, indicating a prehnite-pumpellyite facies grade of burial metamorphism. Locally, there are areas of more intense alteration and quartz-epidote veining in the andesites (Buckland & Ramsay, 1982). Quartz-rich sandstones typically contain sericite, chlorite and carbonate. Plagioclase phenocrysts within the volcanic and intrusive rocks are typically altered to clay, sericite or prehnite-pumpellyite; groundmass glass is recrystallized to fine intergrowths of quartz, albite, chlorite, epidote and pumpellyite. Primary mafic minerals are partially chloritised. Patches and rarer veinlets of radiating prehnite and pumpellyite are commonly present. Other secondary minerals include leucoxene, titanite, chlorite, quartz and sericite.

The structurally deeper levels of the Miga Subzone west of the Escondida Fault are greenschist facies. In the Chatsworth area a zone of greenschist facies is indicated by common actinolite in mafic rocks and foliated biotite in metasediments. The change in metamorphic grade decreases gradually to the west, and abruptly to the east across the fault.

Areally limited (less than 500 m) contact aureoles surround the Bushy Creek Granodiorite, the Buckeran Diorite and other granite plutons north of Chatsworth. Contact metamorphic minerals include fine grained biotite, poikolitic muscovite and ovoid white mica aggregates after cordierite in meta-pelitic rocks.

6. GEOLOGICAL HISTORY

Possibly the oldest rocks in WILLAURA are those of the Miga Subzone that were substantially deformed in the Delamerian Orogeny. After cratonisation of these rocks a post-collisional medium- to high-K calc-alkaline andesitic volcanic arc, the Mount Stavely Volcanic Complex, formed on the active continental margin at about 500 Ma. Similar volcanic rocks, geochemical signatures and overlapping isotopic age determinations of the complex with those of the Mount Read Volcanics in Tasmania suggest that they were generated concurrently in similar tectonic settings (Crawford & Berry, 1992). However, the post-volcanic histories of the two regions diverge. Thick Late Cambrian-Ordovician quartz-rich sediments (Glenthompson Sandstone) interpreted as mid-fan channel-fill turbidite deposits overly the Mount Stavely Volcanic Complex greenstones in Victoria, whereas in Tasmania, only a shallow shelf sequence was deposited. This difference may reflect the lack of a Proterozoic crust below these rocks in Victoria. Such a difference in basement terrane could also account for the different Pb isotope signatures in the Stawell Zone volcanics and the Mount Read Volcanic hosted mineralisation, where significant crustal contamination is evident (Gulson & others, 1991).

The occurrence of interbedded volcanolithic sandstones and quartz-rich flysch within the andesitic sequence of the Mount Stavely Volcanic Complex suggests that eruptions were at least in part submarine and that at least some detritus was derived from a continental crustal source. U-Pb zircon ages of detrital grains in the volcaniclastic sandstone sample from the Towanaway Tuff fall into three pre-Palaeozoic broad age groupings that are consistent with those described by Williams and others (1991) for inherited zircons within Palaeozoic I and S-Type granites and Ordovician flysch throughout the Lachlan Fold Belt. These zircon ages probably reflect periods of considerable igneous activity in southeastern Australia that formed the underplated sources ~~of I-Type granites, generated the~~

of I-Type granites, generated the detritus for the sources of S-Type granites, and after recycling, much of the Early Palaeozoic flysch (Williams & others, 1991).

Both the Mount Stavely Volcanic Complex and Glenthompson Sandstone rocks were affected by one phase of upright NNW-trending folds in response to east-west compression, and were regionally metamorphosed to very low to low grade. Easterly-directed thrusting accompanied the deformation and was focused in the Mount Stavely Volcanic Complex where serpentised ultramafic rocks (Williams Road Serpentinite) were tectonised and remobilised. The timing of the deformation, the final phase of the Delamerian Orogeny, is constrained between the youngest volcanism (495 Ma) and the intrusion of the Bushy Creek Granodiorite at 489 Ma. This granodiorite and several other zoned granodiorite, diorite, and granite plutons, intruded the folded rocks, and represent the final cratonising event in the Adelaide Fold Belt.

A Silurian phase of extension of the Delamerian crust along a continental margin is indicated by the formation of a basin in which over 3000 m of fluvial to shallow-marine clastics (Grampians Group) accumulated. Rhyolitic dyke intrusion both preceded (undated Wickliffe Rhyolite) and post-dated continental deposition in the Late Silurian (412 Ma).

During the Silurian, east-west compression and intense deformation in Lachlan Fold Belt rocks to the east resulted in westerly-directed thrusting on the Moyston Fault (Cayley & Taylor, in prep), and formation of an adjacent overturned syncline in Willaura Sandstone rocks immediately west of the fault. A fold-and-thrust belt formed in the Grampians Group (Cayley & Taylor, 1996) to the north, where it preceded Early Devonian granite intrusion.

The Moyston Fault was further reactivated in the Mesozoic, during formation of the Otway Basin, with a relative uplift to the east of 1 to 2 km (Foster & Gleadow, 1992). A Palaeocene to Miocene transgressive sequence, from high energy fluviatile channel deposits (White Hills Gravel) to low energy Carboniferous swamp and lagoonal deposits (undifferentiated sediments), was deposited in WILLAURA. These deposits are interpreted to have formed during a Miocene marine transgression in the Otway Basin, which culminated locally with the deposition of the overlying marine to littoral deposits of the Clifton Formation.

Deep weathering of older rocks, ongoing since the early Tertiary, continued after the marine transgression, with ironstone and limited continental sand deposition taking place throughout the Pliocene to Pleistocene. The Newer Volcanics were extruded over much of the area as extensive basalt sheets, during late Pliocene to Pleistocene uplift. The late Pleistocene, aeolian, Windgelli Clay was deposited as a thin veneer over most of the Palaeozoic rocks and the Newer Volcanics, and preceded younger blocky lava flows and scoria deposits such as those at Mount Hamilton and Mount Fyans. Younger Quaternary continental deposition continues to the present day in a range of fluvial and lacustrine environments.

7. GEOPHYSICS

As part of the National Geoscience Mapping Accord (NGMA) AGSO flew a regional airborne magnetic and gamma-ray spectrometric (K, Th, U) survey across the Ballarat 1:250 000 sheet area in 1992. Except for ARARAT flown at 200 m spacing, flight lines were 400 m, and nominal elevation was 80 m. Operational details and specifications of the survey are given by Richardson (1993).

A number of images were generated by AGSO, including hue, saturation and intensity (HSI), and grey scale images of magnetic data and three band (Red = K, Green = Th, Blue = U) composite images of spectrometric data. Magnetic data were reduced to the pole. These images, mostly at 1:100 000 scale, were used as a basis for field mapping, in conjunction with black and white aerial photographs at 1:25 000 scale. The geophysical properties of particular rock types enabled demarcation of lithological boundaries and subsurface interpretation of basement. A summary of geophysical characteristics of the main rock units in WILLAURA is given in Table 3.

7.1 PALAEOZOIC ROCKS

7.1.1 Mafic and ultramafic rocks

All the mafic and ultramafic units in the Palaeozoic bedrock have uniformly low gamma-ray spectrometric responses and high magnetic signatures. Magnetic susceptibilities range from 250-1500 x 10^{-5} SI units for the Fairview Andesite Breccia, 700-2000 x 10^{-5} SI units for the Williams Road Serpentinite and 50-600 x 10^{-5} SI units for tholeiitic rocks in the Miga Subzone. Associated anomalies are typically elongate and parallel to the regional north to north west trend. The magnetic character of these rocks enables them to be traced continuously beneath Tertiary and Quaternary cover, even where overlain by magnetic basalt flows of the Newer Volcanics. Magnetic anomalies sourced from these rocks dominate regional magnetic images of the region.

7.1.2 Granite and diorite

Cambrian granite, granodiorite and diorite plutons, and inferred Devonian granite plutons, are dominantly magnetic. Some of the larger bodies, such as the Bushy Creek Granodiorite consist of a number of pseudo-concentrically arranged magnetic zones reflecting original pulses of fractionated magma intrusion. Magnetic susceptibilities range from 550 x 10^{-5} SI units for the Bushy Creek Granodiorite, up to 3000 x 10^{-5} SI units in the Buckeran Diorite. Gamma-ray spectrometric responses in all channels are very low and comparable those of the mafic and ultramafic rocks.

Magnetic anomalies associated with the plutons are broad, subcircular, and show discordant contacts, with north to northwest-trending anomalies in the Mount Stavely Volcanic Complex and Glenthompson Sandstone rocks. On this basis, several granite plutons are interpreted to exist in the subsurface beneath Tertiary sediments and Newer Volcanics cover in the south.

7.1.3 *Metasediments*

Palaeozoic metasediments of the Mount Stavely Volcanic Complex, Glethompson Sandstone and Grampians Group are all non-magnetic with susceptibities generally less than 30 x 10^{-5} SI units. Gamma-ray spectrometric responses are more variable. The Grampians Group sediments and volcaniclastics within the Mount Stavely Volcanic Complex have low responses in all three channels: the Glenthompson Sandstone is distinguished by moderate K responses.

7.1.4 Wickliffe Rhyolite

The Wickliffe Rhyolite forms a swarm of narrrow rhyolite dykes intruding the Glenthompson Sandstone in a zone, about 1 km wide, surrounding an outlier of Willaura Sandstone in the area between Wickliffe and Willaura. The dykes are non-magnetic; however, their concentration can be observed in spectrometric images by elevated K responses in the host Glenthompson Sandstone. The response from individual dykes in other areas cannot be distinguished, owing to swamping by responses from the greater mass of sandstone.

7.2 TERTIARY SEDIMENTS

Except for pisolitic ironstone and ferricrete, the Tertiary units are non magnetic. Continous curvilinear magnetic anomalies in the central part of WILLAURA, coincide with subtle topographic ridges and underlying strandline sand and calcarenite deposits of the Clifton Formation. The anomalies are sourced by elongate bodies of ferricrete preferentially developed along the crests of the Miocene ridges. This distinct pattern can be traced to some extent beneath magnetic basalt cover, enabling the full extent of the peak Tertiary transgressive unit to be traced in subsurface.

Gamma-ray spectrometric responses for the Tertiary units are low, except for ferricrete, which has moderate Th and U responses.

7.3 QUATERNARY UNITS

7.3.1 Sediments

All Quarternary sediments are non magnetic, however, gamma-ray spectrometric responses are variable. Responses of lunette deposits are low in all three channels. Lacustrine deposits frequently have moderate K responses. Responses of alluvial and colluvial deposits are highly variable, and reflect the composition of catchment areas. The Windgelli Clay, an aeolian unit that blankets most of the Palaeozoic and Tertiarty rocks, and the Newer Volcanics, have uniform responses of low to moderate Th and low U.

7.3.2 Newer Volcanics

The Newer Volcanics are uniformly magnetic, with susceptibilities ranging from 300 x 10^{-5} SI units to 2000 x 10^{-5} SI units. Anomalies associated with the basalt flows are typically complex, high amplitude, high frequency and highly variable. Those associated with the younger blocky lavas tend to have higher amplitudes. The anomalies are both positive and negative, reflecting eruption of basalt flows over sufficiently long timespan for reversals in the earth's magnetic field to have occurred. In places, such as in the north east near Fiery Creek, individual flows (in this case a negatively magnetised flow) can be distinguished in magnetic images. In the southeast, east of Woorndoo, a large negative anomaly coincides with an eruption centre, which is interpreted to have an intrusive source.

Gamma-ray spectrometric responses are variable and those on the older basalt flows (Qvn) reflect mainly a thin veneer of aeolian clay (Windgelli Clay). The blocky lava flows in the Mount Fyans area are distinguished by moderate K signatures.

Table 3. *Summary of geophysical properties, Willaura 1:100 000 sheet area*

Unit	*Description*	*Magnetic susceptibility SI units x 10^{-5}*	*Gamma-ray spectrometry tc (cps)*	*K*	*Th*	*U*
QUATERNARY						
Qu	Clay and sand: Lunette deposits	<10	<10	Low	Low	Low
Qra	Clay, silt, sand and minor gravel: Stream alluvium	<10	Variable	Variable	Variable	Variable
Qrm	Clay, silt and sand: Swamp and lagoonal deposits	<10	Variable	Medium	Low	Low
Qrc	Sand and silt: Colluvial deposits	<10	Variable	Variable	Variable	Variable
Qpa	Partly consolidated clay, silt and sand: Older alluivial and colluvial deposits	<10	Variable	Variable	Variable	Variable
Qar	Partly consolidated clay, silt and sand: Older alluvial terrace deposits	<10	Variable	Variable	Variable	Variable
Newer Volcanics						
Qvs	Basalt scoria deposits	300	20	Low	Low	Low
Qvh1	Blocky vesicular basalt flows, Mt. Hamilton area	475	31	Low	Low	Low
Qvh2	Blocky vesicular basalt flows, Mt. Fyans area	350	22	Medium	Low	Low
Qvh3	Blocky vesicular basalt flows, Mondilibi area	2000	22	Low	Low	Low
Qvn	Older basalt flows	300	23	Low	Low	Low
Qvn1	Older olivine-pyroxene-phyric basalt flows	1200	35	Low	Low	Low
		na.	na.	na.	na.	na.
Qvnm	Negatively magnetised basalt intrusions in subsurface					

Table 3. *continued*

Unit	*Description*	*Magnetic susceptibility SI units x 10^{-5}*	*Gamma-ray spectrometry tc (cps)*	*K*	*Th*	*U*
TERTIARY						
Tps	Unconsolidated sand: Continental deposits	nm	nm	Low	Low	Low
Tpl	Laterite, sand, ironstone	nm	nm	Low	Medium	Medium
Clifton Formation Tok	Quartz sand, clay and calcarenite: Swamp and strandline deposits	80	nm			
Tae	Consolidated cross-bedded quartz sandstone, gravel, clay, lignite and coal: Fluvial and swamp deposits	nm	nm			
White Hills Gravel Tlw	Consolidated ferruginous quartzose gravel: Fluvial deposits	<20	18			
DEVONIAN						
Dg	Undifferentiated magnetic granite in subsurface	na.	na.	na.	na.	na.
SILURIAN						
Grampians Group Slk	Pebbly cross bedded quartz sandstone, polymictic conglomerate, siltstone and rhyolite	5	46	Low	Low	Low
Wickliffe Rhyolite Svj	Pink flow-banded rhyolite dyke swarm	10-30	60	Medium	Low	Low
CAMBRIAN						
Cg	Undifferentiated magnetic granite in subsurface	na.	na.	na.	na.	na.
Buckeran Diorite ∈dim	Magnetic diorite	3000	20	Low	Low	Low
∈di	Diorite	nm.	nm.	Low	Low	Low
Bushy Creek Granodiorite	Grey porphyritic bioitite hornblende granodiorite	550	nm	Low	Low	Low
∈gd ∈gdm	Magnetic granite	nm	nm	Low	Low	Low
∈d	Magnetic microporphyritic diorite in subsurface	na	na	na	na	na

Table 3. *continued*

Unit	*Description*	*Magnetic susceptibility SI units x 10^{-5}*	*Gamma-ray spectrometry*			
			tc (cps)	*K*	*Th*	*U*
Glenthompson Sandstone ∈gs	Medium-grained meta quartz sandstone and minor siltstone	<30	60	Medium	Low	Low
∈gm	Meta dolerite, meta-basalt, meta diorite,	50-800	23	Low	Low	Low
Mount Stavely Volcanic Complex						
∈sm	Undifferentuiated magnetic mafic/ultramafic rocks	na	na	na	na	na
Lalkaldarno Porphyry ∈sl	Porphyritic hornblende quartz diorite.	<1500	22			
Williams Road Serpentinite ∈sw	Serpentinite.	700-2000	13	Low	Low	Low
Towanway Tuff ∈st	Dacitic crystal lithic volcanic sandstone. Minor laminated chert and volcanic siltstone.	20-30	35	Low	Low	Low
Narrapumelap Road Dacite Member ∈stn	Dacitic to rhyolitic lava.	10	nm	Low	Low	Low
Nanapundah Tuff ∈sn	Andesitic crystal lithic volcanic sandstone.	10	nm	Low	Low	Low
Fairview Andesite Breccia ∈sf	Massive andesitic breccia, minor andesite and basalt lava.	250-1500	34	Low	Low	Low
Glenronald Shale Member ∈sfg	Laminated black pyritic shale, volcanic siltstone, minor chert.	5-80	36	Low	Low	Low

na Not applicable: Magnetic susceptibility and spectrometric response not known as unit is not exposed
nm No measurement available.

8. ECONOMIC GEOLOGY

7.1 METALLIFEROUS DEPOSITS

Although several occurrences of copper sulphide mineralisation are hosted by rocks of the Mount Stavely Volcanic Complex, no economic mineralisation has yet been discovered. Mineral occurrences and details of mineral exploration of the greenstone belt prior to 1982 are given by Buckland (1987). Results of more recent work are presented by Donaghy (1994). Detailed petrographic and isotopic studies of mineralisation at the Victor 2 prospect by Donaghy showed that the mineralisation is Pb-poor, Cu-Zn-rich volcanic hosted massive sulphide (VHMS) style.

The correlation of the Mount Stavely Volcanic Complex with the Mount Read Volcanics in Tasmania, supported by this study and the work of Donaghy (1994), highlights the significant potential for the complex to host similar and significant VMS deposits. The Mount Read Volcanics is one of the most highly mineralised sequences in Australia. The unit hosts several major polymetallic (Cu, Pb, Zn, Ag & Au) volcanic massive sulphide deposits, which formed as submarine exhalative accumulations (McArthur & Dronseika, 1990; Lees & others, 1990), copper-rich stockworks and hydrothermal replacement deposits (Hills, 1990). It is also worth noting that similarly old or slightly younger, volcanic rocks in the Tasman Fold Belt, found within the Mount Windsor Volcanics (Henderson, 1986) and the Balcooma Metavolcanics (Withnall & others, 1991) in northeast Queensland, also contain economic Cu-Pb-Zn mineralisation.

No economic mineralisation has as yet been located within WILLAURA,. However, the full potential of the Mount Stavely Volcanic Complex for base and precious metals has yet to be realised, as much of the complex is largely unexplored beneath a thin veneer of Cainozoic sediments and basalt.

7.2 NON-METALLIFEROUS DEPOSITS

Deposits of clay, sand, gravel, basalt, scoria, laterite, and sandstone have been worked from numerous quarries within WILLAURA. Most of these are located close to roads and population centres.

The most significant nonmetalliferous deposit in the area is at Glenthompson, where clay is currently being extracted from an open pit developed within kaolinised sediments of the Glenthompson Sandstone. The kaolinisation probably occurred during deep weathering and laterite formation in the early Pliocene to early Pleistocene.

Quaternary deposits form the bulk of sand, basalt, and scoria worked in the area, with well-sorted quartz sand concentrated in lunette deposits. Basalt has been extracted from numerous small quarries, all located within the older flows of the Newer Volcanics and scoria has been worked at Bald Hill and Mount Fyans.

Sandstone from the Grampians Group and Glenthompson Sandstone, together with Tertiary ferricrete form the bulk of materials extracted for road building.

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APPENDIX: U-Pb ISOTOPIC DATA

SHRIMP ANALYTICAL INFORMATION

The U-Pb zircon analyses were obtained from the SHRIMP ion-microprobe at the Research School of Earth Sciences (ANU). The instrument was operated at a mass resolution in excess of 6500 in order to remove significant spectral interferences (Compston and others, 1984). Fractionation between U and Pb was monitored by referencing to a $^{206}Pb/^{238}U$ ratio of 0.0928 (which corresponds with an age of 572 Ma) for interspersed analyses of the SL13 zircon standard. Such fractionation was corrected by means of an established power law relationship($^{206}Pb^+/U^+= a(U0^+/U^+)^2$). Th/U ratios and Th contents were derived from a known linear correlation between ThO^+/U^+ and UO^+/U^+. Radiogenic Pb compositions were determined by subtracting contemporaneous common Pb (Cumming and Richards (1975) from the measured compositions. Ages have been calculated from the U and Th decay constants recommended by Steiger and Jäger (1977).

Ion-microprobe U-Th-Pb data for zircons from the Willaura 1:100 000 Sheet

Grain area	U (μg/g)	Th (μg/g)	Th/U	$^{206}Pb/^{204}Pb$	f_{206} (%)	$^{206}Pb/^{238}U$ ±1 σ error	$^{207}Pb/^{235}U$ ±1 σ error	$^{207}Pb/^{206}Pb$ ±1 σ error	*Age ±1 σ error
					Metadacite (93843111)				
1.1	158	165	1.048	1933	1.15	0.0804±.0016	0.624±.029	0.0563±.0022	499±9
2.1	317	465	1.465	4058	0.09	0.0820±.0016	0.661±.026	0.0585±.0019	507±9
3.1	134	193	1.441	2432	0.95	0.0791±.0015	0.633±.036	0.0581±.0030	490±9
4.1	161	209	1.298	1097	1.36	0.0808±.0016	0.604±.031	0.0542±.0025	503±9
5.1	147	181	1.236	1624	0.43	0.0812±.0016	0.705±.032	0.0630±.0025	500±9
6.1	151	190	1.258	1558	0.59	0.0819±.0016	0.700±.032	0.0620±.0025	504±9
7.1	160	166	1.039	2336	1.00	0.0805±.0016	0.628±.028	0.0566±.0021	499±9
8.1	260	430	1.653	2103	0.01	0.0762±.0015	0.653±.031	0.0622±.0026	470±9
9.1	124	138	1.113	4750	0.65	0.0818±.0016	0.698±.035	0.0618±.0027	504±9
10.1	137	198	1.442	1372	1.48	0.0809±.0016	0.583±.038	0.0523±.0031	504±9
11.1	122	176	1.448	1050	2.15	0.0801±.0016	0.564±.039	0.0511±.0033	500±9
12.1	116	125	1.080	1612	0.01	0.0823±.0016	0.759±.033	0.0669±.0025	504±9
13.1	131	154	1.179	636	0.01	0.0823±.0016	0.866±.036	0.0763±.0027	498±9
14.1	188	241	1.283	1091	0.01	0.0799±.0015	1.116±.033	0.1013±.0020	470±9
15.1	147	167	1.141	2682	0.15	0.0817±.0016	0.677±.030	0.0601±.0023	504±9
16.1	180	223	1.237	1064	0.91	0.0802±.0015	0.656±.029	0.0594±.0023	496±9
17.1	111	115	1.034	1706	1.10	0.0821±.0016	0.674±.033	0.0596±.0026	507±9
18.1	111	131	1.175	842	0.65	0.0811±.0016	0.646±.035	0.0578±.0028	502±9
19.1	178	217	1.220	2195	0.54	0.0823±.0016	0.652±.030	0.0575±.0022	510±9
20.1	105	122	1.161	1561	0.01	0.0813±.0016	0.734±.035	0.0655±.0027	499±9
21.1	118	170	1.438	3274	0.51	0.0771±.0015	0.601±.038	0.0566±.0032	479±9
22.1	108	132	1.225	1810	0.54	0.0783±.0015	0.677±.036	0.0627±.0030	483±9
23.1	306	359	1.172	4879	0.35	0.0761±.0015	0.599±.023	0.0570±.0017	473±9
19.2	108	138	1.283	1965	0.66	0.0774±.0015	0.633±.037	0.0593±.0031	479±9
24.1	96	93	0.963	1028	0.36	0.0813±.0016	0.691±.033	0.0616±.0025	501±9
25.1	273	437	1.601	4979	0.01	0.0782±.0015	0.659±.030	0.0611±.0024	483±9
26.1	135	173	1.281	1399	0.78	0.0731±.0014	0.569±.034	0.0565±.0030	455±8
27.1	137	105	0.766	1256	0.40	0.0796±.0015	0.702±.026	0.0640±.0019	490±9
28.1	139	163	1.172	1979	0.72	0.0779±.0015	0.582±.031	0.0542±.0025	485±9
29.1	188	245	1.303	4251	0.06	0.0792±.0015	0.662±.029	0.0606±.0023	490±9
30.1	78	71	0.911	1086	1.09	0.0802±.0016	0.638±.035	0.0576±.0028	497±9
31.1	212	347	1.635	3061	0.01	0.0795±.0015	0.695±.033	0.0634±.0026	490±9
32.1	101	127	1.255	2843	0.39	0.0784±.0015	0.630±.036	0.0583±.0030	486±9
33.1	116	129	1.110	4625	0.49	0.0797±.0015	0.654±.033	0.0595±.0026	493±9
34.1	173	219	1.266	1279	0.23	0.0796±.0015	0.671±.030	0.0611±.0023	492±9
35.1	127	135	1.067	1034	0.63	0.0789±.0015	0.640±.031	0.0588±.0025	489±9
					Mafic volcaniclastic (93843103)				
60.1	155	191	1.233	3500	0.51	0.0794±.0015	0.645±.035	0.0588±.0029	492±9
61.1	107	77	0.720	2018	0.89	0.0817±.0016	0.612±.042	0.0543±.0034	508±9
62.1	66	48	0.729	6435	0.21	0.4602±.0092	10.216±.235	0.1610±.0015	2466±15
63.1	214	282	1.317	2231	0.80	0.0785±.0015	0.604±.034	0.0559±.0028	488±9
64.1	213	115	0.540	1999	0.89	0.0816±.0016	0.600±.028	0.0533±.0022	508±9
65.1	113	191	1.693	2427	0.69	0.1831±.0036	1.821±.062	0.0721±.0019	989±53
66.1	76	233	3.068	1173	1.51	0.0942±.0019	0.742±.059	0.0571±.0043	582±11
67.1	67	82	1.214	464	3.87	0.0793±.0016	0.480±.079	0.0439±.0071	500±9
68.1	182	296	1.624	4041	0.44	0.0904±.0017	0.759±.029	0.0608±.0019	557±10
69.1	831	274	0.329	25000	0.06	0.1745±.0033	1.808±.037	0.0752±.0004	1073±10
70.1	191	79	0.415	8984	0.19	0.1434±.0027	1.390±.040	0.0703±.0013	936±39
71.1	674	352	0.522	6522	0.27	0.0949±.0018	0.776±.018	0.0594±.0007	585±11
72.1	168	42	0.248	8894	0.15	0.5451±.0106	14.736±.300	0.1960±.0008	2794±6
73.1	512	382	0.746	58200	0.02	0.1766±.0034	1.833±.038	0.0753±.0004	1075±11
74.1	250	8	0.033	20000	0.06	0.5429±.0105	17.842±.353	0.2384±.0007	3109±4
75.1	160	139	0.867	5743	0.30	0.1490±.0029	1.485±.052	0.0723±.0019	994±56
76.1	227	273	1.204	4105	0.40	0.2031±.0039	2.205±.054	0.0787±.0010	1166±25
77.7	154	73	0.475	1692	1.06	0.0795±.0015	0.612±.034	0.0559±.0028	494±9
78.1	51	38	0.748	1226	1.46	0.0831±.0017	0.643±.077	0.0561±.0065	515±10
79.1	330	241	0.732	3328	0.53	0.0932±.0018	0.724±.021	0.0564±.0011	576±10
80.1	722	29	0.040	31300	0.05	0.0955±.0018	0.787±.018	0.0598±.0006	588±11

81.1	71	65	0.912	2065	0.87	0.0823±.0016	0.628±.059	0.0554±.0049	511±9
82.1	278	67	0.241	7893	0.21	0.1740±.0033	1.746±.040	0.0728±.0007	1007±21
83.1	337	181	0.537	9246	0.18	0.1979±.0038	2.170±.048	0.0795±.0007	1185±17
84.1	452	115	0.256	13600	0.13	0.0962±.0018	0.797±.019	0.0601±.0008	592±11
85.1	626	291	0.466	32300	0.04	0.3281±.0063	6.871±.134	0.1519±.0004	2367±4

Meta-andesite breccia (93843112)

120.1	109	47	0.435	8313	0.18	0.3194±.0062	4.860±.113	0.1104±.0011	1805±19
121.1	1003	74	0.074	45400	0.03	0.3019±.0057	4.413±.086	0.1060±.0002	1732±4
122.1	885	77	0.087	38800	0.04	0.2967±.0057	4.277±.084	0.1046±.0003	1707±5
123.1	358	144	0.401	21500	0.07	0.3011±.0058	4.528±.092	0.1091±.0005	1784±9

Bushy Creek Granite (94843504)

1.1	73	67	0.918	2956	0.605	0.0790±.0019	0.584±.028	0.0536±.0021	490±11
2.1	87	64	0.739	7055	0.183	0.0802±.0019	0.623±.025	0.0563±.0017	498±12
3.1	89	90	1.014	18940	0.198	0.0800±.0019	0.620±.028	0.0563±.0020	496±12
4.1	59	45	0.772	10510	0.000	0.0815±.0020	0.673±.029	0.0599±.0020	505±12
5.1	75	56	0.748	1000000	0.000	0.0779±.0019	0.634±.026	0.0590±.0018	484±11
6.1	120	143	1.190	7339	0.344	0.0784±.0019	0.595±.029	0.0550±.0022	487±11
7.1	83	85	1.019	38300	0.330	0.0780±.0019	0.579±.031	0.0539±.0024	484±11
8.1	124	128	1.030	40300	0.373	0.0767±.0019	0.588±.027	0.0556±.0020	476±11
9.1	54	36	0.680	1000000	0.000	0.0781±.0019	0.650±.031	0.0604±.0023	485±11
10.1	72	75	1.036	12400	0.700	0.0776±.0019	0.567±.033	0.0530±.0026	482±11
11.1	120	83	0.697	5814	0.000	0.0790±.0019	0.657±.025	0.0603±.0016	490±11
12.1	83	84	1.015	3684	0.202	0.0779±.0019	0.608±.031	0.0566±.0024	484±11
13.1	142	135	0.950	26700	0.514	0.0768±.0019	0.580±.025	0.0548±.0018	477±11
14.1	72	53	0.730	1000000	0.000	0.0795±.0019	0.646±.028	0.0590±.0020	493±11
15.1	96	110	1.149	102000	1.052	0.0767±.0019	0.532±.031	0.0503±.0025	476±11
16.1	95	77	0.808	1000000	0.116	0.0779±.0019	0.627±.027	0.0583±.0019	484±11
17.1	114	100	0.872	1000000	0.000	0.0798±.0019	0.622±.026	0.0566±.0018	495±12
18.1	76	59	0.777	1789	0.396	0.0795±.0019	0.594±.028	0.0543±.0021	493±11
19.1	142	171	1.208	1000000	0.243	0.0794±.0019	0.618±.029	0.0565±.0021	493±11
20.1	97	83	0.860	40000	0.000	0.0788±.0019	0.634±.026	0.0583±.0018	489±11
21.1	107	96	0.901	1000000	0.245	0.0791±.0019	0.599±.026	0.0549+.0018	491±11
22.1	121	116	0.955	3939	0.319	0.0798±.0019	0.613±.026	0.0557±.0017	495±12
23.1	134	171	1.275	6582	0.599	0.0777±.0019	0.575±.027	0.0537±.0021	482±11

Willaura rhyolite (93843046)

50.1	488	55	0.112	11800	0.122	0.0660±.0013	0.508±.012	0.0559±.0006	411±7
50.2	509	58	0.115	1000000	0.000	0.0652±.0011	0.502±.009	0.0558±.0004	406±6
51.1	686	127	0.185	42700	0.000	0.0654±.0013	0.511±.012	0.0567±.0006	407±7
51.2	405	34	0.083	44700	0.009	0.0663±.0011	0.501±.010	0.0548±.0004	413±6
52.1	79	3	0.038	1856	0.772	0.0675±.0013	0.493±.018	0.0530±.0015	422±7
52.2	127	10	0.078	22500	0.249	0.0686±.0011	0.522±.012	0.0551±.0008	427±6
52.3	27	1	0.048	1202	1.115	0.0672±.0011	0.526±.020	0.0568±.0019	418±6
52.4	79	4	0.046	1000000	0.285	0.0696±.0012	0.528±.014	0.0551±.0010	433±7
53.1	344	54	0.158	4998	0.140	0.0641±.0012	0.484±.012	0.0548±.0008	400±7
53.2	371	57	0.154	21100	0.048	0.0677±.0011	0.516±.010	0.0553±.0005	421±6
54.1	152	16	0.106	1000000	0.234	0.0646±.0012	0.480±.014	0.0539±.0010	404±7
54.2	179	13	0.073	12300	0.124	0.0653±.0011	0.505±.011	0.0562±.0006	406±6
55.1	501	86	0.171	101000	0.175	0.0667±.0013	0.518±.012	0.0563±.0006	415±7
56.1	307	34	0.110	1870	0.447	0.0643±.0012	0.507±.013	0.0572±.0008	400±7
56.2	293	27	0.092	36700	0.082	0.0645±.0011	0.500±.010	0.0562±.0005	402±6
57.1	564	101	0.179	23600	0.000	0.0640±.0012	0.501±.012	0.0568±.0006	398±7
57.2	255	43	0.167	3621	0.066	0.0622±.0010	0.482±.010	0.0563±.0006	388±6
58.1	449	39	0.086	1000000	0.044	0.0653±.0012	0.506±.012	0.0562±.0006	406±7
58.2	470	42	0.088	9607	0.166	0.0652±.0011	0.493±.009	0.0549±.0004	407±6
59.1	522	59	0.112	7284	0.015	0.0678±.0013	0.529±.012	0.0566±.0006	422±7
59.2	363	34	0.093	1000000	0.073	0.0668±.0011	0.509±.010	0.0553±.0005	416±6
60.1	177	13	0.075	2712	0.337	0.0652±.0013	0.506±.014	0.0564±.0009	406±7
60.2	127	9	0.070	31700	0.212	0.0653±.0011	0.509±.012	0.0565±.0008	407±6
60.3	211	15	0.072	1000000	0.101	0.0664±.0011	0.512±.011	0.0559±.0006	414±6
61.1	349	53	0.151	5724	0.277	0.0669±.0013	0.516±.013	0.0560±.0007	416±7
61.2	288	30	0.105	17094	0.151	0.0653±.0011	0.493±.010	0.0548±.0005	407±6
62.1	317	32	0.100	8078	0.134	0.0667±.0013	0.515±.012	0.0560±.0007	415±7
62.2	337	29	0.087	17600	0.020	0.0667±.0011	0.514±.010	0.0559±.0004	415±6
63.1	299	30	0.100	3230	0.117	0.0654±.0013	0.505±.012	0.0560±.0007	407±7

63.2	303	28	0.091	20000	0.083	0.0669±.0011	0.504±.010	0.0546±.0005	417±6
64.1	140	13	0.090	5187	0.293	0.0651±.0013	0.506±.014	0.0564±.0011	405±7
64.2	84	5	0.064	3412	0.258	0.0680±.0011	0.512±.013	0.0546±.0009	424±6
65.1	470	45	0.096	59400	0.027	0.0652±.0011	0.498±.009	0.0554±.0004	406±6
66.1	727	121	0.167	108	16.973	0.0539±.0009	0.437±.012	0.0589±.0011	336±5
67.1	291	24	0.081	16500	0.144	0.0667±.0011	0.502±.010	0.0545±.0005	416±6
68.1	344	54	0.158	8182	0.120	0.0675±.0011	0.508±.010	0.0546±.0005	421±6
69.1	74	4	0.060	1000000	0.342	0.0661±.0011	0.508±.013	0.0557±.0010	412±6

In keeping with normal laboratory practice (Compston and others, 1984), $^{206}Pb/^{238}U$, $^{207}Pb/^{235}U$ and $^{207}Pb/^{206}Pb$ ratios for zircons younger than 600 Ma were derived from 208-corrected data; however, in order to minimise the differential effects of common Pb correction, 207-corrected $^{206}Pb/^{238}U$ ages are reported. For zircons older than 900 Ma, these ratios were derived from 204-corrected data, and 204-corrected $^{207}Pb/^{206}$ ages are reported. f_{206} is the proportion of common ^{206}Pb to total ^{206}Pb, measured as a percentage.