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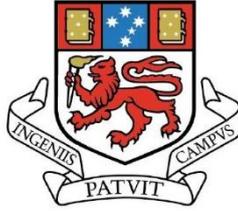
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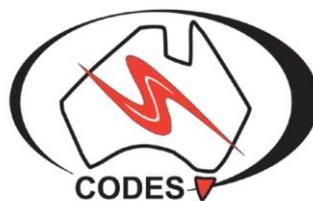
UNIVERSITY
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**TECTONIC ENVIRONMENT AND MINERAL
PROSPECTIVITY OF ROCKLEY-GULGONG VOLCANIC
BELT, OBERON REGION,
NEW SOUTH WALES, AUSTRALIA**

by

PEERAPONG SRITANGSIRIKUL

**A thesis submitted in fulfilment of requirements for the
Master of Science (Earth Sciences)**



CODES, ARC centre of Excellence in Ore Deposits
University of Tasmania (UTAS), Australia

September 2020

Declaration

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ABSTRACT

The Oberon region is dominated by two major lithological successions: The quartz-rich turbidite succession is represented by the Adaminaby Group comprising mainly medium- to thick-bedded sandstone, siltstone, shale, and thinly bedded chert with a minimum thickness of 750 m. The Adaminaby Group was deposited on the eastern Gondwana margin in a distal submarine fan. The other succession faulted against the Adaminaby Group is the Rockley-Gulgong Volcanic Belt of the Ordovician Macquarie Arc, which is represented by the Budhang Chert, the Triangle Formation, the Rockley Volcanics, the Fish River Breccia, and the Swatchfield Monzonite.

The Budhang Chert is characterized by moderately to highly deformed dark thin-bedded chert interbedded with siliceous mudstone ranging between Early to early Late Ordovician (Bendigonian-Gisbornian). The Middle to Late Ordovician Triangle Formation conformably overlies the Budhang Chert and comprises thin- to medium-bedded mafic volcanoclastic fine-grained sandstone and minor conglomerate with common greenschist facies. The Triangle Formation is overlain by Late Ordovician Rockley Volcanics. The Rockley Volcanics are composed of pyroxene-phyric mafic to ultramafic breccia, lava, and volcanoclastic conglomerate and sandstone. The Triangle Formation and the Rockley Volcanics are unconformably overlain by the Fish River Breccia. This is a new unit proposed in this study to describe pyroxene-plagioclase-rich mafic to intermediate volcanoclastic pebbly siltstone breccia occurring near the Fish River 5 km to the east of Oberon. This youngest unit contains minor quartz-rich sandstone clasts which indicate mixing between the Adaminaby Group and the Rockley-Gulgong Volcanic Belt.

Comparisons of the overall stratigraphy of the Macquarie Arc rocks in Oberon with the central Molong Volcanic Belt shows that the rocks around Oberon tend to be finer-grained and more distal to the volcanic centers that were active in the Ordovician.

Whole-rock geochemistry of the volcanoclastic and volcanic rocks was characterized as shoshonitic to high-K calc-alkalic with the Triangle Formation possibly correlated with Phase 2 magmatism of the Macquarie Arc and the Rockley Volcanics correlated to Phase 4 magmatism. The Fish River Breccia are correlated with the coarse conglomerates at the base of the Waugoola Group.

Detrital zircon U-Pb age determination from several quartz-rich sandstones in the Oberon and Black Springs region indicate maximum depositional ages in the Early to Late Ordovician. However, a slightly different provenance in the source of zircons was detected between the Oberon and Black Springs quartz-rich sandstones with a much larger 500 Ma peak in the sandstones from Oberon.

The Fish River Breccia contains detrital zircons that are uncommon in volcanic/volcanoclastic rocks of the Macquarie Arc with old continental-derived zircons recorded both in mineral separates and in situ in polished rock mounts suggesting that this unit is post-collisional deposit formed during the Silurian to Early Devonian.

U-Pb zircon age determinations and whole-rock geochemistry of intrusive igneous rocks in the Oberon region shows that the Swatchfield Monzonite is a Late Ordovician intrusion that may be made up of several intrusive bodies. The Greenslope Porphyry and

Racecourse Porphyry were determined as Early to Middle Silurian and are unrelated to the intrusive suites of the Macquarie Arc.

The whole-rock geochemistry, U-Pb age dating, and stratigraphy demonstrate that the Ordovician volcanic rocks of the Oberon region formed in a distal zone relative to the main volcanic centers and are less likely to host Cu-Au mineralization.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The Lachlan Orogen in central and southeastern New South Wales (NSW), Australia, contains a series of north-south-trending belts of folded Paleozoic metasedimentary and meta-igneous rocks. Some of the most critical rocks within the orogen are the Ordovician-Silurian rocks of the Macquarie Arc (Fig 1-1). The Macquarie Arc is a remarkably fertile belt which accommodates some of the largest gold deposits in Australia (Cadia, North Parkes, Cowal; Cooke et al., 2007). While the depositional environment of the central and western Macquarie Arc (i.e. the Molong Volcanic Belt) is well-characterized, there are limited studies on the paleo-tectonic environment and mineral prospectivity of the Rockley-Gulgong Volcanic Belt, located in the eastern part of the arc, approximately 70 km SE of Orange.

The study area is centered around the town of Oberon, in the Rockley-Gulgong Volcanic Belt of the Macquarie Arc (Fig 1-1). The oldest rocks in the area can be grouped as belonging to two major lithostratigraphic sequences (Fig 1-2):

1. The Ordovician quartz-rich turbidite sequences.
2. The Ordovician to Silurian high-K calc-alkaline mafic volcanic and volcanoclastic successions overlying a thick sequence of chert and shale.

Numerous proposals regarding depositional environment models of the Ordovician rocks in the Oberon area have been proposed (Aitchison and Buckman, 2012; Crawford et al., 2007b, 2007a; Fergusson, 2009; Fergusson and Colquhoun, 2018; Glen et al., 2007a; Meffre et al., 2007; Murray and Stewart, 2001; Percival and Glen, 2007; Zhang et al., 2019a; Zhang et al., 2019b; Zhang et al., 2020), however much work remains to be done in order to gain a thorough understanding of the tectonic evolution of the area. The interaction between the Ordovician quartz turbidite sequences and the Macquarie Arc has been the most challenging problem. Based on lithological and paleontological evidence, Murray (2002) and Murray and Stewart (2001) suggested that the Oberon region was located in the forearc of the Macquarie Arc above a west-dipping subduction zone leading to deposition of volcanoclastic material interbedded with pelagic sediments. Arc reversal was proposed to be the cause of the uplift and change in the arc's chemistry during the Late Ordovician (Fergusson, 2009; Meffre et al., 2007). Aitchison and Buckman (2012) presented an alternative model that the Macquarie Arc developed outboard on a different oceanic plate and subsequently collided with quartz-rich turbidites on the eastern edge of Gondwana margin. Conversely, Quinn et al. (2014) suggested that continental rifting led to the Macquarie Arc volcanism rather the subduction-related island arc origin outlined in previous studies.

In term of mineral prospectivity, the Oberon area is thought to have been located on the Lachlan Transverse Zone (LTZ), an important cross arc structure that is thought to have been important in controlling the location of Cadia and Northparkes (Glen et al., 1998; Glen and Walshe, 1999; Fig 1-1). The area is also thought to contain lateral equivalents of the Weemala Formation (Zhang et al., 2019b) and Forest Reef Volcanics which host the

mineralized porphyritic intrusive rocks in Cadia district (Fig 1-3). The mineralized porphyry intrusions at Cadia are oxidized, evolved shoshonitic magma systems with ages ranging between 460-435 Ma (Glen et al., 2007b). Evidence for intrusions of similar age and composition in the Oberon district are recorded at Swatchfield and Racecourse Prospect located at the southern part of the Oberon area in Black Springs (Benn, 2014; Meffre et al., 2007; Stewart-Smith and Wallace, 1997) indicating that the area may be prospective. However, the uncertainty on the age determinations are relatively large and more dating is required to determine if the intrusive rocks are part of the Macquarie Arc or part of the post-collisional extension and granite related magmatism.

Therefore, this study will primarily investigate the tectonic setting of the Oberon area during the Ordovician, compare the geology of that area with other blocks in the Macquarie Arc (e.g. Molong Volcanic Belt) and explore the prospectivity of porphyry deposits using a range of geological, petrological, geophysical, geochemical techniques and geochronological techniques.

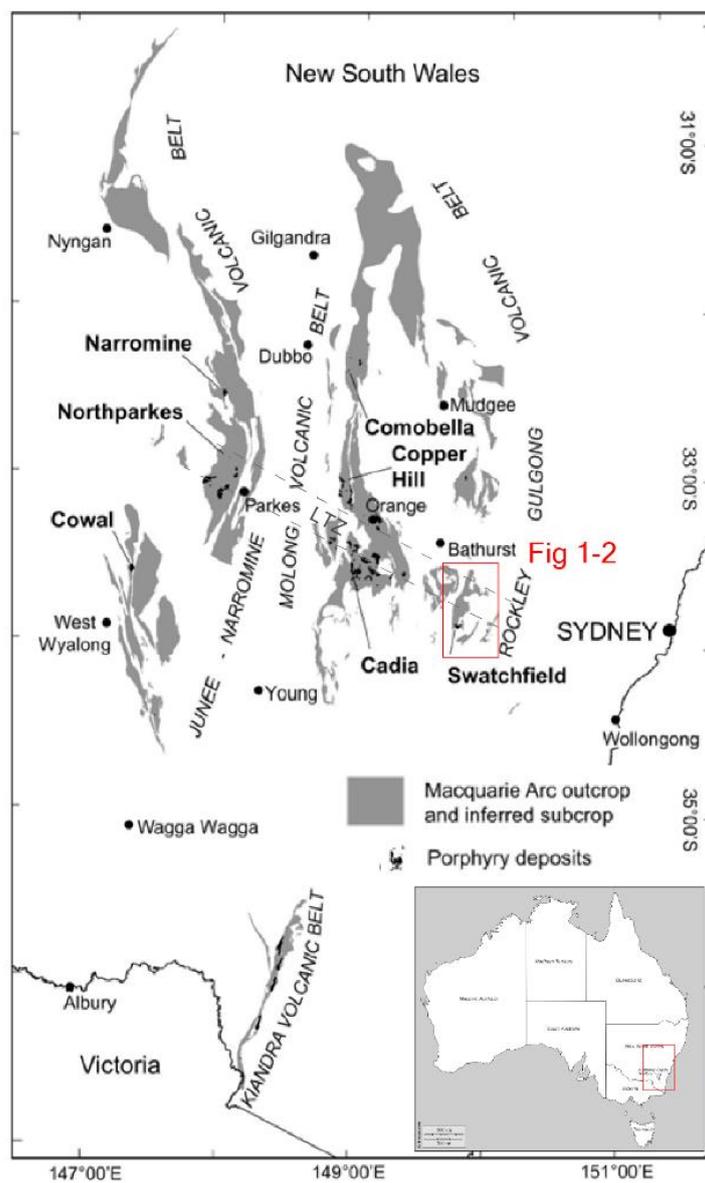


Fig 1-1 The north-south trending Ordovician Macquarie Arc and its four volcanic belts: Junee-Narromine, Molong, Rockley-Gulgong, and Kiandra (after Glen et al., 2007). Oberon, the proposed study area is in the red rectangle which is the southern part of the Eastern Volcanic Belt of Macquarie Arc. LTZ = Lachlan Transverse Zone

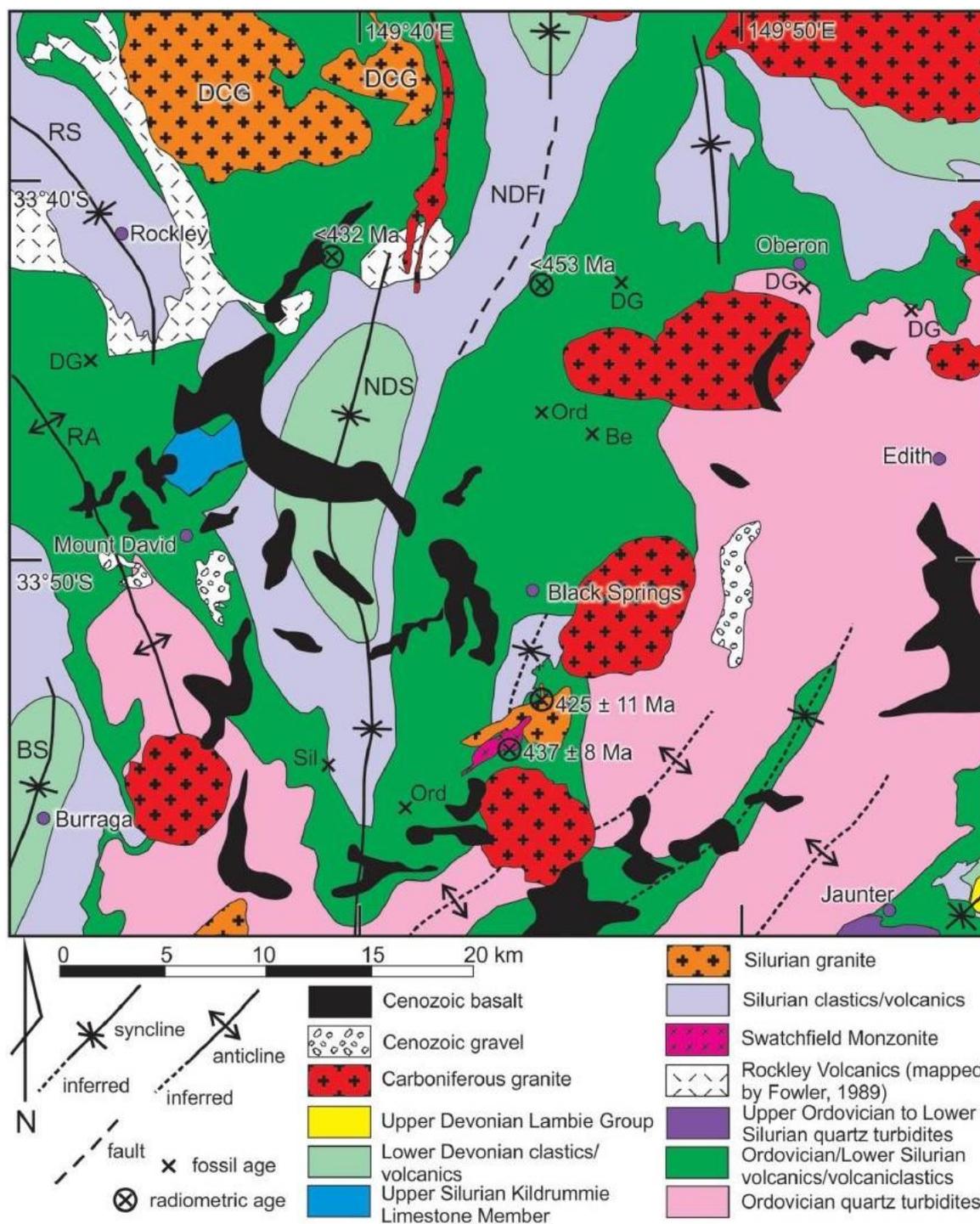


Fig 1-2 Geological map of Oberon region simplified by Fergusson and Colquhoun (2018) showing distribution of Ordovician quartz-rich turbidites and Ordovician-Silurian volcanic-volcaniclastic rocks the main focus of this study. Fossil ages and radiometric ages are also shown.

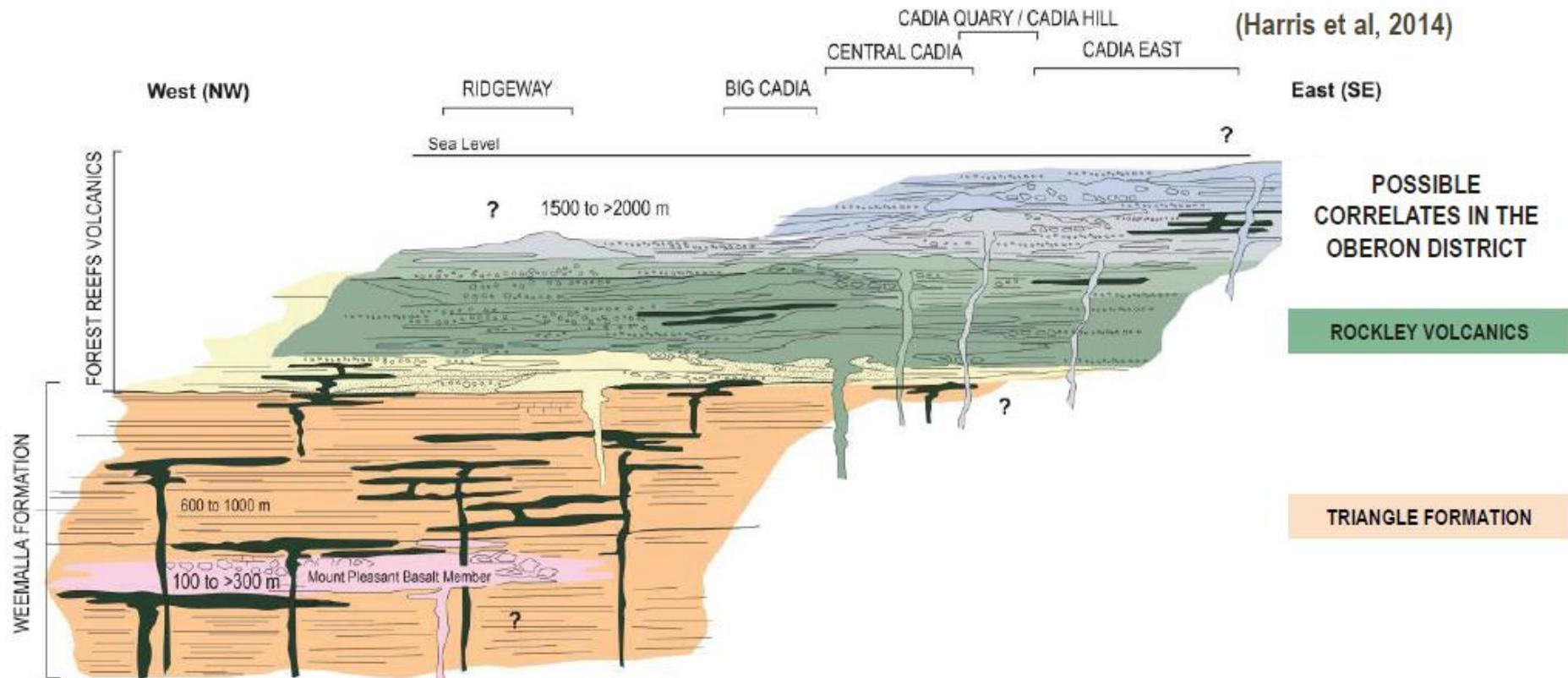


Fig 1-3 Graphic representation of the volcanic facies of the Cadia district shows the position of several key geographic location of ore deposits (Harris et al., 2014). This also indicates possible correlation between volcanic-volcaniclastic successions of the Cadia and Oberon district.

1.2 Aims

The broad aim of this research project is to provide an integrated examination of the geology, geochemistry and geochronology of the Oberon district and the adjacent area. Specifically, this project will fulfill the following objectives:

1. To investigate the tectonic environments of the Ordovician rocks found in Oberon.
 - To characterize and describe the relationship between the Ordovician quartz-rich turbidite and the Ordovician Macquarie Arc
 - To evaluate whether evidence of subduction polarity reversal occurred in this area
2. To examine the correlation of the Ordovician igneous rocks in Oberon with the rest of the Macquarie Arc.
 - To compare between volcanic facies architecture of the Molong Volcanic Belt and the Rockley-Gulgong Volcanic Belt
 - To record the distribution, age, and composition of plutonic rocks, particularly the Ordovician age.
3. To determine the potential, of the area for hosting porphyry Cu ore deposits in Oberon-Black Spring region.

1.3 Field investigation methods

1.3.1 Detailed field mapping in the Oberon area, New South Wales.

Two 2-week field seasons were undertaken during February-March 2017 and March 2018. The first visit involved working around the Oberon township including west and southwest of Lake Oberon to collect samples, lithological, and structural data. The data was documented in lithostratigraphic units (described in detail in Chapter 3). During the second field trip data was collected from the southeast of Oberon around Juanter. Also, during this trip, the boundary of the volcanic pebbly siltstone breccia unit sitting near the Fish River was mapped in detail. The geological data from the fieldwork, together with that from previous studies (e.g. Meffre, 2003; Stewart-Smith and Wallace, 1997 and Geological Survey of New South Wales), were used to make a new detailed district-scale geological map of the study area and assisted the selection of suitable samples for petrography, geochemistry and geochronology.

1.3.2 Sampling

Approximately 120 fresh and weathered rock samples were collected for petrography, geochemistry, and geochronology. The GPS location of each samples was recorded in a field notebook tabulated (see Appendix I).

1.4 Laboratory work

The following work was performed at the Centre for Ore Deposit Research (CODES) and the Central Science Laboratory (CSL), University of Tasmania:

1.4.1 Sample selection.

Approximate 120 samples were chosen from the rock units in the research area. The rocks were then grouped systematically according to their characteristics, and the least altered and weathered were chosen for further analysis.

1.4.2 Petrography

Sixty thin sections were examined under the transmitted and reflected light. Each was described in detail and used to describe the various lithology that occur in the Oberon region. The petrography focused both on the original magmatic and detrital minerals as well as on the alteration assemblages.

1.4.3 Whole-rock Geochemistry.

The whole-rock geochemistry of volcanic, volcanoclastic and plutonic rocks were analysed at CODES using the X-ray fluorescence spectrometer (XRF) to help correlate the Oberon samples with that from the other belt of the Macquarie arc and other lithological units in the region. In particular the geochemistry of rocks from the Oberon area were placed within the Phase 1 to 4 stratigraphy of Crawford et al. (2007b) that has been documented from Molong and Parkes areas.

1.4.4 Geochronology

Thirty rock samples analysed to help constrain the geological evolution of the study area. The samples were crushed and datable minerals, namely zircon, monazite, apatite, and titanite, were separated for U-Pb geochronology. Prior to analysis, the samples were examined using the scanning electron microscope. The minerals were then analysed using the laser ablation ICP-MS at CODES to determine the age of rocks. Detailed methodology description is presented in beginning of each of the relevant chapters and in the appendix.

1.5 Thesis structure

This thesis is divided into the following chapters:

- Chapter 2 includes (a) the regional geology and tectonic setting of the Lachlan Orogen; (b) the regional geology and magmatism evolution of Macquarie Arc; (c) and the regional geology of Rockley-Gulgong Volcanic Belt.
- Chapter 3 presents a new detailed geological map of Oberon including new rock units supported by lithological evidence and petrographic work. The contact relationship between Ordovician quartz-rich turbiditic successions and Rockley Volcanics is examined in detail.
- Chapter 4 shows geochemical data including major elements, trace elements and rare earth elements of (a) Ordovician quartz-rich sandstone; (b) Ordovician-Silurian intermediate-mafic volcanic/volcanoclastic rocks of Rockley Volcanic Belt; and (c) intrusive rocks from Swatchfield, Greenslope and Racecourse.
- Chapter 5 introduces new geochronological data of (a) quartz-rich sandstone from around Oberon and Black Spring; (b) volcanic pebbly siltstone breccia; (c) mafic volcanic breccia; and (d) intrusions exposed near Black Springs and Native Dog Fault called Swatchfield, Greenslope and Racecourse respectively.

- Chapter 6 involves discussion of tectonic environment and mineral prospectivity of Oberon region.
- Chapter 7 concludes the project in terms of regional tectonic setting of the study area.

CHAPTER 2: REGIONAL GEOLOGY

This chapter presents the regional geology and tectonic evolution of Lachlan Orogen, particularly, the Ordovician rocks occurring in eastern part of the package of rocks. The geological setting of the Macquarie Arc is also discussed here based on the existing literature. In the final part of the chapter the district-scale geology of the Oberon area is described standing on previous studies to introduce the detailed geology of the study area. The new data from this research will be presented and discussed in next chapters.

2.1 Lachlan Orogen

2.1.1 Introduction

The Lachlan Orogen was formed along the eastern margin of Gondwana during the Ordovician to Carboniferous (486-368 Ma) after a convergent margin developed in eastern edge of paleo-Pacific Ocean during the Delamerian Orogeny (520-490 Ma). The Lachlan Orogen is one of an internal subdivision of Tasmanides which encompasses the Lachlan, Thompson, New England and Delamerian Orogens (Musgrave, 2015). The rocks within the Tasmanides were formed on the southern and eastern margin of Gondwana following the final stages of the break-up of the Rodinia Supercontinent in the Neoproterozoic (Glen, 2013, 2005; Glen et al., 2012, 2009). The rocks from the Lachlan Orogen crop out throughout central and southern New South Wales including most of Victoria and eastern Tasmania (Fig 2-1). This Orogen preserves Cambrian to Carboniferous rocks formed as the results of collisions between oceanic island arc in proto-Pacific Ocean and continental blocks from south-eastern Gondwana (Aitchison and Buckman, 2012; Meffre et al., 2007) or continuous west-dipping subduction along the plate margin (Fergusson, 2009, 2003; Glen, 2013, 2005). The Lachlan Orogen can be divided into three major subprovinces: the western, central, and eastern subprovinces.

2.1.2 Western and Central subprovinces

Generally, the Western subprovince contains Cambrian to Ordovician basement rocks including (i) boninitic volcanic rocks, (ii) backarc-related tholeiitic basalts and (iii) calc-alkaline volcanic rocks (Fergusson, 2003). These rocks are underlain or juxtaposed by deep-marine sedimentary rocks of chert, quartz-rich turbidites and graptolitic black shale. Age constraints indicate that the turbidites progradated from the west to the east in the Western subprovince (Fergusson, 2003; Glen et al., 2009).

The Ordovician turbidites and overlying black shales also occur in the central subprovince (Fergusson, 2003; Glen et al., 2009). These turbidite successions are spatially associated with the underlying Cambrian tholeiitic and boninitic igneous rocks similar to the Western subprovince (Fergusson, 2003).

2.1.3 Eastern subprovince

The study area is in eastern part of the Eastern subprovince. The Ordovician rocks, mainly consist of two successions: the quartz-rich turbidite successions which tends to occur in the southern and eastern part of the subprovince and the high-K calc-alkaline

intermediate to mafic volcanic, volcanoclastic rocks, intrusive rocks and limestone of the Ordovician Macquarie Arc (Fig 2-1) which tend to occur in the north and west of the area. The tectonic settings of the two successions have been strongly debated. Most previous studies suggested that the Macquarie Arc was located above a west-dipping subduction zone throughout the Early-Middle Ordovician (Fergusson, 2009, 2003; Fergusson and Colquhoun, 2018; Glen et al., 2007b, 2007a, 1998; Meffre et al., 2007; Percival and Glen, 2007). Aitchison and Buckman (2012) and Meffre et al. (2007) proposed that an arc reversal or subduction polarity flip occurred in the late-Middle Ordovician (460-450 Ma) which explain the uplift and change in the chemistry of the arc (Fig 2-2). Zhang et al. (2019a, 2019b and 2020) also presented new results of geochronology and geochemistry which suggest that the Macquarie Arc initiated in a different oceanic plate away from Gondwana margin and later collided with the continent during westward subduction which commenced the Benambran Orogeny. On the contrary, Quinn et al. (2014) proposed an alternative model of the Macquarie Arc based on the stratigraphic architecture suggesting that the arc was formed during continental rifting in a back-arc setting. This model directly opposes the previous interpretation of the Macquarie Arc as being a subduction-related intra-oceanic island arc. One of the weak points of this model is that it still lacks direct supporting evidence and fails to explain how the back-arc closed without initiating a subduction zone.

This controversy is addressed by one of the aims of this research which involves acquiring data to better constrain the tectonic environment of the Rockley-Gulgong Volcanic Belt in the Eastern subprovince.

2.2 Ordovician Adaminaby Group

Most of the Ordovician continental-derived sedimentary rocks in the Lachlan Orogen comprise Lower and Middle Ordovician quartz-rich turbidites overlain by Upper Ordovician black shale associated with minor tholeiitic igneous rocks (Fergusson, 2003; Fergusson and Colquhoun, 2018; Glen, 2013, 2005; Glen et al., 2009; Meffre et al., 2007; Percival and Glen, 2007). These strata were derived from the Neoproterozoic to Cambrian continental margin during the Delamerian Orogeny (Glen et al., 2017). The Ordovician Adaminaby Group thickness are mostly unconstrained apart from a few with some well-dated sections defined by biostratigraphy or U/Pb detrital zircon ages (Crawford et al., 2007b; Fergusson and Colquhoun, 2018; Glen et al., 2007b; Meffre et al., 2007; Murray and Stewart, 2001; Zhang et al., 2019b). Thin-bedded chert and siliceous mudstone are typically found in lower and upper part of the succession but some of them contains fossils indicating specific ages (Fig 2-3; Crawford et al., 2007; Fergusson and Colquhoun, 2018; Murray, 2002; Murray and Stewart, 2001; Quinn et al., 2014). The inherited population ages of detrital zircons from the Ordovician turbidites range in three groups between 620-490, 800-690 and 1200-1050 Ma with some much older dating back to 3450 Ma (Fergusson and Colquhoun, 2018; Forster et al., 2011; Glen, 2013; Glen et al., 2011; Kemp et al., 2009; Meffre et al., 2007; Shaanan et al., 2017). Many previous studies suggested that the Ordovician turbidites deposited in mega submarine fan on an ocean floor or thinned continental crust then incorporated into a subduction complex (e.g. Aitchison and Buckman, 2012; Fergusson, 2003; Glen et al., 2007a, 1998; Meffre et al., 2007; Zhang et al., 2019a and b). Alternatively, Quinn et al. (2014) suggested that the turbidites were deposited as a part in sequences of uplift, collapse, and ocean basin development. However,

this hypothesis fails to explain how the Adaminaby Group contains neither volcanic materials nor syn-deposition detrital zircons which are typical in passive margin sequences.

In the Oberon region, the Ordovician quartz-rich turbidites are widely exposed and belong to the Adaminaby Group (Fig. 2-4, 2-5). Most of the Ordovician quartz-rich successions preserve highly deformed bedding showing broken, discontinuous and folded strata which are typically found in Adaminaby Group (Meffre et al., 2007).

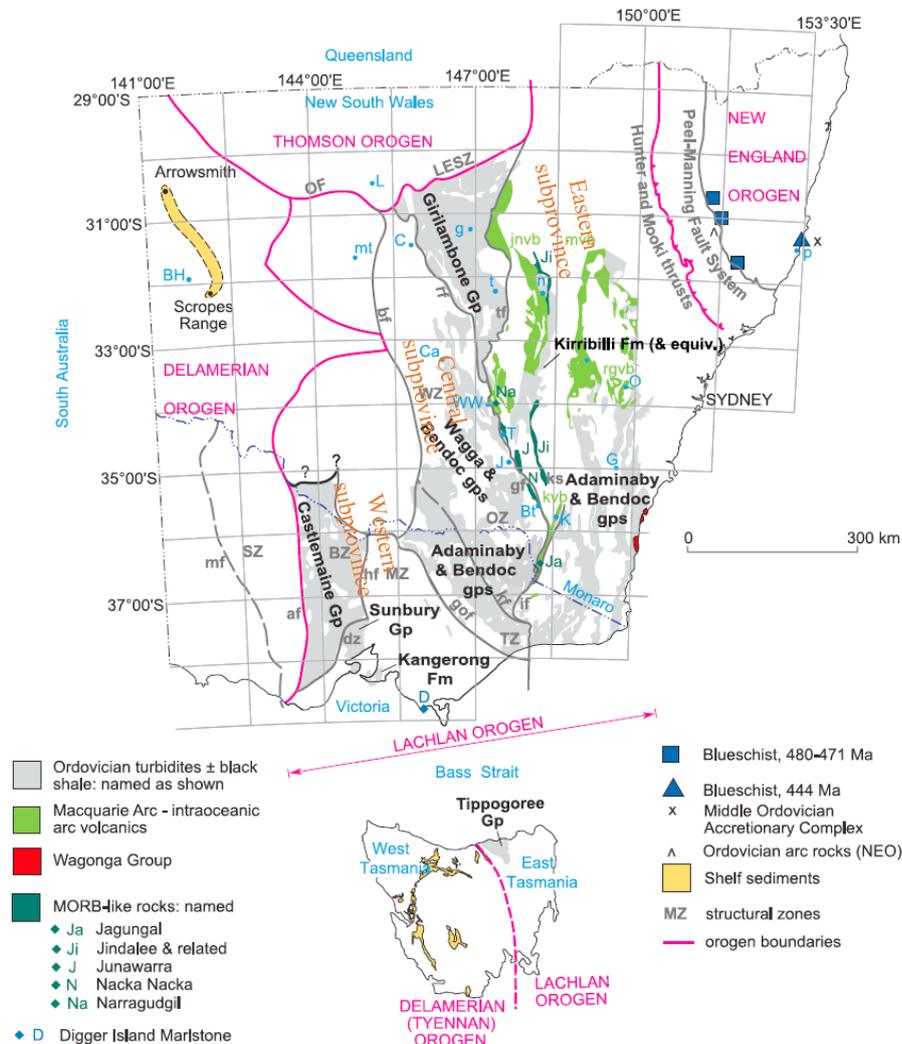


Fig 2-1 Ordovician geology of the Lachlan, Delamerian, and New England orogens of New South Wales and Victoria from Glen et al. (2009) showing two dominant successions of quartz-rich turbidites and Macquarie Arc. Abbreviations for structural subdivisions are SZ, Stawell Zone; BZ, Bendigo Zone; MZ, Melbourne Zone; TZ, Tabberabbera Zone; OZ, Omeo Zone; WZ, Wagga Zone. Abbreviations for fault names are mf, Moyston Fault; af, Avoca Fault; hf, Heathcote Fault Zone; dz, Djerriwah Fault; gof, Governor Fault Zone; kf, Kancoona and Kiewa faults; bf, Boothergandra Fault and extensions; if, Indi-Long Plain Fault; gf, Gilmore Fault Zone; tf, Tullamore Fault; ks, Kiandra-Narromine Structure; rf, Rookery Fault System; OF, Olepoloko Fault; LESZ, Louth-Eumarra Shear Zone. Abbreviations for geographic locations are BH, Broken Hill; Bt, Batlow; C, Cobar; Ca, Cargelligo; G, Goulburn; g, Girilambone; J, Junee; L, Louth; mt, Meadows Tanks, n, Narromine; O, Oberon; p, Port Macquarie; T, Temora; t, Tottenham; WW, West Wyalong.

2.3 Macquarie Arc

2.3.1 Tectonic setting

The Macquarie Arc is interpreted by most previous studies to have formed in a supra-subduction environment during Ordovician to the earliest Silurian. The arc is mostly comprised of mafic-intermediate volcanic and volcanoclastic rocks with minor limestone, chert and intrusions (Cooke et al., 2007; Crawford et al., 2007b, 2007a; Fergusson, 2009; Fergusson and Colquhoun, 2018; Glen et al., 2007b; Meffre et al., 2007; Percival and Glen, 2007; Squire and Crawford, 2007). The arc is preserved in four structural belts located at Eastern subprovince of Lachlan Orogen (Fig. 2-1 and 2-4). The four N-S trending volcanic belts are the Junee-Narromine Volcanic Belt, Molong Volcanic Belt, Rockley-Gulgong Volcanic Belt, and Kiandra Volcanic Belt (Crawford et al., 2007b; Glen et al., 2012, 2007b; Meffre et al., 2007; Percival and Glen, 2007). From an economic geology perspective the arc is one of the most important volcanic belts in eastern Australia because it hosts a significant world-class porphyry Cu-Au deposits at Cadia in the Molong Volcanic Belt, and at Northparkes in Junee-Narromine Volcanic Belt (Cooke et al., 2007; Glen et al., 2007a; Scheibner, 1999) as well a number of epithermal and orogenic deposits (e.g. Lake Cowal, Tomingley).

Lachlan Transverse Zone (LTZ) (Fig. 2-4) is an area or corridor of second order structures that crosses the primary N-S trending faults within the Lachlan Orogen (Glen and Walshe, 1999). Porphyry and epithermal mineralization at Cadia, Northparkes, and Cowal districts, and the Oberon area which is the focus of this study are all located within the LTZ (Fergusson, 2014; Glen et al., 2007c; Glen and Walshe, 1999).

2.3.2 Macquarie Arc Magmatism

Crawford et al. (2007b) and Percival and Glen (2007) defined four magmatic phases using the geochemical and biostratigraphic information combined with U-Pb and Ar-Ar geochronology collected from the Macquarie Arc (Fig 2-3). Each phase is separated by hiatus and/or limestone development which represent breaks in the volcanic activity and/or erosion of small volume volcanic material.

Phase 1: Early Ordovician (ca 489-474 Ma)

Volcanic and intrusive rocks formed in the first magmatic phase crop out in the Molong and the Junee–Narromine Volcanic Belts. These rocks are calc-alkaline high-to medium-K (locally shoshonitic) basaltic-andesitic volcanic and volcanoclastic rocks which interfinger with discontinuous limestone. These carbonates are considered to have been deposited shallow water and then reworked into deep-water. The volcanic rocks are interbedded with fine-grained rocks containing Early Ordovician graptolites and conodonts indicating a deposition age between 480-476 Ma (Percival and Glen, 2007; Crawford et al., 2007b). Glen et al. (2011) reported U-Pb zircon ages of 481 Ma from the monzonitic intrusion with some detrital zircon populations from a Phase 1 volcanoclastic rock contain a small amount of ancient continental derived zircons indicating an early continental influence in the Macquarie Arc. However, Zhang et al. (2019a) presented unimodal U-Pb zircon ages of 479.8 ± 3.8 Ma from Phase 1 Mitchell Formation in Molong Volcanic Belt with no pre-Ordovician zircons suggesting that there was no continental influence.

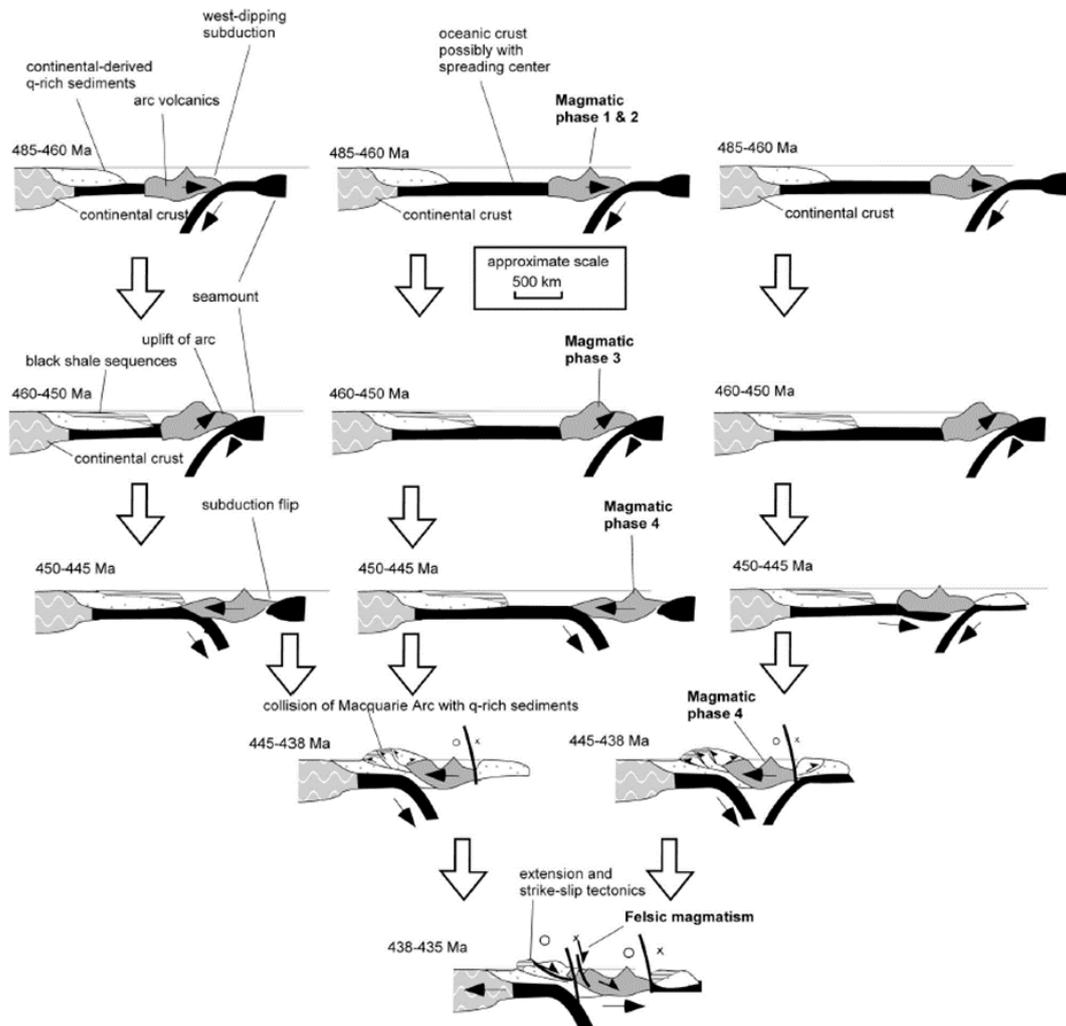


Fig 2-2 Tectonic reconstruction model proposed by Meffre et al. (2007) suggested both West- and East-dipping subduction throughout the Ordovician Macquarie Arc formation.

A hiatus in volcanism of approximately 9 million years is recognized across the belts after the end of Phase 1 magmatism (Percival and Glen, 2007). During this hiatus, some of the Lower Ordovician sequence was uplifted and eroded and redeposited into sediments associated with the second phase magmatism (Crawford et al., 2007b; Percival and Glen, 2007).

Rock belonging to Phase 1 magmatism have not been documented in the Oberon area. However the Lower Ordovician Budhang Chert (Murray and Stewart, 2001) which underlie the fine-grained volcanoclastic siltstone and sandstone is coeval with the Phase 1 magmatism (Fig 2-3).

Phase 2: Middle to Late Ordovician (ca 466-454 Ma)

The second magmatic phase produced Middle Ordovician medium-K calc-alkaline lavas, medium- to high-K dioritic to monzodioritic intrusions, and medium- to dominantly high-K calc-alkaline volcanic and volcanoclastic rocks (Crawford et al., 2007b). Well-defined overlying limestone deposition widely occurs related to the Macquarie Arc magmatism of Phase 2 indicating a gap of volcanism in the area which can be observed

clearly in Junee-Narromine and Molong Volcanic Belt (Crawford et al., 2007b). However, Glen et al. (2011) reported the volcanism detrital U-Pb ages of 468-455 Ma from two volcanoclastic units which are interpreted as submarine Phase 2 volcanism. Conodonts from chert fragments occurring between Junee-Narromine and Molong Volcanic Belt indicate older and/or similar age to Phase 2 arc magmatism (Glen et al., 2012; Quinn et al., 2014).

In the southern Rockley-Gulgong Volcanic Belt, Phase 2 magmatism is represented by the Triangle Formation and Gidyen Volcanics then continue into the overlying Rockley Volcanics (Fig 2-3; Crawford et al., 2007b; Percival and Glen, 2007; Stewart-Smith and Wallace, 1997). Nevertheless, Glen et al. (2012) illustrates volcanic and volcanoclastic in Rockley and Oberon regions as Phase 4 magmatism (Fig 2-4) based on age and geochemical constraints. According to paleontological data, the upper Triangle Formation, which contains late Middle Ordovician conodonts, can be correlated with Mozart Chert and lower chert-rich part of the Sofala Volcanics. At the end of Phase 2, the Late Ordovician volcanic hiatus is characterized by carbonate accumulation in the various belts (Crawford et al., 2007b; Percival and Glen, 2007; Squire and Crawford, 2007). Zhang et al. (2019b) reported new U-Pb zircon ages of 456 ± 16 Ma and Ordovician graptolite from Triangle Formation from Bald Ridge area which indicate the Triangle Formation is Middle to Late Ordovician.

Phase 3: Late Ordovician (ca 454-443 Ma)

Phase 3 magmatism is represented by a widespread but relatively small volume magmatic event, dominated by shallow intrusive rocks of the Copper Hill Suite between 456 and 441 Ma. These distinctive porphyritic dacites as well as the associated holocrystalline diorites and granodiorites show medium-K calc-alkaline compositions. Their emplacement is also linked to a period of regional uplift, erosion and limestone deposition in the Junee–Narromine Volcanic Belt and the western Molong Volcanic Belt (Crawford et al., 2007b; Glen et al., 2012; Percival and Glen, 2007).

Phase 4: Late Ordovician to earliest Silurian (ca 457-438 Ma)

The fourth magmatic phase is characterized by lavas and intrusive porphyries with highly shoshonitic geochemistry (Fig 2-3). This magmatic event began after the second hiatus in the Junee–Narromine and the western Molong Volcanic Belts during Late Ordovician (Crawford et al., 2007b; Percival and Glen, 2007). In the eastern Molong Volcanic Belt and the northern Rockley–Gulgong Volcanic Belt, this fourth phase is represented by a similar significant petrologic and geochemical change which was not precisely constrained in age except by correlation Late Ordovician graptolite bearing rocks (Percival and Glen, 2007).

Crawford et al. (2007b), using geochemical correlations, identified in the Oberon area high-K magmatism from Phase 2 (Triangle Formation or Mozart Chert and Gidyen Volcanics) and high-MgO lavas shoshonitic magmatism from Phase 4 (Rockley Volcanics). These can be correlated with Weemala Formation and Forest Reef Volcanics in the Molong Volcanic Belt, which hosts the porphyry Cu-Au deposits (Crawford et al., 2007b; Harris et al., 2014; Percival and Glen, 2007). Post-Phase 4 felsic intrusions with shoshonitic affinities and high-Th and high-Nb are observed in the Macquarie Arc, especially in Junee-Narromine and the Molong Volcanic Belts (Crawford et al., 2007a). In

Black Springs, southwest of Oberon, the Swatchfield Monzonite, Greenslope Porphyry and Racecourse Porphyry are proposed to be correlated with the post-Phase 4 magmatism Fig 2-5 (Benn, 2014; Meffre, 2003; Meffre et al., 2007; Stewart-Smith and Wallace, 1997).

At the end of Phase 4, subduction stopped probably due to collision with parts of the eastern margin of Gondwana, and arc dismemberment and extension began (Crawford et al., 2007b; Glen et al., 2007b, 2007c; Percival and Glen, 2007).

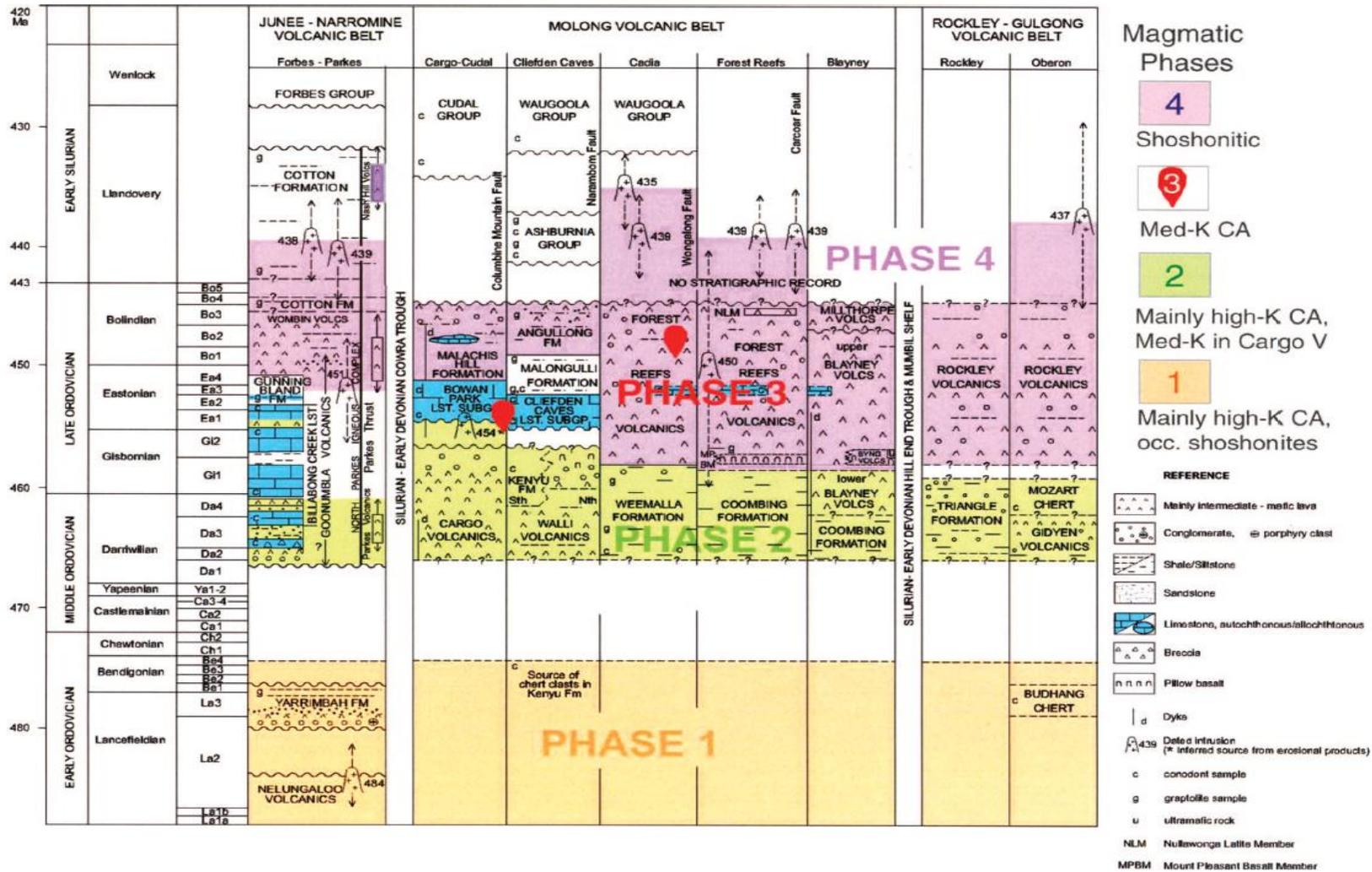


Fig 2-3 The color-coded lithostratigraphic column of the Macquarie Arc shows the magmatic affinities of the major lithostratigraphic units, and the Magmatic Phases 1 – 4 in the Ordovician history of the arc (Crawford et al., 2007b; Percival and Glen, 2007).

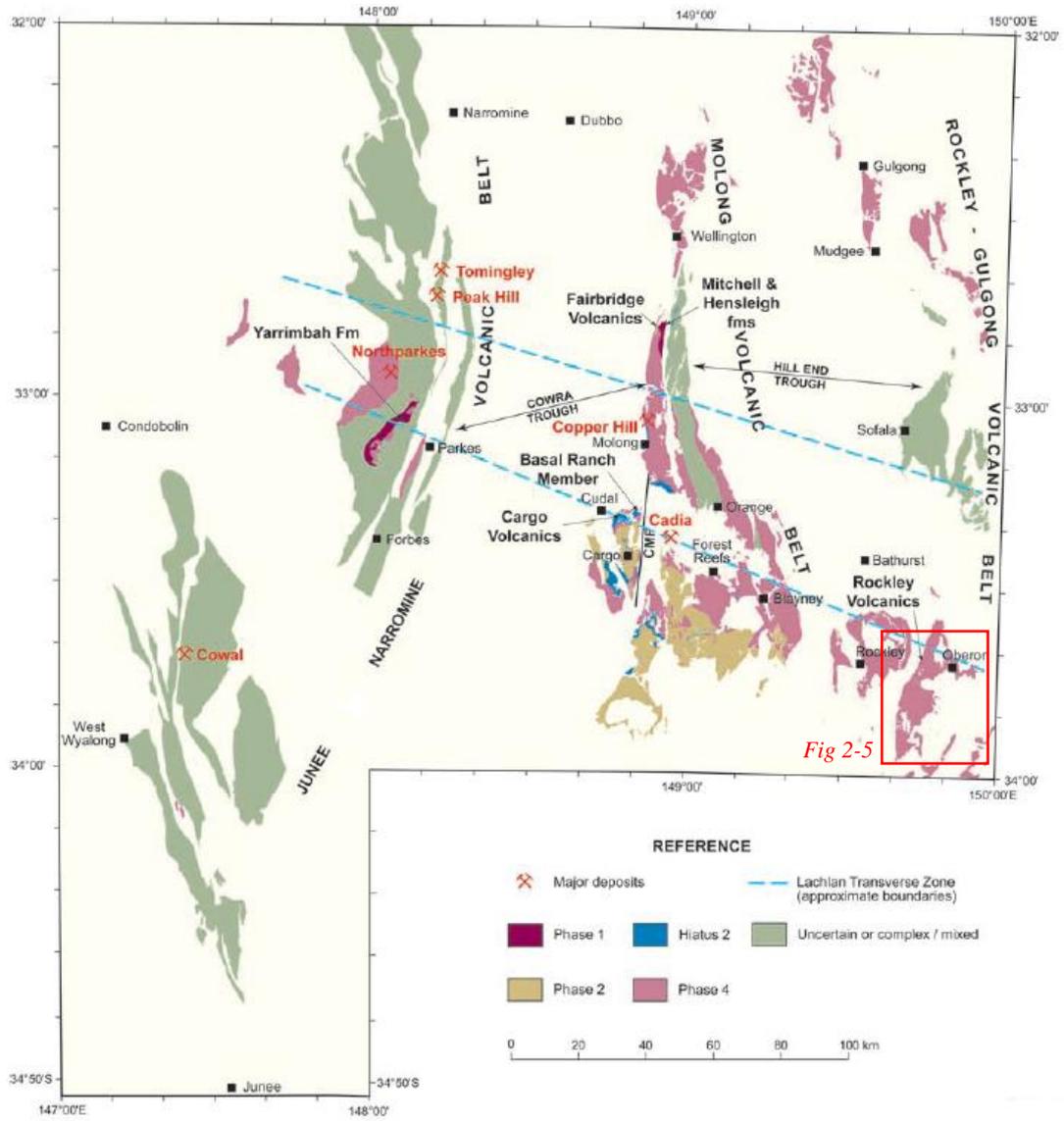


Fig 2-4 Detail of three belts of Ordovician Macquarie Arc showing magmatic phases (Glen et al., 2012)

2.4 Geology of Oberon

2.4.1 Adaminaby Group

The Adaminaby Group is recognized as Ordovician quartz-rich turbidites occurred in all around the eastern subprovince of the Lachlan Orogen (Fergusson, 2003; Glen, 2013; Glen et al., 2009). In the Oberon area, the Adaminaby Group crops out broadly in the southern part of the Oberon 1: 100,000 map sheet area (Fig 2-5). The group was thought to be conformably overlain by the Triangle Formation (Pogson and Watkins, 1998; Stewart-Smith and Wallace, 1997) However, the detailed mapping by Fergusson and Colquhoun (2018) and Meffre et al. (2007) show a fault contact between these units. The quartz-rich sandstones in the Oberon area contain Ordovician (Darriwillian–Gisbornian) conodonts and are much less deformed than the Adaminaby Group in the west region of this area such as at Rockley (Murray and Stewart, 2001; Percival and Glen, 2007).

2.4.2 Budhang Chert

The Budhang Chert is one of the very fine-grained volcanoclastic unit in the Oberon area. This unit was originally described as the lowest unit in the Rockley-Gulgong Belt by Murray and Stewart (2001) and previously defined this unit as one of the Triangle Formation. However, Percival and Glen (2007) reassigned the Budhang Chert to the Adaminaby Group despite the fact that the sample is far from the contact with the Adaminaby Beds. Murray and Stewart (2001) also reported that Budhang Chert contains a deep-water Early Ordovician conodont fauna (Fig 2-3). The Budhang Chert may also be correlated with Yarrimbah Formation in Junee-Narromine Volcanic Belt in west Macquarie Arc (Glen et al., 2007b). A sample was also analysed by Bruce and Percival (2014) which showed that the chert is similar to other cherts in the Lachlan Orogen plotting in the continent margin cherts on geochemical discrimination diagrams.

2.4.3 Triangle Formation

The Triangle Formation contains mostly fine grained volcanoclastic material interbedded with chert and intermediate-mafic volcanoclastic sandstone, siltstone with partly plagioclase-rich andesitic-basaltic breccia (Crawford et al., 2007b; Glen et al., 2009, 2007b, 2007a; Meffre et al., 2007; Percival and Glen, 2007; Pogson and Watkins, 1998; Scheibner, 1999; Squire and Crawford, 2007; Stewart-Smith and Wallace, 1997; Zhang et al., 2019b). The Triangle Formation is well exposed in the Rockley and Oberon area. The Triangle Formation crops out around Rockley region from Triangle Creek in the north to Bald Ridge in further south. Also, Black Springs, and the area between Native Dog Fault and Lake Oberon (Fig 2-5; Meffre et al., 2007; Pogson and Watkins, 1998). The Triangle Formation is correlated to the second phase magmatism of the Macquarie Arc regarding stratigraphic correlation and paleontological data (Crawford et al., 2007b; Murray, 2002; Percival and Glen, 2007). However, recent Middle to Late Ordovician zircons reported by Zhang et al. (2019b) indicate that the Triangle Formation may be related to the final magmatism phases of the Macquarie Arc and formed as trench-fill deposit derived from both Macquarie Arc and Gondwana margin (Adaminaby Group).

2.4.4 *Rockley Volcanics*

The Rockley Volcanics correlate with Phase 4 magmatism of Macquarie Arc (Crawford et al., 2007b). The lithological descriptions of the Late Ordovician Rockley Volcanics are massive to flow banded, coarsely to finely porphyritic, partly schistose, greenschist-facies clinopyroxene-phyric basaltic breccia interbedded with volcanoclastic siltstone and slightly deformed bedded chert (Meffre et al., 2007; Pogson and Watkins, 1998). The Rockley Volcanics conformably overlie the Middle Ordovician volcanoclastic Triangle Formation in Rockley and Oberon area (Meffre et al., 2007; Percival and Glen, 2007; Pogson and Watkins, 1998; Stewart-Smith and Wallace, 1997). In the Racecourse prospect area, southwestern Black Springs; Fig 2-5, the Rockley Volcanics are locally represented as crystal-rich volcanoclastic sandstone and breccia which hornblende is recognized as the most significant mafic mineral (Benn, 2014). In terms of stratigraphic correlation, the Rockley Volcanics are correlated with the Forest Reef Volcanics occurring in Molong Belt (Crawford et al., 2007b).

2.4.5 *Swatchfield Monzonite*

The Swatchfield Monzonite was introduced as Late Ordovician shoshonitic mafic intrusive rock occurring with uncertain boundary in Black Springs (Glen et al., 2007b; Meffre et al., 2007; Stewart-Smith and Wallace, 1997). Meffre (2003) and Meffre et al. (2007) used ICP-MS zircon U-Pb dating to define the age of the monzonite showing it is Early Silurian rock (437 ± 8 Ma). The Swatchfield Monzonite locally intruded both the Triangle Formation and Rockley Volcanics, therefore, indicating this intrusion is post-Phase 4 magmatism (Meffre et al., 2007; Percival and Glen, 2007) which possibly correlates with other similar age of shoshonitic rocks in Junee-Narromine and Molong Volcanic Belt that host the porphyry Cu-Au deposition (Cooke et al., 2007; Crawford et al., 2007b).

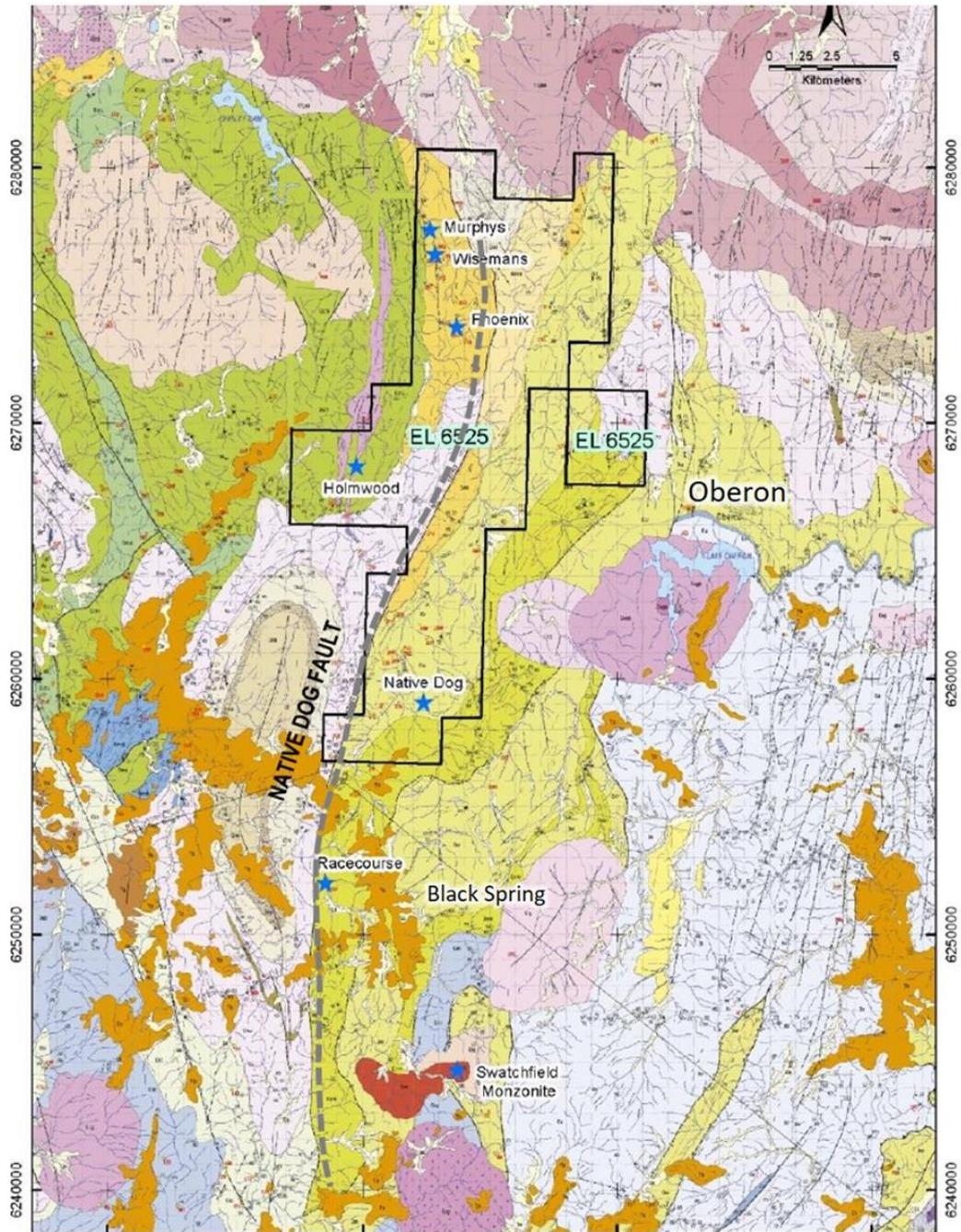


Fig 2-5 Part of the modified Oberon geological map sheet 1: 100,000 (Stewart-Smith and Wallace, 1997) showing geology in the Oberon area which is bounded by the Native Dog Fault (grey dotted line) to the West. Exploration zone number EL-6525 from Nethery (2014) is indicated by the black polygon which covers the areas that have mineralization potential (blue star symbol).

CHAPTER 3: GEOLOGY OF OBERON

3.1 Introduction

This chapter presents new detailed geology of the Oberon area, including a new rock unit based on the results of geological mapping and petrography (see field observation and rock sample detail in Appendix I). The contact relationship between Ordovician quartz-rich turbiditic successions and Rockley Volcanics were also examined and the results of this investigation are presented in the final part of this chapter.

The Oberon study area is geographically located approximately 70 km to the southeast of Orange, New South Wales (Fig 2-4). The area comprises dominantly of farmland, a small area of forest reserves, a lake used for irrigation and a local town center near the lake. Numerous numbers of rock exposures crop out along the local roads, which were used to access the rocks examined and sampled in this study. Hence, road-cut outcrops were the primary target for the fieldwork.

According to 1:100,000 Oberon geological map sheet (Stewart-Smith and Wallace, 1997), this area composed of various rock units ranging from Ordovician to Carboniferous as well as Cenozoic basalt (Late Eocene, 34 Ma; Pogson and Watkins, 1998) and quaternary alluvium. The area is dominated by two contrasting sedimentary successions with similar ages (Early-Late Ordovician): a quartz-rich turbidite succession and low- to high-K calc-alkaline intermediate to mafic volcanic/volcaniclastic rocks (Crawford et al., 2007; Fergusson and Colquhoun, 2018; Glen et al., 2007; Meffre, 2003; Meffre et al., 2007; Murray, 2002; Murray and Stewart, 2001; Percival and Glen, 2007; Stewart-Smith and Wallace, 1997). The Ordovician stratigraphy in the eastern Lachlan subprovince is complicated by its structural complexity and paucity of index fossils that can be used for detailed biostratigraphic correlation. Correlation is possible, but it is difficult to accurately determine each unit's thickness (Crawford et al., 2007b; Fergusson and Colquhoun, 2018; Glen et al., 2007b; Murray, 2002; Percival and Glen, 2007; Quinn et al., 2014). Therefore, the stratigraphic correlation between Rockley-Gulgong Volcanic Belt and Molong Volcanic Belt is addressed here based on age constraint, geochemistry, and lithology observations from the previous and this study. Post-Ordovician sedimentary deposits and intrusive rocks are also described in this chapter. Although these rocks are not as complex as the those from the Ordovician, but they play an important role in illustrating the geological history of the area.

3.2 Ordovician

The Ordovician rocks cropping out in Oberon include two major lithological sequences; quartz-rich turbidites of Adaminaby Group and volcanic/volcaniclastic rocks of Macquarie Arc magmatism. The field observations from this study focussed on differentiating these Ordovician successions and the nature of the contact between the two units, which is critical to tectonic models.

3.2.1 Adaminaby Group

Nomenclature and distribution

The Adaminaby Beds were originally named by Adamson (1951) for the sequences of Ordovician turbidites, chert and shale at Adaminaby Town near Snowy Mountains. Later, the name was published by Fairbridge (1953) to describe metasedimentary rocks in Snowy Mountains, New South Wales. Glen et al. (1990) and Pogson and Watkins (1998) using the term “Adaminaby Group” as a representative of Ordovician quartz-rich turbidite and chert submarine fan deposits which occur widely in the eastern part of the Lachlan Orogen. Murray (2002) divided Adaminaby Group found in Oberon-Taralga and adjacent area into 3 different formations: 1) undifferentiated Adaminaby Group, 2) Numeralla Chert and 3) Bumballa Formation.

The Adaminaby Group broadly crops out in southern-half of the Oberon 1:100,000 map sheet area and occupies the center of a big anticline in the southwest corner of the map sheet (Fig 3-1; Pogson and Watkins, 1998; Stewart-Smith and Wallace, 1997). Exposures display the good preservation, especially for determining the relationship with the Macquarie Arc materials which occurs near Oberon town along Duckmaloi Road, by Lake Oberon and Black Springs area (Fig 3-1). The Ordovician quartz-rich sandstone, siltstone, and mudstone packages to the south of Black Springs were also examined in detail (blue unit in Fig 3-1). There was some suggestion in previous studies that the Adaminaby Group rocks south of Black Springs may belong to the Silurian (Meffre, 2003; Meffre et al., 2007). This is not supported by the findings in this study (see Chapter 5). Although the outcrops of the Ordovician quartz-rich turbidite occur in other areas (e.g. Mount David, Shooter Hill and Juanter) these are highly weathered and no new information was gathered in this study in these areas. Therefore, rocks from these areas are mapped primarily based on their radiometric signature in the publicly available geophysics (Fig 3-1).

Lithology and thickness

The Middle to Late Ordovician Adaminaby Group comprises of quartz-rich sedimentary sequences of sandstone, siltstone, shale, and chert, with graded bedding, cross-bedding, and lenticular lamination indicative of Bouma sequences. These sedimentary structures, found throughout the rock packages, are interpreted to represent turbidite deposition for the entire suite. The lower section of the Adaminaby Group in Oberon is dominated by fine- to very coarse-grained sandstone with sharp erosional basal contacts overlain by laminated- to planar- bedded sandstone grading upward to fine grained sandstone. Individual beds are thin- to thickly bedded, ranging between 0.3 to 0.8 m. However uncommon massive sandstone with bedding ranging from 1.0 m up to 1.5 m occurs near Lake Oberon. These beds are orange brown with iron oxide staining which weathered from light grey in colour of fresh rocks. Good preservation of this quartz-rich sandstone and siltstone successions occur along Duckmaloi Road, Titania Road, Edith Road and near Lake Oberon (Fig 3-2). Going up the sequence, these sandstones gradually change to 5-10 cm thinly bedded siliceous mudstone interbedded with thin beds of chert. Even though they have recrystallized during the emplacement of the nearby Carboniferous granite, this chert-dominated sequence remains recognizable at the eastern area of Lake Oberon and the northeast of Black Springs (Fig 3-1). The upper part of the Adaminaby

Group consists of quartz-rich fine-grained sandstone, siltstone and shale which conformably overlie the chert-dominated successions middle part of the group. The upper section of the group also occurs around Juanter and south of Mount David, and are overlain by black shale which is mapped locally on 1:100,000 Oberon sheet (Murray, 2002; Pogson and Watkins, 1998; Stewart-Smith and Wallace, 1997).

The thickness of this unit is difficult to determine since it is structurally complex and contains no marker horizons. However, the greatest thickness determined in the Oberon is 750 m at minimum, estimated for the middle and upper part of the group (thinly bedded chert and overlying fine-grained turbidites).

Age

In Oberon, the Adaminaby Group have been dated by using both paleontological and geochronological methods. Microfossils in Oberon, mostly conodonts, found in upper section black shale at road to Lake Oberon and Titania-Brien Roads indicating Early and Late Ordovician respectively (see white triangle symbols in Fig 3-1; Geological Survey of New South Wales database). Detrital zircons from the sequence were also analysed. The zircons show typical age population profile of Ordovician quartz-rich sandstone from Lachlan Orogen with minor Early to Middle Ordovician U-Pb zircon ages, dominant 500-600 Ma crystals and with minor older populations (Meffre et al., 2007) (see Chapter 5). Based on the fossils and the maximum depositional age from the detrital zircons it can be inferred that the Adaminaby Group quartz-rich sandstone range in age between Early to Late Ordovician.

3.2.2 Budhang Chert

Nomenclature and distribution

The Budhang Chert was originally named by Murray and Stewart (2001) from the Aboriginal dialect which 'Budhang' means black. This unit was used to describe black chert and siliceous mudstone as the oldest member of Triangle Formation in Oberon area by Murray (2002) and Murray and Stewart (2001). It was later defined as a separate unit which is correlated to Phase 1 magmatism of Macquarie Arc and is older than the Triangle Formation within the stratigraphy (see Fig 2-3; Glen et al., 2007). The Budhang Chert lies approximately northeast-southwest trend (Fig 3-1; 3-3) similar to 1:100,000 Oberon map sheet by Stewart-Smith and Wallace (1997) and crops out widely along Sewells Creek Road and Beaconsfield Road west of Oberon. Its boundaries are mapped on the radiometric images as a distinctive low U, Th and K area in the center of the high K (low U and Th) Ordovician volcanic and volcanoclastic rocks (i.e. the dark-coloured area surrounded by pink on the ternary radiometric map Fig 3-3 right).

Lithology and thickness

The Budhang Chert Member comprises of thinly bedded chert and siliceous mudstone approximately 1 to 10 cm thick in each bedding which the upper part of the unit is dominated by siliceous mudstone. The chert, siliceous mudstone and shaly interbeds are all black to dark grey, weathering to pale grey. They contain cryptocrystalline quartz and partially recrystallized radiolarian tests with organic materials. The thickness of the

Budhang Chert is likely difficult to estimate due to folding and faulting (Fig 3-4), however, field observations in this study suggests that the entire section is between 150-250 m-thick which is similar to what was reported by Murray (2002).

Age

Murray (2002) and Murray and Stewart (2001) reported an age of the Budhang Chert determined using conodonts biostratigraphy from several thin chert beds (see Fig 3-1). The oldest chert sample from the east side of the low U, Th and K zone and contain the conodont elements from *Paracordylodus gracilis* indicating an Early Ordovician (Bendigonian) age. A sample from the north-west of the radiometric low is younger dated as Middle to early Late Ordovician (Darriwillian-Gisbornian).

In this study numerous numbers of radiolarian tests observed in thin sections in this unit from several locations (see Fig 3-3) and 4 samples were processed using HF acid to attempt the recovery of individual radiolarian for further analysis (see method from (Pessagno and Newport, 1972; Whitten, 2015). However, although rounded radiolarians were recovered, the scanning electron images showed that all the radiolarians had been recrystallized (Fig 3-5) and were therefore not useful for biostratigraphy.

3.2.3 Triangle Formation

Nomenclature and distribution

The Triangle Formation is one of the main rock units that occurs in the Rockley-Gulgong Volcanic Belt around Rockley-Oberon region. Stanton (1956) originally named the Ordovician rocks in this area as the 'Triangle Group'. The stratigraphy was later refined by Fowler (1994). It was initially defined as a volcanoclastic rock sequence with basal shales overlain in turn by greywacke and minor conglomerate and quartz-rich siltstone/sandstone (Pogson and Watkins, 1998; Zhang et al., 2019b). In contrast, a number of studies (e.g. Meffre, 2003; Percival and Glen, 2007) argued that the quartz-rich rocks are not included in the Triangle Formation and that the Ordovician volcanoclastic and Ordovician quartz-rich rocks in this area are in faulted contact. In this study, the Triangle Formation is used to describe a succession of moderately- to well-bedded mafic volcanoclastic conglomerate, sandstone and siltstone including minor metabasalt, slate, phyllite and schist.

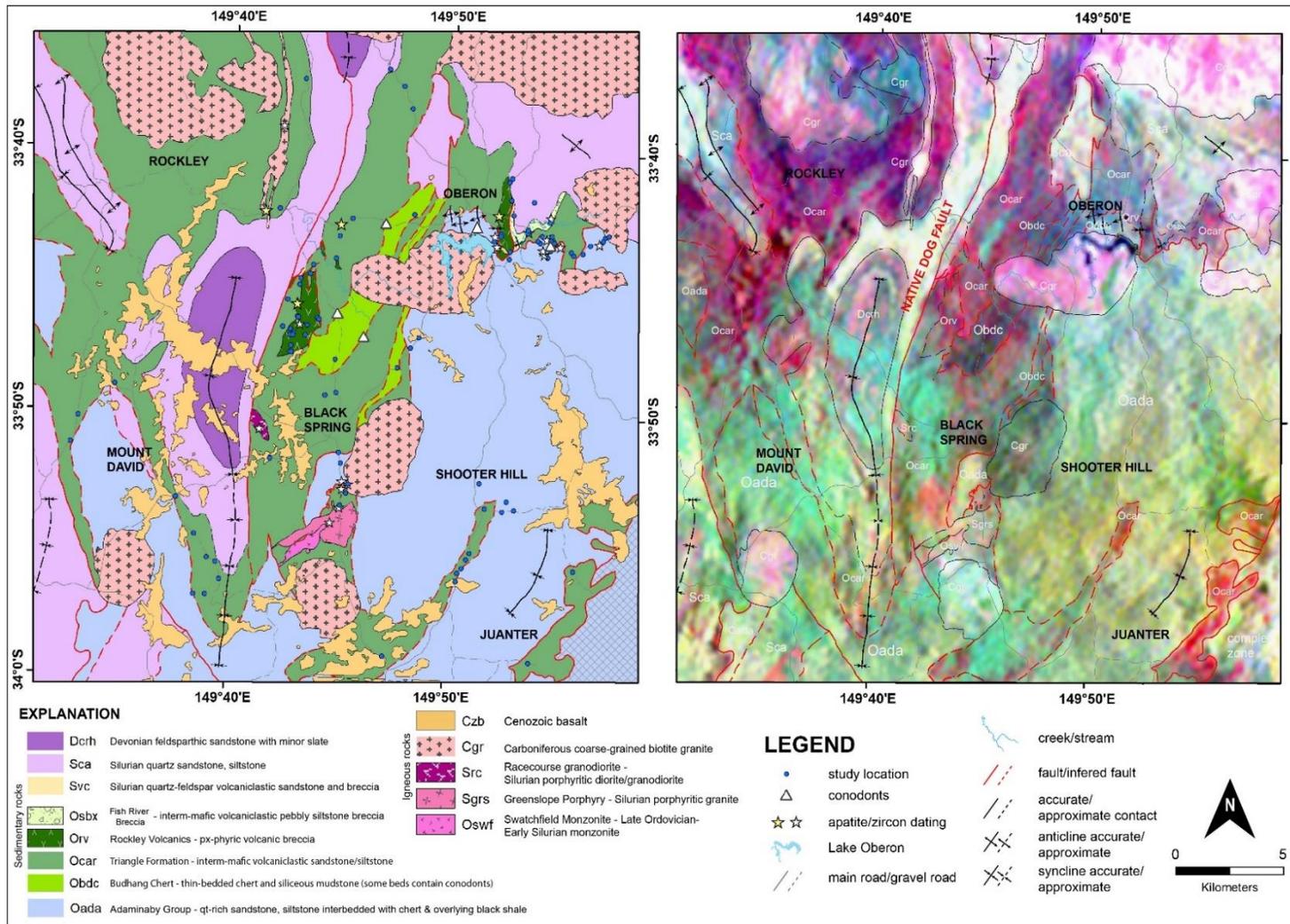


Fig 3-1 (left) Geological map of Oberon and adjacent area modified from 1:100,000 Oberon map sheet (Stewart-Smith and Wallace, 1997). (right) Ternary radiometric K-Th-U map from Geological Survey of New South Wales showing interpreted boundaries of all rock units drawn based on their radiometric distinction.

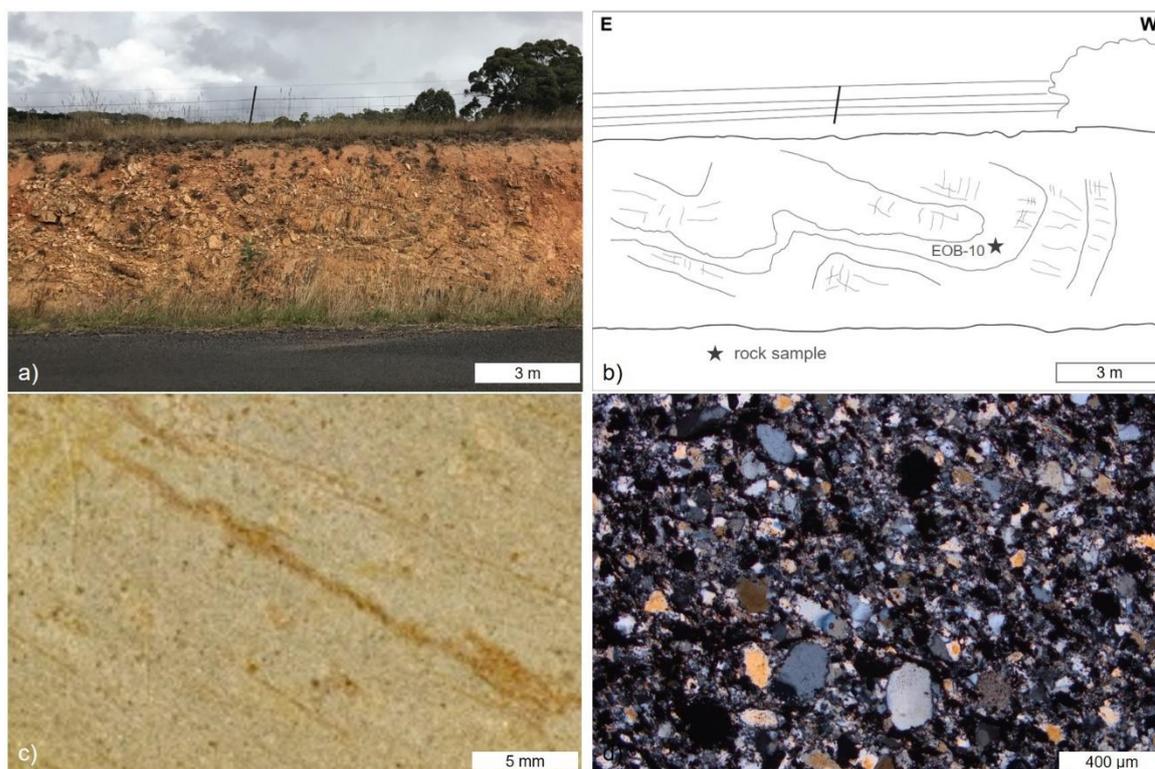


Fig 3-2 Representative of quartz-rich rocks from the Ordovician Adaminaby Group in Oberon. a) Road-cut exposure of typical Ordovician quartz-rich sandstone, siltstone, and chert at Titania Road, 5km east of Oberon (grid reference: 769330 6264509). b) Sketch of the exposure showing refolded isoclinal recumbent fold which is one of the typical features found in the Ordovician quartz turbidites in Lachlan Orogen. c) Hand specimen of fine- to medium-grained quartz-rich sandstone. d) Photomicrograph (cross nicol) showing subangular-subrounded, moderately to poorly sorted quartz-rich sandstone with >90% quartz.

In Oberon region, the Triangle Formation mostly crops out between two major north-south trending faults, termed Native Dog Fault to the east of Oberon and Vulcan Fault on western side of the town (Fig 3-1). The geological maps of the area south of Oberon (e.g. Fig 3-1), also show a narrow wedge-shaped, fault bounded block of the Triangle Formation within the Adaminaby Group at Shooter Hill and Juanter. In Rockley region, the Triangle Formation also crops out widely around Rockley to Mount David (Fig 3-1).

Lithology and thickness

The Middle Ordovician Triangle Formation contains thinly- to thick-bedded volcanoclastic siltstone interbedded with fine- to coarse-grained volcanoclastic sandstone with minor pyroxene-plagioclase-phyric conglomerate and Darriwillian–Gisbornian chert (Murray and Stewart, 2001). The bottom of the formation is dominated by thin-bedded, very fine- to fine-grained volcanoclastic sandstone beds approximately 5-10 cm thick with greenschist facies alteration minerals and a northeast-southwest-striking steeply dipping cleavage. Above these basal beds, the sequence tends to be coarser-grained, dominated by fine sandstone. Conglomerate is rare, but occasionally occur as 10-30 cm beds of polymictic pebble conglomerate. The conglomerate is generally matrix supported with clast comprises of chert, lenticular mudstone and mafic volcanic rock fragments with pyroxene and plagioclase phenocrysts in a fine-grained volcanoclastic matrix (Fig 3-6). However, the

Triangle Formation is relatively finer grained than the overlying units in Oberon such as the Rockley Volcanics and Fish River Breccia.

In thin-section, fine-grained volcanoclastic sandstone comprised of small (<1 mm) subhedral feldspar crystal fragments and abundant angular to sub-rounded volcanic lithic fragments, whereas massive coarse- to very coarse-grained sandstone and conglomerate contains 1-2 mm euhedral to subhedral pyroxene, plagioclase and minor primary hornblende crystal fragments. Meffre (2003) and Murray (2002) mentioned that very few sub-rounded quartz were found in thin section from the Triangle Formation in upper part of the sequence. However, in this study, quartz in volcanoclastic rocks were only observed in breccias around the Fish River 3 km to the east of Oberon. Mapping of these rocks showed that these rocks belongs to a new unit called 'Fish River Breccia' which will be described below. Common alteration products in the volcanoclastic sandstones include actinolite, chlorite, amphibole, and plagioclase.

Pogson and Watkins (1998) reported that true thickness of the Triangle Formation along Triangle Creek in Rockley region is approximately 2 kilometres. This includes 600 m of chert and siltstone unit, 1200 m-thick of volcanoclastic and tuffaceous sedimentary rocks and 450 m of siltstone and chert. However, as mentioned above, the newer studies (e.g. Meffre, 2003; Percival and Glen, 2007) reassigned 450 m-thick of the upper unit into the same lithology of lower section that were juxtaposed together by fault. Therefore, the recalculated true thickness of the Triangle Formation is 1.55 km. In Oberon, a true thickness of 700 m was estimated for the Triangle Formation by Fergusson and Colquhoun (2018) and Murray (2002). This is very similar to the thickness measured in this study (around 670 m-thick). This contains volcanoclastic siltstone, sandstone, and conglomerate from western boundary Native Dog Fault to the area a few kilometres east of Oberon.

Age

No age-specific fossils have been found within the volcanoclastic rocks. However, Murray and Stewart (2001) recovered *Pygodus* conodont elements indicating Darriwillian-Gisbornian (late Middle to Late Ordovician) from siliceous mudstone and chert beds at the upper part of Triangle Formation, termed Mozart Chert. U-Pb dating data is limited in this area. Glen et al. (2011) reported U-Pb zircon maximum deposition age for a volcanoclastic sample from the area suggesting the Triangle Formation is Middle to Late Ordovician.

3.2.4 Rockley Volcanics

Nomenclature and distribution

Rockley Volcanics were initially named by Stanton (1956) to describe rock unit consisting of andesitic pyroclastic rocks with lava flows or sills. The Rockley Volcanics conformably overlie the Triangle Formation and are overlain by Campbells Group (Pogson and Watkins, 1998; Stanton, 1956). In this study, the Rockley Volcanics is used to describe mafic to ultramafic volcanic breccia consisting of pyroxene-phyric volcanic breccia and mafic lava flows or sills that overlying the mafic-intermediate volcanoclastic rocks of the Triangle Formation.

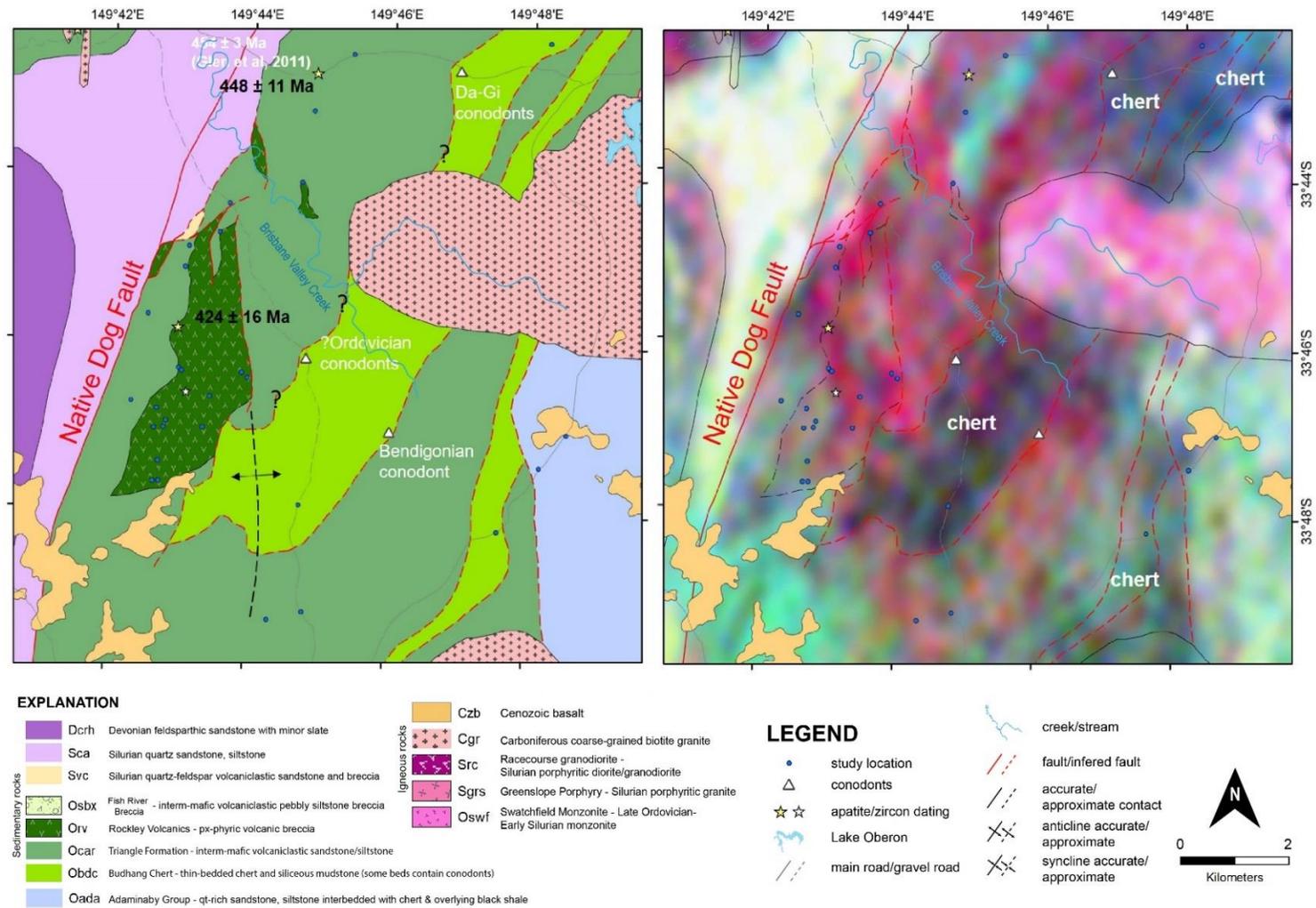


Fig 3-3 Comparison between (left) Geological boundaries modified from Stewart-Smith and Wallace (1997) in Native Dog Fault area and (right) Ternary radiometric K-Th-U map showing high contrast of dark area that are interpreted as the Early to Middle Ordovician Budhang Chert. Locations of observation point, conodonts and U-Pb apatite/zircon dating are also shown.



Fig 3-4 Representative of Budhang Chert in Oberon (a)-(b) Road-cut exposure of deformed thinly bedded chert interbedded with mudstone at Sewells Creek Road (grid reference: 757835 6266275) showing synform-antiform series and displacement of local fault. (c)-(d) Road-cut outcrop of thinly bedded chert with siliceous mudstone at Abrecrombie Road between Oberon and Black Springs (grid reference: 758591 6256141).

In Oberon area, the Rockley Volcanics crops out between Native Dog Fault and Brisbane Valley Creek with (Fig 3-1 and 3-3). The Rockley Volcanics unit also occur within eastern part of Oberon town (Fig 3-7) continuing to the north and south at least 1 kilometre.

Lithology and thickness

In the study area, the Rockley Volcanics consists of mafic to ultramafic volcanic and volcanoclastic breccia and occasional conglomerate occurring with associated dominantly coarse-grained volcanoclastic sandstone and mudstone (Fig 3-8a). Conglomerates are characterized as matrix-supported containing angular to subrounded porphyritic mostly vesicular basalt clasts (Fig 3-8b). The pyroxene-phyric volcanic breccias normally contain 3 to 15 cm basalt clasts ranging with large euhedral clinopyroxene crystals (4-8 mm) and smaller plagioclase crystals with occasionally olivine relic. In Brisbane Valley Creek, the Rockley Volcanics are dominated by both mafic volcanic breccia and

coarse- to fine-grained clinopyroxene-plagioclase crystal-rich volcanoclastic sandstone. Within Racecourse area near Black Springs the Rockley Volcanics are locally represented as crystal-rich volcanoclastic sandstone and breccia which hornblende is identified as the most significant mafic mineral (Benn, 2014). In terms of stratigraphic correlation, the Rockley Volcanics are possibly correlated with the Forest Reef Volcanics occurring in Molong Belt (Crawford et al., 2007b). The Rockley Volcanics have experienced regional metamorphism and most of the rocks examined contain alteration minerals characteristic of the greenschist facies (e.g. albite epidote, amphibole, chlorite and relict euhedral clinopyroxene).

Between the Native Dog Fault and Oberon areas, the thickness of the Rockley Volcanics is estimated to be at least 200-300 m. In contrast, the Rockley Volcanics in around the Oberon township are estimated to be around 50-100 m thick. However, the rocks in both areas are associated with faults so the thickness estimates are difficult.

Age

No index fossils have been recovered from the Rockley Volcanics and stratigraphic relationship are used to constrain age of the Rockley Volcanics. The lower part conformably overlies the Triangle Formation and the upper part unconformably underlies the Fish River Breccia and Silurian Campbells Group. Therefore, the Rockley Volcanics ranges from the Gisbornian to the Early Silurian.

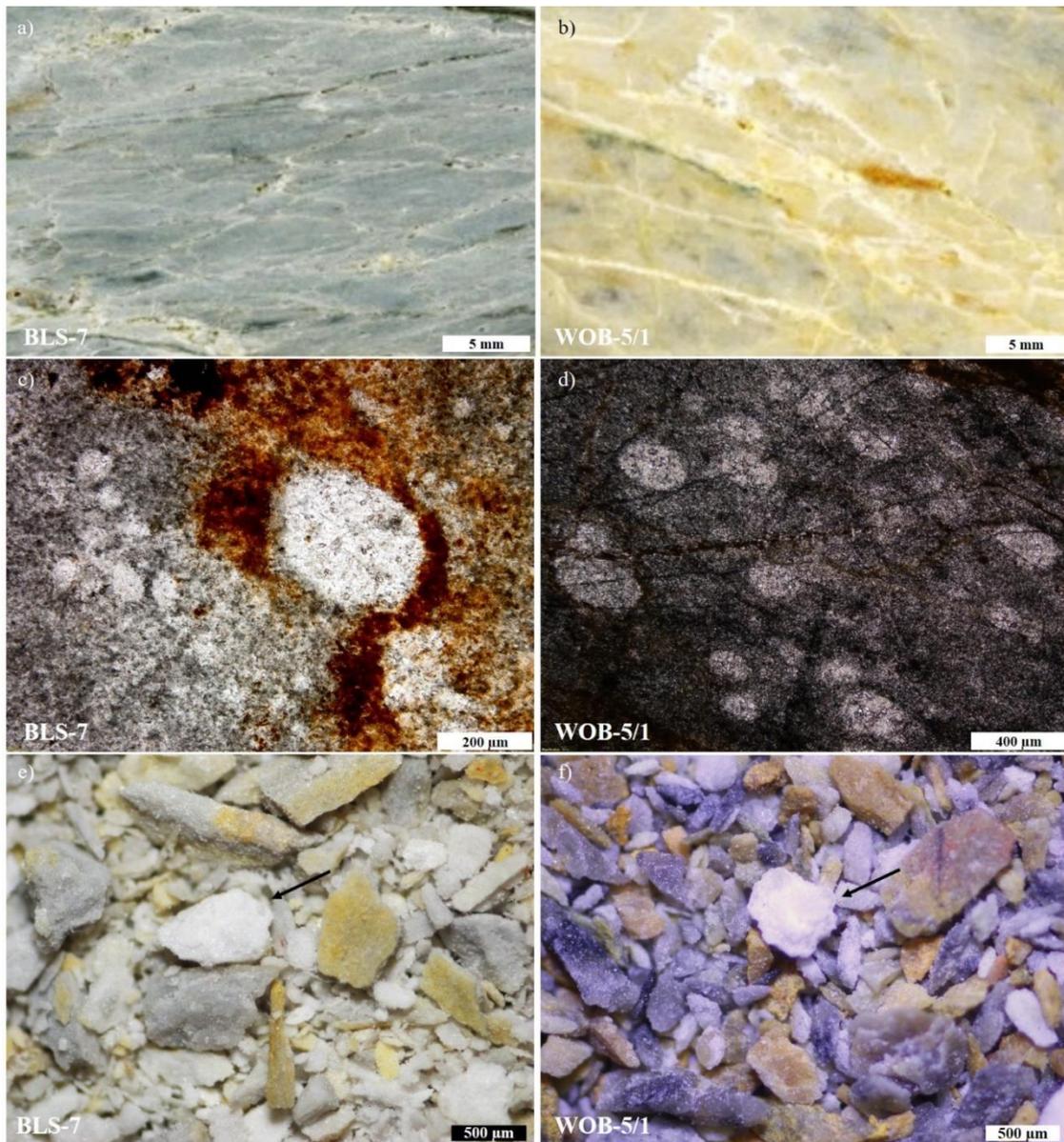


Fig 3-5 (a)-(b) Hand specimen from outcrops in Fig 3-4(a) and (c) of thin-bedded chert with lots of veinlet. (c)-(d) Photomicrograph of Budhang Chert unit showing plenty of rounded grains with probably internal structure suggesting a typical feature of radiolarian. (e)-(f) Photos taken under microscope showing possible radiolarians (black arrow) but indicating they had been all recrystallized and are not useful for biostratigraphy.

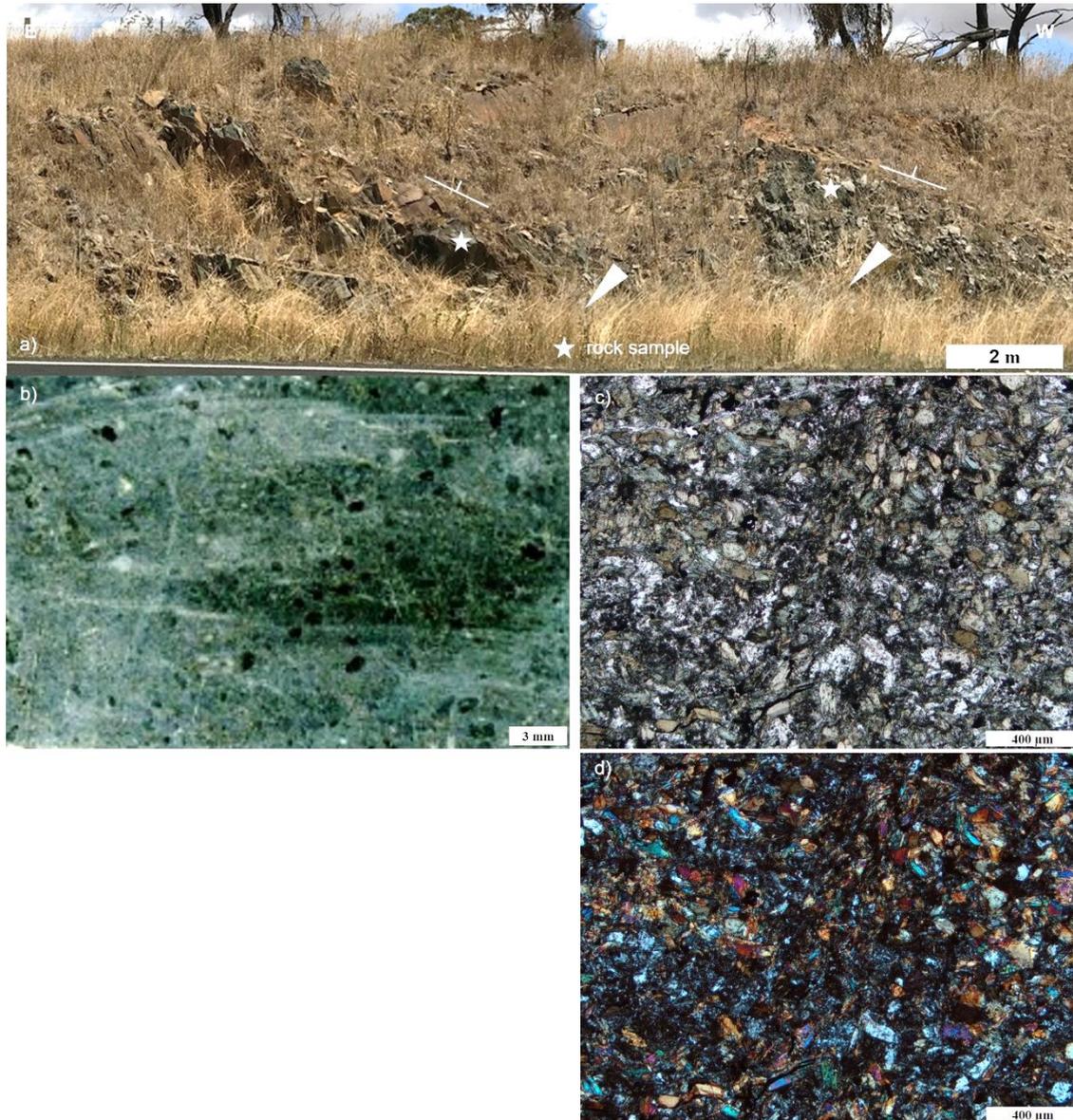


Fig 3-6 (a) Outcrop of well-bedded basaltic-andesitic volcanoclastic sandstone and conglomerate dipping southwest (grid reference: 769727 6264868). (b) Hand specimen from the outcrop (a) showing volcanoclastic texture which have undergone burial metamorphism. Photomicrographs, (c) ppl and (d) xpl, showing euhedral to subhedral pyroxene and plagioclase phenocrysts in matrix consisting of volcanoclastic materials.

3.2.5 Fish River Breccia (new name)

Nomenclature and Distribution

The Fish River Breccia is a new unit introduced for mafic to intermediate volcanoclastic pebbly siltstone breccia found along Fish River and nearby area, 5 km to the east of Oberon town (Fig 3-7). Type section of this unit is located at Fish River bridge to the east of Oberon (Fig 3-7 left, red rectangle) cropping out in road-cuts and exposures within paddocks. More outcrops of mafic volcanoclastic pebbly breccia have been found to

the east of the type section along with Fish River. However, only loose blocks of highly weathered volcanoclastic material was found to the west of Fish River Bridge breccia.

Relationship between the Fish River Breccia and the underlying rocks (Triangle Formation, Rockley Volcanics and Adaminaby Group) is difficult to determine because no sharp conformable contact has been observed in these outcrops. Although the Fish River Breccia are deformed, like the other Paleozoic rocks in Oberon the FRB is less deformed (Fig 3-7) than the underlying units which record much more complex geological structures, e.g. recumbent fold, isoclinal folding and faulting (Fig 3-2 and 3-4). Therefore, an unconformable contact is inferred between the Fish River Breccia and the underlying sequences. The upper contact of Fish River Breccia is placed at the base of a fine-grained volcanoclastic sandstone turbidite with shell fragments from the Campbells Group. This contact is inferred to be conformable based on the bedding measurements along the Fish River and further north, the measurements from basal units of the Campbell Group and from the measurements shown on the maps (Fig 3-7).

Lithology and thickness

The Fish River Breccia is characterized by both clast-supported and matrix-supported breccias often with graded bedding. Clasts of the Fish River Breccia comprise mostly clinopyroxene and plagioclase. The clasts reworked from volcanic rocks showing minor volcanic rock fragments varying from 2 cm up to 20 cm (Fig 3-9 a, c, and Fig 3-10a, c, e). Breccia and conglomerate containing quartz clasts up to 15 cm are rare, but these were observed both in outcrop next to the type section in a breccia with a calcareous matrix (Fig 3-9b, d and 3-10b, d, f). In the type section, the pebble clasts have been elongated trending north-south (Fig 3-9a-c). The breccia and conglomerate are moderately- to well-bedded, polymictic and clast-supported. FRB has an inferred thickness of 100-200 m estimated from field observation and the geological map (Fig 3-7).

Age

No fossils were observed in this unit. However, the stratigraphic relationships suggest that it unconformably overlies the mafic-ultramafic volcanic breccia and lava flows of the Late Ordovician Rockley Volcanics and is conformably overlain by intermediate to felsic volcanoclastic of the Late Silurian Campbells Group (Pogson and Watkins, 1998) Therefore, the Fish River Breccia age is constrained between the Late Ordovician to Early Devonian.(see Chapter 5 and 6 for further discussion).

Reworked volcanic, volcanoclastic, and calcareous pebbles that are present in the FRB indicate possible correlation to the conglomerate units at the base of the Waugoola Group, overlying unit of Forest Reefs Volcanics, in Molong Volcanic Belt (Harris et al., 2014).

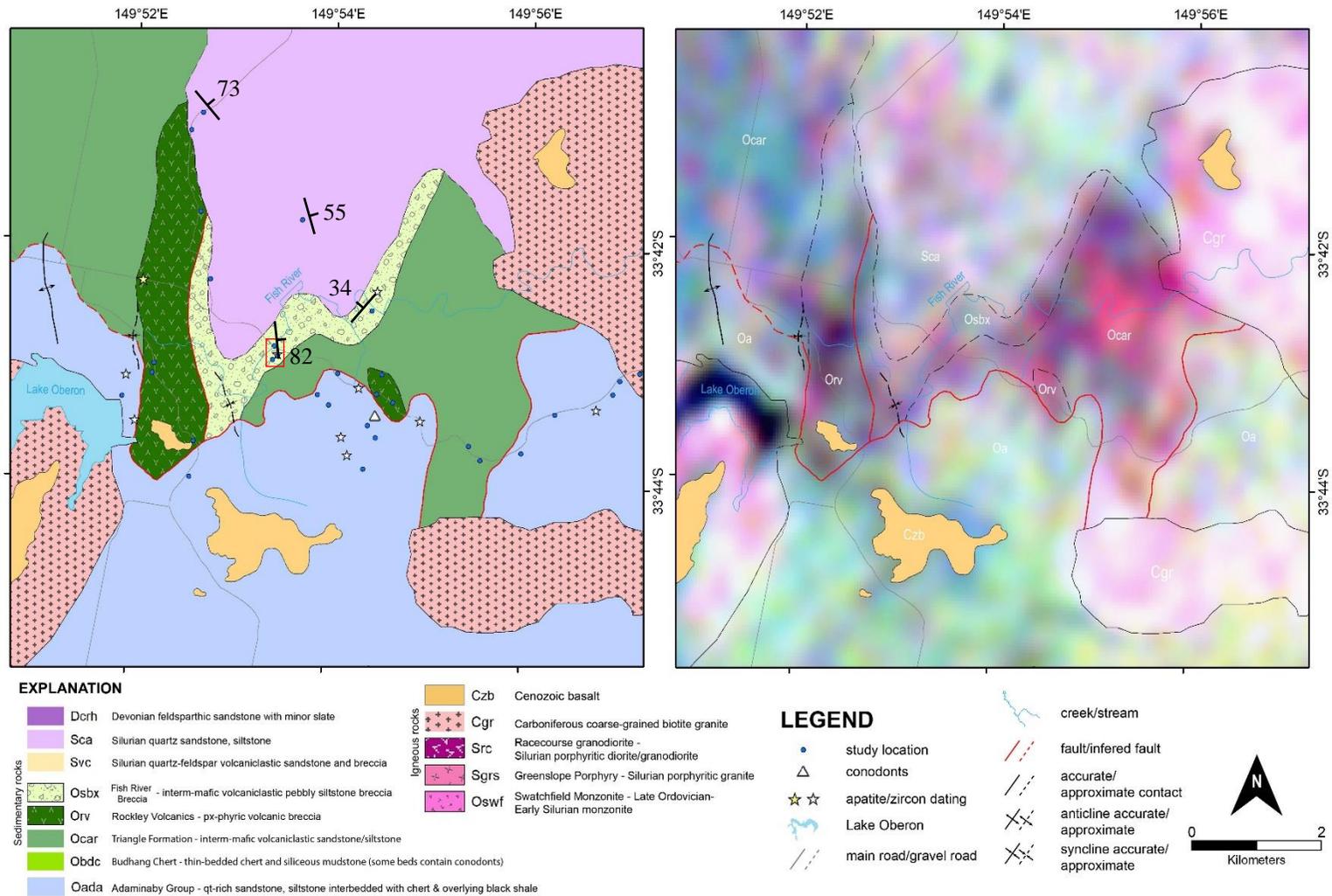


Fig 3-7 Detailed geological map showing boundaries of the Ordovician high-K volcanic rocks were mapped using the radiometric images combined with field observation (red square showing the location of Fish River Breccia type section; see outcrop Fig 3-9).



Fig 3-8 (a) and (b) Representative rocks of the Rockley Volcanics in Oberon comprising dominantly mafic volcanic breccia and conglomerate (grid reference: 750976 6257301 and 751105 6257297). (c) Hand specimen from (a) showing a basaltic clasts (d) Hand specimen from outcrop (b) showing large crystals of epidote and lath shape crystals of plagioclase. (e) - (h) Photomicrographs of (c) illustrating abundant large euhedral crystals of clinopyroxene with plagioclase and chlorite.

3.2.6 Swatchfield Monzonite

The Swatchfield Monzonite was initially mapped on Oberon 1:100,000 map sheet to describe outcrops of monzonite and relative mafic intrusion near Swatchfield approximately 5-km south of Black Springs (Pogson and Watkins, 1998; Stewart-Smith and Wallace, 1997). The Swatchfield Monzonite contains altered plagioclase, clinopyroxene and apatite with interstitial K-feldspar and minor quartz in some rocks. K-feldspar and plagioclase were determined in approximate same proportion.

The Swatchfield Monzonite intrusive body directly intruded both the Triangle Formation and Rockley Volcanics. U-Pb zircon geochronology analysed by Meffre (2003) indicating that this intrusion was formed around Late Ordovician to Early Silurian (437±8 Ma, 2σ). In contrast, new U-Pb zircon dating result demonstrates that the Swatchfield Monzonite is late Middle to early Late Ordovician (see details in Chapter 5) and possibly correlate with the intrusions that occur in the Molong Volcanic Belt.



Fig 3-9 (a) type section of the Fish River Breccia (red square in Fig 3-7; grid reference: 771091 6376546). (b) abundant of angular quartz clasts in volcaniclastic siltstone breccia in the farmland area near the type section. (c) close-up view of (a) showing north-south orientation of clasts referred as foliation. (d) quartz-rich calcareous matrix volcaniclastic breccia.

3.3 Post-Ordovician

3.3.1 Silurian

Campbells Group crops out extensively in Oberon area (Stewart-Smith and Wallace, 1997). No sharp contact between the Fish River Breccia and the Campbells Group was found but the bedding measurements infer that the Campbells Group in Oberon conformably overlies the Fish River Breccia. There is a disconformable contact between

the Campbells Group and the underlying Triangle Formation, and Rockley Volcanics. The Campbells Group consists of thinly bedded felsic volcanoclastic siltstone overlain by interbedded slate and feldspathic metasandstone. The thickest succession of the Campbells Group occurs at Native Dog Syncline which is approximately 800 m-thick in total (Pogson and Watkins, 1998). The Campbells Group probably ranges from Late Silurian to Early Devonian (Pogson and Watkins, 1998).

The Silurian Greenslope Porphyry and Racecourse Porphyry were also mapped in the Oberon area near Black Spring. The Greenslope Porphyry crops out around Oberon-Goulburn Road approximately 5 km south of Black Springs (Fig 3-11). In thin section the massive blue grey porphyritic granite contains large quartz phenocryst crystals (40-50%) showing granophyric texture and K-feldspar (20%), plagioclase crystals (20%) in fine-grained felsic groundmass (10-15%; Fig 3-12). Associated discontinuous quartz porphyry dykes also occurs near the Greenslope granite. Previous (Meffre, 2003) and new U-Pb zircon dating (Chapter 5) consistently demonstrate that the Greenslope Porphyry formed around Middle to Late Silurian.

The Racecourse Porphyry or Racecourse Intrusive Suite crops out around 4 km to the west of Black Springs near the Native Dog Fault zone (Fig 3-11). The area was explored as part of the Bushranger project of Anglo American Exploration Australia. Benn (2014) described it as consisting of intermediate intrusive rocks ranging from monzodiorite through to K-feldspar-phyric monzonite porphyry and quartz monzonite porphyry. The mineralogical, geochemical and geochronological results from both this study and Benn (2014) indicate that the Racecourse Intrusive Suite is younger than the Ordovician magmatism associated with the development of alkalic porphyry deposits in other parts of the Macquarie Arc.

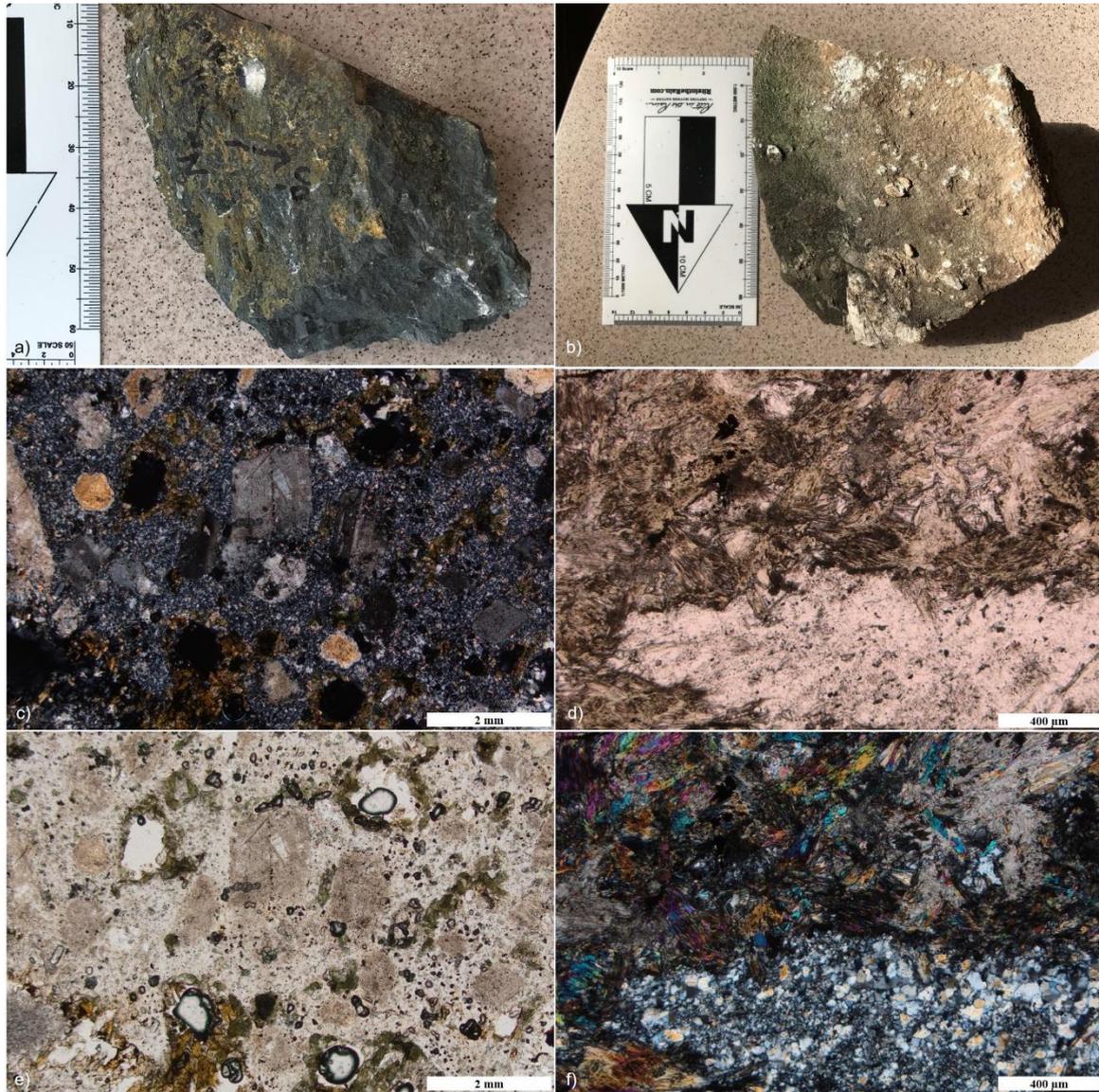


Fig 3-10 (a) Hand specimen of Fish River Breccia at the type section location. (b) breccia hand specimen with angular to sub angular quartz pebbles. (c) and (e) Photomicrographs showing euhedral altered plagioclase and pyroxene within fine-grained sandstone matrix. (d) and (f) Photomicrographs showing large rock fragments with polycrystalline quartz at right bottom with pyroxene and calcareous minerals.

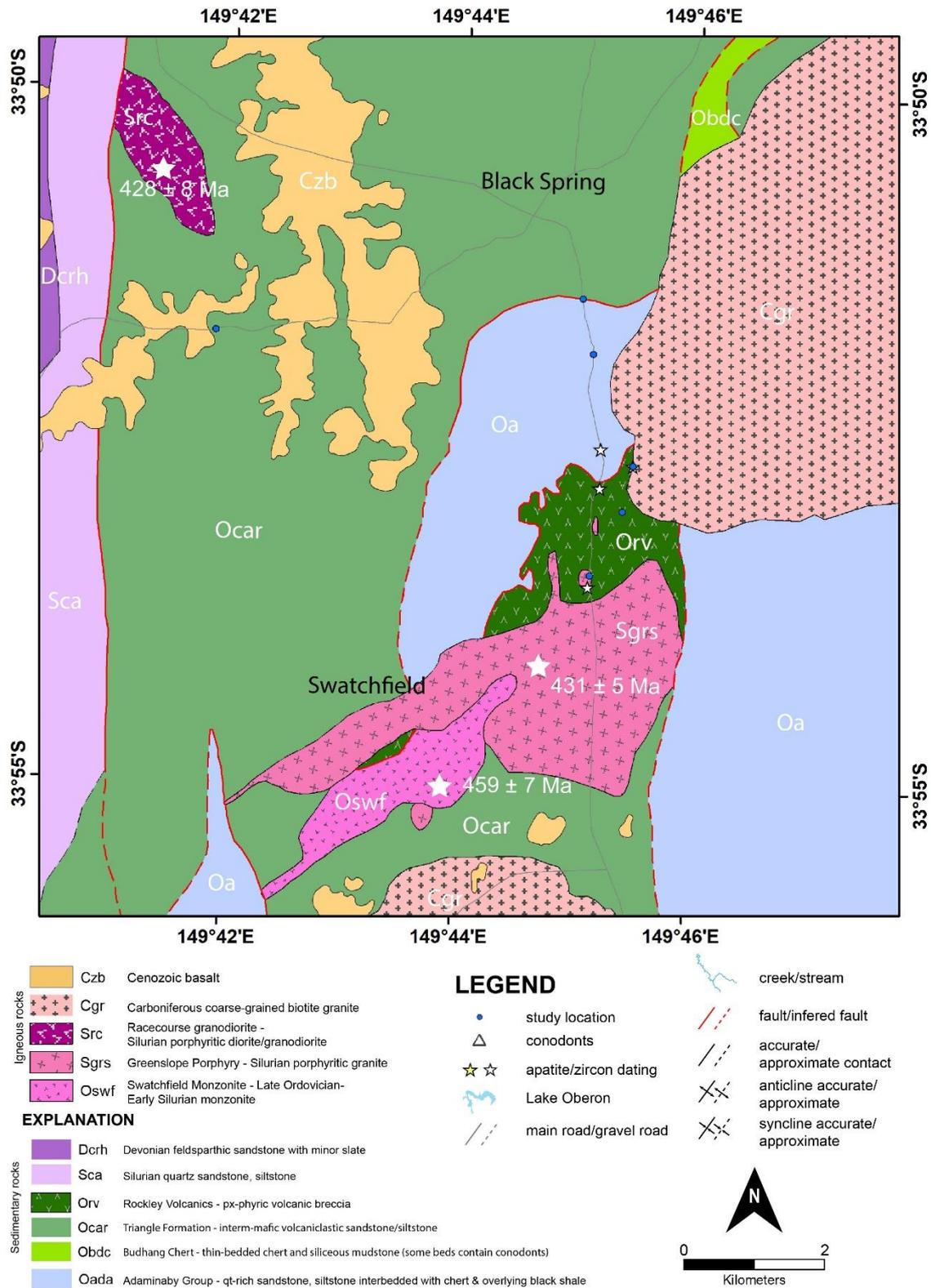


Fig 3-11 Geological map around Black Springs modified from Stewart-Smith and Wallace (1997) showing relationships between the Adaminaby Group, Macquarie Arc materials and the younger intrusions including Swatchfield Monzonite, Greenslope Porphyry, Racecourse porphyry and Carboniferous granite.

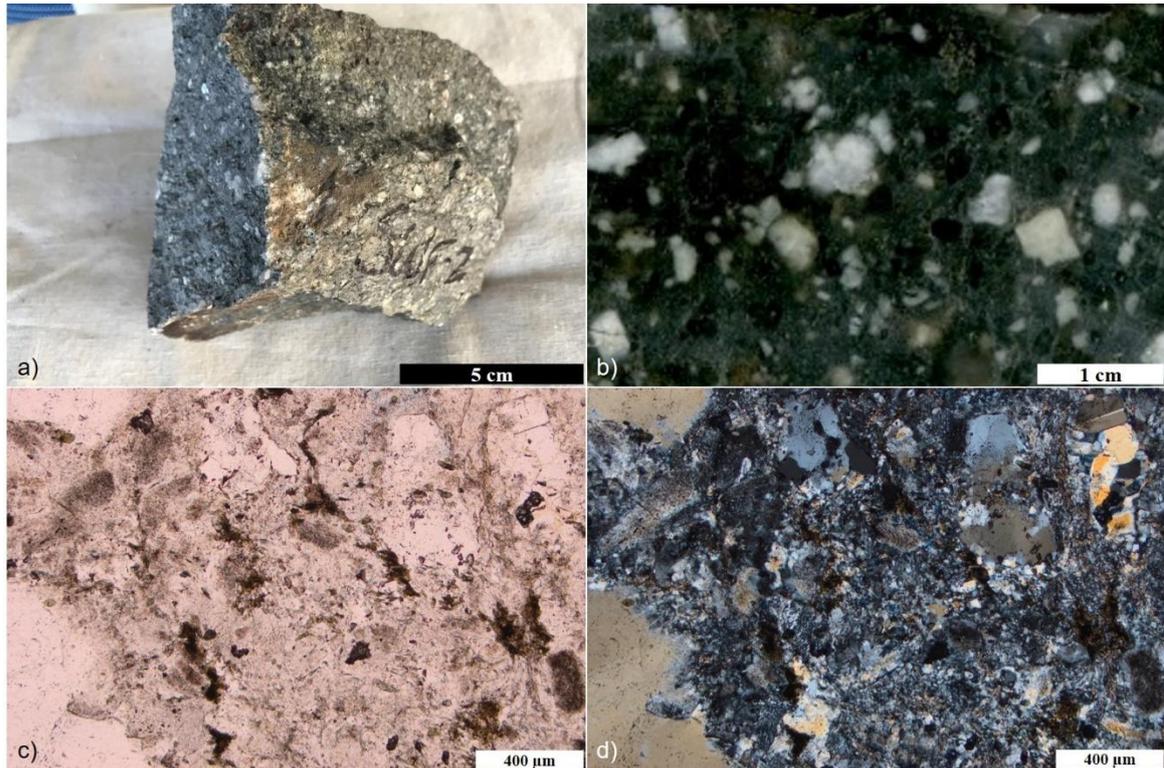


Fig 3-12 (a) Hand specimen of Greenslope Porphyry showing quartz phenocrysts and its porphyritic texture within K-feldspar and plagioclase groundmass. (b) Rock slab of hand specimen (a) displaying close-up view of the Greenslope Porphyry texture and euhedral quartz phenocrysts. (c) and (d) Photomicrographs of the Greenslope Porphyry containing abundant euhedral to subhedral quartz phenocrysts with typical myrmekitic texture unlike the Swatchfield Monzonite.

3.3.2 Devonian

The Devonian Dunchurch Formation occurs along the Native Dog Synclines 15 km to the west of Oberon and on the eastern side of Oberon 1:1000,000 map sheet area (Stewart-Smith and Wallace, 1997). The Dunchurch Formation conformably underlain by the Campbells Group and conformably overlain by the Buckburruga Slate (Pogson and Watkins, 1998). Lithologically, the Dunchurch Formation contains a sequence of massive, coarse-grained feldspathic sandstone and quartz-feldspathic sandstone with minor rock fragments, hornblende and augite (Pogson and Watkins, 1998). These are overlain by unnamed upper section metadacite consisting quartz, euhedral feldspar, hornblende with epidote in alteration. Thickness of the unit at the Native Dog Synclines was estimated about less than 500 m. The Dunchurch Formation was characterized by its depositional environment as massive flow or turbidite and was formed in the Early Devonian.

3.3.3 Carboniferous

Carboniferous rocks in Oberon area are represented by multiple bodies of granite in northern part of the 1:100,000 Oberon map sheet. These are coarse-grained, strongly porphyritic biotite granites which contain dominantly K-feldspar (30-50%), plagioclase (30-50%) and relatively less proportion of quartz (25-30%) and biotite (3-5%). The granites also occur in the south of the map sheet near Black Spring, the Carboniferous granites where they are finer grain size and mostly equigranular with slightly porphyritic texture.

The granites comprise mostly quartz and plagioclase with small amount of K-feldspar, hornblende, and biotite. Chlorite is also present due to alteration from biotite.

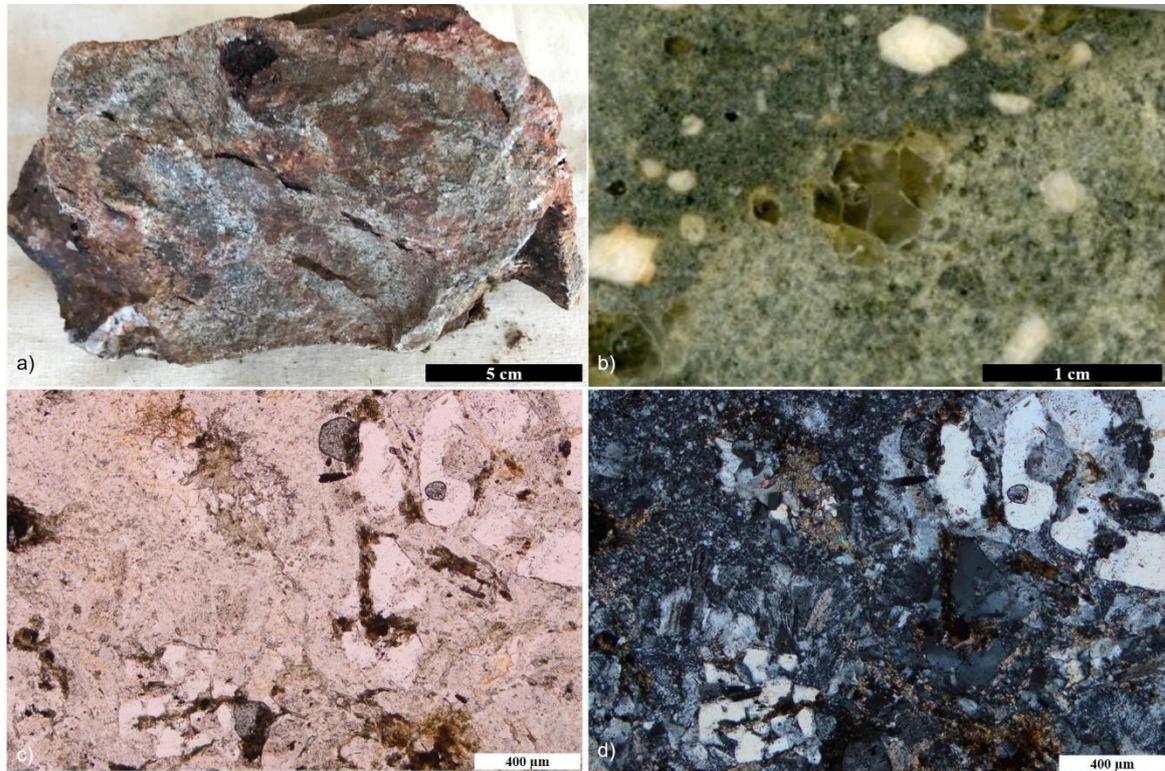


Fig 3-13 (a) Hand specimen of quartz-monzodiorite near the Racecourse prospect showing coarse-grained porphyritic texture. (b) Rock slab from the sample (a) showing euhedral quartz phenocrysts up to 5 mm within medium-grained groundmass. (c) and (d) Photomicrographs displaying abundant granophyric quartz phenocrysts among plagioclase and minor biotite.

CHAPTER 4: GEOCHEMISTRY

4.1 Introduction

This chapter presents and discusses the geochemistry of the Ordovician volcanic, volcanoclastic and intrusive rocks of the Rockley-Gulgong Volcanic Belt including the Ordovician quartz-rich turbiditic sequences that crop out around the Oberon region to determine their chemical composition and magmatic affinities. The whole-rock major and trace elements analysed as part of this thesis were combined with data from previous studies in this area (Andrew, 1980; Benn, 2014; Meffre, 2003; Murray, 2002) and compared to similar rocks from the Molong Volcanic Belt (Crawford et al., 2007b; Kitto, 2005; Wilson, 2003).

4.2 Sampling and analytical methods

Thin sections from the 56 samples collected from the Oberon district, Native Dog Creek and Black Springs were examined under a microscope and the 19 least-altered and least-weathered samples were then selected for whole-rock geochemical analysis. These rocks were from the Triangle Formation, the Rockley Volcanics, the Fish River Breccia, the Greenslope Porphyry, and the Adaminaby Group (Table 4-1, Fig 4-1). The Swatchfield Monzonite was also analysed from a sample provided by Londonderry Drillcore Library, Geological Survey of New South Wales. The only major unit that was not examined in detail was the Budhang Chert as the rocks at outcrops examined were very weathered and not suitable for analysis.

Seven of the 19 samples selected for geochemical analysis were further analysed for low level trace elements and rare earth element (REE) determination (Table 4-1). These analyses were compared to 115 analyses from previous studies (Andrew, 1980; Benn, 2014; Crawford et al., 2007b; Meffre, 2003; Murray, 2002; Squire and Crawford, 2007; Wilson, 2003) to help with interpretation and correlation (see details on Appendix II).

4.2.1 XRF major and trace element analysis

Whole rock geochemistry analysis for major and trace elements was performed at CODES, University of Tasmania, using a PANalytical (Philips) PW 1480 X-Ray fluorescence (XRF) spectrometer (see Robinson (2003) for details). Major elements were measured using fusion discs that were prepared at 1,100 °C in 5 % Au/95 % Pt crucibles, using 0.500 g of sample, 4.500 g 12/22 Flux (lithium tetraborate mixture) and 0.0606 g LiNO₃. To determine loss on ignition (LOI), 1 to 2 g of each sample was heated at 1,000 °C for 12 hours then reweighted. Trace elements were measured on 32 mm diameter pressed powder pellets prepared at 3.5 tonnes/cm² using 10 g of sample and polyvinylpyrrolidone-methylcellulose (PVP-MC) as a binder. Analysis on the XRF spectrometer was performed with a 3kW Au anode X-Ray tube and ScMo anode X-Ray tube (Watson, 1996).

4.2.2 Low level trace elements and the rare earth elements (REE) analysis using solution ICP-MS

Solutions of each selected sample were prepared for inductively coupled plasma mass spectrometer (ICP-MS) analysis by using PicoTrace® high-pressure acid (HF/H₂SO₄) digestion. Approximately 100 mg of sample powder was prepared in 30 ml Polytetrafluoroethylene (PTFE) digestion containers. A few drops of ultra-pure water, 0.1 ml indium solution, 3 ml HF and 3 ml H₂SO₄ was then added to each digestion container. These were thoroughly mixed by shaking, and the PTFE containers were placed in the digestion block at 180 °C for 16 hours. The digestion mixture was then evaporated at 180 °C for four days in the evaporation block. A millilitre of HClO₄ was added to the residue and dried, followed by further additions of 2 ml HNO₃ and 1 ml HCl. The residue was dissolved by warming the solution in the digestion block at 60 to 70 °C for approximately one hour. Once the solution became clear, it was transferred into a polypropylene bottle and diluted to 100 ml, then analysed using an Agilent ICP-MS at CODES, University of Tasmania.

4.3 Geochemistry of Ordovician volcanic and volcanoclastic rocks

4.3.1 Triangle Formation

Major element geochemistry

The geochemistry of volcanoclastic rocks from the Triangle Formation, the Native Dog Fault and Black Springs was investigated using 59 samples which are 3 new samples and 56 samples from previous studies (Andrew, 1980; Benn, 2014; Meffre, 2003; Murray, 2002; Stewart-Smith and Wallace, 1997). The three new samples comprise greenish grey fine-grained volcanoclastic meta-sandstone and clinopyroxene-rich volcanoclastic sandstones. The chemistry shows that the sediments were mostly derived from a basaltic source based on their silica contents (Table 4-1, Fig 4-2) and immobile trace element plots (Fig 4-3). These are mostly sourced from high-K calc-alkaline basalt to basaltic andesite and volcanoclastic rocks (Fig 4-2, Fig 4-3 and Fig 4-6), however, some Triangle Formation silica-rich chert samples with 60 to 86 wt% SiO₂ were also analysed by previous studies (Fig 4-4). This geochemistry is slightly different to recent analyses from the Triangle Formation in the Bald Ridge area (Zhang et al., 2019b) where more felsic to intermediate composition have been reported.

Bivariate plots for most of the major elements plotted against SiO₂ (Fig 4-4) and MgO (Fig 4-5) show moderate to well-correlated trends that can be interpreted as resulting from fractional crystallization. The plots show increasing TiO₂, Al₂O₃ and Na₂O, and decreasing Fe₂O₃, MnO, MgO and CaO with increasing SiO₂ and decreasing MgO. Scatter in K₂O and P₂O₅ (Fig 4-4 and Fig 4-6) suggests element mobility caused by regional metamorphism or local hydrothermal alteration. Nineteen samples from Andrew (1980) are unusually high in CaO but low in most other major elements (most obvious in Na₂O, Al₂O₃ and SiO₂). These odd samples are all identified as hornfels collected from few hundred metres north of Oberon near a Carboniferous granite. These may have had carbonate veins or some other high Ca mineral diluting the original major element compositions.

Due to the mobility of K_2O during regional metamorphism the P_2O_5/Al_2O_3 vs K_2O/Al_2O_3 plot of Crawford et al. (2007) (Fig 4-6b) was used to define the magmatic affinities instead of using the K_2O vs SiO_2 plot (Fig 4-6a). On this diagram, the data mostly groups within shoshonitic field. This classification is also supported by the P_2O_5 vs MgO diagram (Fig 4-6c) proposed by Crawford et al. (2007) for classifying magmatic samples with MgO higher than 3 wt%. However, on the Ce/Yb vs Ta/Yb diagram (Pearce, 1982; Fig 4-6d), the data of the Triangle Formation plot in the calc-alkaline not in shoshonitic field boundaries. An oceanic to late oceanic island arc tectonic setting is inferred from Zr/Al_2O_3 vs TiO_2/Al_2O_3 and Zr/Al_2O_3 vs P_2O_5/Al_2O_3 discrimination diagrams (Müller et al., 1992; Fig 4-6e and 4-6f)

Trace element and REE geochemistry

The results for available low abundance trace elements and rare earth elements of the Triangle Formation are shown in Table 4-1. Variation plots of these elements versus SiO_2 (Fig 4-7) and MgO (Fig 4-8) show moderate correlation between trace elements and SiO_2 and show well correlated trends as a function of MgO . The variation diagrams demonstrate decreasing concentrations of Ni, Cr and V with decreasing MgO . However, V correlates negatively with MgO above 9 wt% MgO . Large ion lithophile elements (LILE: Rb, Sr and Ba) scatter widely but high field strength elements (HFSE: Ce, Y, Zr and Sc) show obvious negative trends for Sc and positive trends of Ce, Y and Zr with decreasing MgO .

Rare earth elements normalized data using values from Sun and McDonough (1989) are presented in Fig 4-11. In Fig 4-11c samples WOB-2 (the highest green line) and BLS-14 (the lowest green line) are two new analyses from this study. The sample no. BLS-14 is an ultramafic rock occurring in south of Black Springs which shows a negative Ce anomaly and very low REE. In contrast, WOB-2 has no anomaly and contains much higher amount of rare earth elements.

The MORB-normalized incompatible trace element diagram (Fig 4-12c) shows that the Triangle Formation samples are enriched in Ba, U, Pb, K and Eu and are depleted in La, Ce, Nb, Rb, Sr, Zr and Ti relative to typical ocean basalts. Trace element pattern of all samples are similar except for the ultramafic sample (BLS-14, Fig 4-12c) which has lower trace element concentrations in all elements except for Pb.

4.3.2 Rockley Volcanics

Major element geochemistry

The Rockley Volcanics in the study area are dominated by pyroxene-phyric volcanoclastic breccia with minor pyroxene-rich basalt and ultramafic volcanic rocks cropping out in three different zone including three samples from Native Dog Fault area, two from Oberon town and Black Springs. Whole-rock geochemistry analysis of 61 samples from the literature were also investigated (Meffre, 2003; Murray, 2002; Stewart-Smith and Wallace, 1997). The new samples from this study were classified as basalts to basaltic andesite based on their silica contents (47-60 wt% SiO_2 ; Table 4-1) and immobile elements (Fig 4-2 and Fig 4-3). However, some of the data from the previous studies plot in the trachybasalt to trachyandesite fields which probably caused by Na and K mobility.

A few of these samples plot in the alkali basalt field using immobile elements plots (Pearce, 1996; Fig 4-3).

Major elements are well correlated with SiO₂ and MgO (Fig 4-4 and Fig 4-5). The variation trends including the inflection points associated with changes in crystal fractionation phases are very similar to those documented above for the Triangle Formation. There are, however, a few differences in Na₂O and Al₂O₃ which demonstrate differences at MgO concentration below 10 wt% (Fig 4-5e and Fig 4-5g). A small group of Rockley Volcanics samples have low Na₂O and Al₂O₃. Apart from that at high MgO, TiO₂, Al₂O₃, CaO and P₂O₅ are negatively correlated with MgO content (10-40 wt% MgO) but at lower MgO (7-10 wt%) are positively correlated (Fig 4-5d). These trends suggest olivine-dominated fractionation above 10% MgO with crystallization of plagioclase and clinopyroxene below this point.

Rockley Volcanics have shoshonitic magmatic affinities (Fig 4-6b) and with very similar geochemical characteristics to some of the Triangle Formation.

Trace element and REE geochemistry

Variation diagrams of trace elements (Fig 4-7 and Fig 4-8) show that the Rockley Volcanics have similar composition to the Triangle Formation. Ni and Cr decrease with decreasing MgO while the LILE (Rb, Sr and Ba) and the HFSE (Y, Ce, and Zr) rise steeply with increasing SiO₂ (Fig 4-7). These diagrams reveal multiple correlated trends for some trace elements (V, Y, Sc and Zr) with an inflection point at 5-10 wt% MgO suggesting zircon and clinopyroxene crystallization.

The chondrite normalized REE patterns of the Rockley Volcanics are also like the volcanic rocks from Triangle Formation and Byng Volcanics from the Molong Volcanic Belt (Fig 4-11c). The main difference between the Rockley Volcanics and the Triangle Formation are as follows:

1. A greater proportion of ultramafic igneous rocks (>15% MgO)
2. Slightly higher TiO₂ (+0.2%) at any a given MgO and P₂O₅ contents

The remainder of the chemistry is similar and there is a large overlap between the two formations.

4.3.3 Fish River Breccia

Major element geochemistry

The Fish River Breccia (FRB) is a new proposed rock unit (see descriptions in Chapter 3). The breccias contain angular pebbles of clinopyroxene-plagioclase-rich volcanoclastic siltstone and sandstone together with chert, minor limestone, and rare polycrystalline quartz. Four samples of the FRB were selected for XRF whole-rock geochemistry analysis and two of them were then analysed for low-level trace elements and REE. The Fish River Breccia samples have higher SiO₂ and lower MgO than the volcanic siltstone/sandstone of the Triangle Formation and the Rockley Volcanics (Table 4-1) although they plot within the basalt field in the immobile elements diagram (Fig 4-3). They show moderately well correlated trends on major elements variation diagrams with TiO₂, Al₂O₃, Fe₂O₃, MnO, MgO and P₂O₅ decreasing with increasing SiO₂ (Fig 4-4 and Fig 4-5).

Trace element and REE geochemistry

The trace elements of the Fish River Breccia are mostly like those of the Triangle Formation and Rockley Volcanics (Fig 4-7 and Fig 4-8). However, FRB has relatively high Rb and Ba compared to the Triangle and Rockley Volcanics, ranging between 76 to 120 ppm and 553 to 1240 ppm respectively (Table 4-1). Other trace elements are well correlated and show negative trends in plots against SiO₂ and positive trends in diagrams against MgO (Fig 4-7 and Fig 4-8). The REE concentrations of the FRB are also very close to the Rockley Volcanics but the heavy rare earth elements tend to be slightly higher. On the MORB-normalized trace elements diagrams the FRB (Fig 4-12) the FRB are enriched in Rb, Ba, K and Pb relative to the Ordovician volcanic rocks of the Macquarie Arc.

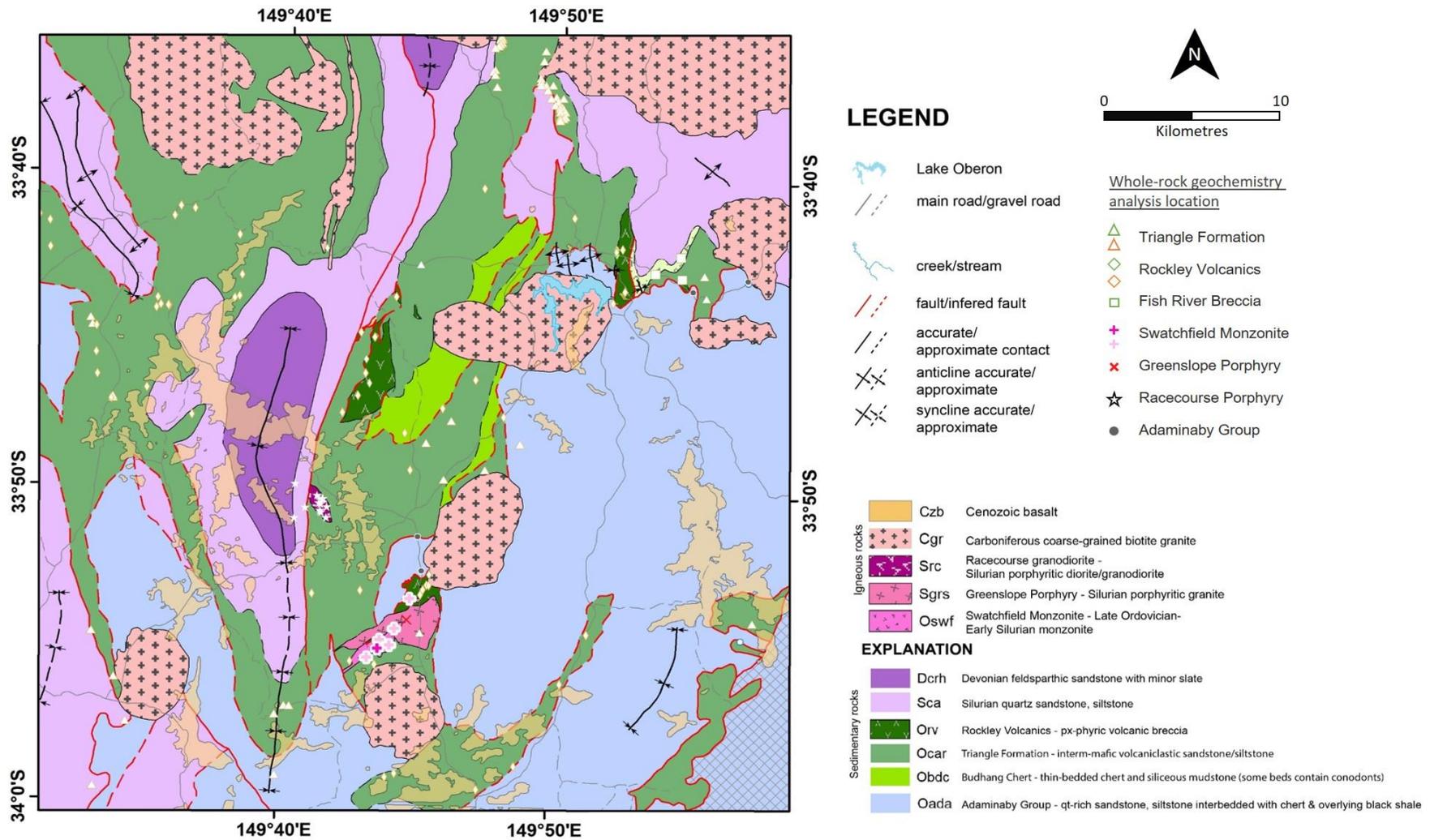


Fig 4-1 Geological map of Oberon region modified from Stewart-Smith and Wallace (1997) showing sample locations of whole-rock geochemistry analyses including this study and the previous studies. Green and orange symbols represent sample location of this study and previous studies respectively for the Triangle Formation and Rockley Volcanics. Pink and purplish pink symbols represent sample location from this study and the Londonderry Drillcore Library for the Swatchfield Monzonite.

Table 4-1 Representative of whole-rock major and trace elements analyses for Ordovician Adaminaby Group, Ordovician volcanic and volcanoclastic rocks of Macquarie Arc and Silurian Greenslope Porphyry. *QLSS* = quartz-lithic sandstone, *QtSS* = quartz-rich sandstone, *PxVS* = pyroxene-rich volcanoclastic sandstone, *CPVS* = Chloritic-Pyroxene rich volcanoclastic sandstone, *QRhP* = quartz rhyolite porphyry.

Group	Adaminaby Group				Triangle Formation			Rockley Volcanics						Fish River Breccia				Greenslope Porphyry	Swatchfield Monzonite
Sample ID	EOB-14/3	EOB-20	BLS-8	BLS-12	EOB-19	WOB-2	BLS-14	ND-2	ND-4	NDC-2	EOB-22	EOB-V16	SMC-4	EOB-4/1	EOB-4/3	EOB-V10	EOB-V13	SWF-2	T78819
Rock type	QLSS	QtSS	QtSS	QtSS	PxVS	PxVS	CPVS	pyroxene-rich volcanic breccia						mafic volcanoclastic pebbly sandstone-siltstone breccia				QRhP	diorite
SiO ₂	65.46	88.37	69.03	88.37	49.79	49.74	48.47	46.95	49.51	52.60	49.44	49.75	51.17	60.27	65.92	53.04	65.33	73.40	50.40
TiO ₂	0.82	0.45	0.51	0.30	0.65	0.96	0.23	0.46	0.45	0.52	0.53	0.49	0.53	0.77	0.51	0.67	0.48	0.38	0.54
Al ₂ O ₃	23.65	6.72	14.55	6.47	11.13	16.62	6.08	7.76	9.72	11.41	10.53	9.90	14.70	14.74	13.17	16.19	10.18	13.40	19.07
Fe ₂ O ₃	3.32	2.68	4.66	1.26	10.05	12.25	10.45	12.69	11.92	11.18	12.08	11.47	10.30	8.82	7.30	9.88	6.98	2.81	9.56
MnO	0.01	0.01	0.03	0.01	0.22	0.21	0.17	0.20	0.22	0.22	0.19	0.18	0.21	0.11	0.08	0.16	0.09	0.04	0.16
MgO	1.03	0.23	2.46	0.74	8.27	6.79	26.14	20.25	10.63	8.79	10.81	10.91	9.56	5.59	4.14	5.48	2.69	0.77	4.2
CaO	0.01	0.01	2.88	0.06	18.00	7.65	8.24	11.41	14.08	11.08	12.14	13.60	9.79	2.58	1.81	7.56	9.84	0.69	9.94
Na ₂ O	0.12	0.05	2.81	2.69	1.41	3.94	0.04	0.06	2.33	2.90	2.05	2.42	1.93	2.45	2.98	4.33	0.63	3.41	3.37
K ₂ O	5.53	1.25	2.87	0.06	0.25	1.48	0.04	0.02	0.93	0.89	1.94	1.01	1.55	4.45	3.86	2.32	3.56	5.02	2.24
P ₂ O ₅	0.06	0.23	0.19	0.03	0.23	0.35	0.15	0.20	0.21	0.42	0.30	0.28	0.25	0.23	0.24	0.38	0.21	0.09	0.52
LOI	5.50	2.50	3.14	1.51	0.92	4.16	6.72	5.20	4.93	2.85	3.20	3.91	2.33	2.47	1.58	1.63	6.61	1.21	2.48
Ni	16.68	11.32	79.11	24.56	78.82	22.28	1051.94	268.87	59.65	39.70	184.31	131.42	135.75	53.52	39.25	57.26	57.07	10.25	6.00
Cr	138.40	108.07	66.45	43.44	547.30	45.99	3180	1310.98	519.67	298.89	883.29	675.65	492.51	189.80	180.57	219.94	389.53	15.65	11.89
V	135.65	50.88	231.29	31.92	256.28	373.84	143.73	267.30	272.91	273.79	293.47	262.55	271.04	220.76	254.01	228.76	183.68	47.64	364.16
Sc	16.56	7.62	13.78	4.10	69.07	35.09	30.90	57.38	62.12	56.16	49.43	46.22	42.48	42.37	24.38	28.77	28.24	8.05	29.80
Zr	128.63	394.10	67.19	311.58	31.42	69.86	11.26	22.92	19.27	27.47	34.39	29.29	47.92	52.67	49.28	73.32	38.89	181.96	47.57
Y	37.02	21.45	48.28	12.78	17.00	21.20	4.51	11.02	9.55	10.70	12.28	11.32	12.91	14.69	13.41	19.47	14.45	41.52	19.33
Sr	41.42	15.99	464.57	115.13	325.33	419.02	36.88	55.32	201.54	460.18	283.76	224.24	607.40	215.89	194.82	623.88	148.44	114.43	999.25
Rb	235.02	52.13	73.51	1.19	17.53	18.53	2.67	1.59	14.46	11.49	36.95	16.08	51.51	119.37	81.52	76.65	117.86	174.85	57.01
Ba	1064.61	311.19	1264.67	71.19	177.82	191.62	13.35	49.70	330.98	387.57	266.34	293.24	532.85	1136.01	1240.37	553.37	840.98	671.27	786.89
Pb	9.37	16.76	3.46	3.10	6.39	4.19	29.33	1.05	7.23	3.04	4.09	3.88	12.36	5.66	5.45	14.07	13.74	30.87	8.11
Zn	55.49	17.83	25.50	11.62	105.10	117.74	89.14	84.99	105.41	85.82	95.56	81.77	165.84	94.84	62.42	151.50	79.80	39.97	74.00
Cu	30.11	13.85	204.36	7.93	198.35	86.90	40.29	94.05	154.64	305.35	119.74	93.45	97.16	11.70	6.52	182.18	8.93	8.43	33.98

Table 4-1 Representative of whole-rock major and trace elements analyses for Ordovician Adaminaby Group, Ordovician volcanic and volcanoclastic rocks of Macquarie Arc and Silurian Greenslope Porphyry. (Continued)

Sample ID	Adaminaby Group				Triangle Formation			Rockley Volcanics						Fish River Breccia				Greenslope Porphyry	Swatchfield Monzonite
	EOB-14/3	EOB-20	BLS-8	BLS-12	EOB-19	WOB-2	BLS-14	ND-2	ND-4	NDC-2	EOB-22	EOB-V16	SMC-4	EOB-4/1	EOB-4/3	EOB-V10	EOB-V13	SWF-2	T78819
Nb	17.54	9.50	5.47	7.19	1.86	4.20	0.62	1.09	1.53	2.74	1.20	1.60	2.82	4.60	3.61	4.11	3.08	9.40	7.46
Hf						1.78	0.35					0.84	1.13		1.30		1.02	5.08	
Ta						0.27	0.04					0.09	0.21		0.27		0.22	1.03	
Pb						4.87	29.64					4.58	12.93		4.96		12.94	29.38	8.11
Th						1.59	0.36					0.95	1.28		2.01		1.88	20.53	3.63
U						0.88	0.06					0.49	0.52		0.76		0.79	4.22	<3
La	43.82	26.34	12.72	39.69	7.59	12.52	4.23	4.62	6.88	8.72	7.39	5.77	6.01	6.98	9.13	12.47	8.98	37.20	28.07
Ce	91.58	63.18	32.71	58.97	10.66	25.54	4.35	13.85	13.76	13.58	16.22	12.08	11.93	23.23	15.64	27.92	15.95	74.99	49.41
Pr						3.56	1.00					1.75	1.63		2.15		2.09	8.77	
Nd	39.16	18.83	22.05	19.63	4.63	16.10	3.83	8.66	9.35	10.43	10.14	8.39	7.16	14.76	8.74	9.07	8.90	32.70	13.84
Sm						4.20	0.92					2.37	1.91		2.16		2.18	7.19	
Eu						1.44	0.27					0.74	0.58		0.68		0.67	0.91	
Gd						4.14	0.97					2.46	2.14		2.21		2.33	6.84	
Tb						0.67	0.17					0.39	0.37		0.38		0.38	1.20	
Dy						3.83	1.04					2.16	2.25		2.27		2.29	7.13	
Ho						0.78	0.21					0.43	0.48		0.48		0.49	1.44	
Er						2.24	0.57					1.18	1.42		1.41		1.42	4.18	
Tm						0.31	0.09					0.17	0.22		0.21		0.21	0.61	
Yb						2.03	0.56					1.08	1.45		1.35		1.30	3.80	
Lu						0.32	0.08					0.17	0.23		0.21		0.21	0.57	

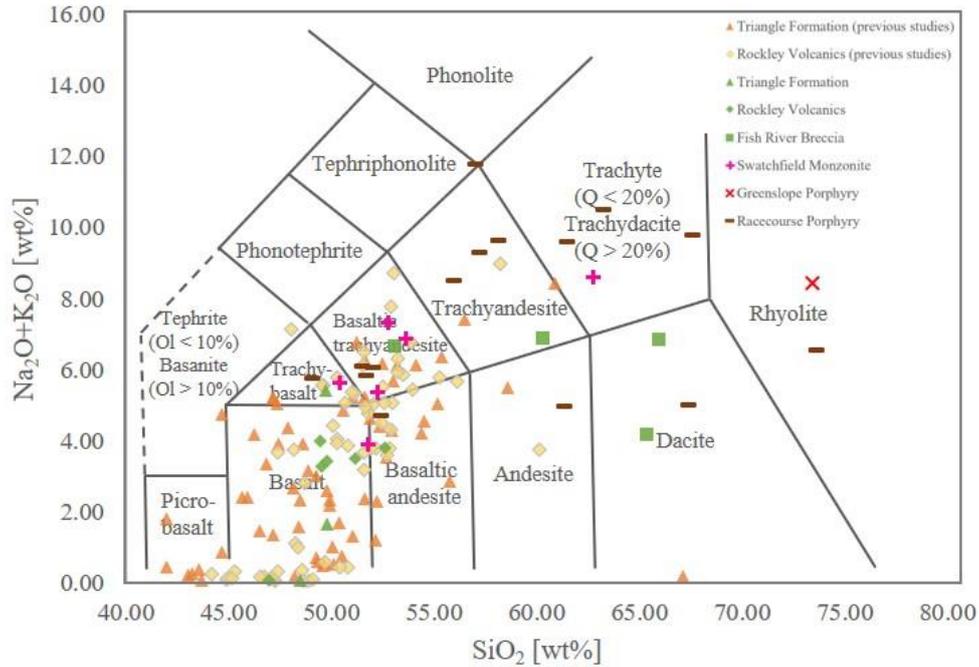


Fig 4-2 Chemical classification and nomenclature of volcanic and volcanoclastic rocks from Oberon region, central New South Wales on the total alkali-silica (TAS) diagram after Le Maitre et al. (1989). Q = quartz, Ol = olivine.

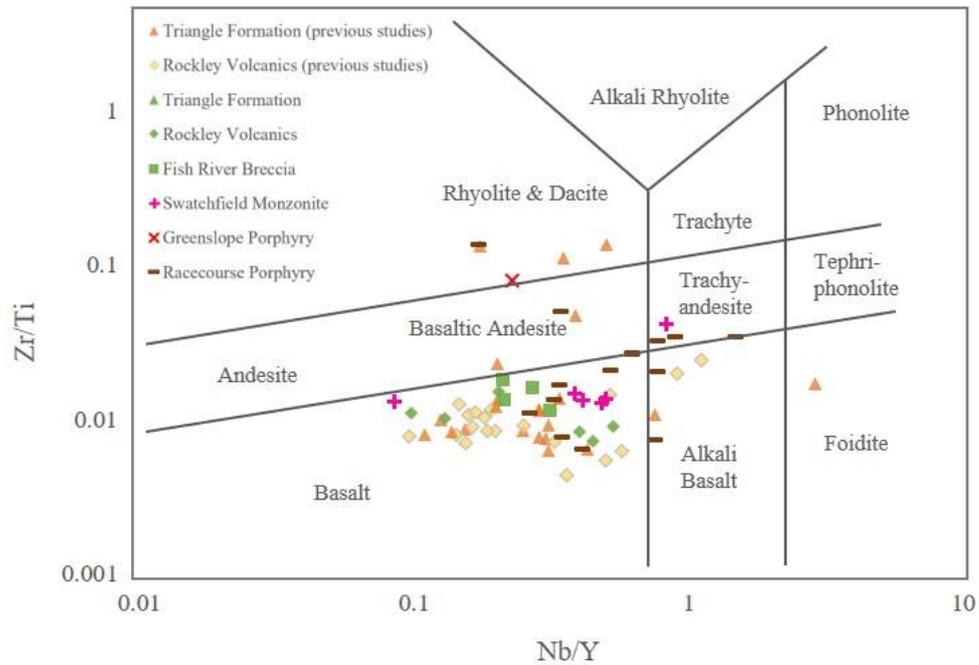


Fig 4-3 Classification diagram after Pearce (1996) using Nb/Y versus Zr/Ti ratios for volcanic, volcanoclastic and intrusive rocks from Oberon region, New South Wales.

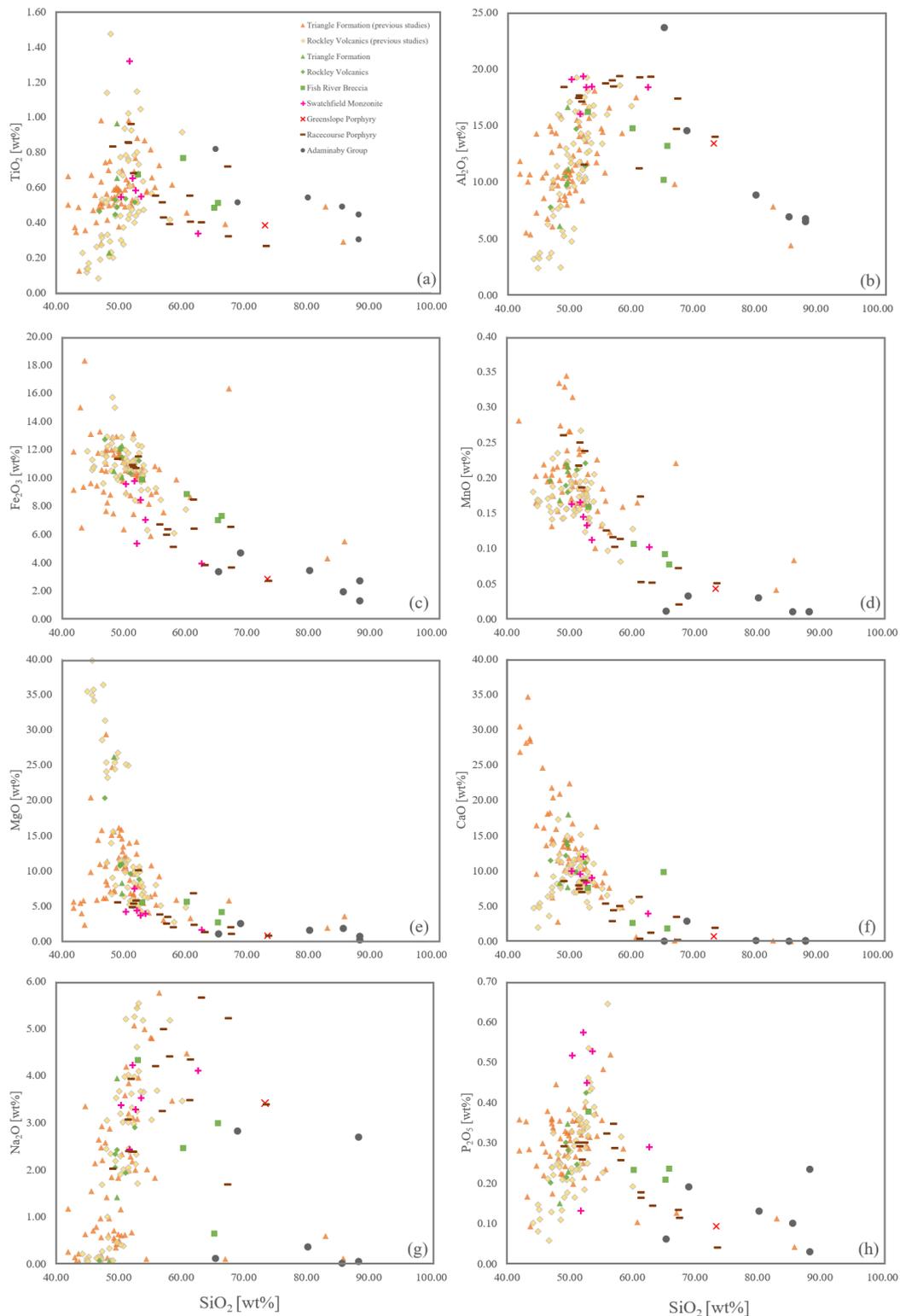


Fig 4-4 Major elements bivariate diagram plotted as function of SiO₂ for quartz sandstones, volcanic, volcanoclastic and intrusive rocks from Oberon region, New South Wales. (a) TiO₂ vs SiO₂ showing positive crystal fractionation trends for the Triangle Formation and the Rockley Volcanics but negative trends for the Fish River Breccia, Swatchfield Monzonite and Racecourse Porphyry (b) Al₂O₃ vs SiO₂ showing high Al₂O₃ values for all rock units in Oberon region (c) and (d) Plots of Fe₂O₃ and MnO vs SiO₂ showing negative trends of all units in the study area (e) and (f) MgO and CaO vs SiO₂ plots showing unusual Ca values at low silica range between 40-45 wt% SiO₂ (g) and (h) The plots of Na₂O and P₂O₅ vs SiO₂ showing distinct fractional crystallization trends for all rock units.

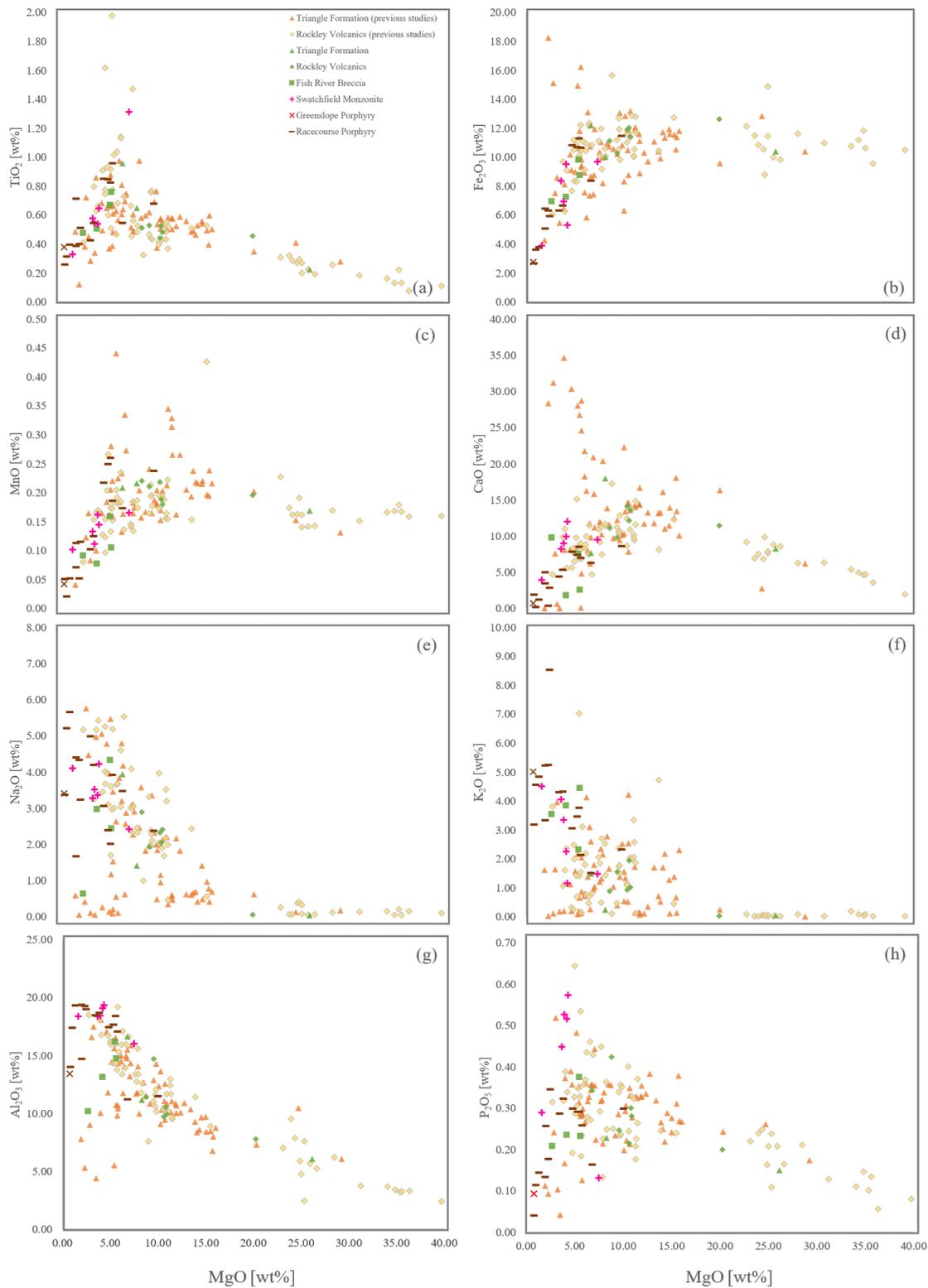


Fig 4-5 Major elements bivariate diagram as function of MgO for volcanic, volcanoclastic and intrusive rocks from Oberon region, New South Wales showing a correlation trend of the selected oxide elements. (a) MgO vs TiO₂ showing two separate trends for the Triangle Formation and the Rockley Volcanics while others show positive single trending at low TiO₂. (b) and (c) the plots of total iron oxide and manganese oxide showing positive trends for all data. (d) MgO vs CaO plot showing diverse trend for the Triangle Formation at MgO between 2 to 7 wt% whereas the others showing similar positive trends to (a)-(c). (e) and (f) The plots showing relatively low Na₂O and K₂O for Triangle Formation and part of Rockley Volcanics.

4.4 Geochemistry of the Ordovician and Silurian Intrusive Rocks

Most of the intrusions in the Oberon region are Carboniferous granite but older Ordovician and Silurian intrusions also occur in this area (Stewart-Smith and Wallace, 1997). Intrusive rocks samples from Black Springs area and Racecourse Prospect were analysed in this project. These include the Swatchfield Monzonite, Greenslope Porphyry and Racecourse Porphyry (Table 4-1). These were investigated as part of this study to establish correlations with the Macquarie Arc magmatism and to provide information to evaluate the prospectivity of the area for porphyry deposits which have been found in other parts of the Macquarie Arc, associated with Late Ordovician to Early Silurian monzonitic intrusive rocks. For this study, no new samples of Swatchfield Monzonite and Racecourse Porphyry were collected but a Swatchfield sample (T78819) from Londonderry Drillcore Library was analysed for XRF whole-rock geochemistry (Table 4-1). Whole-rock geochemical data and ICP-MS for REE results of mineralised intrusions in the Cadia district are included for comparative purposes (Fig 4-10 to Fig 4-12).

Major element geochemistry

Intrusions show decreasing contents of TiO_2 , Fe_2O_3 , MnO , MgO , CaO and P_2O_5 and increasing Na_2O and K_2O with increasing SiO_2 and coincident with decreasing MgO (Fig 4-4, Fig 4-5, and Fig 4-6a). The results show comparable trends to the Triangle Formation and the Rockley Volcanics but with generally higher Al_2O_3 , K_2O and P_2O_5 at similar SiO_2 and MgO contents

Trace element and REE geochemistry

The trace elements show of the intrusive rocks in the Oberon region are presented in Table 4-1 as well as bivariate diagrams versus SiO_2 (Fig 4-7) and MgO (Fig 4-8). All intrusive rocks have much lower Ni and Cr than Triangle Formation, Rockley Volcanics and Fish River Breccia. Together with the Fish River Breccia they tend to have higher incompatible element contents (Rb, Sr, Ba, Zr and LREE) This is partially due to the tendency for the intrusive rocks to be more fractionated but also evident at similar SiO_2 content.

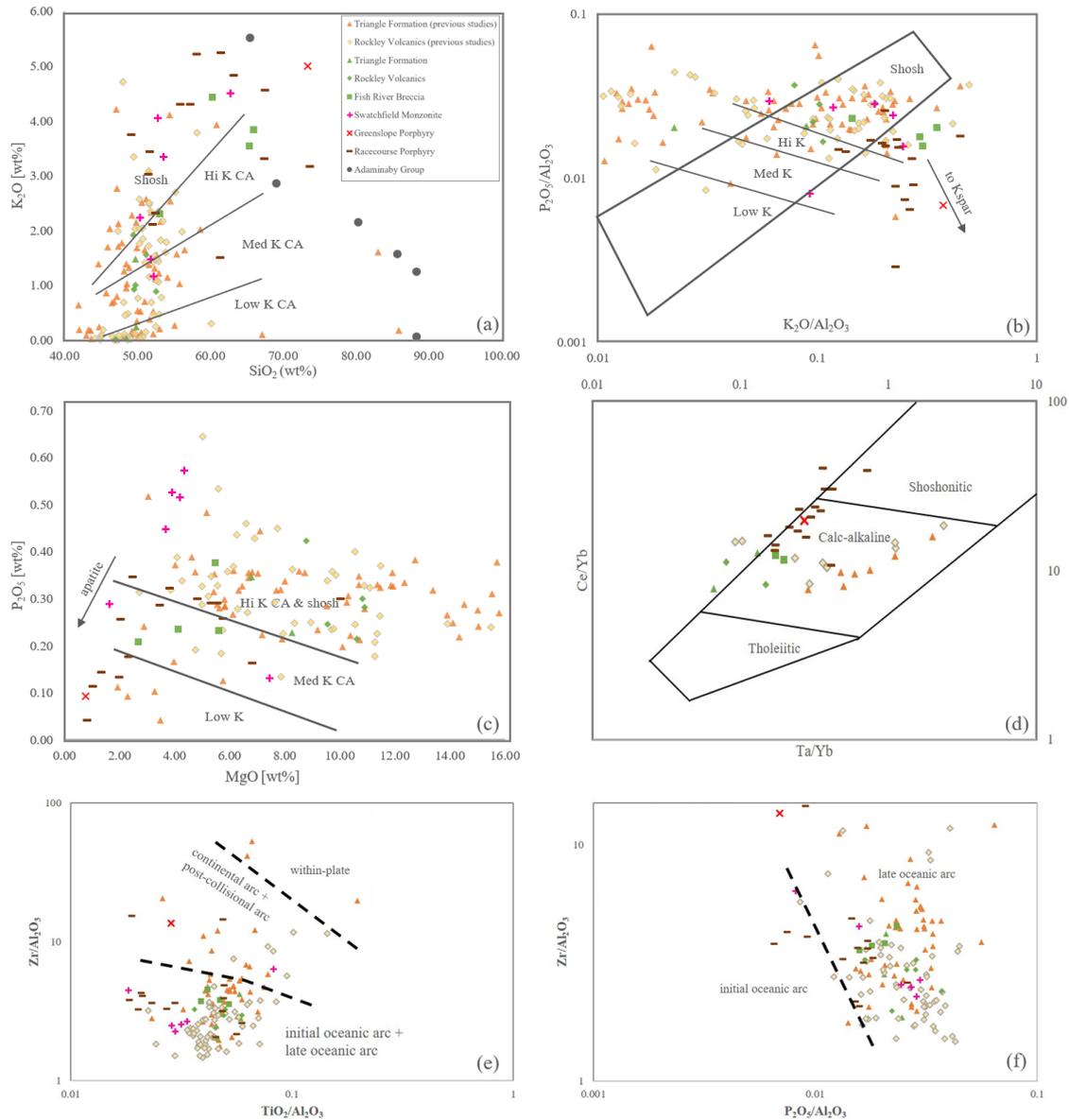


Fig 4-6 (a) SiO_2 vs K_2O showing Triangle Formation, Rockley Volcanics, Fish River Breccia, Swatchfield Monzonite, Racecourse Porphyry and Greenslope Porphyry from Oberon region. (b) K_2O/Al_2O_3 vs P_2O_5/Al_2O_3 for the units shown in (a) field boundaries from Crawford et al. (2007); data plot to the left of the boundaries suggesting loss K_2O during alteration and data plotting to the right out of field boundaries suggesting K-feldspar crystallization. (c) MgO vs P_2O_5 for the units shown in (a) compositional field boundaries defined by modern lavas from Crawford et al. (2007). (d) Ce/Yb vs Ta/Yb (e) and (f) discrimination diagrams using Zr/Al_2O_3 vs TiO_2/Al_2O_3 and Zr/Al_2O_3 vs P_2O_5/Al_2O_3 to define tectonic setting (Müller et al., 1992).

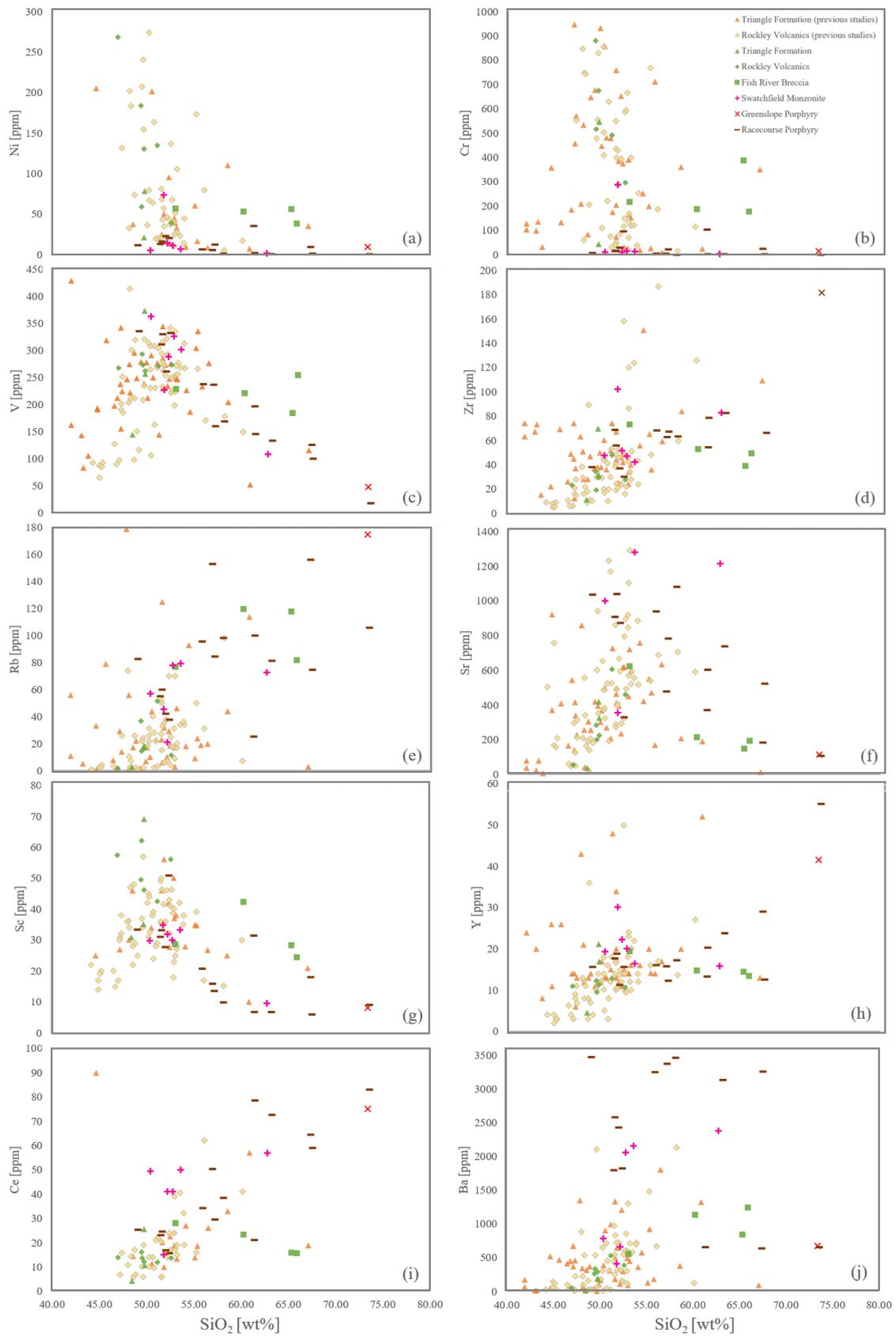


Fig 4-7 Bivariate diagram of selected trace elements plotted against SiO₂ for the volcanic, volcanoclastic and intrusive rocks from the Oberon region, New South Wales. (a) Ni, (b) Cr, (c) V (d) Zr, (e) Rb, (f) Sr, (g) Sc, (h) Y, (i) Ce and (j) Ba.

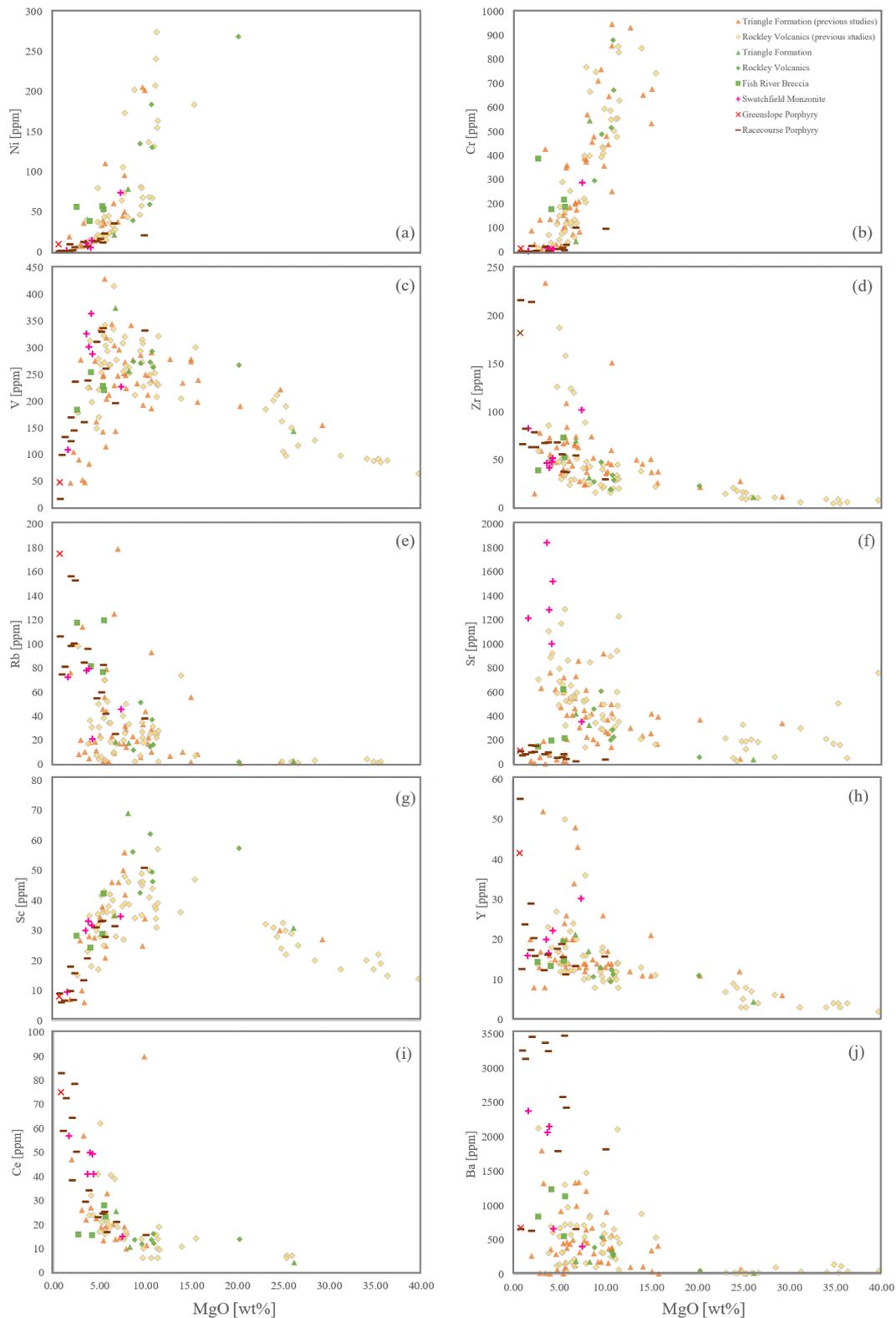


Fig 4-8 Bivariate diagram of selected trace elements plotted against MgO for samples in Fig 4-7. (a) and (b) Ni and Cr showing strong positive trends for all rock units. (c) and (d) showing at least two separate trends for the Triangle Formation and Rockley Volcanics (e) Rb vs SiO₂ presents scatter data of Triangle Formation and Rockley Volcanics but well correlated trends of Racecourse and Swatchfield unit, (f), (g), (h) and (i) showing well correlation of each units and suggesting multiple trends in the Triangle Formation and Rockley Volcanics, (j) Ba vs MgO showing widely scattered data.

4.5 Discussion

4.5.1 Major and Trace element geochemistry of the Triangle Formation and Rockley Volcanics

The volcanic and volcanoclastic rocks of the Triangle Formation and Rockley Volcanics have similar geochemical signatures with slight variations in major and trace elements (Fig 4-4 to 4-8). The geochemical diagrams show three main stages of magmatic evolution:

1. Mafic-ultramafic rocks (>10% MgO) dominated by the fractional crystallization of olivine with most elements increasing with decreasing MgO.
2. Mafic rocks (5-10% MgO) show a similar trend but with decreasing CaO and Sc indicating that the elements are controlled by the fractionation of clinopyroxene.
3. Rocks with intermediate composition show trends on the bivariate diagrams indicating extensive fractionation of plagioclase, titanomagnetite and apatite with decreasing Al₂O₃, FeO, TiO₂ and P₂O₅ with decreasing MgO.

The chemistry of the Rockley Volcanics samples in the Oberon, Black Springs and Native Dog areas are broadly similar, confirming the results of previous studies which show that the pyroxene-rich volcanics and breccias can be correlated regionally. Samples of the Triangle Formation collected from 10 km to the north of Oberon (Andrew, 1980) are clearly differentiated from other Triangle Formation samples especially on major element concentrations (low TiO₂, Al₂O₃, Na₂O and high MgO, MnO, CaO and LOI). However, both these Ordovician volcanic suites demonstrate high K calc-alkali to shoshonitic magmatic affinities (Fig 4-6b). The Triangle Formation has less mafic composition than the Rockley Volcanics, even though both Triangle Formation and Rockley Volcanics have ultramafic rocks with very high MgO. The Rockley Volcanics have a higher proportion of mafic rocks shown by the presence of pyroxene-phyric basaltic breccia. Some of the samples of the Rockley Volcanics from previous studies have very high MgO (20-39%) suggesting an ultramafic composition and possibly the accumulation of olivine phenocrysts in the original lavas. Compared to the Triangle Formation, the Rockley Volcanics tend to have lower TiO₂, Zr, Nb and Y (HFSE) and higher K₂O, P₂O₅, Rb and Sr (LILE). For example, the two formations are partially separated on the TiO₂ vs P₂O₅ diagram (Fig 4-9). However, some of Rockley Volcanics samples (polymictic volcanoclastic breccia and dolerite; see The OZchem 2007 database) contain higher TiO₂ and Zr (Fig 4-9). These also suggest two separate lavas for the Rockley Volcanics formed by different volcanism.

Comparison of major elements versus SiO₂ between the volcanic rocks of the Rockley-Gulgong Volcanic Belt (RGVB), Junee-Narromine Volcanic Belt (JNVB) and Molong Volcanic Belt (MVB) show the similarity of the Rockley Volcanics and Triangle Formation to the other volcanic belts in the Macquarie Arc (Fig 4-10) with the greatest similarity with the Molong Volcanic Belt.

4.5.2 Geochemistry of Fish River Breccia

The Fish River Breccia is a new geological unit that is located stratigraphically between the Rockley Volcanics and the Silurian volcanic rocks and sedimentary units near Oberon. In this study investigation of the geochemistry of the Fish River Breccia was used to provide insights into changes in the depositional environment between the end of the Ordovician

Macquarie Arc and the beginning of the Silurian rift-related magmatism. The FRB shares some geochemical signatures with the older units; the Triangle Formation and the Rockley Volcanics (Fig 4-4 to Fig 4-8) but has higher silica. This is consistent with the petrography discussed in Chapter 3, which showed the presence of quartz-rich sedimentary rock clasts. However, these silica values are still much less than the turbiditic sequences from the Adaminaby Group in adjacent areas. The Fish River Breccia has similar values of trace elements when compared to the main rock units of the Oberon region, except for relatively high Rb and Zr probably derived from micas and from zircons. Chondrite-normalised REE and MORB-normalised trace elements plots show mostly similar patterns to those of the Triangle Formation, Rockley Volcanics, and rocks from the Molong Volcanic Belt (Fig 4-11 and 4-12). However, the REE profiles of the FRB (Fig 4-11c) have slightly positive slope in the heavy rare earth elements whereas the Triangle Formation and Rockley Volcanics are flat. Therefore, the geochemistry of the Fish River Breccia supports the petrography in suggesting that the unit was most likely derived from reworking of the Triangle Formation, the Rockley Volcanics, the Adaminaby Group and the possibly Silurian volcano-sedimentary sequences when the Rockley-Gulgong Volcanic Belt was moving toward continent in the Late Ordovician or being rifted in the Early Silurian (see Glen et al., 2007a; Meffre et al., 2007).

4.5.3 Geochemistry of Swatchfield Monzonite and Racecourse Porphyry

The Swatchfield Monzonite and Racecourse Porphyry are possibly related to intrusive rocks found in the Cadia district, Molong Volcanic Belt. Major and trace elements variation diagrams suggest that the Swatchfield Monzonite possibly comprises two different magmatic suites suggested by MgO content which are mafic (> 5 wt% MgO) and intermediate intrusive rocks (<5 wt% MgO; Fig 4-5 and 4-8). However, due to time and land access constraints this was not further investigated in this study.

4.5.4 Comparison to the other parts of Macquarie Arc

High-K calc-alkaline to shoshonitic mafic to ultramafic volcanic and volcanoclastic rocks widely crop out within Oberon area. In this study a detailed geochemical comparison was undertaken (Fig 4-10) with the volcanic rocks from the other parts of the Macquarie Arc.

The results show that:

1. Similar fractional crystallization trends are observed in the least mobile elements in all three belts (Junee-Narromine Volcanic Belt, Molong Volcanic Belt and Rockley-Gulgong Volcanic Belt).
2. The distinct high Mg contents of the Rockley Volcanics in the study area can be compared to similar high Mg rock unit in southern Molong Volcanic Belt from the Byng Volcanics (Crawford et al., 2007b).
3. The Junee-Narromine Volcanic Belt rocks tend to be much more evolved than the Molong and Rockley-Gulgong rocks (Fig 4-10).
4. Geochemical comparison using chondrite-normalised rare earth elements (Fig 4-11) and MORB-normalised trace elements (Fig 4-12) also highlight the similarity of the Oberon rocks with those from the Macquarie Arc. The rocks from Junee-Narromine Volcanic Belt tend to have higher REE elements, probably related to the more fractionated nature of the magmatism (Fig 4-11b).

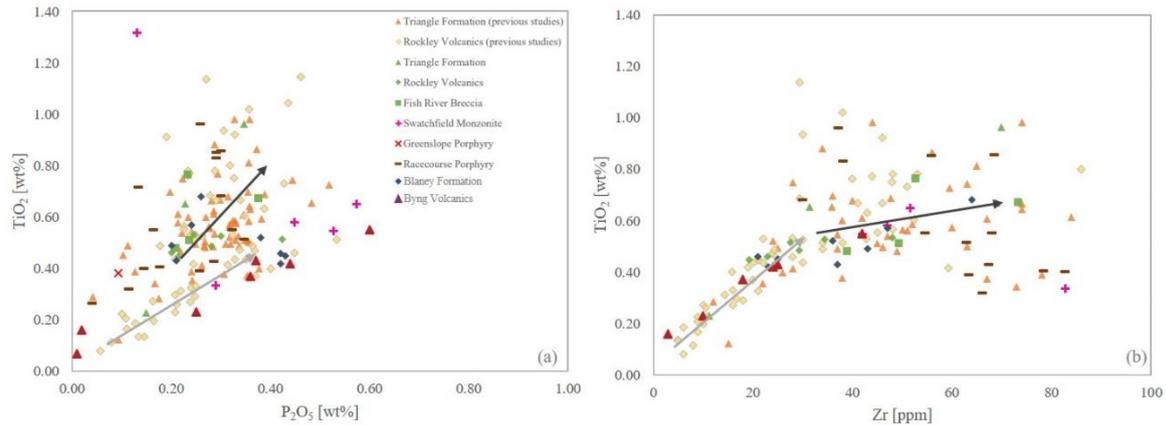


Fig 4-9 Plot of (a) TiO_2 vs P_2O_5 and (b) TiO_2 vs Zr showing differences between the Triangle Formation and the Rockley Volcanics with other lithological units in Oberon region. Arrows represent proximately fractionation trends for Triangle Formation (dark grey) and Rockley Volcanics (light grey). Some samples of Rockley Volcanics plot on separate trend characterized by higher TiO_2 .

There are however some differences between the Oberon area and the Molong Volcanic Belt,

1. The Oberon area has fewer lavas than reported in the in the Molong Volcanic Belt (Crawford et al., 2007b; Fergusson and Colquhoun, 2018; Glen and Watkins, 1994; Meffre et al., 2007; Stewart-Smith and Wallace, 1997)
2. No large outcrop of Ordovician limestone have been observed in Oberon These limestone crop out in the Junee-Narromine Volcanic Belt and Molong Volcanic Belt (Crawford et al., 2007b; Glen et al., 2007b; Meffre et al., 2007)

These differences indicate that although the Molong and Oberon area had similar magmatism it is likely that the Oberon area was deeper and more distal in the Ordovician respect to the volcanic source. The Junee-Narromine area may have differed in having thicker crust allowing more extensive fractional crystallization to occur relative to the other belts.

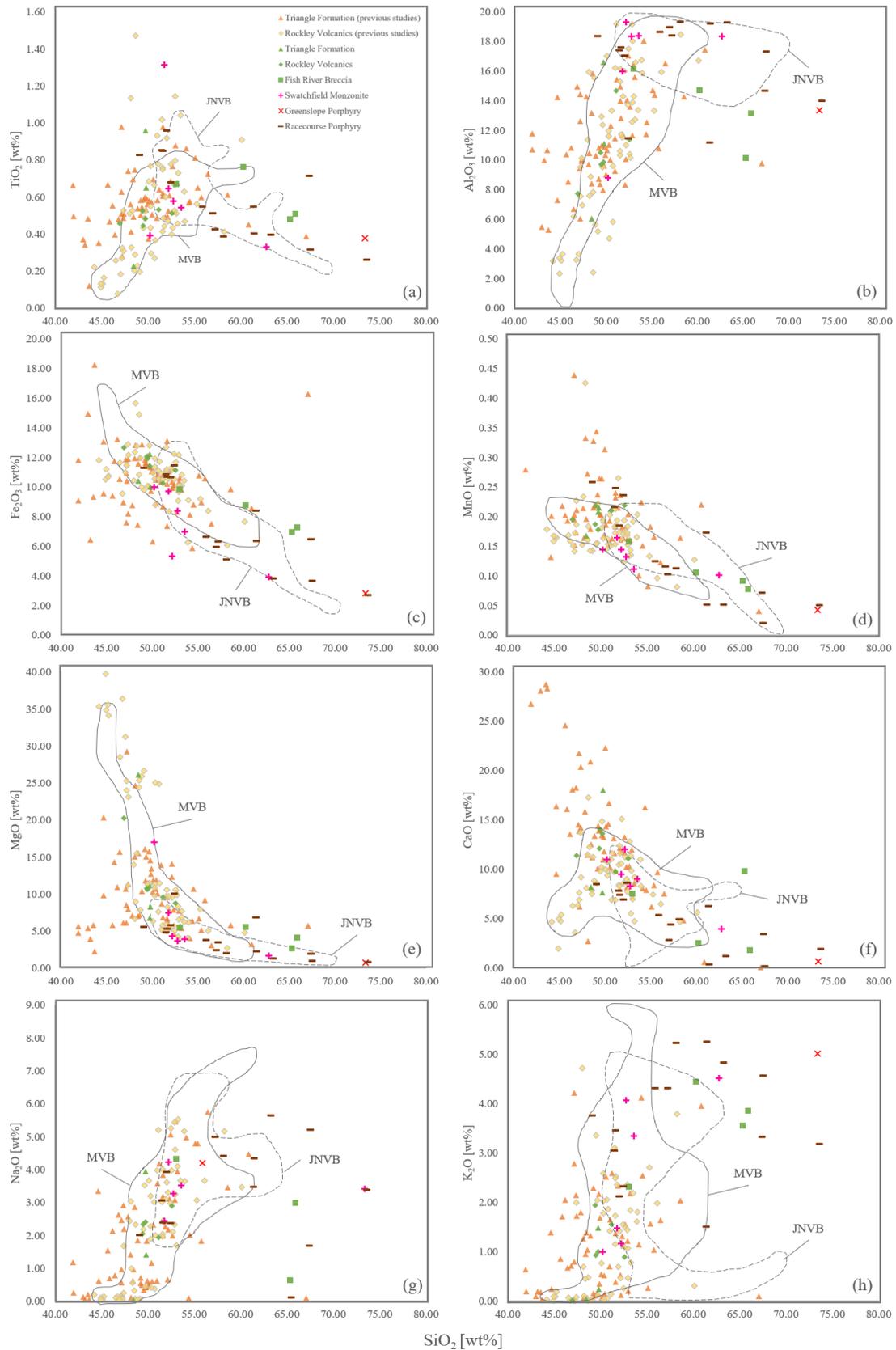


Fig 4-10 Major elements bivariate diagram plotted as function of SiO_2 for the Triangle Formation, Rockley Volcanics, Fish River Breccia, Swatchfield Monzonite, Greenslope Porphyry and Racecourse Porphyry comparing with Molong Volcanic Belt and Junee-Narromine Volcanic Belt data from Crawford et al. (2007).

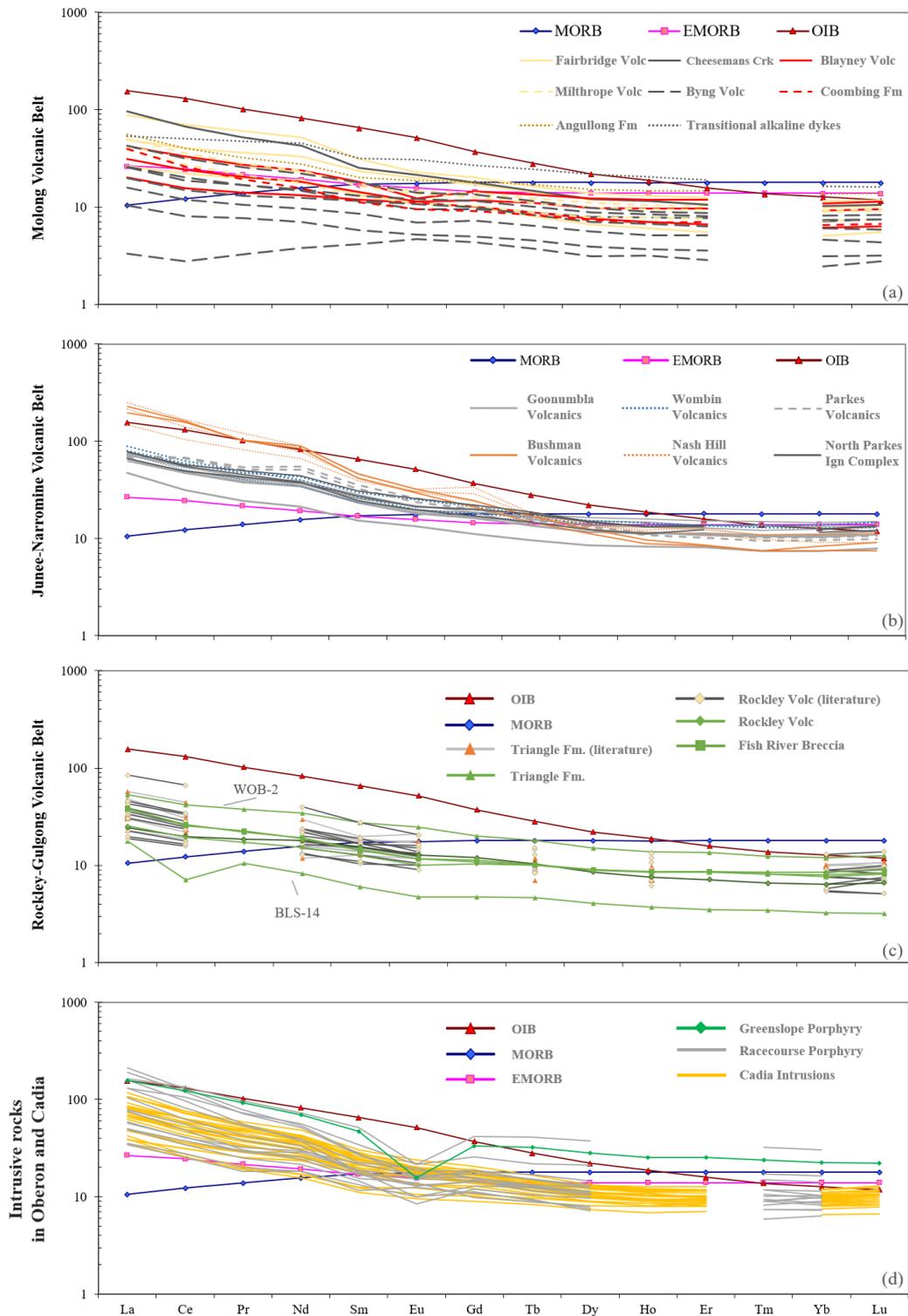


Fig 4-11 Chondrite normalised rare earth elements diagram for the data (a) from Molong Volcanic Belt, (b) Junee-Narrormine Volcanic Belt (Crawford et al., 2007b), (c) the Triangle Formation, Rockley Volcanics and Fish River Breccia from Oberon region and (d) intrusive rocks from Oberon region comparing to the data from Cadia region (Squire and Crawford, 2007).

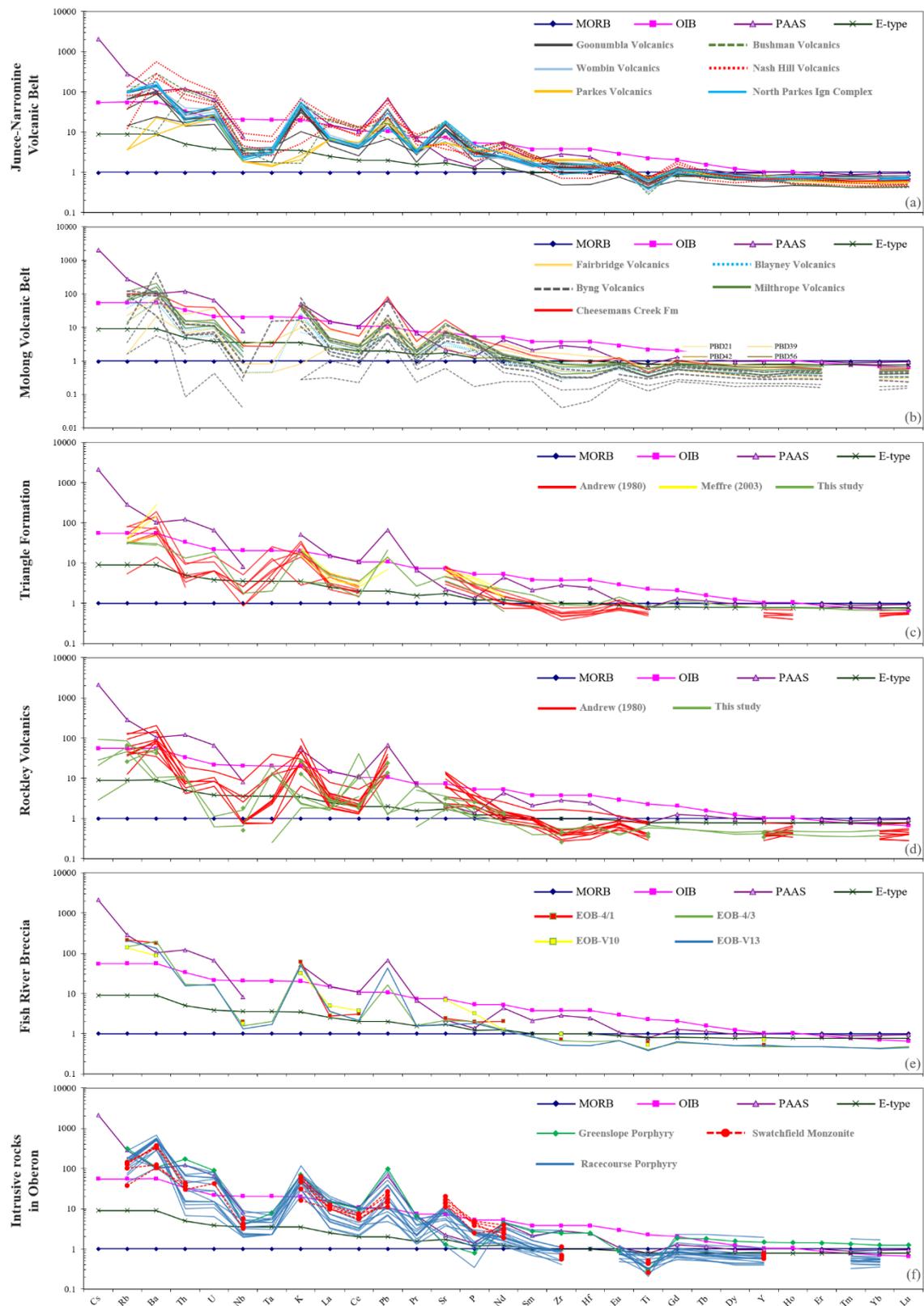


Fig 4-12 MORB-normalized trace elements patterns for the data from different parts of Macquarie Arc, (a) Junee-Narrormine Volcanic Belt, (b) Molong Volcanic Belt (Crawford et al., 2007b), (c) volcanoclastic rocks from Triangle Formation, (d) volcanic and volcanoclastic rocks from Rockley Volcanics, (e) volcanoclastic breccia from Fish River Breccia and (f) intrusive rocks crop out in Oberon region. The N-MORB composition values were from Sun and McDonough (1989).

CHAPTER 5: GEOCHRONOLOGY

5.1 Introduction

This chapter presents new U-Pb geochronology results on sedimentary and igneous rocks in the Rockley-Gulgong Volcanic Belt (RGVB) in the area around Oberon. Zircon and apatite U-Pb dating was performed using laser ablation inductively coupled plasma mass spectrometer (LA-ICPMS) at the University of Tasmania. The ages were used to better understand the volcanic, plutonic rocks and sedimentary rocks in the area. The results were also used to correlate rock units to other parts of Macquarie Arc particularly the Molong Volcanic Belt (MVB) and to determine if the intrusive rocks in the area are prospective for porphyry copper mineralisation.

5.2 Analytical Methods

Nine intrusive rocks, eleven volcanic and volcanoclastic rocks and ten quartz-rich sandstones were analysed using the U-Pb LA-ICPMS technique (see Meffre et al., 2007) at CODES, University of Tasmania. As zircons are rare in the volcanic and volcanoclastic rocks a number of different techniques were employed for analysis including analysis of both zircons and apatite in mineral separates (Cherry et al., 2017) and in situ U-Pb analysis of zircon crystals (Sack et al., 2011). List of samples and results are presented on Appendix III.

5.2.1 U-Pb zircon geochronology on heavy mineral separates

The samples of sedimentary, volcanic, and plutonic rocks (Fig 5-1; Table 5-1) were crushed using a hydraulic crusher and milled using Cr-steel ring mill to size <180 μm . The powdered samples were repeatedly panned to produce a heavy mineral concentrate which comprises magnetic and non-magnetic heavy minerals. The heavy minerals were then dried, and magnetic minerals were separated with a hand magnet. Zircons were handpicked from the non-magnetic fraction by using a sharp needle and a tiny paint brush. Selected zircons were mounted in 25 mm diameter epoxy resin disk. The mounts were polished using fine clean sandpaper and aluminium oxide on a polishing lap. The polished mounts were then washed using distilled water in an ultrasonic bath and then dried prior to acquiring cathodoluminescence (CL) images and laser analysis.

The zircon mounts were analysed using Agilent 7900 quadrupole LA-ICPMS at CODES, University of Tasmania coupled to an ASI S155 laser ablation system and a COMPex Pro 110 excimer laser at 193 nm. The analyses were performed at least 1 hour after ignition of the mass spectrometer to stabilise the machine and the primary and secondary standards zircons were analysed at the beginning, at the end and throughout the analytical run. The downhole fractionation, instrument drift and mass bias correction factors for Pb/U ratios on zircons were calculated using analyses on the primary standard (91500; Wiedenbeck, 1995) and checked on secondary standards (Temora; Black et al., 2003), and Plešovice; Sláma et al., 2008). The correction factor for the $^{207}\text{Pb}/^{206}\text{Pb}$ ratio was calculated using analyses on NIST610. The zircons were analysed with a laser beam at 29 μm spots at 5 Hz and approximately 2 J/cm². The 30-second gas blank was analysed at beginning of each analysis measurement followed by 30 seconds of ablation. The particles ablated by the laser were transported throughout the

chamber by helium gas flow to be combined with Ar gas and carried to the plasma torch. Each of the elements was measured successively every 0.16 seconds and recorded for data reduction. Data reduction was conducted using the LADR software program. Data were reported in Excel spreadsheet using ISOPLOT4.11 to generate Concordia diagrams, probability density plots and age calculations.

5.2.2 U-Pb small in situ zircon geochronology of mafic volcanic and volcanoclastic siltstone pebbly breccia

In many samples particularly mafic rocks, very few or no zircons were recovered with during the heavy mineral separation process. In these cases, automated scanning electron microscopy (SEM) was used to search for small zircons (10-50 μm) either in 25 mm diameter polished rock mounts or in polished-thin sections. The zircons were recognised and located using a FEI MLA 650 ESEM controlled by an automated software Mineral Liberation Analyzer or MLA at Central Science Laboratory (CSL), University of Tasmania prior to analysis by LA-ICPMS, using similar instrument and procedures to that outlined above but with a smaller spot size (13 microns) for both the samples and the standards. For detailed description of the methods see Sack et al. (2011). Data reduction calculations were also done using the same software and techniques as described above (Section 5.2.1).

5.2.3 U-Pb apatite geochronology

Apatite U-Pb geochronology was performed using the same techniques as described above (Section 5.2.1), except that different standards were used for the calibration. The primary standard used was the OD306 apatite (Thompson et al., 2016) and the calibration was checked on the Durango (McDowell et al., 2005), Kovdor (Amelin and Zaitsev, 2002), McClure Mountain (Schoene and Bowring, 2006), Otter Lake (Barfod et al., 2005) standards.

5.3 Results

5.3.1 U-Pb zircon geochronology

Magmatic zircons were not found in any of the 11 volcanic rocks selected using both the heavy mineral separation and the small in situ zircon technique. All analysed magmatic zircons were separated from 9 intrusive rocks in Black Springs from southern part of the study area (Fig 5-1). The nine samples are from the Racecourse Porphyry, the Greenslope Porphyry, and the Swatchfield Monzonite (Table 5-1). The samples consist of granodiorite, quartz granodiorite, diorite, porphyritic granite, dacite and monzonite (see Fig 5-1 for locations). Zircon grains are euhedral and prismatic crystals with most displaying zoning oscillatory typical of crystallization in igneous rocks (Fig 5-2). Many of zircons show black areas in cathodoluminescence images (CL-images) reflecting high uranium contents within particular dark zones in the crystals (Fig 5-2).

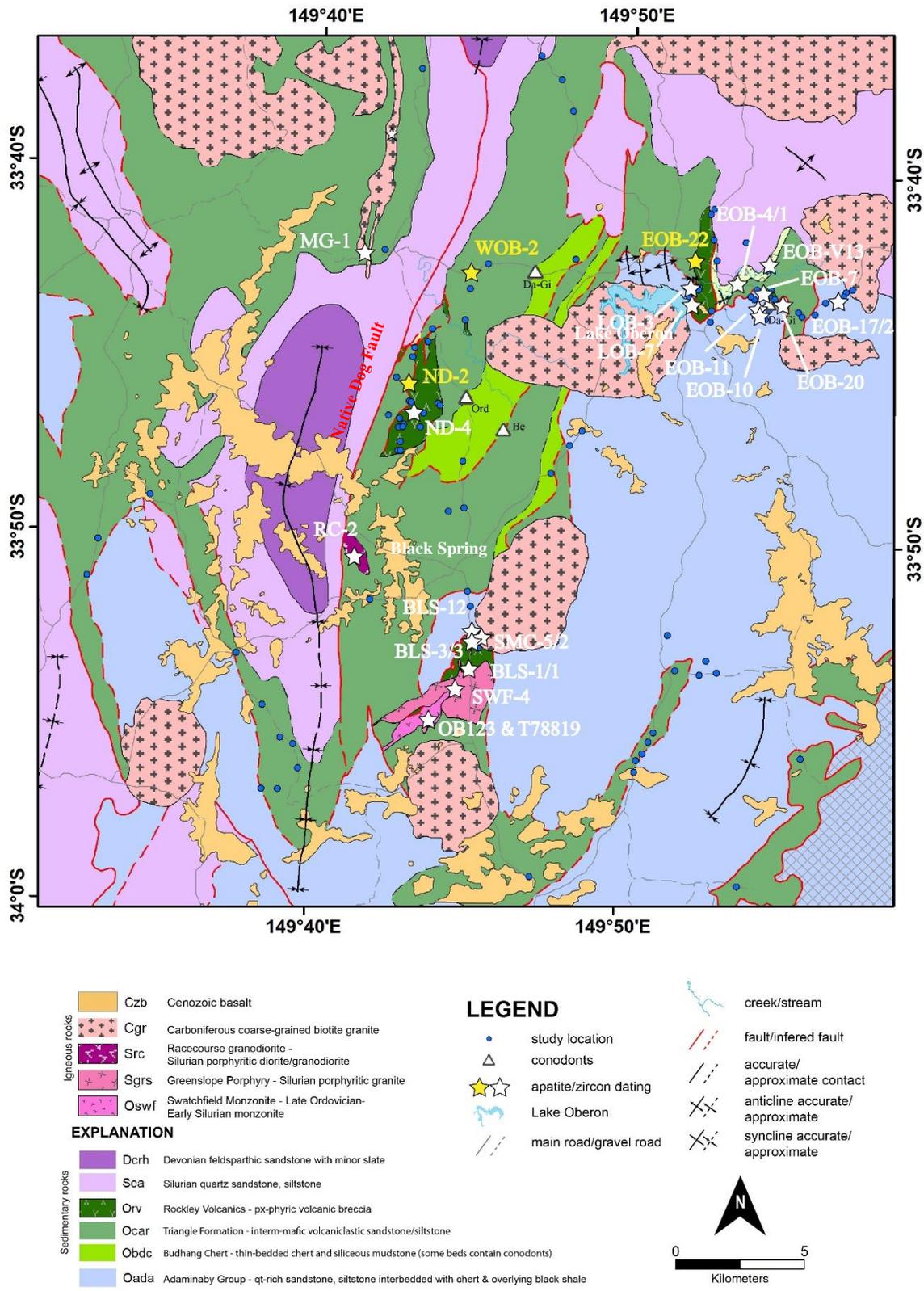


Fig 5-1 Geological map of the Oberon region modified from Stewart-Smith and Wallace (1997) showing locations of zircon and apatite geochronology.

Table 5-1 LA-ICPMS U-Pb zircon ages from this study. CG = Carboniferous Granitic rocks, FRB = Fish River Breccia, GRP = Greenslope Porphyry, RCP = Racecourse Porphyry RV = Rockley Volcanics, SWF = Swatchfield Monzonite, TRF = Triangle Formation.

Field name	Rock type	Unit	Latitude	Longitude	U-Pb ages (Ma)	error 2 σ (Ma)	MSWD
U-Pb zircon							
RC-2	quartz granodiorite	RCP	33° 50' 37" S	149° 41' 22" E	429.4	2.1	0.88
SWF-1	granite	GRP	33° 54' 07" S	149° 44' 42" E	425.6	3.5	1.8
SWF-2	granodiorite	GRP	33° 54' 07" S	149° 44' 42" E	430.2	3.7	1.8
SWF-4	granodiorite	GRP	33° 54' 07" S	149° 44' 42" E	428.8	2.1	1.2
SMC-9	porphyritic granite	GRP	33° 52' 40" S	149° 45' 29" E	430.1	4.2	0.98
SMC-10	porphyritic granite	GRP	33° 52' 40" S	149° 45' 29" E	425.8	3.1	1.6
BLS-1/1	quartz granodiorite	GRP	33° 53' 33" S	149° 45' 07" E	432.1	2.1	1.4
OB123	monzonite	SWF	33° 53' 57" S	149° 43' 41" E	451.6	3.2	1.6
T78819	diorite	SWF	33° 53' 57" S	149° 43' 41" E	443.5	2.4	1.16
U-Pb small in situ zircon							
EOB-4/1	mafic volc. ss bx	FRB	32° 42' 56" S	149° 53' 32" E	460	19	0.23
EOB-V13	mafic volc. ss bx	FRB	33° 42' 23" S	149° 54' 28" E	415	4	0.91
EOB-4/4	mafic volc. ss bx	FRB	32° 42' 56" S	149° 53' 32" E	-	-	-
WOB-2	mafic volc. bx	TRF	33° 42' 48" S	149° 44' 53" E	419	23	2.4
ND-4	mafic volc. bx	RV	33° 46' 37" S	149° 43' 06" E	-	-	-
U-Pb apatite							
ND-4	mafic volc. bx	RV	33° 46' 37" S	149° 43' 06" E	444	64	0.56
ND-2	mafic volc. bx	RV	33° 45' 51" S	149° 42' 58" E	427	16	0.96
NDC-2	mafic volc. bx	RV	33° 42' 21" S	149° 41' 25" E	n/a	n/a	n/a
WOB-2	mafic volc. bx	TRF	33° 42' 48" S	149° 44' 53" E	452	11	0.98
EOB-22	mafic volc. bx	RV	33° 42' 20" S	149° 52' 05" E	431	13	0.75

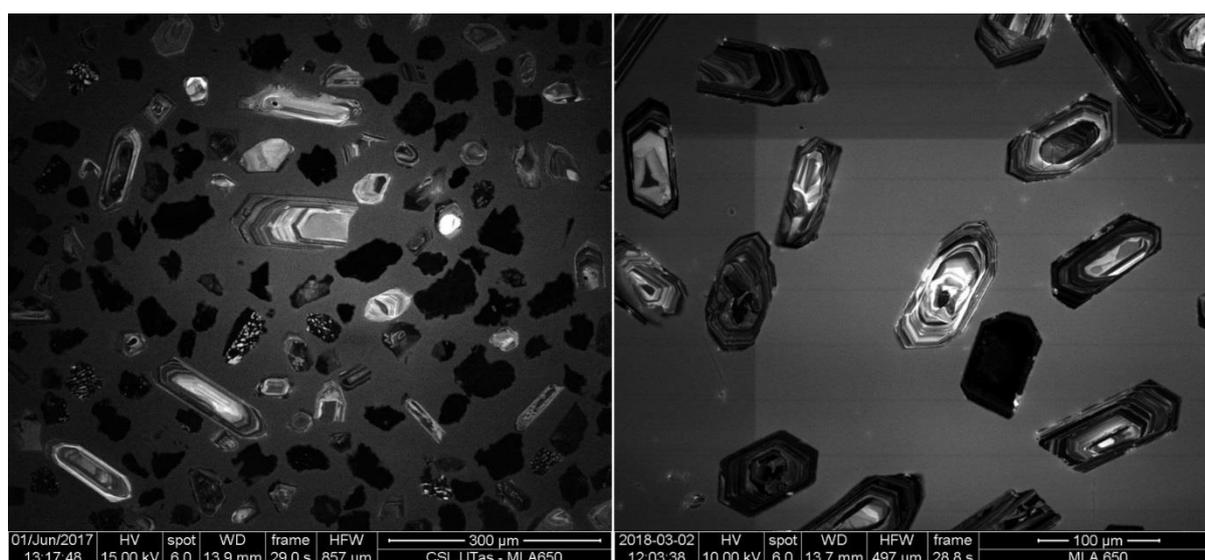


Fig 5-2 Cathodoluminescence (CL) images for representative analysed zircons of sample RC-2 from the Racecourse Porphyry (left) and SWF-4 from Greenslope Porphyry (right) showing high U contents (dark CL) in many of the zircons.

Table 5-2 Detrital zircon age populations of Adaminaby Group and Fish River Breccia in Oberon and Black Springs region. (Lithology description: qtss = quartz-rich sandstone, qlss = quartz-lithic sandstone, mtss = metasandstone, vcbx = volcanoclastic breccia).

U-Pb detrital zircon ages / sample no	Lake Oberon		Oberon					Black Spring			Fish River
	LOB-3	LOB-7c	EOB-11	EOB-10	EOB-7	EOB-20	EOB-17/2	BLS-12	SMC-5/2	BLS-3/3	EOB-4/1
Lithology	qtss	qtss	qtss	qtss	qtss	qtss	qlss	qtss	qtss	mtss	vcbx
Number of zircons	30	30	30	44	15	36	71	72	30	47	29
youngest zircon age (Ma)	485 ± 8	485 ± 12	467 ± 10	476 ± 8	448 ± 10	507 ± 14	480 ± 14	457 ± 12	450 ± 12	460 ± 12	416 ± 12
youngest zircon group (Ma)	n/a	486 ± 10	485 ± 9	478 ± 6	n/a	512 ± 9	498 ± 6	471 ± 5	n/a	490 ± 10	501 ± 6
<490 Ma	3%	7%	10%	14%	20%	0%	1%	10%	7%	4%	3%
490 – 550 Ma	10%	17%	20%	16%	33%	8%	15%	13%	17%	21%	24%
551 – 800 Ma	10%	13%	17%	30%	7%	25%	20%	26%	43%	28%	10%
801-1100 Ma	27%	20%	3%	18%	20%	39%	21%	26%	17%	15%	21%
1101 – 1600 Ma	23%	17%	27%	9%	7%	22%	17%	11%	3%	17%	17%
1601-1900 Ma	7%	17%	10%	7%	7%	0%	10%	3%	7%	6%	3%
>1900 Ma	20%	10%	13%	7%	7%	6%	15%	11%	7%	9%	21%

- Racecourse Porphyry

The Racecourse Prospect is located to the west of Black Springs in an area explored for porphyry Cu deposits by Anglo American Exploration Australia in 2014. In this study, a total 63 zircons were analysed from a granodiorite boulder (Sample RC2, see Table 5-1 and Fig. 5-1 for location). The analyses spread along Concordia from a main central group indicating both inheritance and Pb loss. Analyse interpreted to represent inherited grains or which show evidence of Pb loss based on U contents and isotopic homogeneity in the time resolved data, have been excluded from the final weighted average age determination. The most concordant group of zircons have $^{206}\text{Pb}/^{238}\text{U}$ average age of 429.4 ± 2.1 Ma (RC-2, MSWD = 0.88, probability of fit = 0.62, Fig 5-3A). A sample in this area was previously dated at 411 ± 5 Ma (Benn, 2014) which is younger than the results calculated from this study.

- Greenslope Porphyry

The Greenslope Granite or Greenslope Porphyry is a quartz-feldspar porphyritic granite that intrudes into the Swatchfield Monzonite and the older volcanic-volcanoclastic rocks of south Black Springs area. A total 283 zircons were analysed from 6 different samples (Table 5-1). All samples show extensive Pb loss (Fig 5-3, B-F) with a small concordant group that give a weighted average age of 428.8 ± 3.1 Ma. Three samples also have of older zircon indicating inheritance (Fig 5-3 C, E, F).

- *Swatchfield Monzonite*

The Swatchfield Monzonite was not directly sampled in this study due to issues accessing private land. Therefore, the two samples from previous collections were analysed in this study. These are OB123 collected by Meffre (2003) and T78819 from Geological Survey of New South Wales (GSNSW) core library.

A total 45 zircons were analysed from a monzonite (OB123 - 24 zircons) and 21 zircons from a diorite (T78819). These two samples different ages with zircons from OB123 demonstrating a single age with weighted average of 451.6 ± 3.2 Ma (17 of the 24 zircons analysed, MSWD = 1.6, probability of fit = 0.053, Fig 5-3 H). One high U zircon has a younger apparent age probably caused by Pb loss and 4 zircons are slightly older than the main group. The diorite (T78819) has a zircon concordant population with weighted average of 443.5 ± 2.4 (MSWD = 1.16, probability of fit = 0.29). One young zircon is suggested to have Pb loss and the three oldest are probably inherited. These ages from two samples might indicate two different phases of magma may be present within the Swatchfield intrusive body.

5.3.2 *U-Pb small in situ zircon geochronology*

Five samples of the volcanic and volcanoclastic rocks where zircons were not recovered using the heavy mineral separation techniques were analysed using the automated SEM as described in 5.2.2. Five samples containing 3 to 45 small zircons from Triangle Formation, Rockley Volcanics and Fish River Breccia were analysed (Table 5-1). The zircons are very small, ranging from 20-30 μm with irregular shapes. Most of zircons contain very high uranium and Fe contents indicating extensive Pb loss in these small zircons especially in zircons from Triangle Formation and Rockley Volcanics. In the Triangle Formation, sample (WOB-2) the U content of zircons ranged from 1,115 ppm to 6,716 ppm which is similar to the Rockley Volcanics sample (ND-4) that had zircons with U contents ranging from 1,261 ppm to 3,486 ppm. In contrast, the zircons from the Fish River Breccia samples show both high and low U contents (100 ppm to 4,400 ppm) mostly are less than 800 ppm.

The analyses from the small zircons are relatively imprecise. A total of 7 zircons were analysed from the Triangle Formation (WOB-2). Two analyses were rejected because of the extensive Pb loss and another analysis was rejected due to high common Pb. The two best analyses give a U-Pb age of 419 ± 23 Ma with a MSWD of 2.4 (Fig 5-4 B). No zircons from total 6 zircons in a mafic volcanic breccia (Rockley Volcanics, ND-4) was concordant (Fig 5-4 A). Therefore, no precise absolute age was determined for the Triangle Formation and Rockley Volcanics in this study. Further geochronology work needs to be undertaken to better constrain the age of the Triangle Formation and Rockley Volcanics.

A total of 61 zircons from three samples of volcanoclastic pebbly siltstone breccia belonging to the Fish River Breccia were analysed. Most of the zircons were rejected due to high Fe content, common and Pb loss. Notably the samples contain numerous old detrital grains possibly derived from Adaminaby Group. As these were analysed in situ in polished rock mounts, laboratory contamination can be ruled out as a source of the old crystals. The youngest zircons in EOB-4/1 resulted maximum depositional U-Pb age of 460 ± 19 Ma with MSWD of 0.23 and the youngest group of EOB-V13 resulted the maximum U-Pb age of 415 ± 4 Ma with MSWD of 0.91 respectively (Fig 5-4 C and D). There is a possibility that these ages are not reliable and too young due to Pb loss.

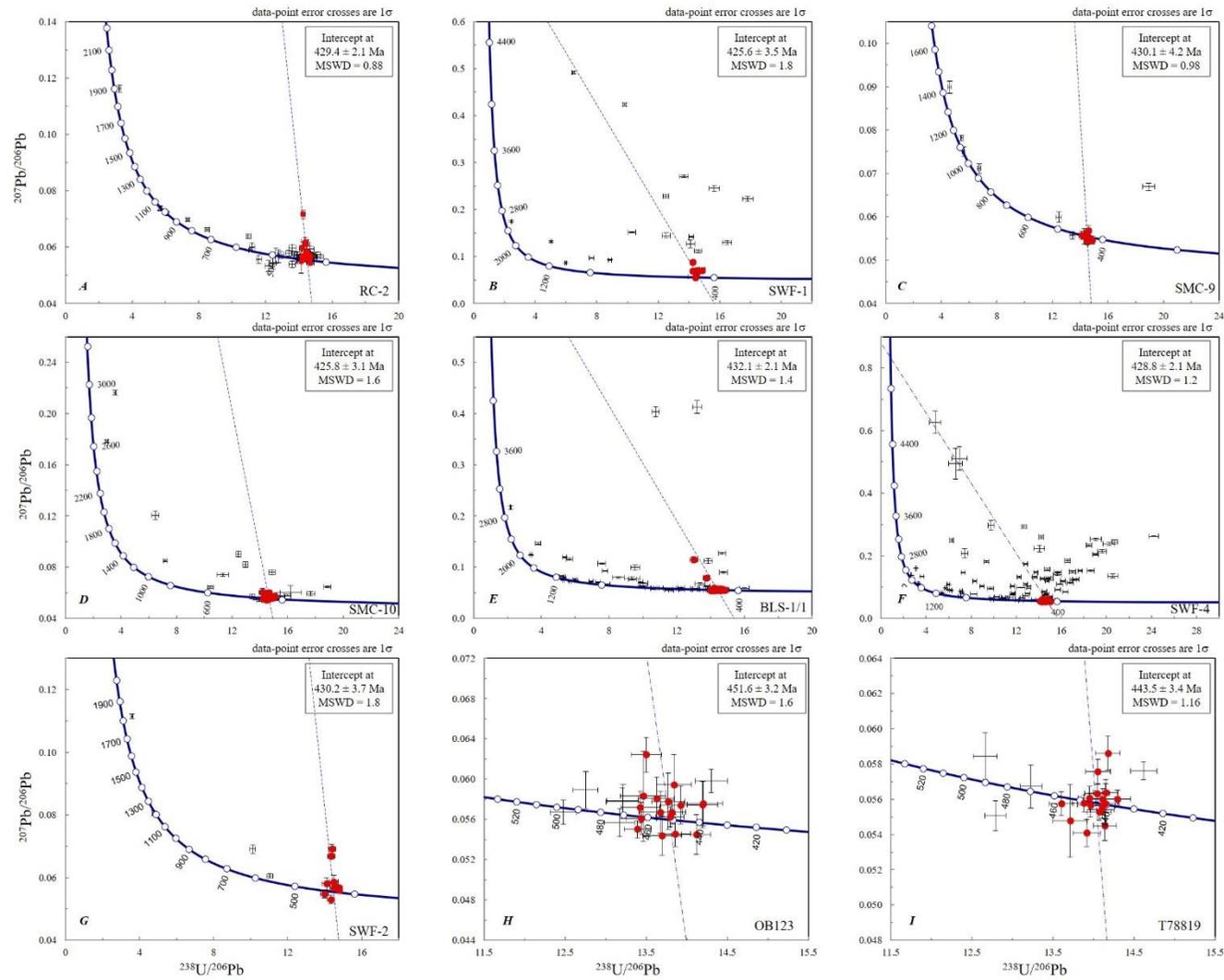


Fig 5-3 U-Pb zircon geochronology concordia plots for (A) Racecourse Porphyry, (B)-(G) Greenslope Porphyry, (H)-(I) Swatchfield Monzonite (analyses in red used in age calculation)

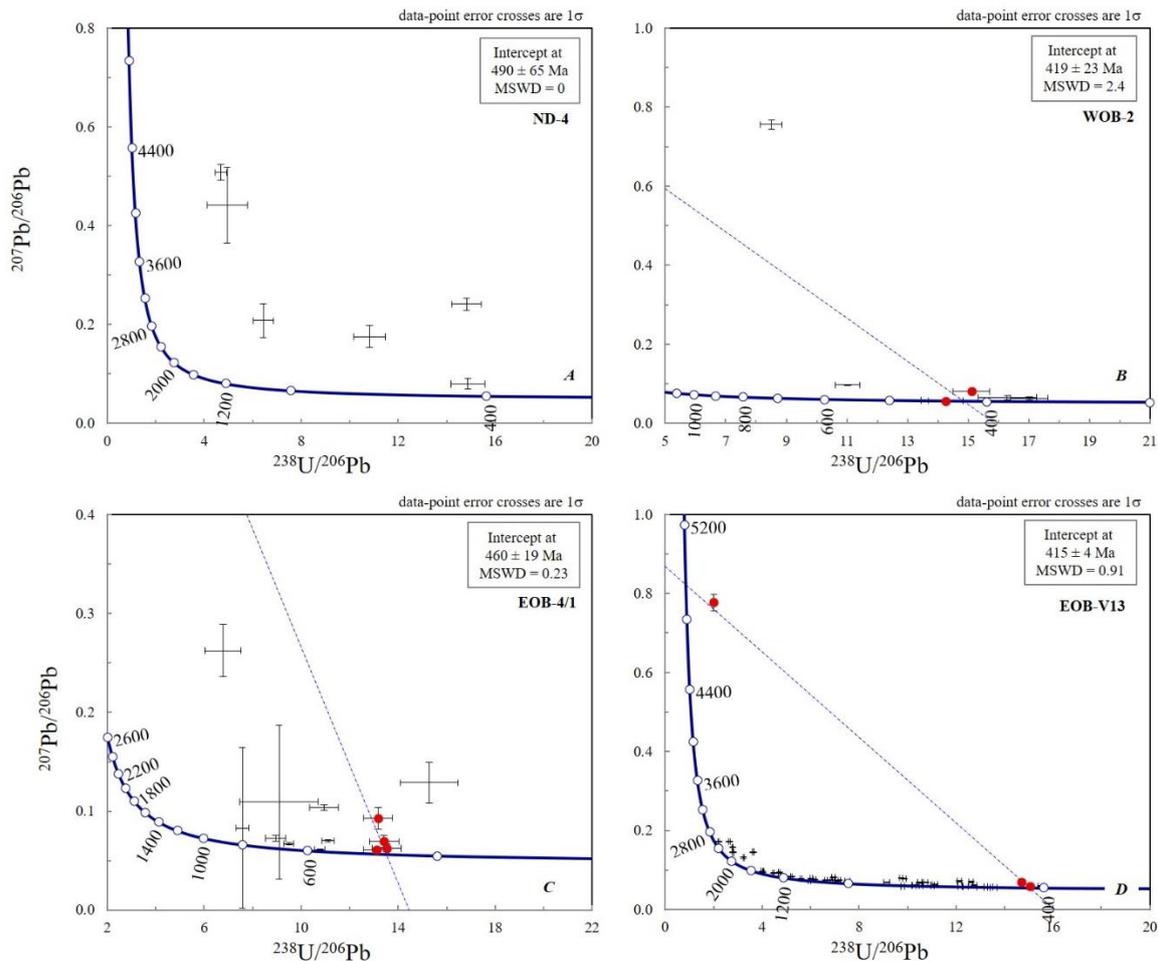


Fig 5-4 U-Pb in situ zircon geochronology Concordia plots for (A) Rockley Volcanics, (B) Triangle Formation, (C) and (D) Fish River Breccia.

5.3.3 U-Pb detrital zircon geochronology in quartz-rich sandstone and inherited zircons in the Fish River Breccia

Detrital zircons were analysed from ten samples of fine- to coarse-grained sandstone from the Oberon and Black Springs areas (Table 5-2). The biggest group of zircons recovered from quartz-rich sandstone from both Oberon and Black Springs have U-Pb ages around 500-600 Ma with minor group of 800-1100 Ma (Table 5-2; Fig 5-5). Small groups of older age zircons were also present in the samples at 1500 Ma and 2300 Ma. After removing zircons which have suffered Pb loss, the youngest zircons in most samples were Early to Middle Ordovician. There are however some differences in the age population of detrital zircons from Oberon and Black Springs area (Fig 5-6) with the Cambrian to Neoproterozoic zircons in the Oberon rocks being bimodal (500 and 600 Ma) but the Black Springs samples have a single U-Pb zircon age mode at 558 Ma (Fig 5-6A). This difference can be quantified using the KS-statistic which shows significant (Fig 5-6B) difference in the populations between the two areas. The zircon populations in the quartz-rich sandstones at Duckmaloi Road (EOB-17/2 and EOB-20) near the contact with the volcanoclastic rocks are more similar to zircons to the Black Springs sandstone than those from the samples from Oberon (Fig 5-5B).

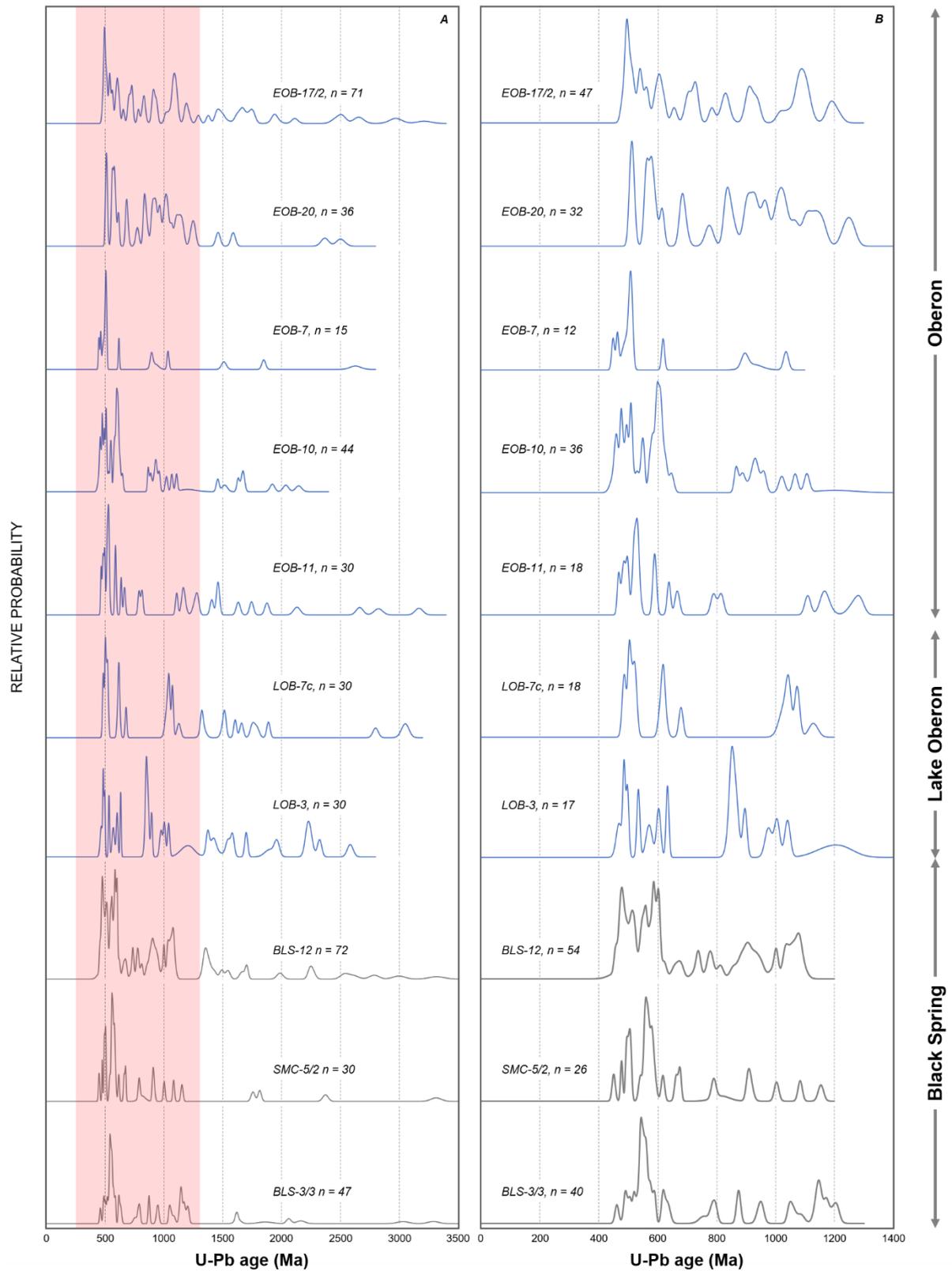


Fig 5-5 (A) U-Pb age population of detrital zircons from the Adaminaby Group occurring in separate area (Oberon town, Lake Oberon and Black Spring) showing the youngest peak at around 500 Ma and other various peak consistent with main geological events in East Australia. (B) U-Pb age population from red area in (A) showing distinctive peaks between 400-1400 Ma.

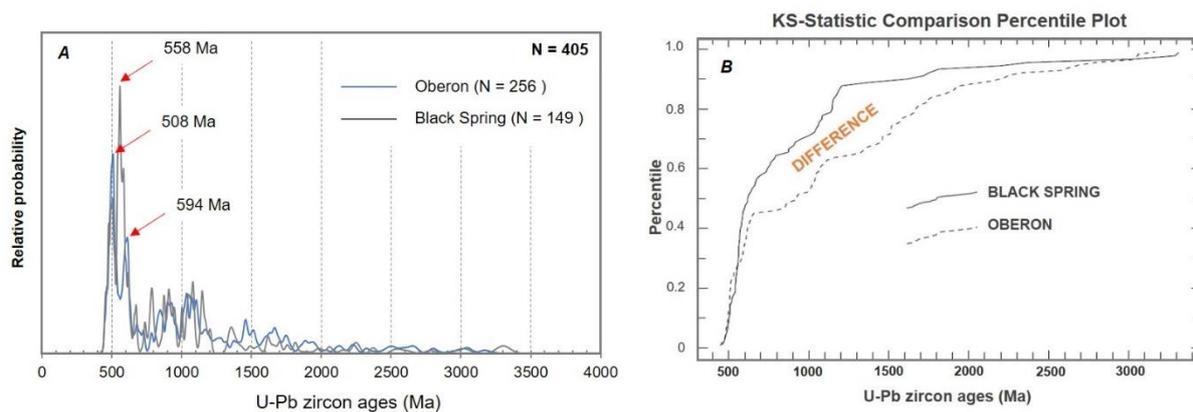


Fig 5-6 Detrital zircon U-Pb geochronology (A) Probability density plot of detrital zircon ages of Adaminaby Group from Oberon (blue line) showing the highest peak at 508 Ma compared with Black Springs (black line) showing the highest peak at 558 Ma. (B) Kolmogorov–Smirnov (KS) statistic showing difference of cumulative population of data shown in (A).

The 29 detrital zircons were recovered from mafic pebbly siltstone of the Fish River Breccia, 5-km to the east of the town of Oberon. These show a major group of U-Pb detrital zircon ages at 525 Ma (Fig 5-7) with minor groups at, 600 and 1,000. These are most like the zircons in the Oberon group of quartz-rich sandstones.

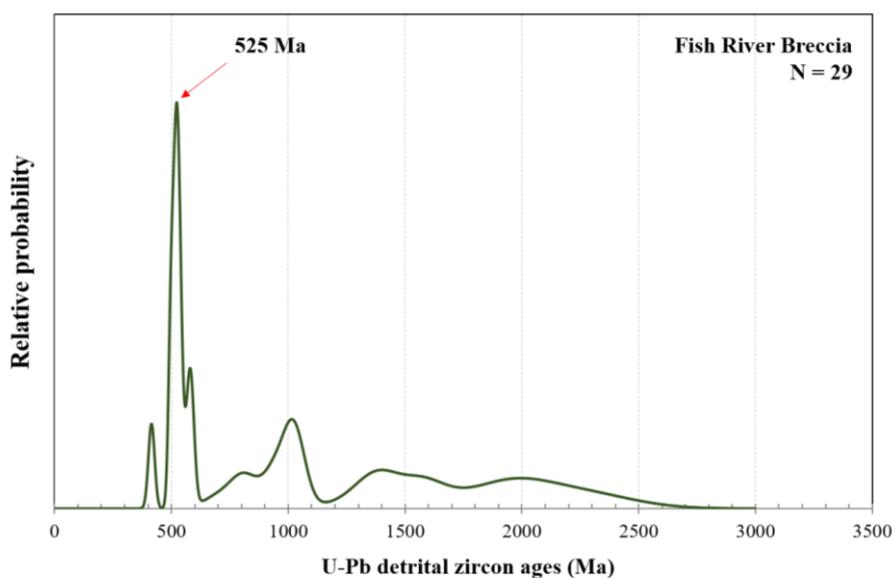


Fig 5-7 U-Pb age population of detrital zircons from the Fish River Breccia showing a single major group of U-Pb age.

5.3.4 U-Pb apatite geochronology

60 apatite grains were recovered in the heavy mineral concentrates from the mafic volcanoclastic sandstones of the Triangle Formation and pyroxene-rich mafic volcanic breccia of the Rockley Volcanics. Most of the apatite show prismatic euhedral crystal shapes indicating

that they crystallised in magmatic rocks. The 18-best apatite from sample WOB-2 (Triangle Formation) give a concordia intercept age of 452 ± 11 Ma, MSWD of 0.98 (anchored to common Pb from the model of Stacey and Kramers (1975)). A further 13 apatite of EOB-22 (Rockley Volcanics) give an intercept age of 431 ± 13 Ma, MSWD of 0.75 (Fig 5-8 A and B). The apatite grains analysed from Sample ND-4 (Rockley Volcanics) contain high common Pb and low U so that the analyses have very large uncertainties giving an intercept age calculation of 444 ± 64 Ma, MSWD of 0.56 (Fig 5-8C). Another sample from the same area (ND-2) has apatite which give a concordia intercept age of 427 ± 16 Ma, MSWD of 0.96 with two slightly older apatite that were excluded from the age calculation (Fig 5-8D). Apatite from another Rockley Volcanics sample from this area (NDC-2) has a U content too low for geochronology.

All the apatite dated from these rocks have U-Pb ages that range from the Late Ordovician to Silurian with large overlapping uncertainties that do not further constrain the age of these rocks beyond confirming what is already known.

5.4 Discussion of the U-Pb geochronology results

5.4.1 Age constraint of the Triangle Formation and Rockley Volcanics

The Triangle Formation in Oberon area is dominated by pyroxene-rich volcanoclastic sandstone with rare or no quartz mixing in the rock composition and zircons are also rare. The mafic volcanoclastic sandstone (WOB-2) has yielded the U-Pb age from small in situ zircons of 419 ± 23 Ma. However, U-Pb apatite ages (452 ± 11 Ma; WOB-2) indicate the maximum age of deposition of the Triangle Formation between Middle-Late Ordovician which is similar to the results from Zhang et al. (2019b) that reported a new U-Pb zircon age of 456 ± 16 Ma from Bald Ridge area.

The Rockley Volcanics occur in central town area in Oberon where the rocks are dominated by pyroxene-rich volcanic breccia which has the youngest U-Pb apatite age of 431 ± 13 Ma. The Rockley Volcanics which crop out near the Native Dog Fault are dominated by mafic volcanic breccia and conglomerate with large pebble clasts. These have a U-Pb apatite age of 427 ± 16 Ma. These ages with significant analytical uncertainties due to the low U in these apatite. These ages are younger than the single magmatic age for Phase 4 Rockley Volcanics in this area of 454 ± 3 Ma (U-Pb zircon, Glen et al., 2011). More geochronological analyses are required to constrain the age of these Ordovician volcanic rocks in Oberon, however the mafic composition and lack of zircons make this difficult.

5.4.2 Age constraint of the Fish River Breccia

The Fish River Breccia composition comprises a mixing of quartz-rich detrital sandstone rocks and intermediate to mafic volcanic rocks. The zircons in the mineral separates were rare (<10 per 500g of rock). Therefore, the U-Pb in situ zircon geochronology method was used to attempt to constrain the age of this unit (see Sack et al., 2011). The age of the youngest concordant zircons were much younger ages than expected (average of 3 crystals at 415 ± 4 Ma). (Figure 5-7). This age could either be due to Pb loss or they could indicate a younger than expected age for Fish River Breccia. Pb loss is the significant problem for in situ zircon geochronology due to the small size of the zircons. A previous study showed that the small in situ zircons were significantly more prone to Pb loss than the larger separated crystals from the same sample (Sack et al., 2011)

This could be resolved with further work targeting quartz-rich pebble or higher silica rocks in this unit.

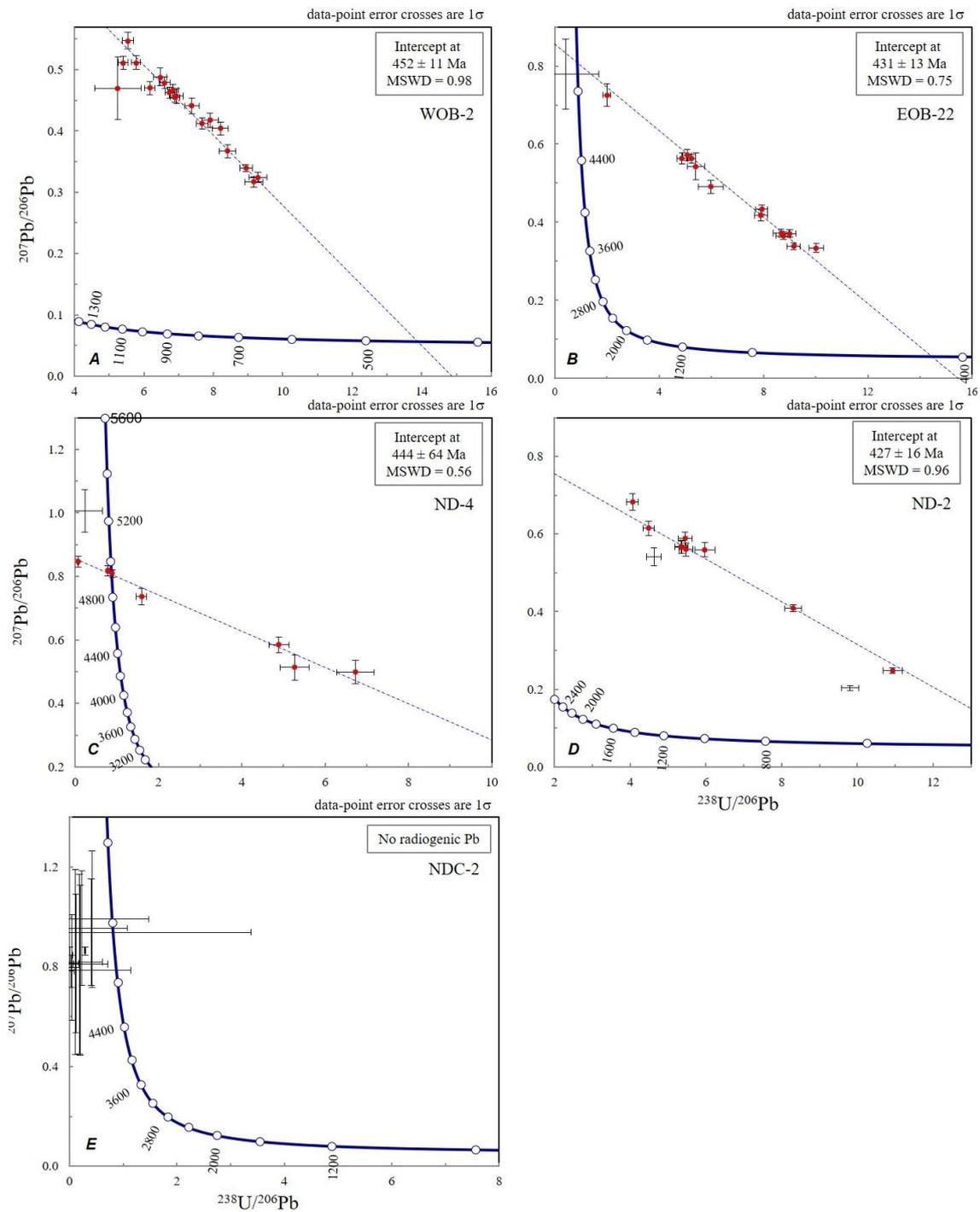


Fig 5-8 Apatite U-Pb geochronology concordia plots for (A) Triangle Formation, (B)-(E) Rockley Volcanics.

CHAPTER 6: DISCUSSION

The results from the previous chapters are discussed in this chapter to document the volcanic and sedimentary facies architecture of the Ordovician rocks around Oberon and then compare these to the other regions of Macquarie Arc. The tectonic environment and mineral deposit prospectivity of Oberon are also discussed using the results of the geology, geochemistry, and geochronology.

6.1 Comparison to Macquarie Arc

6.1.1 *Volcanic and sedimentary facies of Oberon*

The stratigraphy of the rocks in the Macquarie Arc have been documented and discussed by multiple authors (e.g. Crawford et al., 2007; Fergusson and Colquhoun, 2018; Glen et al., 2007; Harris et al., 2014; Quinn et al., 2014). These studies have subdivided the rocks based on their characteristics and ages into four phases (Fig 6-1). The geological data from this study shows that the Oberon rocks are mostly related to Phase 1, Phase 2, and Phase 4 of the Macquarie Arc. Due to the complex structure in the area and extensive the weathering and erosion, it is very hard to create a detailed stratigraphy. However, combining results from previous studies and new results from this study demonstrates that the Ordovician cherts and volcanoclastic rocks form a thick (700-1000 m) coarsening upward sequence. The sequence begins with few hundred meters of Early Ordovician thin-bedded chert. After a possible stratigraphic gap, the Early Ordovician chert are overlain by Middle Ordovician chert, which are in turn overlain by the very fine- to fine-grained volcanoclastic sandstone and minor conglomerates of the Triangle Formation. The cherts were only observed in west Oberon area and do not occur east of the town Oberon. It is very hard to correlate the cherts across the area because fossils are rare especially those that indicate ages of deposition. The few conodonts recovered from a previous study (Murray and Stewart, 2001) indicate both Early and Middle to Late Ordovician ages. This study searched the bedded chert for radiolarian, but no useful fossils were found after processing the rocks in acid. Thin to thickly bedded volcanoclastic turbidites then transition into the coarser mafic volcanic sandstone and pyroxene-rich breccia of the Rockley Volcanics indicating a major influx of volcanic material following the deposition of the Triangle Formation. The relationship between these two volcanic units in this area is still unclear due to the structural complexity and the paucity of bedding. The uppermost of the volcanic facies is the clinopyroxene-rich ultramafic rock present at one outcrop in the town of Oberon. This not been recognized elsewhere in this study but have been described by previous studies in other parts of Macquarie Arc such as at Rockley and Blayney in the eastern part of Molong Volcanic Belt (Crawford et al., 2007b; Meffre et al., 2007). They are described as clinopyroxene-rich, olivine-rich ultramafic rocks which mainly related to Phase 4 magmatism. This suggests that the clinopyroxene-rich mafic/ultramafic rocks are a key horizon correlated to the latest stage of the Macquarie Arc volcanism.

The change from fine to coarse facies was widely observed through the Macquarie Arc associated with the change from Phase 3 to Phase 4. In the Junee-Narromine and Molong Volcanic Belt limestones separate these two phases. In the Rockley-Gulgong Volcanic Belt no

limestones occur. However, fine- to coarse-grained limestone clasts were recognized in Fish River Breccia in the outcrop located 5 km east from Oberon.

The Fish River Breccia was mapped on the geological map of Oberon sheet (Stewart-Smith and Wallace, 1997) as belonging to the Rockley Volcanics. The radiometric signature of the Fish River Breccia strongly resembles the Phase 4 Macquarie Arc as most of the clasts in this unit are reworked from the underlying Macquarie Arc rocks. However, this unit contains rare clasts of quartz-rich sandstone, limestone clasts and rare Precambrian zircons which help differentiate it from the underlying Macquarie Arc. It is likely Fish River Breccia unconformably overlies the Triangle Formation and the Rockley Volcanics and is stratigraphically above Phase 4 magmatism of the Macquarie Arc. Therefore, the Fish River Breccia may be correlated with the coarse conglomerates from the Early to Middle Silurian Waugoola Group from Cadia in Molong Volcanic Belt (Harris et al., 2014). Alternatively, it could be the Late Silurian to Early Devonian basal unit within the Campbells Group.

6.1.2 Geochemical Affinity

The geochemistry of the Macquarie Arc shows very distinctive characteristics relative to the other parts of Lachlan Orogen. Each phase of magmatism of Macquarie Arc also display differences which can be used to correlate across the volcanic belts. In Oberon, the geochemical signatures of Triangle Formation and Rockley Volcanics show that they are similar but slightly different and related to Phase 2 and 4, respectively. The younger rocks found in the area including Fish River Breccia, Racecourse Porphyry, Greenslope Granite and Swatchfield Monzonite are recognized as high silica rocks (Fig 6-2 and 6-3) suggesting that these were formed after the Macquarie Arc magmatism. The geochemistry of rocks in Oberon also suggest the similarity to Molong Volcanic Belt than Junee-Narromine Volcanic Belt (dashed-line Fig 6-2; Fig 6-4; Fig 6-5; Fig 6-6).

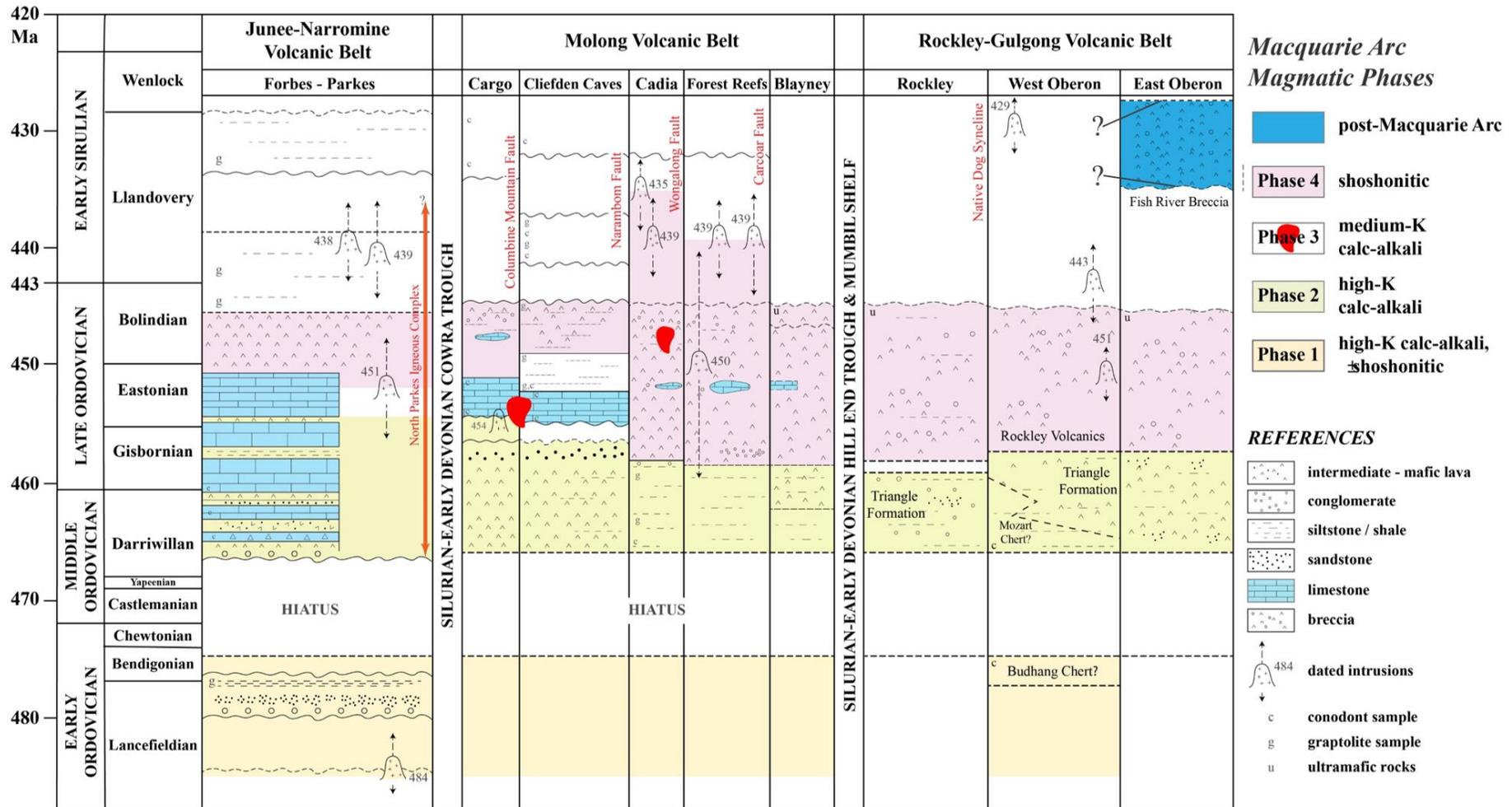


Fig 6-1 Time-space diagram of Macquarie Arc (except Kiandra Volcanic Belt) showing rock units related to Macquarie Arc magmatism (after Crawford et al., 2007; Fergusson and Colquhoun, 2018; Glen et al., 2007; Meffre et al., 2007).

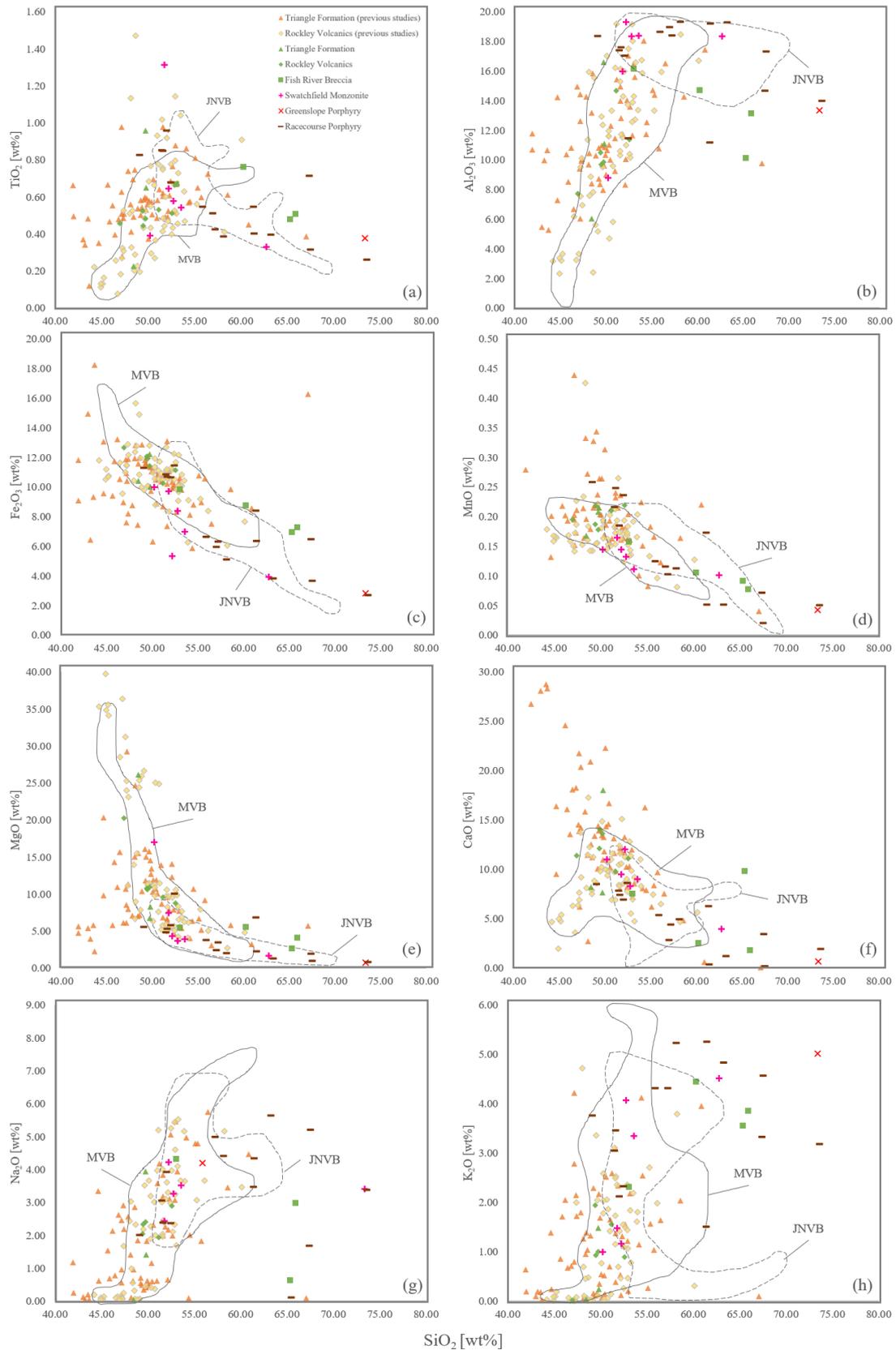


Fig 6-2 Major elements bivariate diagram plotted as function of SiO_2 for the Triangle Formation, Rockley Volcanics, Fish River Breccia, Swatchfield Monzonite, Greenslope Porphyry and Racecourse Porphyry comparing with Molong Volcanic Belt and Junee-Narromine Volcanic Belt data from Crawford et al. (2007).

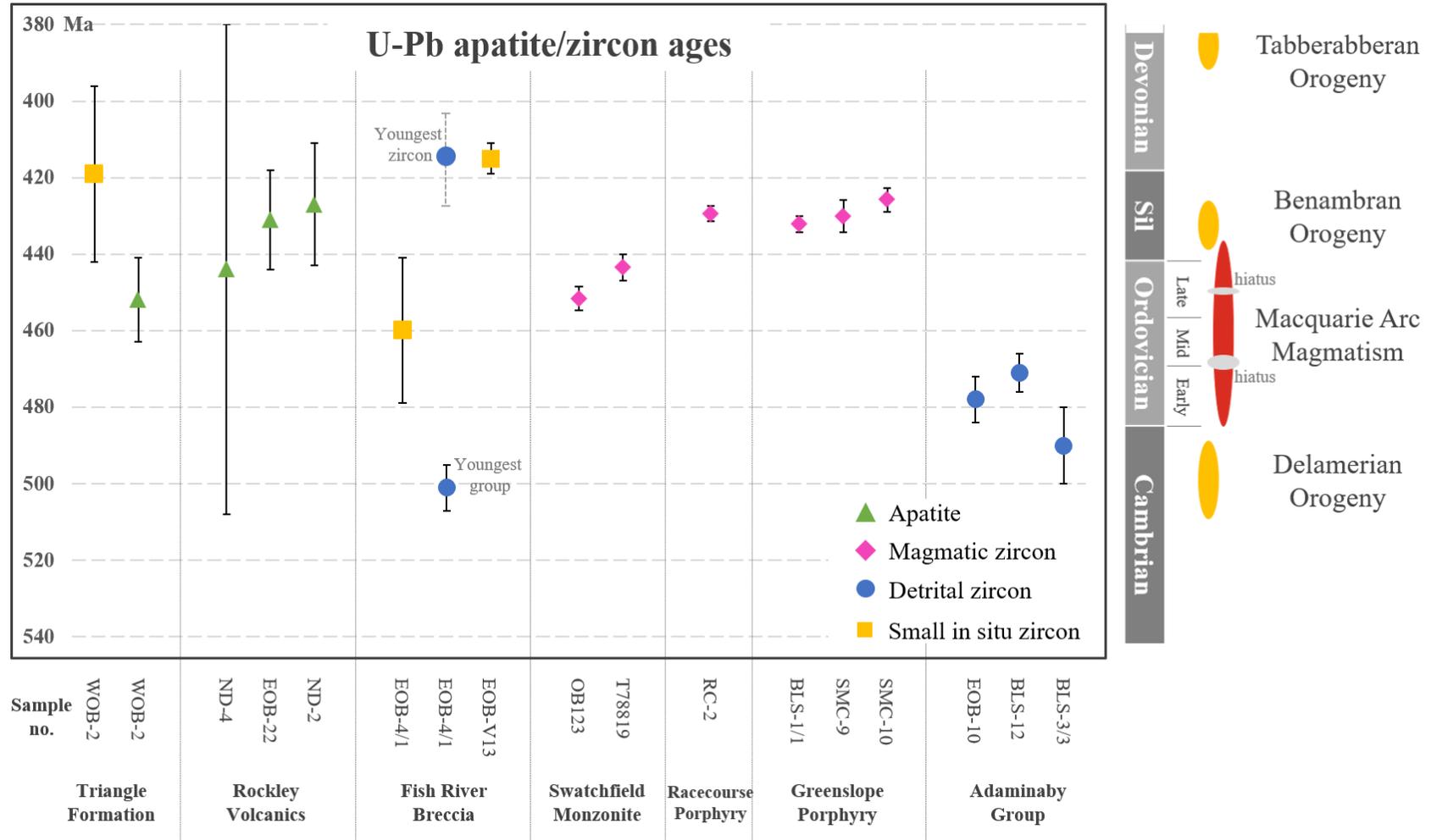


Fig 6-3 U-Pb zircon ages showing relation between the rock units in Oberon and Macquarie Arc magmatism as well as significant tectonic events in Lachlan Orogen.

6.2 Implication of geochemistry for tectonic environment of the Rockley-Gulgong Volcanic Belt

The major and trace elements discriminant diagrams for volcanic and plutonic rocks indicate that volcanic and volcanoclastic rocks cropping out in Oberon region were formed in subduction-related tectonic setting (Fig 6-4, 6-5 and 6-6). Older volcanic-volcanoclastic rocks are high-K to shoshonitic but younger rocks (Fish River Breccia, Greenslope Porphyry, Racecourse Porphyry) are contaminated by crustal materials (Fig 6-7) suggesting during that these formed after the end of the Macquarie Arc magmatism and in a Silurian rift-related tectonic setting.

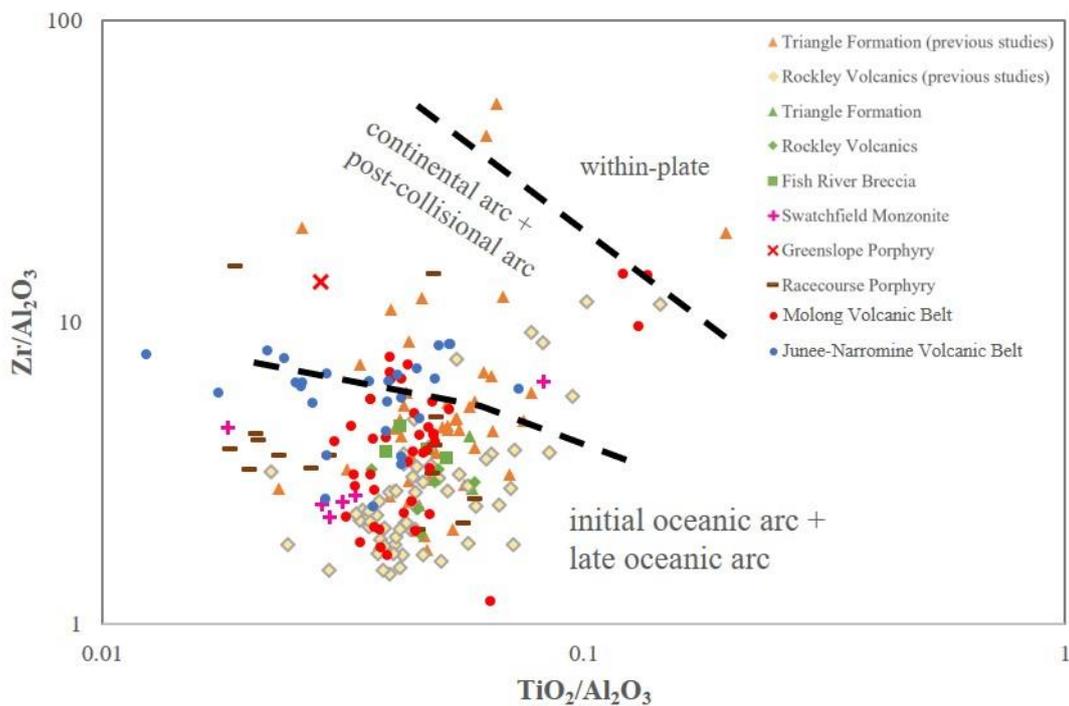


Fig 6-4 Tectonic discrimination diagram of Müller et al. (1992) for arc-related potassic rocks showing most of all results plotting in the oceanic arc field with some plotting in continental arc and post-collisional arc fields.

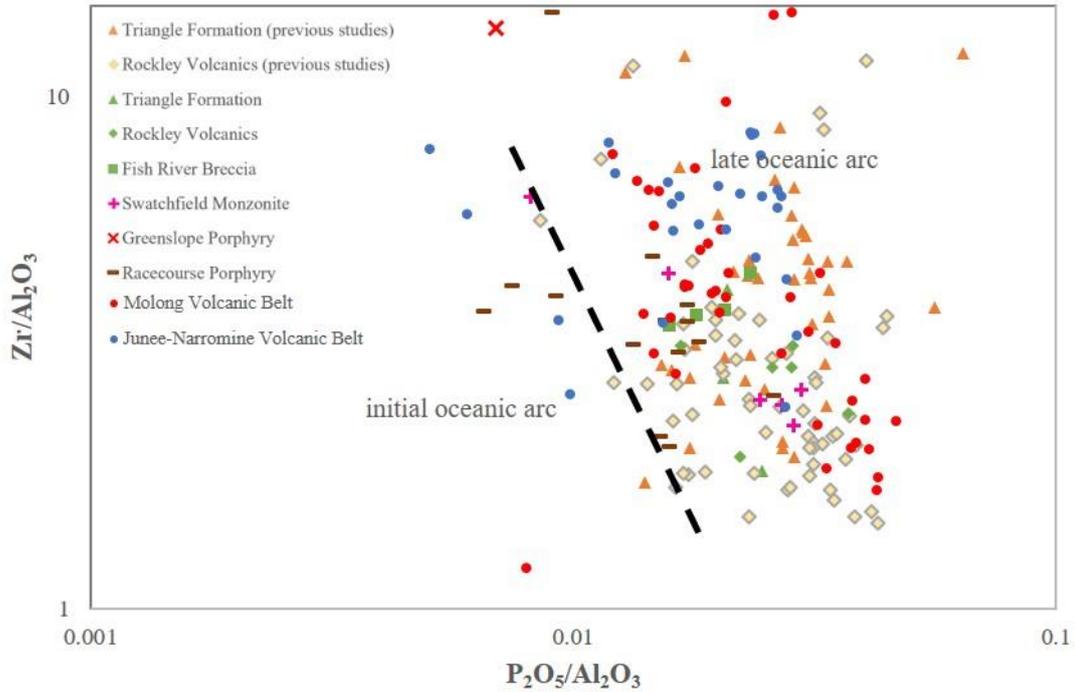


Fig 6-5 Tectonic discrimination diagram of Müller et al. (1992) for arc-related potassic rocks showing most of all results plotting in the late oceanic arc field.

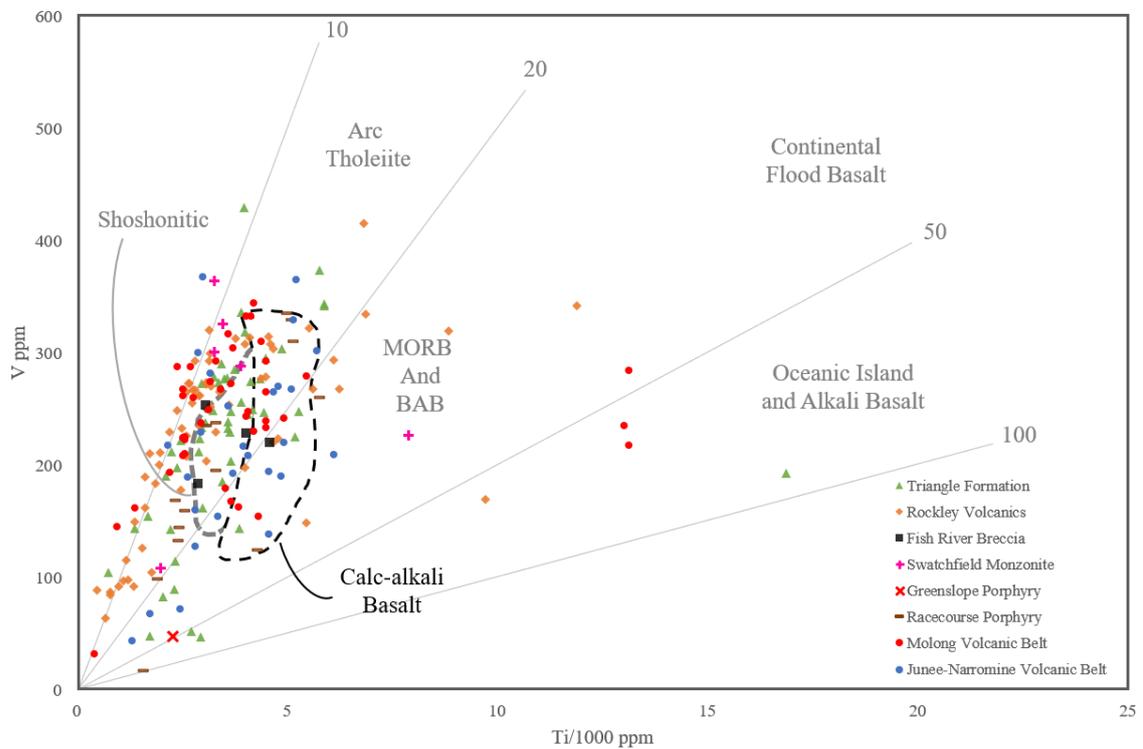


Fig 6-6 V vs Ti/1000 diagram showing the arc characteristic of the Molong and Junee-Narromine Volcanic Belts including rocks in Oberon which are Triangle Formation, the Rockley Volcanics and the Fish River Breccia. Discrimination diagram field boundaries based on data from Rogers and Setterfield (1994); Rollinson (1993) and Shervais (1982).

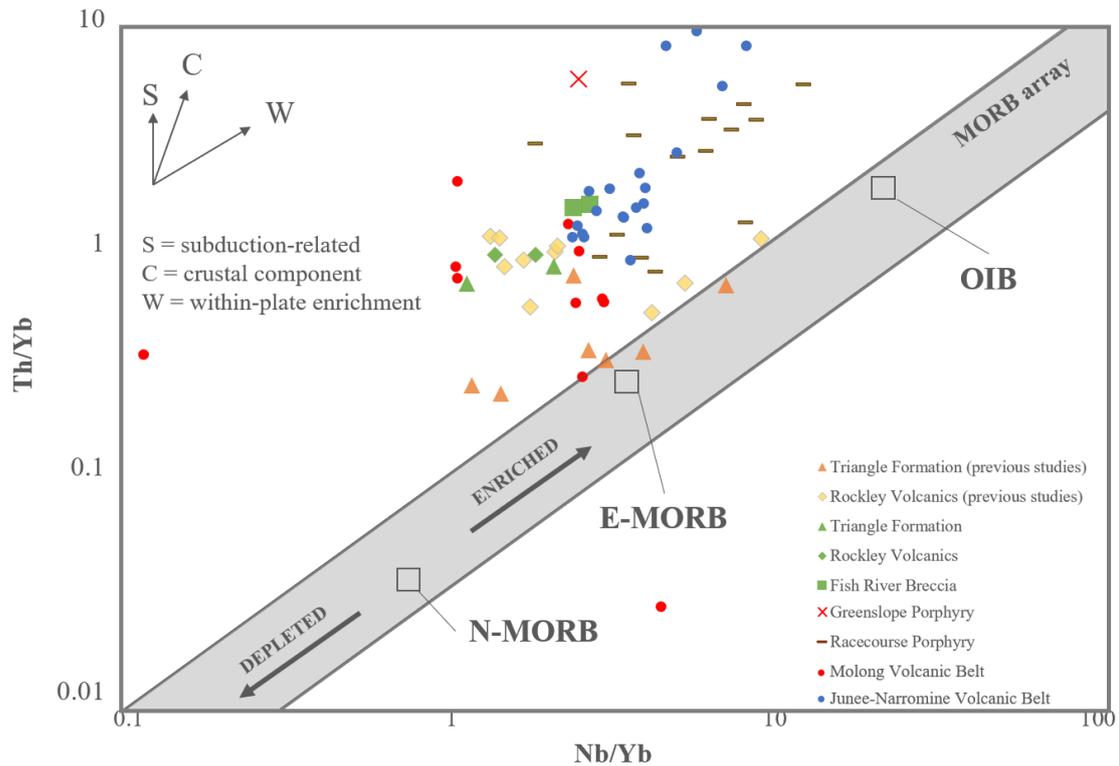


Fig 6-7 Plots of Th/Yb versus Nb/Yb after Pearce (2008) with the data point of selected rocks in Molong and Junee-Narromine Volcanic Belts which and rocks in Oberon region showing that volcanic and volcanoclastic rocks of Triangle Formation, Rockley Volcanics and Fish River Breccia are subduction-related and the intrusive rocks of Greenslope Porphyry and Racecourse Porphyry were formed in area related with continent.

6.3 Implication for Ore Deposit Prospectivity

Porphyry magmas have been documented to form through the accumulation of dissolved water in magma chambers that have undergone multiple cycles of replenishment and extensive fractional crystallisation deep within the crust (Loucks, 2014). Magmatic rocks formed in this way have particular geochemical signatures that are characterised by high Sr/Y ratios in intermediate to felsic magmas (Fig. 6-8). The majority of the magmatic rocks in the Oberon area are too low in Si and Sr and too high in Y to be prospective for porphyry Cu deposits. One analysis from the Swatchfield Monzonite is the exception to this.

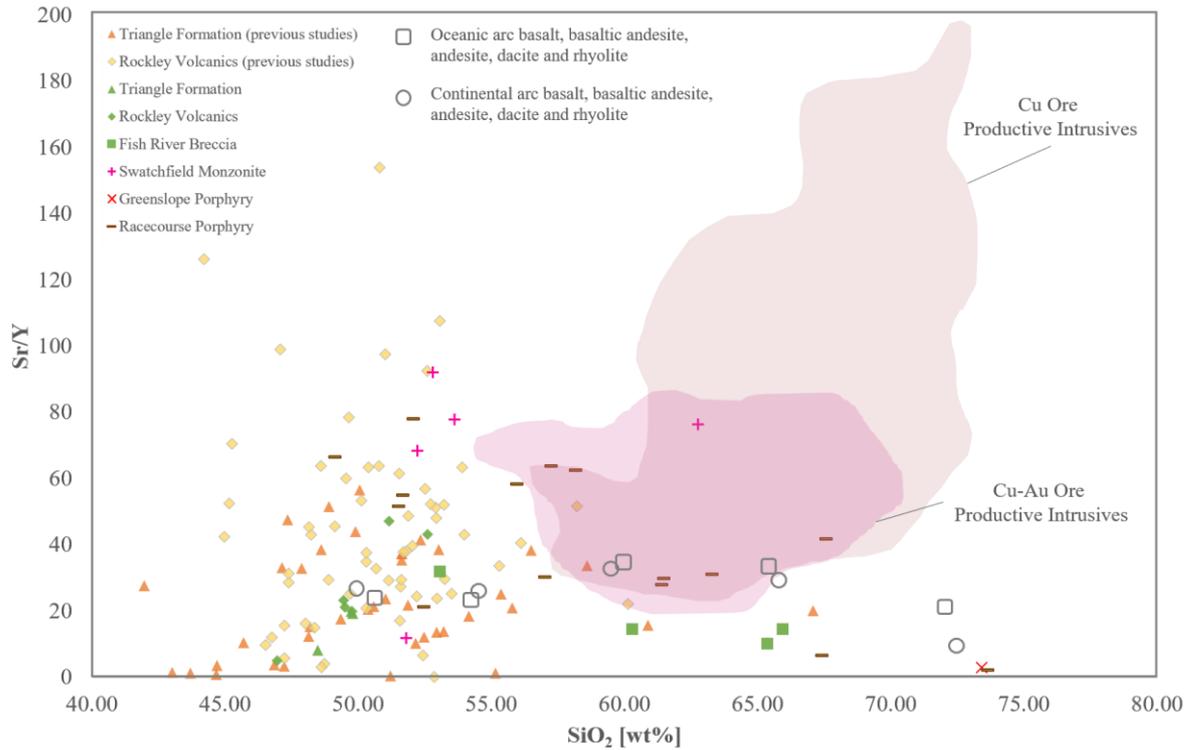


Fig 6-8 Plot of whole-rock Sr/Y vs wt% SiO₂ showing comparison between rocks in Oberon and the global references of productive intrusive rocks together with oceanic arc volcanic rocks and continental arc volcanic rocks (Loucks et al., 2014). The diagram shows that only few Oberon rocks plotting in intercept area of Cu-Au Ore productive intrusives.

CHAPTER 7: CONCLUSION

This chapter summarizes the key findings of this study. The stratigraphy of the Ordovician rocks around Oberon comprises two main lithological provinces, the Ordovician juvenile island arc rocks of the Macquarie Arc and the coeval, mature, quartz-rich turbidites of the Adaminaby Group. The Macquarie Arc rocks are intruded by Late Ordovician and Early Silurian intermediate to felsic igneous rocks and overlain by two Silurian sedimentary sequences.

1. The quartz-rich turbidites of the Adaminaby Group occur in the south-east of the 1:100,000 Oberon map sheet and consist of Early and Middle Ordovician quartz-rich sequences with no volcanic material. Detrital zircons show two distinct continental-derived provenances with zircon age populations of 490-600 Ma (Delamerian Orogeny) and 800-1000 Ma (Grenvillian Orogeny).
2. The Rockley-Gulgong Volcanic Belt consists of a coarsening upwards sequence with the Budhang Chert, the fine to coarse mafic volcanoclastics of the Triangle Formation and the mafic volcanic breccia with upper ultramafic lavas of the Rockley Volcanics. These correlate with the Phase 1, 2 and 4 magmatism of the Macquarie Arc.
3. The intermediate-mafic pebble breccia and conglomerates of the Fish River Breccia contain rare quartz and limestone clasts and old continental-derived zircons. The dominant mafic to intermediate clasts may be derived from the Triangle and Rockley Volcanics. This unit is a post-collisional deposit containing both Ordovician Macquarie Arc and Adaminaby Group which is probably equivalent to the Waugoola Group in the Molong Volcanic Belt or alternatively represents the base of the Campbells Group.
4. The Swatchfield Monzonite intrudes into the rocks of the Rockley-Gulgong Volcanic Belt and may consist of multiple intrusions as zircons from samples from previous collections returned ages between 451-443 Ma and the rocks are geochemically heterogeneous. These geochronological and geochemical results indicate the Swatchfield Monzonite is related to the final stage of Macquarie Arc magmatism.
5. The Silurian fine-grained quartz and feldspar-rich sedimentary sequences of the Campbells Group overlie the rocks of the Rockley-Gulgong Volcanic Belt.

The tectonic environment of deposition and emplacement can be summarized as follows:

In the Early Ordovician the depositional environment of the rocks in Oberon was deep marine and distal from the arc center for both the Adaminaby Group and the Budhang Chert.

In the Middle to Late Ordovician the Triangle Formation was deposited in the distal part of an oceanic island arc which received arc-derived volcanic detritus as sources from the Macquarie Arc. The Adaminaby Group structurally underlies the Triangle Formation received no arc-derived sediments during this time.

During the Late Ordovician to Early Silurian, the deposition and emplacement of Ordovician igneous rocks occurred closer to the oceanic island arc center, possibly due to the beginning of the arc's collision with the continental crust.

The volcanoclastic pebbly siltstone breccia of the Fish River Breccia which reworked Macquarie Arc intermediate-mafic volcanics, were deposited in higher energy environment during Silurian. The deposition was probably related to the extensional tectonic setting occurred widely in this region.

The Early to late Ordovician rocks around Oberon are not prospective for porphyry Cu deposits as the rocks are distal to the volcanic center. During the Late Ordovician and the Early Silurian Swatchfield Monzonite is the only intrusive phase, which is potentially prospective, but more work needs to be done mapping and dating these rocks as there is evidence for multiple intrusions in that area.

REFERENCES

- Aitchison, J.C., and Buckman, S., 2012. Accordion vs. quantum tectonics: Insights into continental growth processes from the Paleozoic of eastern Gondwana. *Gondwana Research*, 22(2), 674–680.
- Adamson, C.L., 1951. Reconnaissance geology of the Snowy Mountains area: Unpublished Progress Report No.4. Department of Mines, New South Wales.
- Amelin, Y. and Zaitsev, A.N., 2002. Precise geochronology of phoscorites and carbonatites: The critical role of U-series disequilibrium in age interpretations. *Geochimica et Cosmochimica Acta*, 66(13), pp.2399-2419.
- Andrew, A.S., 1980. A Geochemical and Stable Isotope Study of Some Altered Mafic Volcanites and Their Metamorphism: The Rockley Volcanics from Within the Aureole of the Bathurst Batholith, New South Wales: PhD thesis, University of Sydney. pp.296.
- Barfod, G.H., Krogstad, E.J., Frei, R. and Albarède, F., 2005. Lu-Hf and PbSL geochronology of apatites from Proterozoic terranes: A first look at Lu-Hf isotopic closure in metamorphic apatite. *Geochimica et Cosmochimica Acta*, 69(7), pp.1847-1859.
- Benn, A.E., 2014. Geology of the Racecourse Prospect, New South Wales: Unpublished Honours thesis, University of Tasmania. pp.95.
- Black, L.P., Kamo, S.L., Allen, C.M., Aleinikoff, J.N., Davis, D.W., Korsch, R.J. and Foudoulis, C., 2003. TEMORA 1: a new zircon standard for Phanerozoic U–Pb geochronology. *Chemical geology*, 200(1-2), pp.155-170.
- Cherry, A.R., McPhie, J., Kamenetsky, V.S., Ehrig, K., Keeling, J.L., Kamenetsky, M.B., Meffre, S. and Apukhtina, O.B., 2017. Linking Olympic Dam and the Cariewerloo Basin: Was a sedimentary basin involved in formation of the world's largest uranium deposit? *Precambrian Research*, 300, pp.168-180.
- Cooke, D.R., Wilson, A.J., House, M.J., Wolfe, R.C., Walshe, J.L., Lickfold, V. and Crawford, A.J., 2007. Alkalic porphyry Au–Cu and associated mineral deposits of the Ordovician to Early Silurian Macquarie Arc, New South Wales. *Australian Journal of Earth Sciences*, 54(2-3), pp.445-463.
- Crawford, A.J., Cooke, D.R. and Fanning, C.M., 2007a. Geochemistry and age of magmatic rocks in the unexposed Narromine, Cowal and Fairholme igneous complexes in the Ordovician Macquarie Arc, New South Wales. *Australian Journal of Earth Sciences*, 54(2-3), pp.243-271.
- Crawford, A.J., Meffre, S., Squire, R.J., Barron, L.M. and Falloon, T.J., 2007b. Middle and Late Ordovician magmatic evolution of the Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences*, 54(2-3), pp.181-214.
- Fairbridge, R.W., 1953. *Australian stratigraphy*. 2nd edition. University of Western Australia Press, Perth.

- Fergusson, C.L., 2014. Late Ordovician to mid-Silurian Benambran subduction zones in the Lachlan Orogen, southeastern Australia. *Australian Journal of Earth Sciences*, 61(4), pp.587-606.
- Fergusson, C.L., 2009. Tectonic evolution of the Ordovician Macquarie Arc, central New South Wales: arguments for subduction polarity and anticlockwise rotation. *Australian Journal of Earth Sciences*, 56(2), pp.179-193.
- Fergusson, C.L., 2003. Ordovician-Silurian accretion tectonics of the Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences*, 50(4), pp.475-490.
- Fergusson, C.L. and Colquhoun, G.P., 2018. Ordovician Macquarie Arc and turbidite fan relationships, Lachlan Orogen, southeastern Australia: stratigraphic and tectonic problems. *Australian Journal of Earth Sciences*, 65(3), pp.303-333.
- Forster, D.B., Carr, G.R. and Downes, P.M., 2011. Lead isotope systematics of ore systems of the Macquarie Arc—Implications for arc substrate. *Gondwana Research*, 19(3), pp.686-705.
- Glen, R.A., 2013. Refining accretionary orogen models for the Tasmanides of eastern Australia. *Australian Journal of Earth Sciences*, 60(3), pp.315-370.
- Glen, R.A., 2005. The Tasmanides of eastern Australia. *Special Publication-Geological Society of London*, 246, pp.23.
- Glen, R.A., Crawford, A.J. and Cooke, D.R., 2007a. Tectonic setting of porphyry Cu–Au mineralisation in the Ordovician–Early Silurian Macquarie Arc, Eastern Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences*, 54(2-3), pp.465-479.
- Glen, R.A., Crawford, A.J., Percival, I.G. and Barron, L.M., 2007b. Early Ordovician development of the Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences*, 54(2-3), pp.167-179.
- Glen, R.A., Fitzsimons, I.C.W., Griffin, W.L. and Saeed, A., 2017. East Antarctic sources of extensive Lower–Middle Ordovician turbidites in the Lachlan Orogen, southern Tasmanides, eastern Australia. *Australian Journal of Earth Sciences*, 64(2), pp.143-224.
- Glen, R.A., Meffre, S. and Scott, R.J., 2007c. Benambran orogeny in the eastern Lachlan orogen, Australia. *Australian Journal of Earth Sciences*, 54(2-3), pp.385-415.
- Glen, R.A., Percival, I.G. and Quinn, C.D., 2009. Ordovician continental margin terranes in the Lachlan Orogen, Australia: implications for tectonics in an accretionary orogen along the east Gondwana margin. *Tectonics*, 28(6).
- Glen, R.A., Quinn, C.D., and Cooke, D.R., 2012. The Macquarie Arc, Lachlan Orogen, New South Wales: its evolution, tectonic setting and mineral deposits. *Episodes*, 35(1), pp.177-186.
- Glen, R.A., Saeed, A., Quinn, C.D., and Griffin, W.L., 2011. U–Pb and Hf isotope data from zircons in the Macquarie Arc, Lachlan Orogen: Implications for arc evolution

- and Ordovician palaeogeography along part of the east Gondwana margin. *Gondwana Research*, 19(3), pp.670-685.
- Glen, R.A. and Walshe, J.L., 1999. Cross-structures in the Lachlan Orogen: The Lachlan Transverse Zone example. *Australian Journal of Earth Sciences*, 46(4), pp.641-658.
- Glen, R.A., Walshe, J.L., Barron, L.M. and Watkins, J.J., 1998. Ordovician convergent-margin volcanism and tectonism in the Lachlan sector of east Gondwana. *Geology*, 26(8), pp.751-754.
- Harris, A.C., Percival, I.G., Cooke, D.R., Tosdal, R.M., Fox, N., Allen, C.M., Tedder, I., McMillan, C., Dunham, P. and Collett, D., 2014. Marine Volcanosedimentary Basins Hosting Porphyry Au-Cu Deposits, Cadia Valley, New South Wales, Australia. *Economic Geology*, 109(4), pp.1117-1135.
- Kemp, A.I.S., Hawkesworth, C.J., Collins, W.J., Gray, C.M. and Blevin, P.L., 2009. Isotopic evidence for rapid continental growth in an extensional accretionary orogen: The Tasmanides, eastern Australia. *Earth and Planetary Science Letters*, 284(3-4), pp.455-466.
- Kitto, J.C., 2005. Lithostratigraphy, Alteration and Geochemistry at the Cadia East Gold-Copper Porphyry Deposit, New South Wales: Honours thesis, University of Tasmania. pp.136.
- Loucks, R.R., 2014. Distinctive composition of copper-ore-forming arc magmas. *Australian Journal of Earth Sciences*, 61(1), pp.5-16.
- McDowell, F.W., McIntosh, W.C., and Farley, K.A., 2005. A precise ^{40}Ar - ^{39}Ar reference age for the Durango apatite (U-Th)/He and fission-track dating standard. *Chemical Geology*, 214(3-4), pp.249-263.
- Meffre, S., 2003. Review of mapping on the Oberon geological map sheet (No. GS 2003/224). Geological Survey of New South Wales.
- Meffre, S., Scott, R.J., Glen, R.A. and Squire, R.J., 2007. Re-evaluation of contact relationships between Ordovician volcanic belts and the quartz-rich turbidites of the Lachlan Orogen. *Australian Journal of Earth Sciences*, 54(2-3), pp.363-383.
- Murray, S.I., 2002. Tectonic relationship between the Ordovician sedimentary and volcanic successions of the Lachlan fold belt, central/southern tablelands, New South Wales: PhD thesis, University of Wollongong. pp.340.
- Murray, S.I. and Stewart, I.R., 2001. Palaeogeographic significance of Ordovician conodonts from the Lachlan Fold Belt, southeastern Australia. *Historical Biology*, 15(1-2), pp.145-170.
- Musgrave, R.J., 2015. Oroclines in the Tasmanides. *Journal of Structural Geology*, 80, pp.72-98.
- Müller, D., Rock, N.M.S. and Groves, D.I., 1992. Geochemical discrimination between shoshonitic and potassic volcanic rocks in different tectonic settings: a pilot study. *Mineralogy and Petrology*, 46(4), pp.259-289.

- Pearce, J.A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. *Lithos*, 100(1-4), pp.14-48.
- Pearce, J.A., 1996. A user's guide to basalt discrimination diagrams. Trace element geochemistry of volcanic rocks: applications for massive sulphide exploration. Geological Association of Canada, Short Course Notes, 12, pp.79-113.
- Pearce, J.A., 1982. Trace element characteristics of lavas from destructive plate boundaries. *Andesites*, 8, pp.525-548.
- Percival, I.G. and Glen, R.A., 2007. Ordovician to earliest Silurian history of the Macquarie arc, Lachlan orogen, New South Wales. *Australian Journal of Earth Sciences*, 54(2-3), pp.143-165.
- Pessagno Jr, E.A. and Newport, R.L., 1972. A technique for extracting Radiolaria from radiolarian cherts. *Micropaleontology*, pp.231-234.
- Pogson, D.J. and Watkins, J.J., 1998. Bathurst 1: 250 000 Geological Sheet SI/55-8: Explanatory Notes. Geological Survey of New South Wales. pp.430.
- Quinn, C.D., Percival, I.G., Glen, R.A., and Xiao, W.J., 2014. Ordovician marginal basin evolution near the palaeo-Pacific east Gondwana margin, Australia. *Journal of the Geological Society*, 171(5), pp.723-736.
- Robinson, P., 2003. XRF analysis of flux-fused discs, in: *Geoanalysis*, 90. Presented at The 5th International Conference on the Analysis of Geological and Environmental Materials, Wiley-Blackwell.
- Rogers, N.W. and Setterfield, T.N., 1994. Potassium and incompatible-element enrichment in shoshonitic lavas from the Tavua volcano, Fiji. *Chemical Geology*, 118(1-4), pp.43-62.
- Rollingson, H.R., 1993, *Using geochemical data: evaluation, presentation and interpretation*, Longman, 352 p.
- Sack, P.J., Berry, R.F., Meffre, S., Falloon, T.J., Gemmill, J.B. and Friedman, R.M., 2011. In situ location and U-Pb dating of small zircon grains in igneous rocks using laser ablation-inductively coupled plasma-quadrupole mass spectrometry. *Geochemistry, Geophysics, Geosystems*, 12(5).
- Scheibner, E., 1999. *The Geological Evolution of New South Wales: A Brief Review*. Department of Mineral Resources.
- Schoene, B. and Bowring, S.A., 2006. U-Pb systematics of the McClure Mountain syenite: thermochronological constraints on the age of the $^{40}\text{Ar}/^{39}\text{Ar}$ standard MMhb. *Contributions to Mineralogy and Petrology*, 151(5), pp.615.
- Shaanan, U., Rosenbaum, G. and Sihombing, F.M.H., 2018. Continuation of the Ross-Delamerian Orogen: insights from eastern Australian detrital-zircon data. *Australian Journal of Earth Sciences*, 65(7-8), pp.1123-1131.

- Shervais, J.W., 1982. Ti-V plots and the petrogenesis of modern and ophiolitic lavas. *Earth and planetary science letters*, 59(1), pp.101-118.
- Sláma, J., Košler, J., Condon, D.J., Crowley, J.L., Gerdes, A., Hanchar, J.M., Horstwood, M.S., Morris, G.A., Nasdala, L., Norberg, N. and Schaltegger, U., 2008. Plešovice zircon—a new natural reference material for U–Pb and Hf isotopic microanalysis. *Chemical Geology*, 249(1-2), pp.1-35.
- Squire, R.J., and Crawford, A.J., 2007. Magmatic characteristics and geochronology of Ordovician igneous rocks from the Cadia–Neville region, New South Wales: implications for tectonic evolution. *Australian Journal of Earth Sciences*, 54(2-3), pp.293-314.
- Stanton, R.L., 1956. The Palaeozoic rocks of the Wiseman's Creek—Burruga area, NSW. In *Journal and Proceedings of the Royal Society of New South Wales* (Vol. 89, pp. 131-145).
- Stewart-Smith, P., Wallace, D.A., 1997. Oberon. sheet 8830.
- Sun, S.S. and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geological Society, London, Special Publications*, 42(1), pp.313-345.
- Watson, J.S., 1996. Fast, simple method of powder pellet preparation for X-ray fluorescence analysis. *X-Ray Spectrometry*, 25(4), pp.173-174.
- Whitten, M.D., 2015. Formation de Koné: Recording the final stages of Gondwana breakup in New Caledonia: Honours thesis, University of Tasmania. pp.80.
- Wiedenbeck, M.A.P.C., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F.V., Quadt, A.V., Roddick, J.C. and Spiegel, W., 1995. Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and REE analyses. *Geostandards newsletter*, 19(1), pp.1-23.
- Wilson, A.J., 2003. The geology, genesis and exploration context of the Cadia gold-copper porphyry deposits, New South Wales, Australia: PhD thesis, University of Tasmania. pp.335.
- Zhang, Q., Buckman, S., Bennett, V.C., Nutman, A., 2019a. Inception and early evolution of the Ordovician Macquarie Arc of Eastern Gondwana margin: zircon U–Pb–Hf evidence from the Molong Volcanic Belt, Lachlan Orogen. *Lithos* 326, 513–528.
- Zhang, Q., Buckman, S., Bennett, V.C., Nutman, A., Song, Y., 2019b. Lachlan Orogen, eastern Australia: triangle formation records the Late Ordovician arrival of the Macquarie Arc terrane at the margin of eastern Gondwana. *Tectonics* 38, 3373–3393.
- Zhang, Q., Nutman, A., Buckman, S. and Bennett, V.C., 2020. What is underneath the juvenile Ordovician Macquarie Arc (eastern Australia)? A question resolved using Silurian intrusions to sample the lower crust. *Gondwana Research*, 81, pp.362-377.