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# Geochronology of Meso-Neoproterozoic Units near Savage River, Western Tasmania

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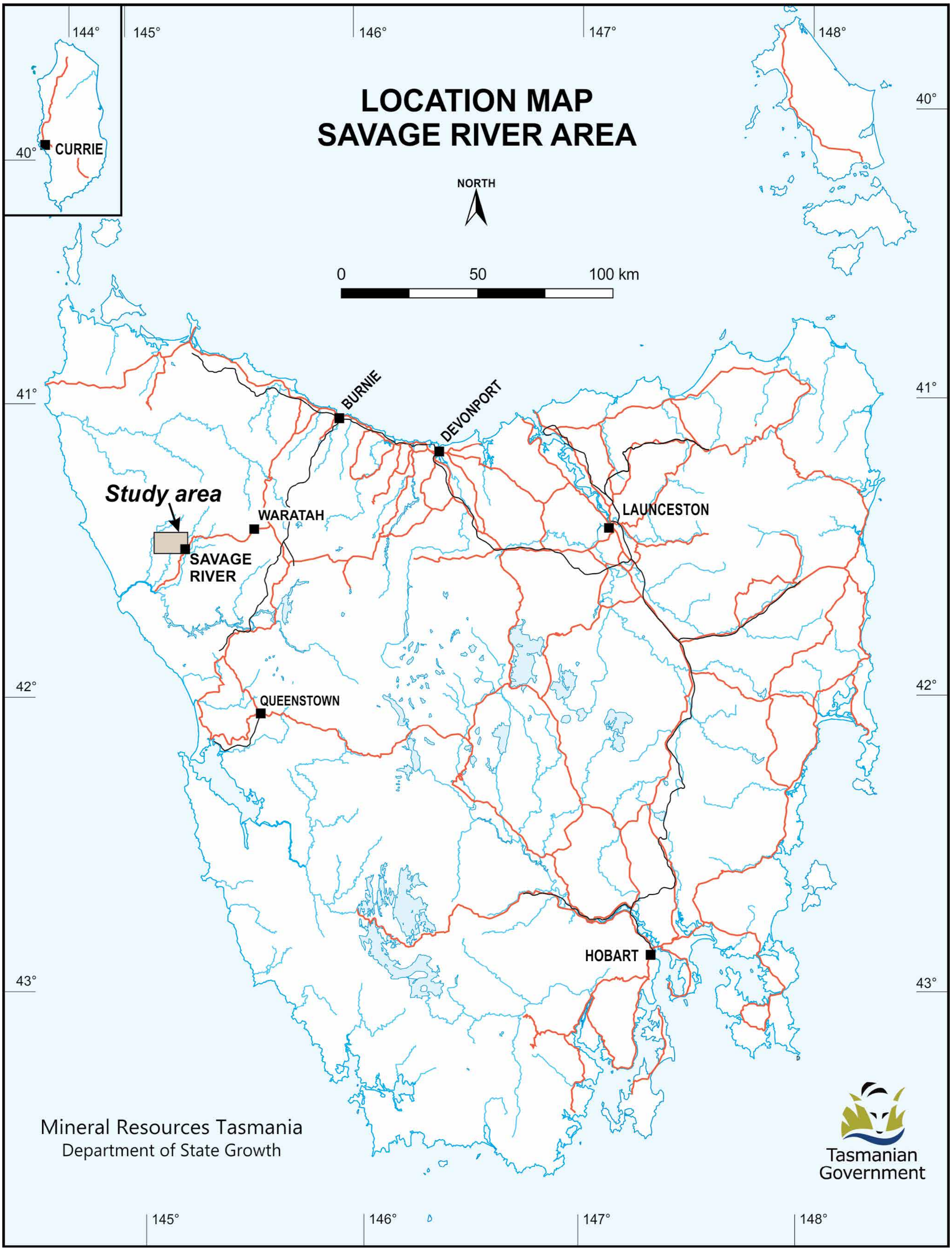
## Geological Survey Technical Report 24

Tasmanian Government




Location of Study Area.

Mineral Resources Tasmania
Department of State Growth

# Geological Survey Technical Report 24: Geochronology of Meso-Neoproterozoic Units near Savage River, Western Tasmania

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Cover: Blocky exposures of quartz-mica schist (Keith Schist) exposed along Savage River (353081mE/5407734mN).

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# Geochronology of Meso-Neoproterozoic Units near Savage River, Western Tasmania

by G. Cumming[1], R. Bottrill[1], J. Halpin[2], J. Mulder[3], C. Calver[4] and S. Meffre[5]

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**_Abstract_**

*To support geological mapping of the poorly-dated Arthur Metamorphic Complex (in the Savage River Area), the detrital zircon provenance and magmatic crystallisation age of some major geological units were characterised. Detrital and magmatic zircon grains were obtained from several units within the Ahrberg Group, Timbs Group (including Bowry Fm., "Fulfords Creek Schist", and "Armstrong Creek Schist") and Keith Schist. All samples were dated by the U-Pb method using laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS).*

*Results from the Donaldson Formation (basal Ahrberg Group) indicate that deposition occurred after 1358 Ma. The detrital zircon age spectra are comparable to those previously obtained from the Forest Conglomerate (basal Togari Group) and Oonah Formation, and support a previously suggested correlation with these units (Mulder et. al., 2018). However, this age is much older than the youngest zircons obtained from the Oonah Formation and correlatives elsewhere (~750 Ma). Our results from the Bernafai Volcanics (upper Ahrberg Group) indicate deposition occurred after ~577 Ma, which, along with field relationships, supports a correlation with the Kanunnah Subgroup of the Togari Group.*

*In contrast, samples from the Bowry Formation (Timbs Group) cannot be easily related to other units in Tasmania (based purely on the zircon age spectra alone). If the albitite units (in the Bowry Fm.) represent metasedimentary rocks, rather than magmatic rocks (as previously thought by Turner et al., 1998) a maximum age for the Timbs Group is somewhat younger than previously thought (~733 Ma). Four detrital zircon age assemblages have been characterised from the Bowry Formation. Two of these have restricted ages, and the remainder show complex and varied age spectra. Samples with restricted detrital age profiles between 780 and 750 Ma were most likely sourced from syn-sedimentary rift-related magmatism, whereas samples with diverse components were probably derived from older sedimentary rocks or basement terranes exposed during rifting. Furthermore, samples from the Timbs Group cannot be easily correlated with the Ahrberg Group, an idea proposed by some previous workers (Turner & Crawford 1993; Holm and Berry, 2002). Prominent detrital zircon age peaks at 1400 and 1700 Ma in the "Armstrong Creek Schist" and "Fulfords Creek Schist" are comparable with those from new samples analysed from the Keith Schist, and previously recorded from the "upper" and "lower-middle" Rocky Cape Group.*

*The varied detrital zircon age spectra in samples from Savage River is foreseeable, given that they were obtained from narrow fault-enclosed blocks in a melange zone, in the highest strain portion of the Arthur Metamorphic Complex. The Timbs Group likely represents an assemblage of fault bounded allochthonous assemblages of Meso- to Neoproterozoic siliciclastic, carbonate-rich and rifted-related magmatic rocks. These assemblages were deformed, albitised and faulted together during the Early-middle Cambrian Tyennan Orogeny and emplaced against the late Neoproterozoic Bernafai Volcanics.*

## 1.0 Introduction

The Savage River 1:25 000 scale map sheet was geologically mapped during the 2017 –2018 field season by Mineral Resources Tasmania (Cumming et. al., 2020) in an attempt to define the stratigraphic and structural framework of the area. The region includes the large (> 590 mt) iron ore deposit at Savage River, which is currently being mined Grange Resources Pty. Ltd. Detailed mapping traverses were carried out in the areas adjoining the mine lease, and this new work has been combined with previous detailed geological mapping by Turner et al., (1991).

Three broad, largely gradational or fault-bound lithostratigraphic units have been mapped in the vicinity of the Savage River mine. These are, from west to east; the Ahrberg Group, the Timbs Group (including Bowry Fm., which host the Savage River ore deposits) and the Keith Schist (Figures 1&2).

This report documents these key geological units, based on new geological mapping work and descriptions in Bottrill and Taheri (2006); Holm et al. (2003) and Morris (2012). We estimate the magmatic, depositional age and sedimentary provenance of representative samples dated by the U-Pb method, using laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS).

## 2.0 Geological Setting

The Savage River region occurs in the central area of the Arthur Metamorphic Complex (AMC). The AMC is a 5-10 km wide, 100 + km long, high-strain metamorphic belt which trends northeast from Ahrberg Bay on the west coast, to Freestone Cove at Wynyard on the north coast of Tasmania (Figure 1). The AMC at Savage River includes the Timbs Group (comprising the "Armstrong Creek Schist", Bowry Formation and "Fulfords Creek Schist"), and the Keith Schist. These units are considered an allochthonous package of rocks, emplaced during the Middle Cambrian Tyennan Orogeny (Holm et al., 2003). The Tyennan Orogeny involved an intra oceanic arc-continent collision, in which parts of the oceanic island arc were obducted westwards or south-westwards (present-day coordinates) over an east-facing continental margin (Berry and Crawford, 1988). Parts of the east-facing continental margin of Tasmania, mostly comprising Mesoproterozoic and Neoproterozoic sedimentary rocks, were partially subducted to lower crustal and mantle depths (up to 20—60km) and subsequently uplifted during post-collisional crustal re-equilibration (Meffre et. al, 2000).

The lithologic units in the Savage River region have been subject to both high and low-strain. To the west of the AMC (Figure 2 and 3), the Ahrberg Group (Donaldson Formation, Savage Dolomite and Bernafai Volcanics) exhibit the lowest strain and share a faulted contact with the Timbs Group. To the east, the Timbs Group has a gradational geological boundary with the Keith Schist. The Keith Schist also comprises zones of both high and low-strain. The Timbs Group shows relatively high-strain, schistose, tightly folded units, but also contains low-strain, fault-bound blocks of weakly metamorphosed to phyllitic units entrained within strongly foliated schist. The western section of the Timbs Group was interpreted by Holm and Berry (2002) as a parautochthonous slice of the Ahrberg Group, and they referred to it as the "eastern" Ahrberg Group. For consistency, the terms "eastern" and "western" Ahrberg Group are omitted in this report and the Timbs Group is used to denote the structurally complex assemblage of fault bound units (inclusive of the Bowry Formation) to the east of the Arthur Lineament. Each unit is described in detail below.

### *2.1 Ahrberg Group*

*Donaldson Formation*

The Donaldson Formation, west of Savage River, unconformably overlies the Rocky Cape Group (Spry, 1964; Turner et al., 1991) and faces east. It consists of a basal siltstone and poorly sorted conglomerate with minor planar laminated pelitic siltstone, mudstone and fine-grained interbedded sandstone. The basal conglomerate is thickly bedded, and consists of massive, generally clast supported, poorly-sorted bedforms composed of well-rounded pebble to cobble-sized clasts of quartzite (Figure 3; a). Above the basal units, micaceous quartz sandstone with interlayered slaty pelite is inter-layered with dolostone (Figures 3b and 3c).

*Savage Dolomite*

Between the Donaldson Formation and Bernafai Volcanics, the Savage Dolomite consists of thick units of massive dolostone, thinly laminated and/or stromatolitic dolostone, and pale, pelitic mudstone and black carbonaceous, silty dolostone. This unit also contains minor chert, siltstone and mudstone which are gradational into mixed dolostone and siltstone layers. No zircons could be found in samples of this unit.

*Bernafai Volcanics*

A north-northeast trending belt of basalt and related volcaniclastic sedimentary facies overlies the Savage Dolomite and trends between Little Savage River and directly west of the Savage River mine. The volcanic facies are extremely sheared close to where they abut numerous faults along the western edge of the Arthur Lineament. Key facies in the Bernafai

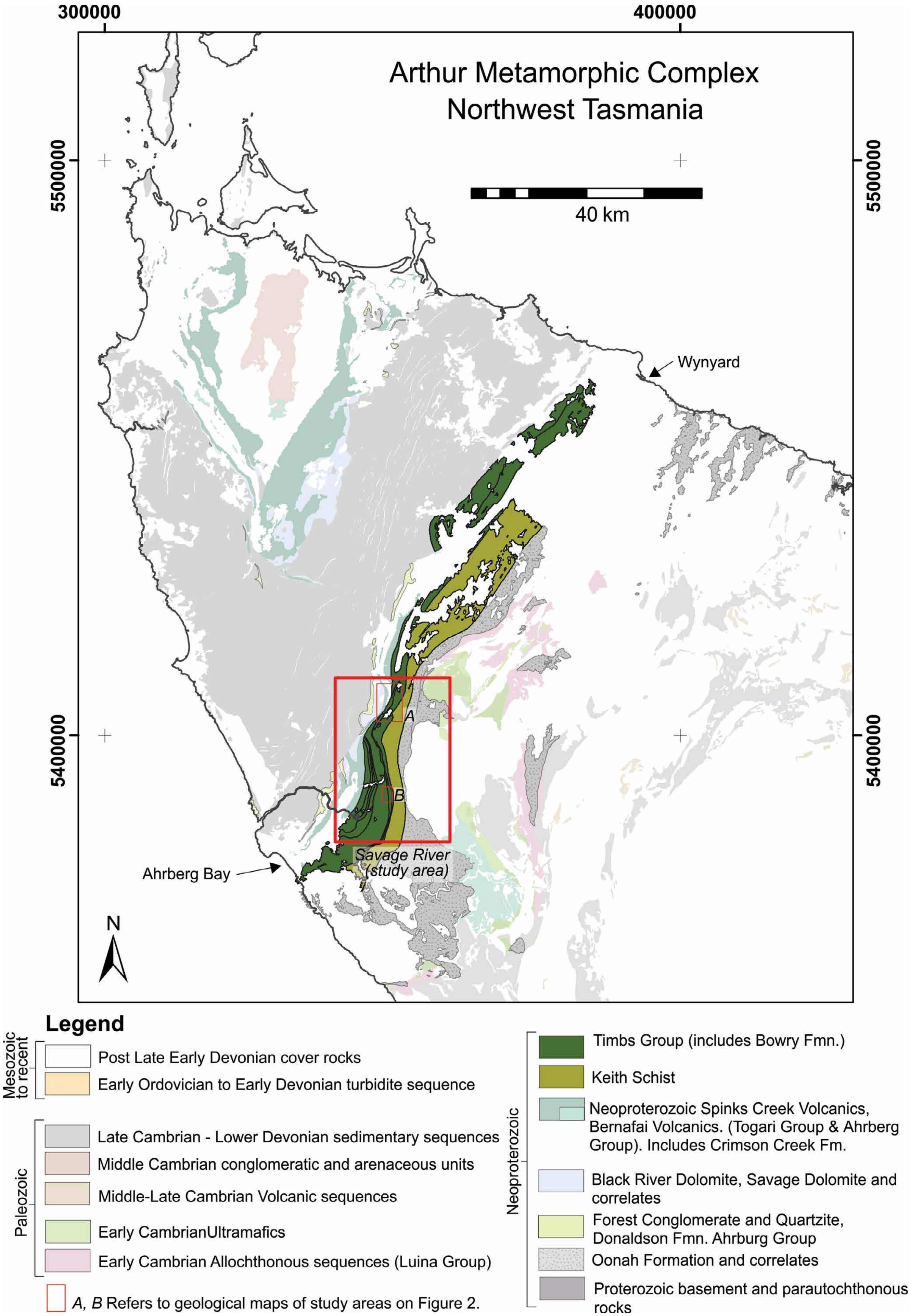



Figure 1. NW Tasmania showing the extent of the Arthur Metamorphic Complex, and other Neoproterozoic to Cambrian rock units with the location of Savage River area.

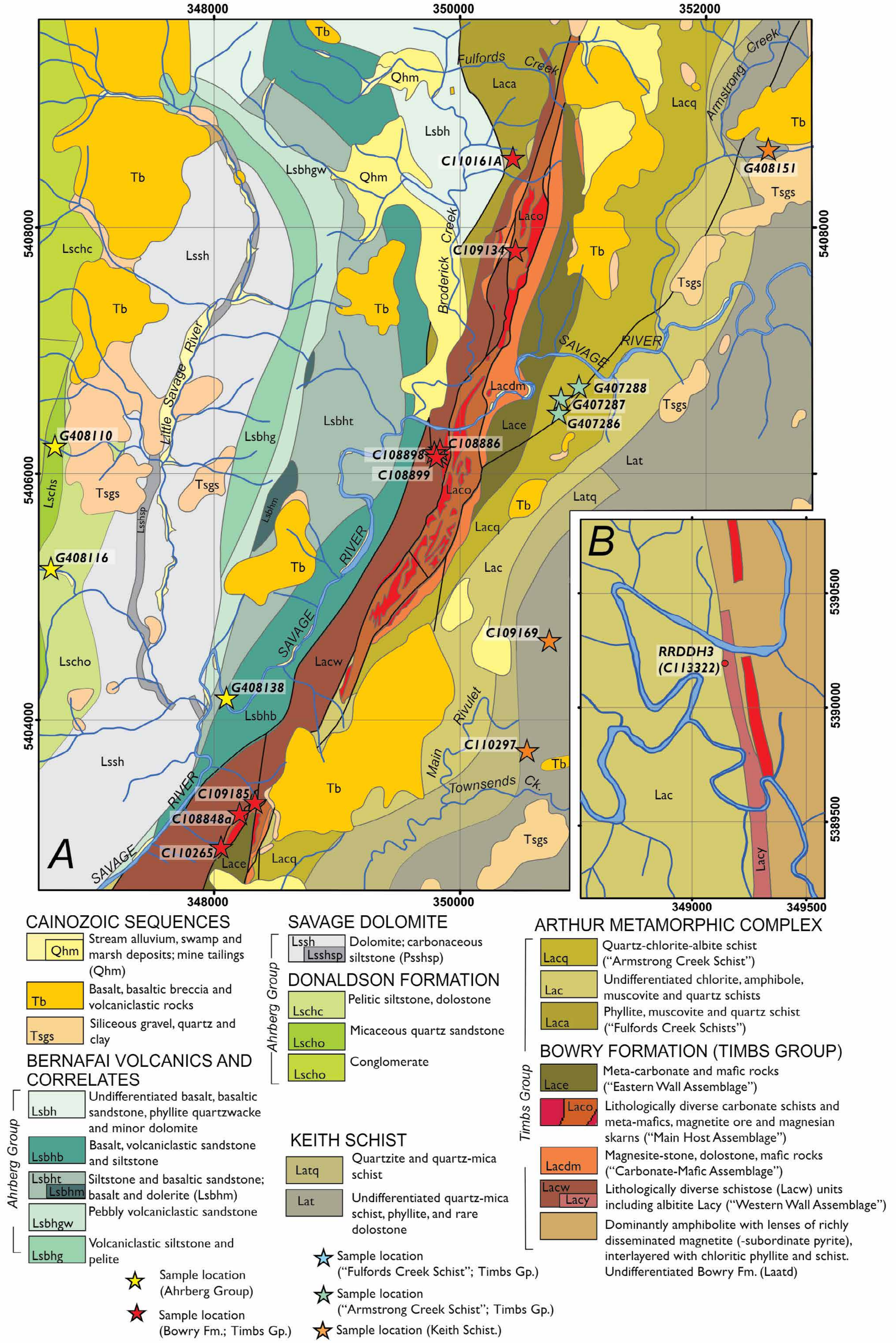



Figure 2. A. Geology of the Savage River area, including the Donaldson Fm., the Bernafai Volcanics, Timbs Group and Keith Schist and sample locations. B. Geology of the Rocky River area showing the location of albitite sample C113322 taken from drillcore (RRDDH3).

a)

b)

c)

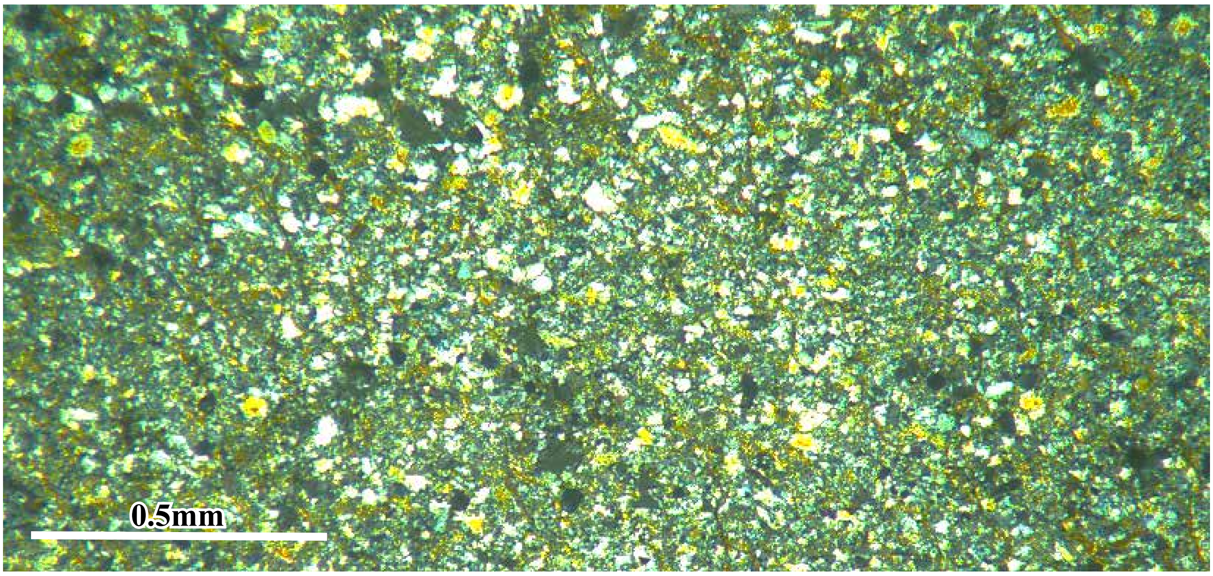



Figure 3. Photographs conglomerate (a); bedded quartz sandstone ( b); photomicrograph of mixed quartz sandstone (sample G408110) typical of the Donaldson Formation (base of the Ahrberg Group).

Volcanics include (from base to top) (1) grey-black planar siltstone intercalated with dolomite with wavy bedding and slump features; (2) matrix supported, pebbly, volcaniclastic breccias and conglomerate with lenticular to rounded polymictic clasts; (3) very deeply weathered massive, volcaniclastic (chloritic) and pelitic siltstone and sandstone with gutter casts and; (4) massive medium to fine-grained, chloritic, variably amygdaloidal, feldspar - pyroxene phyric basalt with intercalated basaltic breccia and volcaniclastic siltstone (Figure 4: a-c).

### *2.2 Timbs Group*

The Timbs Group is intensely to mildly deformed and is truncated by major north-east trending structures. It shares a faulted contact with the Donaldson Formation, Savage Dolomite and Bernafai Volcanics to the west. The Timbs Group is made up of (from west to east) the “Fulfords Creek Schist”, the Bowry Formation, and the “Armstrong Creek Schist”. Within the Bowry Formation, three major sub-units have been defined by Bottrill and Taheri (2006). These include the “Eastern Wall Assemblage”; “Main Host Assemblage” and the “Western Wall Assemblage”.  All of these units form linear, NNE striking bands.

The Timbs Group was previously considered a possible correlate of the Ahrberg Group (Turner et al., 1992; Turner and Bottrill, 2001; Holm and Berry, 2002), yet there is no geochronological evidence to support this claim. It may instead correlate with the Crimson Creek Formation to the east and south, based on similar lithologies and igneous geochemistry (Crawford and Berry, 1992). Holm and Berry (2002), however, consider the Timbs Group/Bowry Formation to predate the Crimson Creek Fm., based on a 778 Ma albitite body, interpreted as a deformed granitoid, thought to cross-cut the Bowry Formation (Turner et al., 1998). This interpretation appears uncertain based on recent investigation (Bottrill et al., In prep), as most albitite bodies in the region have been re-interpreted as albitised metasedimentary rocks (Bottrill et al., in prep).

A description of each key unit in the Timbs Group is summarised from Bottrill and Cumming, 2021 (In prep.) below. These subdivisions are based from new mapping and historic data and build on from the work of Bottrill and Taheri (2008).

#### *Bowry Formation*

The Bowry Formation is composed of metamorphic rocks showing very high variability in metamorphic grades and mineral assemblages. The main rock types observed in the field are mafic schists and diopside skarn, but also include albitites, quartzites, muscovite ± chlorite schists, dolomite and magnesite rich carbonate rocks and magnesian skarns. Characteristically, many parts of the sequences are highly mixed, and carbonate inter-banded with mafic rocks is very common. Rocks of the Bowry Formation have been metamorphosed to upper greenschist to amphibolite facies and metasomatically altered but remnant lenses with original sedimentary and igneous textures can still be observed. Many of the mafic rocks have clastic sedimentary textures suggesting they were originally basaltic volcaniclastic sandstones or lithic arenites. Igneous rocks, including meta-dolerite and possibly minor meta-basalt, have also been identified. Dolomite and magnesite-rich carbonate rocks have locally been partly to totally altered into prograde and retrograde magnesian and calc-silicate skarns (including amphibolites, serpentinites, talc schists and rarely diopside skarn).

#### *“Eastern Wall Assemblage” (EWA)*

This unit is used informally by Savage River mine geologists for mostly unmineralised mafic schists and amphibolites (Unpub. ABM mapping). This assemblage is dominated by a thick unit of massive to weakly banded mafic rocks, including basalt with lobate morphology, lying immediately east of the main ore zone. The unit is commonly interbedded with carbonate, and some slightly siliceous zones, which grade into the “Main Host Assemblage” to the west. This transitional zone of carbonate-rich amphibolite and schist form a major part of the EWA. It was defined (Bottrill and Taheri, 2008) as containing >20% carbonate minerals, >10% albite and >30% mafic minerals. The boundary between the EWA and the “Main Host Assemblage” is marked by a major fault zone. Further details of the EWA can be found in Bottrill and Cumming, 2021 (In prep.). No zircons were found in samples collected from the EWA.

#### *“Main Host Assemblage” (MHA)*

The “Main Host Assemblage”, where relatively unaltered, consists of a massive to banded magnesite ± dolomite rich carbonates with minor inter-banded meta-mafic rocks. Along the eastern boundary of this unit the proportion of carbonate rich facies increases. Much of it is highly altered to massive to semi-massive magnetite-rich bodies (magnetite ore) and magnesian skarns (the main host of iron ore at the mine). Shearing has locally intermixed these with the magnesian skarns and ores. Deformation, including shearing and boudinage is widespread, and locally intense.

The magnesian skarns are highly variable mixtures of tremolite-actinolite, talc, serpentine, magnetite, pyrite, chlorite and dolomite. The mafic rocks intercalated with these carbonates and skarns are mostly altered to chlorite and amphibole; some relatively unaltered mafic boudins can be found; these are probably mostly dolerite, but may possibly include basalt and basaltic sedimentary rocks.

The ore and surrounding rocks have undergone multiple deformational and metamorphic events, including a high pressure - low temperature blueschist facies event followed by retrogression to lower greenschist facies (Turner and Bottrill, 2001). Early to late, tightly folded to relatively undeformed, vein and breccia mineralisation is also common. No zircons were found in this unit.

*"Western Wall Assemblage" (WWA)*

The "Western Wall Assemblage" is a term used by mine geologists and companies to describe this lithologically diverse package of rocks including units of variably deformed and metamorphosed muscovite ± biotite ± chlorite ± albite ± amphibole ± quartz ± dolomite schists, massive to banded albitite, quartzite, dolostones, magnesite-stones, albite ± amphibole ± chlorite meta-mafic rocks and minor, quartz-amphibole rocks and diopside skarns (Bottrill and Taheri, 2008). Overall, it appears to transition from the carbonate-rich "Main Host Assemblage" into more siliceous (variably psammitic to pelitic) lithologies, with sparser mafic zones towards the west. The mafic rocks in this sequence have mostly tholeiitic geochemical affinities but some are discretely alkaline; it is uncertain if they were lavas, mafic volcaniclastic rocks, or intrusive bodies as intense alteration has obscured primary textures in these rocks. Several samples show an interlocking igneous texture and are interpreted as meta-gabbro (Bottrill and Cumming, in prep., 2021).

Albitisation is one of the most widespread and intense types of alteration in the WWA. Areas that locally contain up to 95% albite are referred to as albitites in the text. Albitite bodies are characterised by distinct greyish-greenish (amphibole ± chlorite rich) and pinkish (albite ± carbonate) bands, from sub-mm to about 1 m thick (Figure 5: a-h). They grade into quartzites, mica schists and mafic rocks. The original mineralogy and textures in the albitite zones have been destroyed, and they show very little stratigraphic continuity. The albitite bodies are locally rich in both rounded and euhedral zircon (Figure 5: d and h). Disseminated tourmaline is also widespread as an alteration mineral throughout the WWA (but not limited to) the albitite bodies. The albitites have similar immobile element geochemistry to the adjacent sedimentary rocks (Bottrill, in prep.). The albitites in the WWA have previously been interpreted to represent granitoid bodies (Turner et al., 1998). More recently, Bottrill and Taheri, (2008) suggest that the geochemical uniformity (between the albitites and neighbouring sedimentary rocks) provides strong evidence that these albite-rich rocks were derived from albitisation of pelitic to psammitic and even mafic sedimentary rocks. Albitisation is common in association with magnetite deposits of the Iron-oxide-copper-gold (IOCG) style (Sillitoe, 2003). The albitite bodies are locally rich in rounded zircon, which suggest that they either have a sedimentary origin, or if they have an igneous protolith, then they include inherited zircons.

*"Fulfords Creek Schist"*

Very poor and limited exposures of inter-banded phyllite, micaceous quartz schist and actinolitic amphibolite occur to the west of the Bowry Formation north of North Pit, Savage River Mine. The unit includes carbonaceous muscovite-quartz schist and minor meta-conglomerate. This unit was mapped by Turner et al., (1991) and has since been mostly buried by waste rock at the mine. Hence, exposures are currently rare.

*"Armstrong Creek Schist"*

This unit is used informally by mine geologists for relatively unmineralised psammitic schists along the eastern side of the Bowry Formation. It shows patchy albite spotting. The unit appears complex with variable mineralogy; the few samples examined include chlorite and albite-bearing schists, chloritic quartzite (with <85% quartz) and some amphibolite (Figure 6). Some dolerite bodies also occur within this unit. The "Armstrong Creek Schist" appears to transition gradually into the Keith Schist to the east.

### *2.3 Keith Schist*

The Keith Schist consists of quartz-mica schist with lesser quartzite, phyllite, and rare dolomite. A detailed description of the Keith Schist in the northern part of the AMC is provided in Cumming et. al., (2020). Parts of the Keith Schist east of Savage River were mapped previously as Oonah Formation (Turner et al., 1991). Previous workers have interpreted the Keith Schist and the Oonah Formation as probable correlates, differing mainly in the much higher strain of the Keith Schist (Calver et. al., 2014 In Corbett et al., 2014). Isoclinal folds and a well-developed schistosity are observed in both, yet the Keith Schist has been subject to higher intensity greenschist to amphibolite facies metamorphism and the intensity of metamorphism increases to the west (observed along the Savage River). However, within the Keith Schist there are pod-like zones, up to 2 km across, which display less intense metamorphism, where primary sedimentary features are preserved.

## 3.0 Geochronology

### *3.1 Previous Age Constraints*

Within the Arhberg Group, the Donaldson Formation is gradationally overlain by the Savage Dolomite. The Savage Dolomite has been correlated on the basis of lithostratigraphy and chemostratigraphy with the latest Tonian (i.e. 750 -720 Ma), lower part of the Black River Dolomite (of the Togari Group) (Calver, 1995; Calver, 1998; Calver et al., 2014). Kendall et al. (2009) produced a Re-Os isochron age of 640.7 ± 4.7 Ma from black shale near the top of the Black River Dolomite in the Togari Group. Field relationships also support a correlation of the Bernafai Volcanics (Arhberg Group) with the Kanunnah Subgroup of the Togari Group. A U-Pb SHRIMP age of 582 ± 4 Ma was previously obtained from a rhyodacite within the Kanunnah Subgroup, below the Croles Hill Diamictite (Calver et al., 2004).

Recent work by Mulder et. al. (2020) indicates that the Keith Schist has a distinctly different detrital zircon provenance compared to the Oonah Formation, consistent with an allochthonous origin for the unit (Mulder et. al., 2020).

Historically, work at Savage River to unravel the timing of the main iron-ore assemblages and intrusive phases in the Bowry Fm. (Timbs Group) has been problematic. The lack of fossiliferous units within the sedimentary and metasedimentary rocks has meant that age and stratigraphic relationships of the different units within the Bowry Formation, both to each other and to other sedimentary rocks in Tasmania, are poorly constrained. Previously, published absolute age constraints on the Bowry Formation is restricted to a sample collected near the confluence of the Rocky and Whyte Rivers and was dated via U-Pb on zircon at 777 ± 7 Ma by Turner et al., (1998). The contact relationships within this outcrop are uncertain. However, in the nearby drillhole and along the western zone of open cut pits at Savage River albitite zones occur as discontinuous veins, replacement and patchy alteration adjacent and within surrounding lithologies. Further work to characterise the lithology and geochemistry of units in this drill-core by Bottrill et al., (in prep.) suggests that the rock dated by Turner et al., (1998) could represent an albitised meta-sediment.

Previous work by Morris (2012) to characterize zircons in albitite exposures immediately west of the ore lenses gave a range of ages from about 1400 Ma down to about 744 Ma.

Samples from the locally pyrite-rich magnetite ores of the Savage River deposits were examined via LA-ICPMS by Bottrill et. al., (in prep) to determine their age and the genetic history. There is a large late Devonian granite batholith (the Meredith Granite, 340-360 Ma) exposed just a few km to the east of the Savage River area, and a similar Devonian Batholith (the Interview Granite) lies some 20-30 km to the west. A small porphyritic granite dyke intruding the Timbs Group a few km southwest of the Savage River Township has been dated at 380 Ma (Turner et al., 1998). There is no proven relationship between any of these Devonian intrusives and the mineralization at Savage River, but a 400Ma U-Pb date on apatite in the ores suggests the Devonian igneous activity may have contributed a strong thermal overprint, at least locally at Savage River (Bottrill, in prep). Fluoro-apatite from an apatite-pyrite-magnetite ore in the MHA, South Pit, gave an age of 400 ± 5 Ma. Monazite from two pyrite-carbonate rocks in the same ore zone, South Pit, gave dates of about 499 ± 12 Ma, an age that is very similar to the Mt Read Volcanic-hosted sulphides ores (Bottrill, pers. comm., 2021). Pyrite from the same rocks also gave Pb-isotopic model ages of about 500 Ma.

### *3.2 Sample Selection*

Representative samples from the Ahrberg Group, Timbs Group and Keith Schist were collected during geological mapping of the region in the period 2016–2018 (Figure 1). Many samples of the Timbs Group were also collected by Ralph Bottrill and Jafar Taheri during an investigation into the mineralogy and geochemistry of the Savage River Mine host rocks and ore assemblages (Bottrill & Taheri, 2008). Samples of relatively coarse-grained clastic rock were selected for zircon U-Pb dating, following petrographic and geochemical characterisation (Figure 2). All lithologic units were sampled from the Bowry Formation and Timbs Group, however zircons could not be recovered from the “Main Host Assemblage” and the “Eastern Wall Assemblage” (of the Bowry Fm.). Sample details are given in Table 1. Details of the geological context and sample characteristics for each dated unit are included below.

*Ahrberg Group - Donaldson Fm.*

A distinctive succession of planar bedded sandstone, massive matrix and clast supported conglomerate and highly foliated conglomerate with elongate clasts is exposed beneath an escarpment in the upper region of the Little Savage River. Two samples (G408110 and G408116) (Figures 3a and 3b) were collected from a micaceous quartz sandstone, about 1.2 km apart, from outcrop along the tributaries that drain into Little Savage River. These quartz-rich sandstones contain 70– 90% clastic quartz grains, minor muscovite (2–10%), titanite and monazite (1-2%) set in a quartz and sericite matrix. Clastic grains measure up to 0.2 mm in diameter, with an average grain size of approximately 0.05 mm (shown in Figure 3c).

*Ahrberg Group - Bernafai Volcanics*

Two samples from the Bernafai Volcanics were taken from outcrops in the Savage River catchment. A sample (G408124) of a fine-grained, lithic rich, volcaniclastic sandstone (Figure 4a) is moderately sorted, consisting of wispy chlorite, rounded to angular grains of quartz and Fe-Ti magnetite crystals. Sample G408138 comprises a mixed glass shard and lithic-rich volcaniclastic granule to pebble sandstone (Figures 4b and c). Large sub-rounded clasts with needle pyroxene microlites (Figure 4b) occurs along with lenticular siltstone and lithic clasts (Figure 4c). These clasts are generally supported in a silty, grey, crystal-rich matrix.

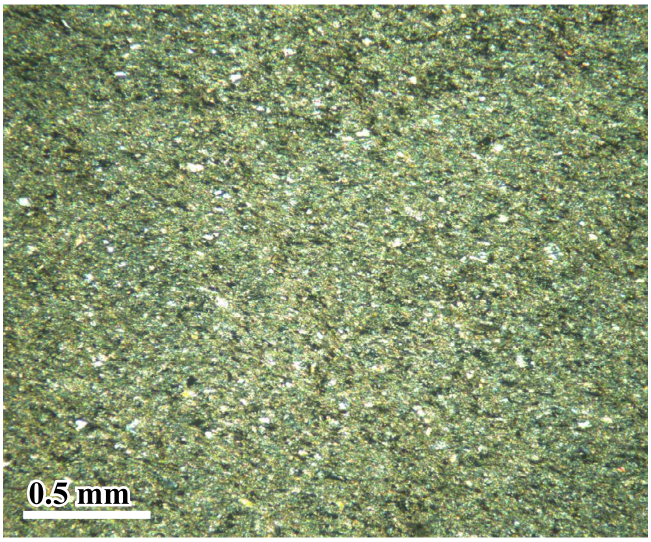
*Timbs Group - "Western Wall Assemblage"*

Six samples were selected from the "Western Wall Assemblage" peripheral to and west of the main Savage River open cut pits. Of the samples selected from the open cut pits, three samples were selected from exposures to the south (C110265, C108848a and C109185), and north (C109134, C110161A). Three samples (C108886, C108898 and C108899) were selected from exposures at Centre Pit. An additional sample was selected from the Broderick Creek catchment to the north-west of the mine. A single sample of albitite (C113322) was selected from drillcore (Rocky R. DDH3; Figure 2, B) that intersects rocks mapped as 'Dominantly felsic albite schist with relict medium-grained microcline-albite granitoid' by Turner et.al. 1992. The drillcore is located a few metres from the purported granitoid sample dated by Turner et. al., (1998). Photographs of outcrops, sample hand specimens and photomicrographs of relevant samples are included in Figure 5.

*Timbs Group - "Armstrong Creek Schist"*

Three samples were selected from the "Armstrong Creek Schist" (Figure 6 a, b and c). These were collected from a fairly narrow outcrop of the unit directly south

a)

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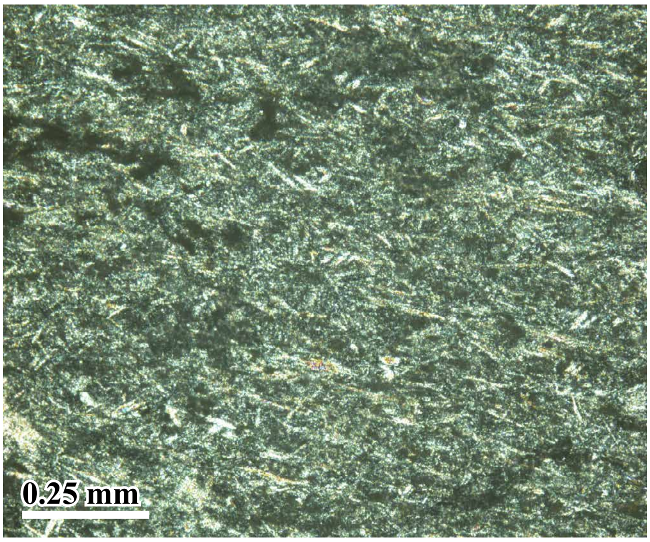


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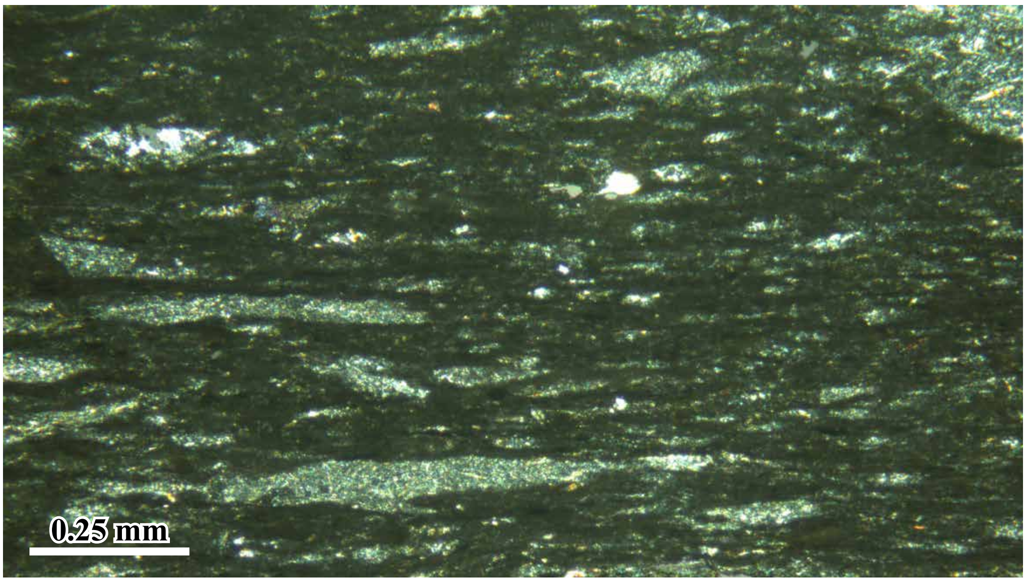



Figure 4. Photomicrographs of samples from the Bernafai Volcanics. a) Well sorted volcaniclastic sandstone (G408124), b) basalt clast (from sample G408138) with needle-shaped pyroxene? micro-phenocrysts; c) pebble to granule volcaniclastic sandstone with fine grained matrix and polymictic, lenticular (foliated) basalt and siltstone clasts (sample G408138).

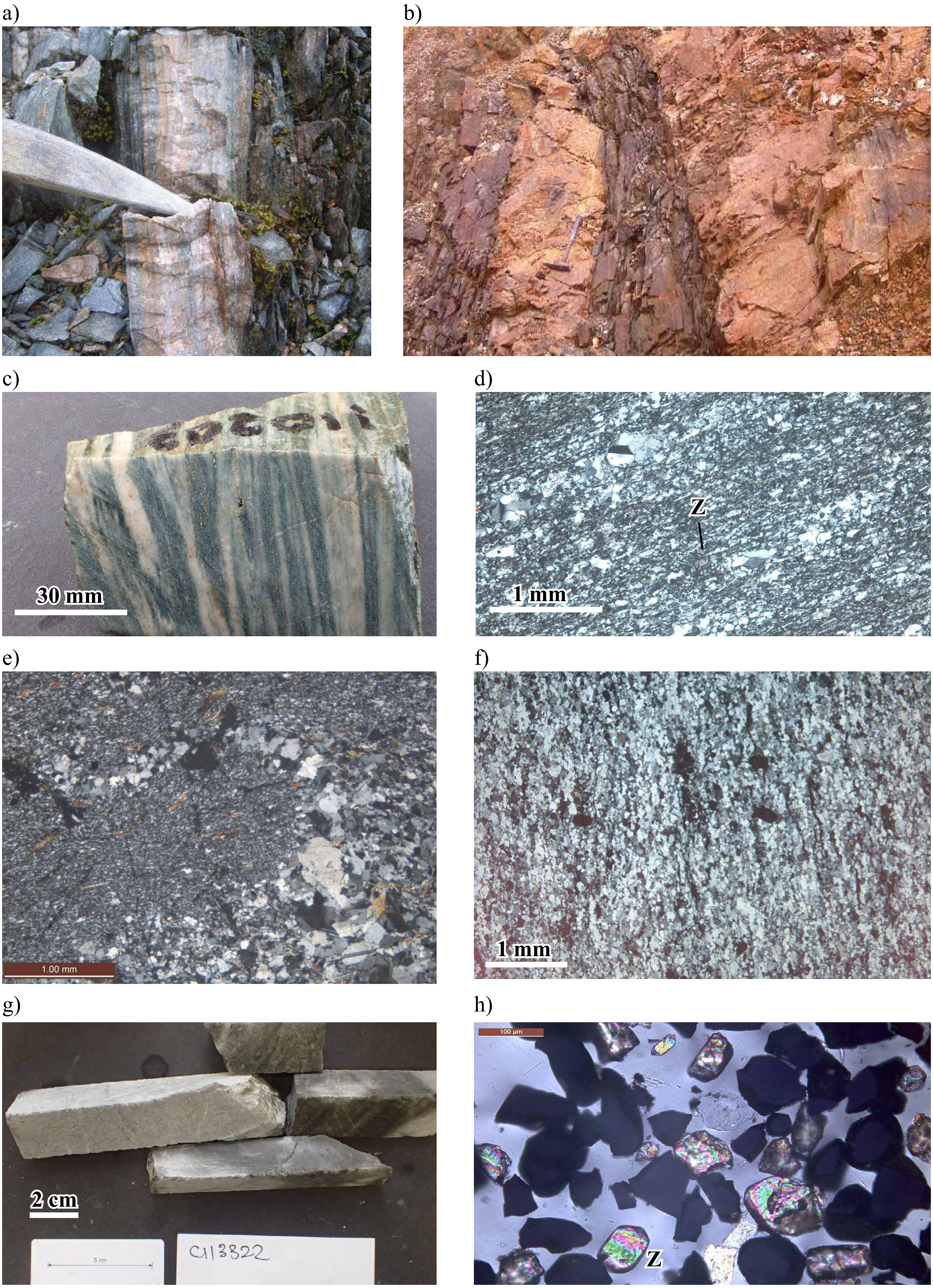



Figure 5. Photos of facies in the Western Wall sequence and photomicrographs of samples selected for geochronology a) Albitised meta-sediment, “Western Wall Assemblage”, South Pit. b) Albitised meta-sediment, “Western Wall Assemblage”, South Pit. c) Sample C110203; Albitised chloritic metasediment, “Western Wall”, South Pit. d) Sample C108898; Albitised sediment, showing small detrital zircon near centre (indicated with “2”). e) Sample C108848A Fine grained albitised, foliated amphibolite with coarse albite veining. “Western Wall” Bowry Fm. f) C108886 Ab-quartzite with a small rounded zircon “Western Wall” Bowry Fm. g) Sample C113322. Quartz-albitite meta-sediment, “Western Wall” Bowry Fm., Rocky River. h) Rounded and euhedral zircon crystals (high birefringence grains) shown in cross-polarised transmitted light for sample C113322.

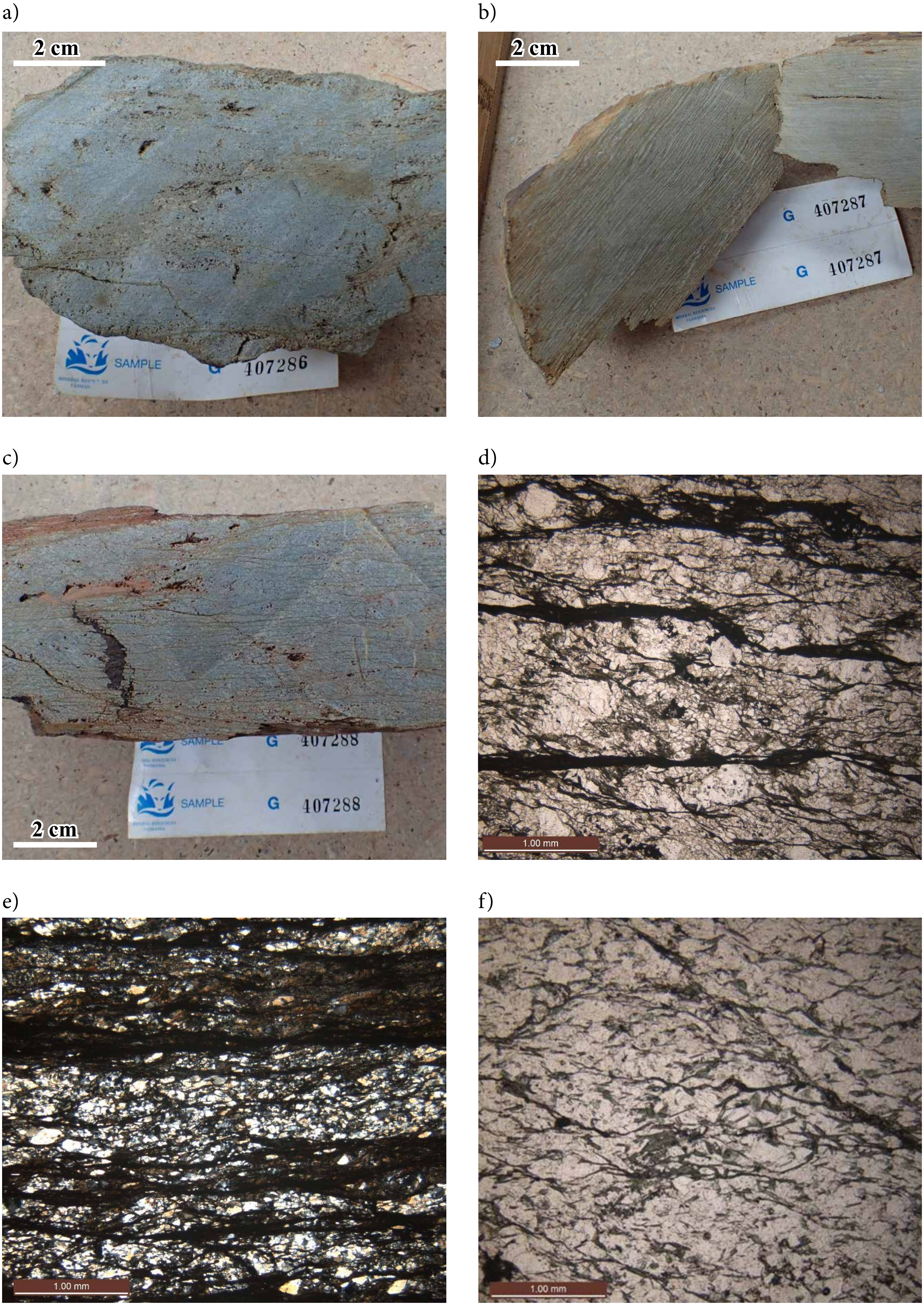



Figure 6. Hand specimens and photomicrographs of samples selected for geochronology from the Armstrong Creek Schist. a) Sample G407286; Armstrong Creek Schist, chloritic variant. b) Sample G407287; Laminated chlorite-quartz schist Armstrong Creek Schist. c) Sample G407288; Laminated chlorite-quartz schist. d) Chlorite schist (sample G407288) showing alternating dark bands of elongate chlorite fibres and quartz. Circular zones have a porphyroblastic texture. e) Chlorite-quartz-schist with dark chlorite bands (sample G407287) and f) Weakly foliated quartz-mica schist with platey to tabular stubby chloritoid? Crystals.

of Savage River near the pipeline span. These samples consist of variably banded quartz chlorite-albite schist (sample G407288) with alternating dark bands of elongate chlorite fibres and quartz-albite and circular zones of albite which display a porphyroblastic texture. Additional samples of chlorite-quartz-albite schist with dark chlorite bands (sample G407287; Figure 6b) and weakly foliated quartz-albite schist with platy to tabular stubby chloritoid crystals (sample G408286; Figure 6c) were sampled directly south of G407287.

*Timbs Group - "Fulfords Creek Schist"*

A single sample (C110161A) of "Fulfords Creek Schist" was selected 350 m east of Broderick Creek in an area now used for storage of waste and tailings to the north east of North Pit. The sample consists of carbonaceous phyllite.

*Keith Schist*

Three samples of quartzite and intercalated quartz-chlorite schist (Figure 7) and phyllite were selected from exposures of Keith Schist at a variety of locations east of the Savage River mine. A sample of quartzite was selected from a small tributary draining into Armstrong Creek from the east (G408151). The sample consists of foliated quartz-muscovite-chlorite schist. Two samples were also selected from road exposures along the

Table 1. Locations and rock types dated from the Western Ahrberg Group (Donaldson Fm. And Bernafai Volcanics), the Timbs Group (Bowry Fm., "Fulfords Creek Schist", "Armstrong Creek Schist") and the Keith Schist. Coordinates are quoted in GDA94Z55.

| **Sample No.** | **Locality** | **Rock Type** | **Stratigraphic Unit** |
|---|---|---|---|
| G408110 | 346685mE/5406207mN | Quartz sandstone | Donaldson Formation |
| G408116 | 346557mE/5405213mN | Siltstone | Donaldson Formation |
| G408138 | 348088mN/5404179mN | Basaltic breccia | Bernafai Volcanics |
| G408124 | 346275mN/5401747mN | Volcaniclastic sandstone | Bernafai Volcanics |
| C108898 | 349755mE/5406170mN | Albitite metasedimentary rock | "Western Wall Assemblage" Bowry Fm. |
| C110265 | 348022mE/5402963mN | Quartz-albitite meta- sedimentary rock | "Western Wall Assemblage" Bowry Fm. |
| C113322 | 349040mE/5389970mN | Quartz-albitite meta- sedimentary rock | "Western Wall Assemblage" Bowry Fm. |
| C109134 | 350447mE/5407801mN | Albite-chlorite volcaniclastic | "Western Wall Assemblage" Bowry Fm. |
| C108848A | 348173mE/5403349mN | Amphibolite | "Western Wall Assemblage" Bowry Fm. |
| C108886 | 349815mE/5406163mN | Albite-quartzite metasedimentary rock | "Western Wall Assemblage" Bowry Fm. |
| C108899 | 349756mN/5406170mE | Albitite | "Western Wall Assemblage" Bowry Fm. |
| C109185 | 348374mE/5403351mN | Dolerite | "Western Wall Assemblage" Bowry Fm. |
| G407288 | 350986mE/5406729mN | Albite-chlorite-mica schist | "Armstrong Creek Schist" |
| G407287 | 350833mE/5406614mN | Quartz-muscovite chlorite schist | "Armstrong Creek Schist" |
| G407286 | 350784mE/5406456mN | Quartz-chlorite schist | "Armstrong Creek Schist" |
| C110161A | 350412mE/5408584mN | Quartz schist | "Fulfords Creek Schist" |
| G408151 | 352627mE/5408625mN | Banded quartzite and phyllite | Keith Schist |
| C109169 | 350643mE/5404633mN | Quartz-muscovite schist | Keith Schist |
| C110297 | 350516mE/5403717mN | Laminated siltstone | Keith Schist |

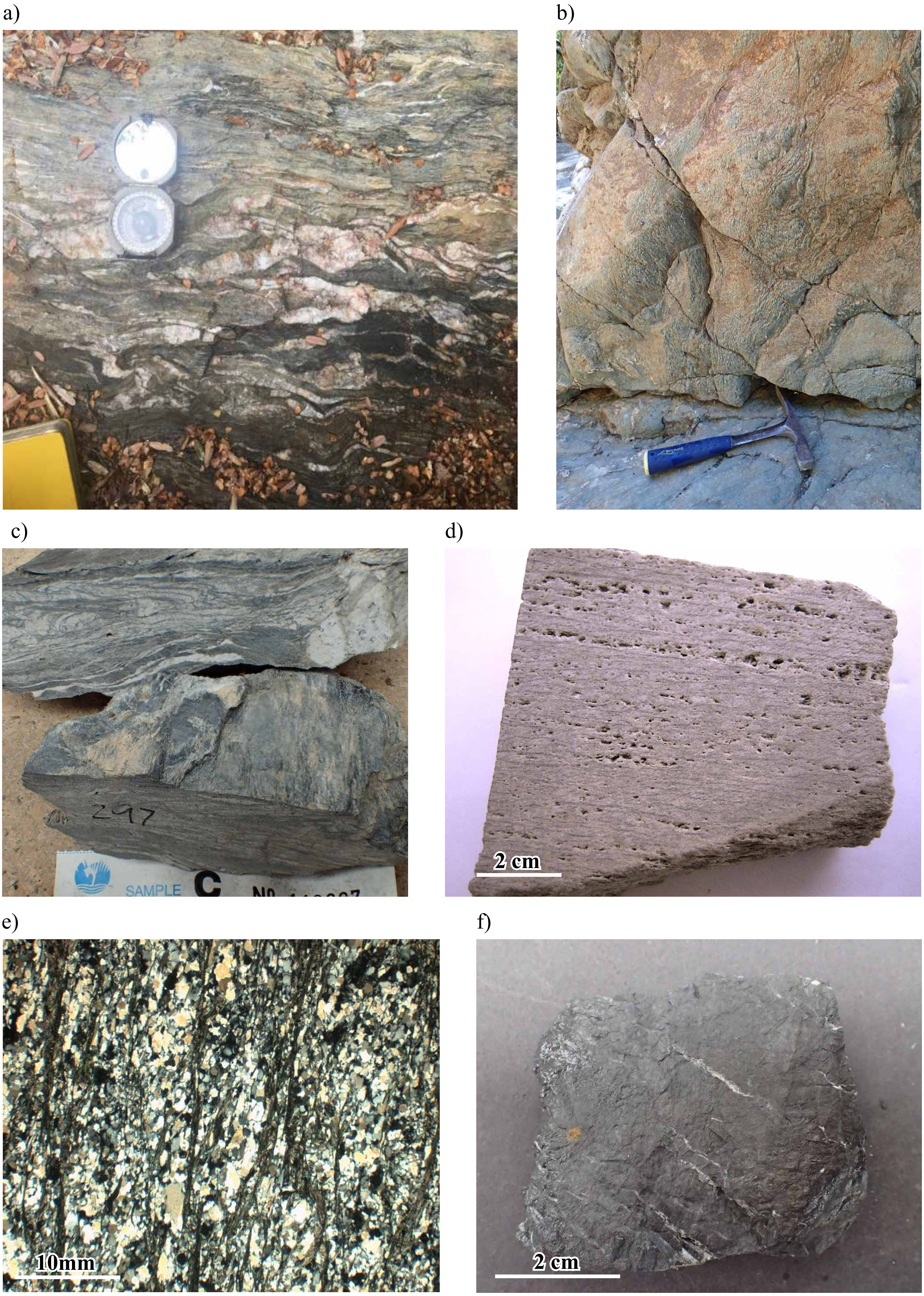



Figure 7. Outcrop photographs showing a) intensely folded Quartz-chlorite schistose outcrop (Keith Schist) along Savage River and b) intensely folded and cleaved chlorite ± quartz schist (Keith Schist). c) Cut slab of sample C110297 (highly deformed pelite and quartzite); d) Sample C110297; Laminated siltstone (Keith Schist). e) Photomicrograph of sample C109169 Quartz-muscovite schist (Keith Schist), and f) Photomicrograph of sample C109169 Quartz-muscovite schist ("Oonah") Keith Schist.

western edge of the main tailing dam (C109169 and C110297). The best exposures of Keith Schist occur along Savage River as shown in Figure 7a and 7b.

## 4.0 Methods

### *4.1 Detrital and In-situ zircon geochronology*

U-Pb geochronology was undertaken at the University of Tasmania using the LA-ICPMS technique. Zircons were separated from all samples, except for two samples of albitite and dolerite (C108899 and C109185), where zircon was analysed in situ. The analysis and data reduction protocol was similar for all samples, as further described below.

The meta/sedimentary rock sample detrital zircons were separated using a gold pan and a hand magnet from 200 g of rock powder crushed to a coarse sand using a ring mill. The zircons were hand-picked from the non-magnetic concentrate, mounted in epoxy resin, polished using a clean lap, washed in distilled water in an ultrasonic bath and dried. In the igneous sample and the albitite zircons were identified in polished 25 mm diameter mounts using a FEI Quanta 600 SEM controlled by an automated software package (Mineral Liberation Analyser or MLA) developed by JKTech© (Fandrich et al., 2007).

Zircon grains were analysed using an Excimer (193 nm) laser coupled to a Resonetics M50 ablation cell and an Agilent 7500 quadrupole ICPMS. Samples were analysed using a 32-35 µm spot at 5 Hz and 1.5-2 J/cm2. Each analysis on the zircons began with a 30 second blank gas measurement followed by a further 30 seconds of analysis time when the laser was switched on. A flow of He carrier gas at a rate of 0.5 litres/minute carried particles ablated by the laser out of the chamber to be mixed with Ar gas and carried to the plasma torch. Isotopes measured include $^{49}$Ti, $^{96}$Zr, $^{146}$Nd, $^{178}$Hf, $^{202}$Hg, $^{204}$Pb, $^{206}$Pb, $^{207}$Pb, $^{208}$Pb, $^{232}$Th and $^{238}$U with each isotope being measured sequentially every 0.14 s with longer counting time on the Pb isotopes compared to the other elements.

For the detrital zircon samples, the 91500 zircon (Wiedenbeck et al., 1995, 2005) was used as a primary standard and the Temora 1, GJ-1 and Plesovice zircons (Black et al., 2003; Jackson et al., 2004; Sláma et al., 2008) were used as secondary standards. For sample dolerite sample C109185, Temora 1 was used as a primary standard, with 91500 as a secondary standard. The correction factor for the $^{207}$Pb/$^{206}$Pb ratio was calculated using large spots (100 micron, 10 Hz) on NIST610 analysed at the beginning and end of the session using the values recommended by Baker et al., (2004). The data reduction was based on the method outlined in detail in Halpin et al. (2014). Age calculations were performed using the mean age ($^{207}$Pb corrected $^{206}$Pb/$^{238}$U age or $^{207}$Pb/$^{206}$Pb age) of the youngest three or more concordant grains that overlap in age at 2σ (referred to YC2σ(3+) by Dickinson et. al. 2009). Element abundances on zircons were calculated using the method outlined by Kosler (et. al., 2001) using Zr as the internal standard element, assuming stoichiometric proportions and using the 91500 standard to correct for mass bias.

## 5.0 Results

Numerical results for each sample are presented in Table 2 and on Tera-Wasserburg concordia diagrams (Figs. 8, 9, 10, 11, 12). For each individual zircon analysis, a "preferred age" was chosen based on a ± 10 % discordance filter (as outlined in Halpin et. al., 2014), the amount of common Pb and the age of the zircons. For younger zircons the $^{206}$Pb/$^{238}$U age is used and corrected for common lead (using the $^{207}$Pb method). In most cases, the uncorrected and common Pb corrected ages differ by less than 10 Ma. For older zircons (older than ~ 1500 Ma) $^{207}$Pb /$^{206}$Pb ages are referred to. For those analyses for which lead loss is identifiable, the preferred age has been taken as the $^{207}$Pb/$^{206}$Pb age. Zircons with high (>2500 ppm) levels of $^{56}$Fe were filtered from the results. The preferred zircon ages from each sample are also presented as probability density plots (Figures 13, 14, 15, 16, 17, 18). Probability plots were created using the Isoplot add-on in Excel and IsopltR (after Vermeesch, P., 2018) was used to construct the concordia diagrams.

### *5.1 Ahrberg Group – Donaldson Formation*

*G408110 Quartz sandstone*

Many of the 43 grains analysed exhibit lead loss, and for most, the $^{207}$Pb/$^{206}$Pb age is preferred. The youngest grain is 1247 (101% concordant; Figure 8; a., b). A mean age of 1358 ± 16 Ma (MSWD 0.90) was calculated based on a cluster of 3 concordant ages (Table 2), which provides a maximum depositional age for the sample. Most grains have ages between ca. 1430 Ma and ca. 2000 Ma (Figure 8: a and b). There is a major age peak at ca. 1714 Ma (Figure 13) and minor age peaks at ca. 1955 Ma and 1429 Ma (with some 100% concordant grains). There are six older grains with ages ranging from 2638 to 2431 Ma; but these experienced Pb-loss due to alteration of zircon grains, as evidenced by higher levels of Fe and lower levels of Pb. The oldest concordant grain is 1984 ± 15 Ma ($^{207}$Pb/$^{206}$Pb).

Table 2. Summary of ages for the Ahrberg Group, the Timbs Group (including the Bowry Fm.) and the Keith Schist.

| Sample Number | Rock Type | Stratigraphic Unit | Youngest concordant zircon age (Ma) and uncertainty 2σ | Weighted mean age (Ma) with uncertainty (Ma) 2σ of youngest zircons | MSWD | Number of zircons used for age calculation/total zircons analysed |
|---|---|---|---|---|---|---|
| G408110 | Quartz sandstone | Donaldson Formation | 1343 ± 18 | 1358 ± 16 | 0.90 | 3/44 |
| G408116 | Siltstone | Donaldson Formation | 1354 ± 24 | 1425 ± 9 | 0.17 | 5/54 |
| G408138 | Basaltic breccia | Bernafai Volcanics | 569 ± 8 | 577 ± 10 | 2.2 | 4/17 |
| G408124 | Sandstone | Bernafai Volcanics | 1176 ± 27 | 1232 ± 21 | 0.19 | 4/29 |
| C108898 | Albitite metasedimentary rock | "Western Wall" Bowry Fm. | 1090 ± 32 | 1124 ± 21 | 0.37 | 3/34 |
| C110265 | Quartz-albitite metasedimentary rock | "Western Wall" Bowry Fm. | 735 ± 32 | 781 ± 24 | 1.2 | 7/32 |
| C113322 | Quartz-albitite metasedimentary rock | "Western Wall" Bowry Fm. | 717 ± 18 | 733.5 ± 7 | 1.9 | 9/59 |
| C109134 | Albite-chlorite meta-mafic | "Western Wall" Bowry Fm. | 759 ± 28 | 777 ± 37 | 1.2 | 3/19 |
| C108848A | Amphibolite | "Western Wall" Bowry Fm. | 788 ± 10 | 1158 ± 14 | 0.32 | 4/58 |
| C108886 | Albite-quartzite metasedimentary rock | "Western Wall" Bowry Fm. | 1032 ± 14 | 1161 ± 15 | 0.24 | 4/60 |
| C108899 | Albitite | "Western Wall" Bowry Fm. | 1099 ± 146 | 1099 ± 73 | 0.99 | 6/12 |
| C109185 | Dolerite | "Western Wall" Bowry Fm. | 760 ± 28 | 774 ± 12 | 0.83 | 7/11 |
| G407288 | Quartz schist | "Armstrong Creek Schist" | 988 ± 26 | 1063 ± 12 | 0.73 | 3/100 |
| G407287 | Albite-chlorite-mica schist | "Armstrong Creek Schist" | 977 ± 20 | 993 ± 19 | 2.0 | 5/89 |
| G407286 | Quartz-muscovite chlorite schist | "Armstrong Creek Schist" | 1010 ± 20 | 1199 ± 13 | 0.27 | 3/97 |
| C110161A | Quartz schist | "Fulfords Creek Schist" | 801 ± 34 | 1228 ± 25 | 0.51 | 3/49 |
| G408151 | Banded quartzite and phyllite | Keith Schist | 1066 ± 14 | 1196 ± 15 | 0.91 | 4/91 |
| C109169 | Quartz-muscovite schist | Keith Schist | 1034 ± 14 | 1147 ± 8.5 | 0.80 | 3/95 |
| C110297 | Laminated siltstone | Keith Schist | 1233 ± 16 | 1419 ± 72 | 0.71 | 11/86 |

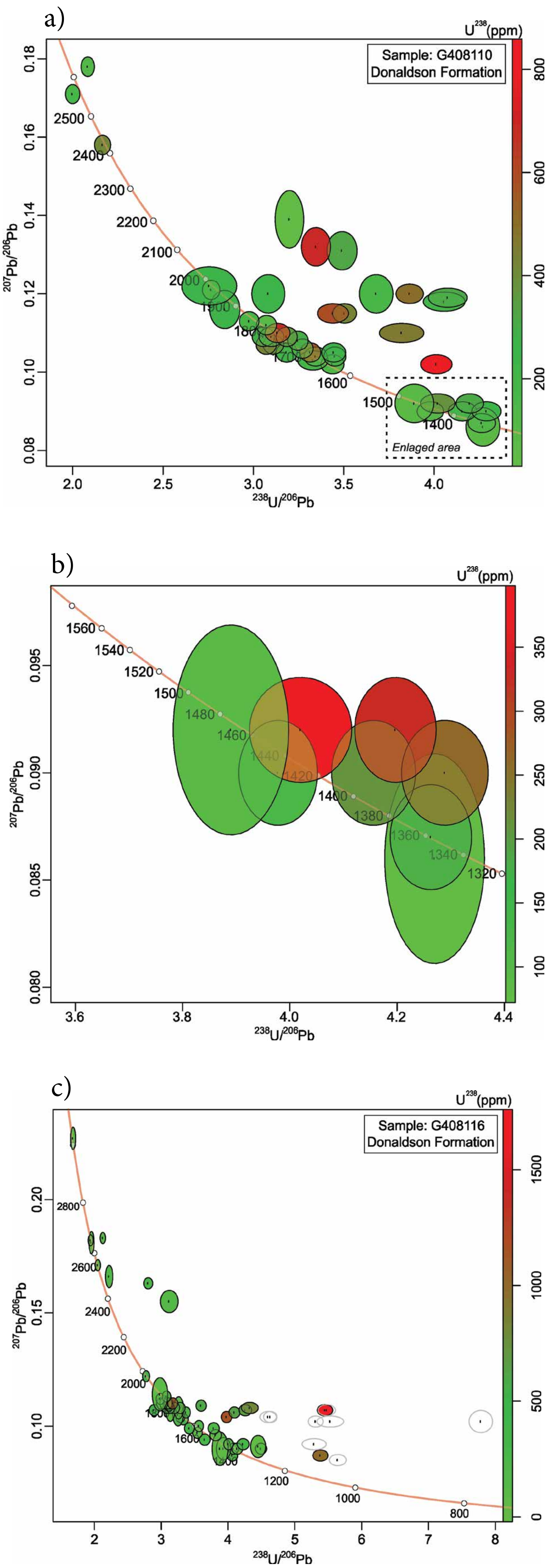



Figure 8. Tera-Wasserburg plots of U–Pb zircon analyses for the Donaldson Formation a) Concordia plot for sample G408110 with b) enlargement. c) Concordia plot for sample G408116. Analyses are coloured based on $U^{238}$ content and levels are shown in the vertical column on the right.

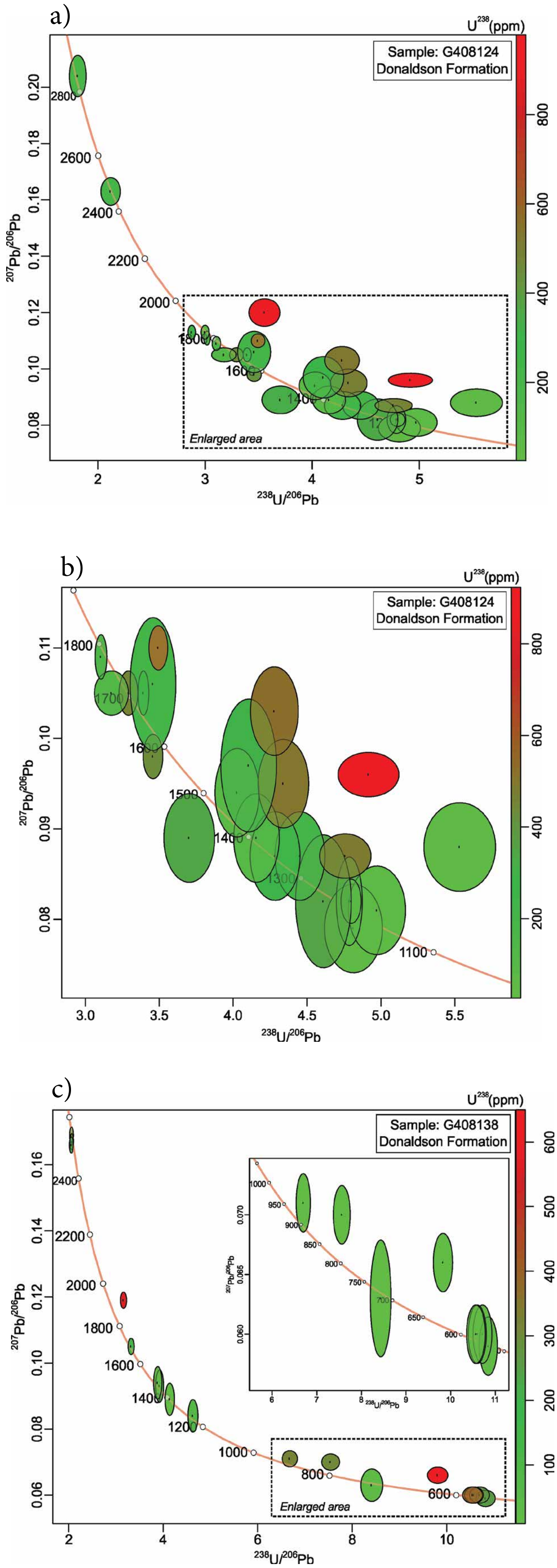



Figure 9. Tera-Wasserburg plots of U–Pb zircon analyses for Bernafai Volcanics sample G408124 (a, b) and G408138 (c).

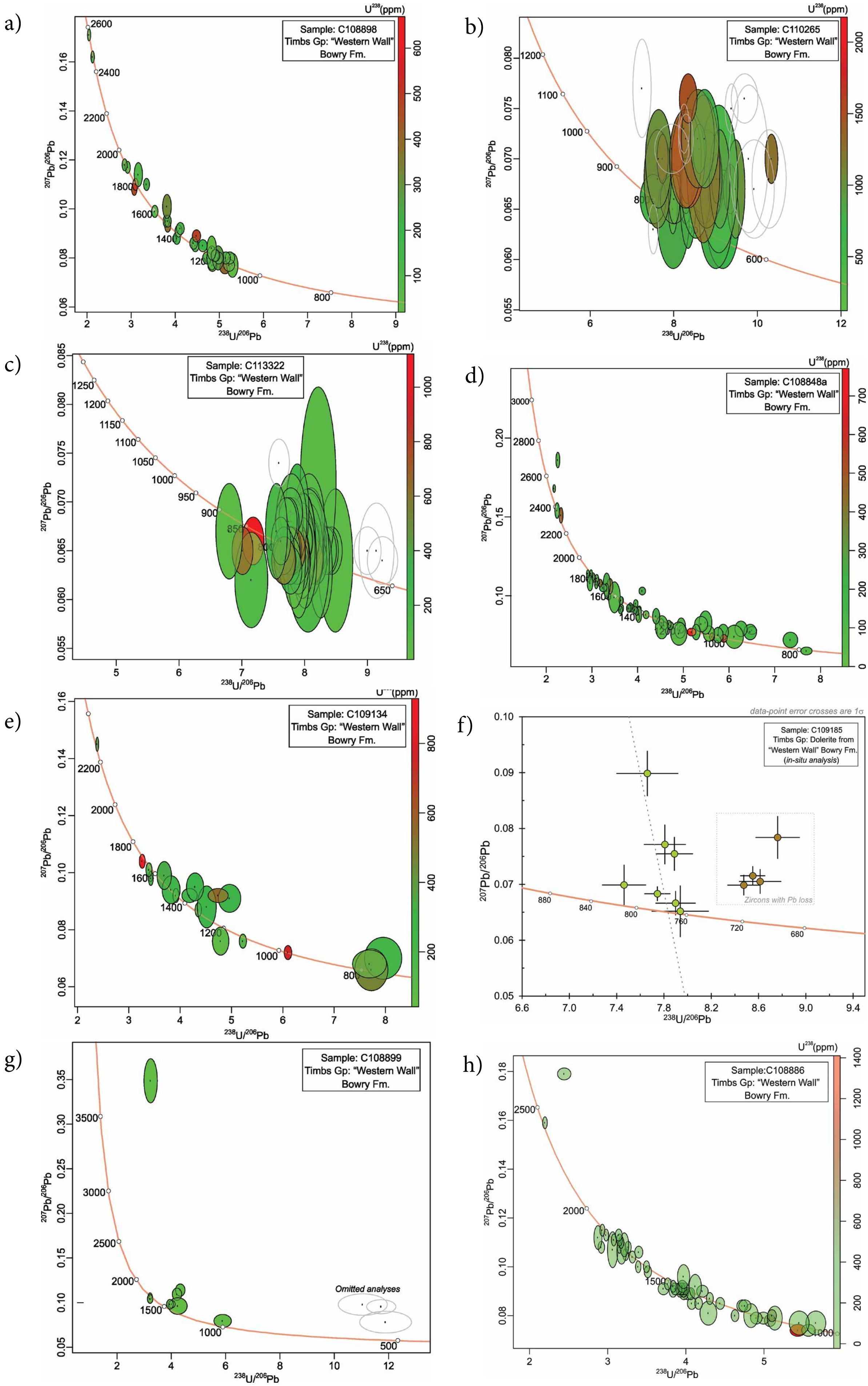
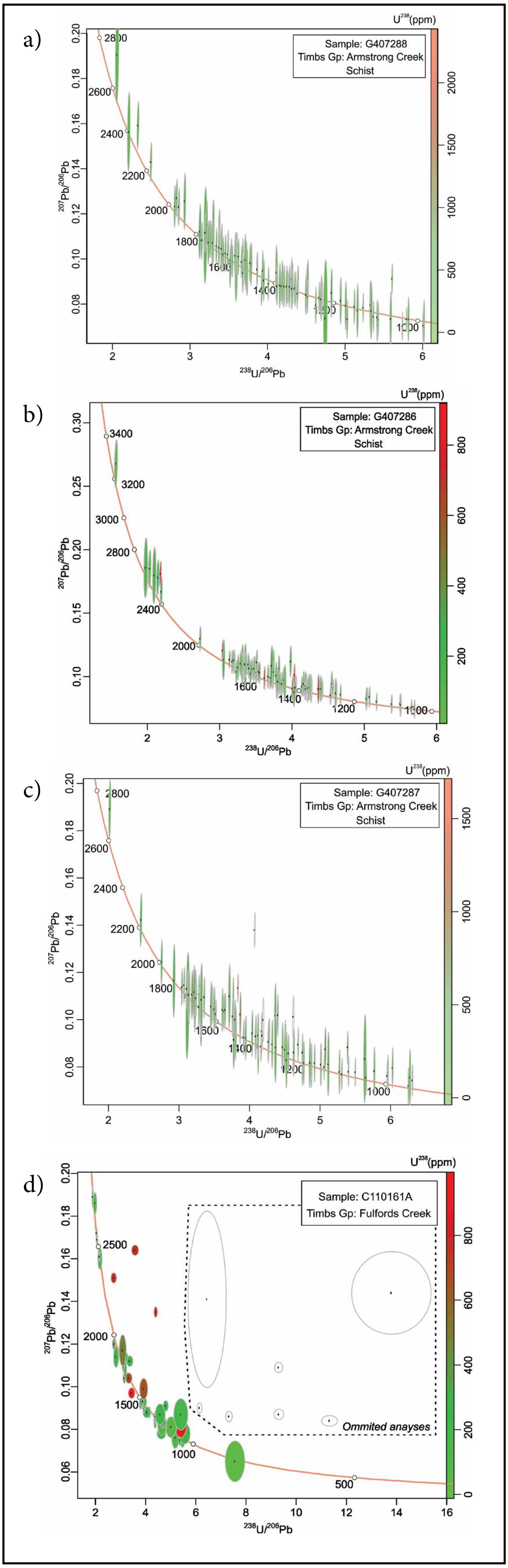



Figure 10. Tera-Wasserburg plots of U–Pb zircon analyses for the "Western Wall Assemblage" (Bowry Fm.) a-e, g and h show Tera-Wasserburg plots of U–Pb zircon analyses for all the sedimentary and meta-sedimentary rocks from the "Western Wall Assemblage" (Bowry Fm.) while f shows ages for a sample of dolerite, whereby the zircon ages were calculated from in-situ analysis. Figures b, c and g, show omitted analyses as hollow grey circles. Uranium (238) content is shown for all samples except C108899 (as no trace element data was available).



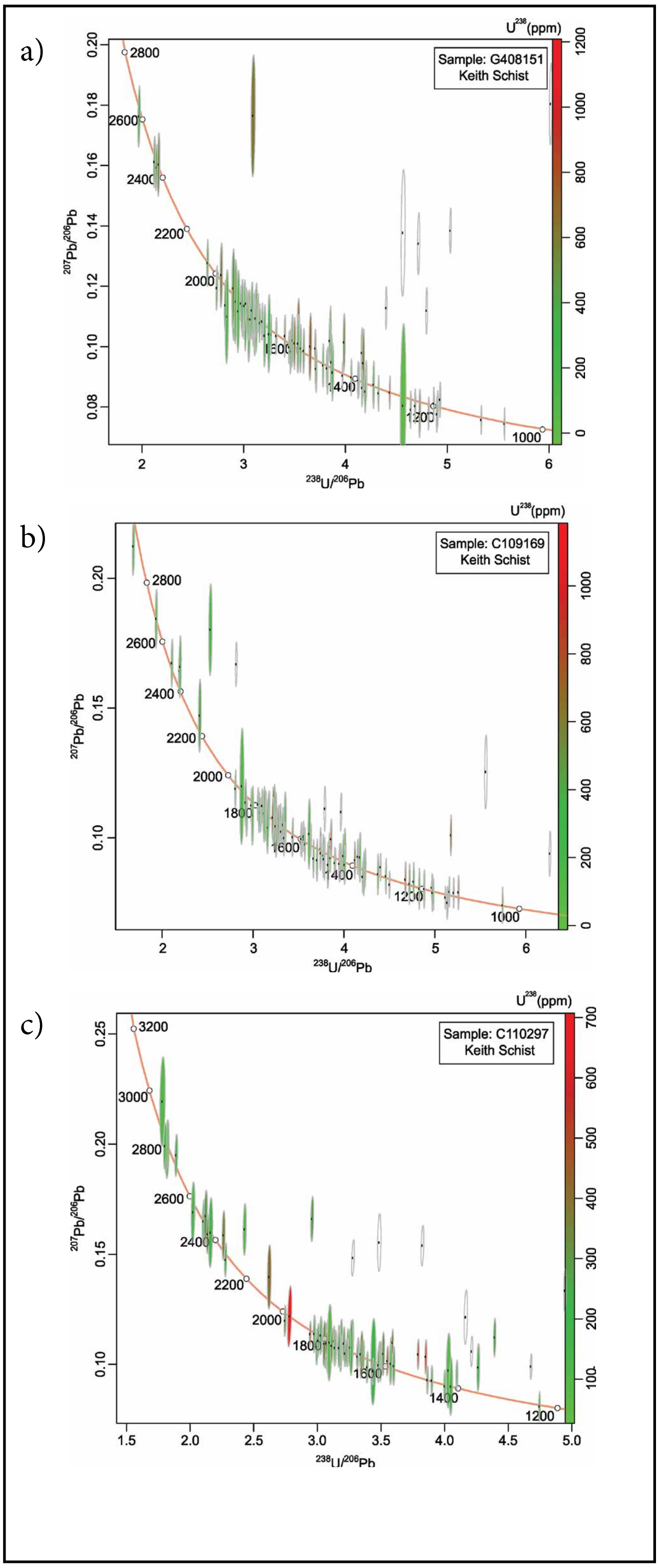




Figure 11 (Left). Tera-Wasserburg plots of U–Pb zircon analyses for the Armstrong Creek Schist and Fulfords Creek Schist: a) Sample G407288; b) Sample G407286; c) Sample G407287 and d) Sample C110161A.

Figure 12 (Above). Tera-Wasserburg plots of U–Pb zircon analyses for the Keith Schist: a) Sample G408151; b) Sample C109169 and c) Sample C110297.

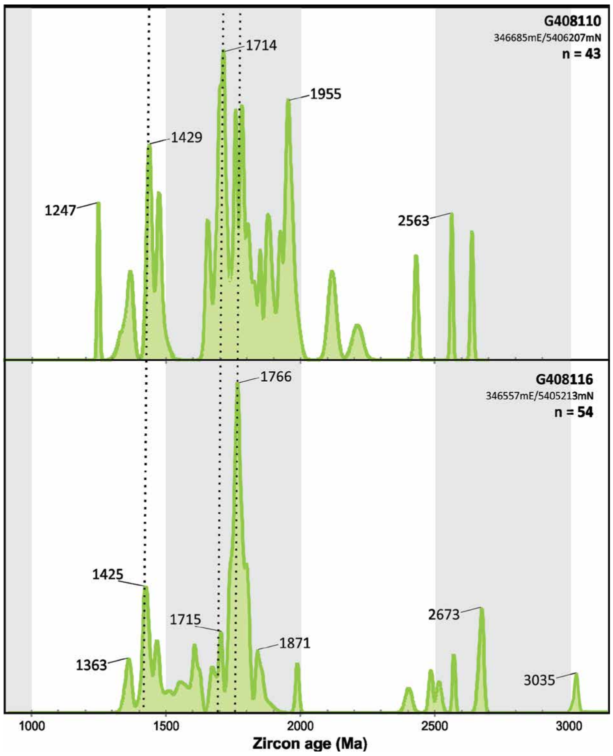



Figure 13. Probability plots of U-Pb ICPMS ages of detrital zircons from the Donaldson Formation (samples G408110 and G408116; Ahrberg Group).

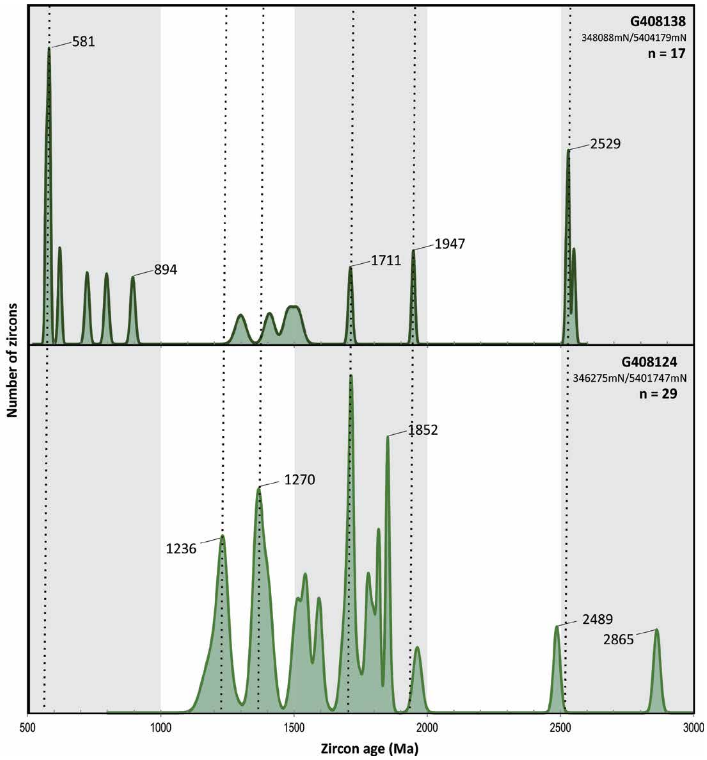



Figure 14. Probability plots of U-Pb ICPMS ages of detrital zircons from the Bernafai Volcanics (sample G408138 and G408124; Ahrberg Group).

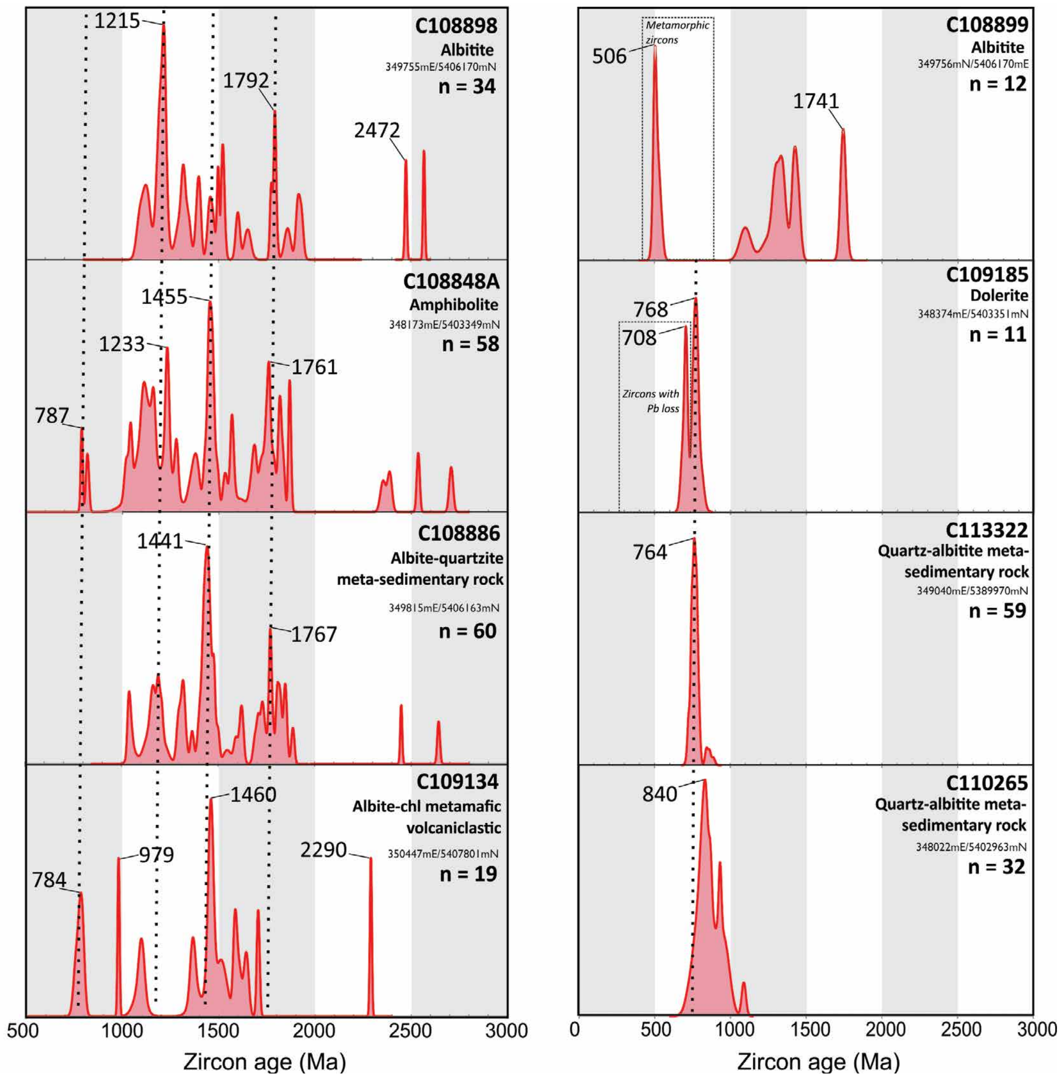



Figure 15. Probability plots of U-Pb ICPMS ages of detrital and magmatic zircons from the “Western Wall Assemblage” facies of the Bowry Fm. (Timbs Group).

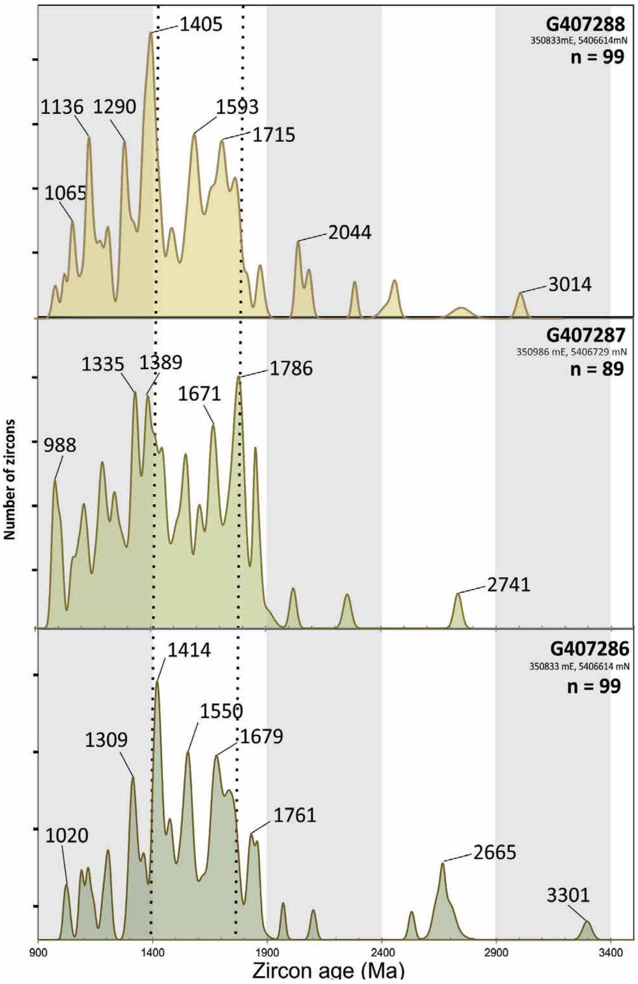



Figure 16 (Top left). Probability plots of U-Pb ICPMS ages of detrital zircons from the "Armstrong Creek Schist".

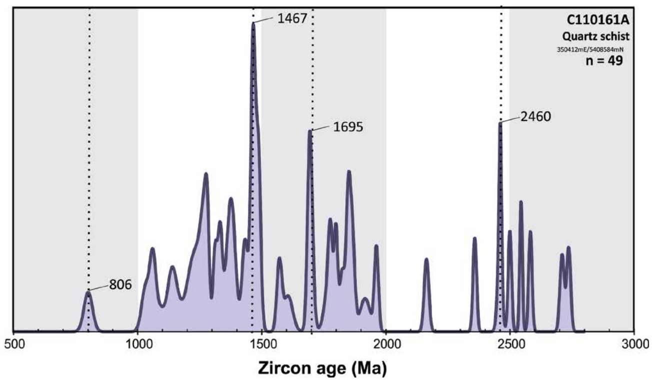



Figure 17. (Above) Probability plots of U-Pb ICPMS ages of detrital zircons from the Fulfords Creek Schist (sample C110161A).

*G408116 Siltstone*

Generally, the 54 grains show a similar age spectrum to the other Donaldson Formation sample (Figure 13; G408110), although they have a somewhat higher proportion of 1700-1880 Ma ages. Most of the zircons in this age range are concordant or nearly so (Figure 8c). The youngest apparent age is 1354 ± 24 Ma (Figure 8c) with 81 % concordance. There are large clusters of ages between 1422 and 1500, and between 1871 and 1705 Ma with a peak at ca. 1783–1748 Ma. The youngest cluster provides a preferred weighted mean age of 1425 ± 9 Ma (mostly concordant analyses; MSWD 0.17). There is a single older, 3035 Ma zircon.

### *5.2 Ahrberg Group - Bernafai Volcanics*

*G408138 Basaltic breccia*

Seventeen grains yield preferred ages ranging from 569 Ma ($^{206}Pb/^{238}U$ ) to 2530 Ma ($^{207}Pb/^{206}Pb$) and most of the analyses are concordant (Figure 9c). A cluster of grains yield concordant $^{207}Pb/^{206}Pb$ ages between 1711 and 1299 Ma (Figure 9c). The youngest grain that yields an intercept age with the concordia curve is zircon is 569 ± 8 Ma (98 % concordant) and the weighted mean age (Table 2) and maximum depositional age is 577 ± 10 Ma (with MSWD of 1.8; Figure 9c). There is a scattering of ages between 1900 Ma and 1300 Ma (Figures 9 and 14) and three older zircons (2549, 2530 and 2522 Ma).

*G408124 Volcaniclastic sandstone*

Twenty nine grains form a fairly sparse spread of zircon ages in this sample (Figure 9: a and b). The preferred $^{207}Pb/^{206}Pb$ ages with a spread of uncertainty (up to 29 Ma) range from 1176 ± 27 Ma (103 % concordance) to 2862 Ma. This sample (G408124) was taken from a faulted segment of Bernafai Volcanics to the south of sample G408138. The intervening faults could be important, as this sample contains much older zircons

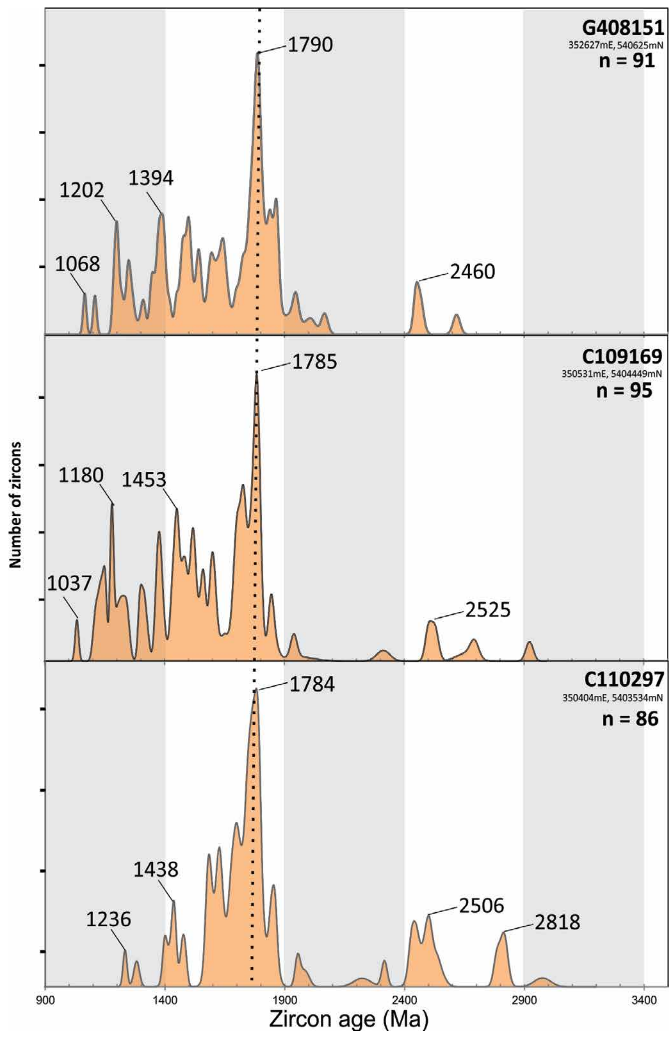



Figure 18 (Bottom left). Probability plots of U-Pb ICPMS ages of detrital zircons from the Keith Schist.

compared to G408138, and the age peaks (1247–1216 Ma, 1400–1349 Ma, 1726–1698 Ma, 1857–1818 Ma) are also quite different to those observed in sample G408138 (Figure 14). Both G408124 and G408138 yield multimodal detrital zircon age spectra (Figure 14).

The sample yielded two late Archaean-early Proterozoic zircons. Numerous zircons also show Pb-loss and some zonation in age (especially in the 1708–1519 Ma age range). In these cases the zone showing the most concordant values were selected.

### *5.3 Timbs Group – Bowry Fm. ("Western Wall Assemblage")*

*C108898 Albitite metasedimentary rock*

Of the thirty-five zircons analysed, two were omitted from the final age calculation due to higher levels of iron throughout the zircon grains (Figure 10a). Most (~90 %) of grains from the sample showed only very minor discordance (1%-5%), minor Pb loss and some variable iron levels along the rim of some grains (Figure 10a). A $^{207}Pb/^{206}Pb$ age is preferred and the youngest grain yielded an age of 1090 ± 32 Ma (Table 2). The sample generated a complex age spectrum similar to sample C109134 and shares some age populations with C108848a. The weighted mean age is 1124 ± 21 (MSWD of 0.37). Most grains yield ages between 1234 Ma and 1184 Ma. Older grains form small age peaks between 1947 Ma and 1299 Ma. There are two older zircon grains with ages of 2473 Ma and 2567 Ma (Figure 15).

*C110265 Quartz-albitite meta- sedimentary rock*

Out of 51 grains analysed, 20 analyses were rejected due to Pb loss, high iron levels and potential age zonation of the zircons. The rejected analyses were excluded from probability (Figure 15) or concordia (Figure 10b) plots and are not reported in Table 2. Many of the 32 grains used in the final age calculations exhibit some discordance indicating Pb loss or show some potential zoning, and in these cases, the most concordant part of the analysis was used. In all cases, the $^{207}Pb/^{206}Pb$ age is preferred.

The youngest grain is 735 ± 32 Ma (Figure 10b) but this zircon shows some variability of $U^{206}/Pb^{238}$ and potentially elevated iron. The next youngest concordant grain has a $^{207}Pb/^{206}Pb$ age of 769 ± 19 Ma. Most of the remaining grains have ages between ca. 998 ca. and 771 Ma (Figure 15) and a weighted mean age of 781 ± 24 Ma. This provides a maximum depositional age for the sample (Table 2). Compared to other samples analysed from the Western Wall Assemblage, this sample has a unique age populations at ca. 840 Ma, ca. 929 Ma and 1088 Ma.

*C113322 Quartz-albitite meta- sedimentary rock*

Of the 65 grains analysed from sample C113322, 59 were accepted. The sample has a unimodal age distribution between 794 Ma and 737 Ma. The 9 youngest zircon grains yield a weighted mean age of 733.5 ± 7 Ma (MSWD 1.9), with the youngest grain in this population dated at 717 ± 9 Ma (with 96 % concordance). Grains from the sample showed some minor discordance (± 25% - 6%), especially in the older zircons (Figure 10c). Some zircons seemed to show isolated zones with very high levels of iron, which may indicate the presence of inclusions or fractures in the crystal lattice. Both euhedral and round zircons were observed (Figure 5h). The euhedral zircons have the younger age ranges, whereas the rounded zircons often revealed older ages. The unimodal age population suggests the protolith of this albitite sample could have been a volcaniclastic rock, or a magmatic rock with sedimentary inclusions.

The sample was collected approximately 17 km south of Savage River and exhibits a peak age range (of 764 Ma; Fig. 15) which contrasts to the youngest peak age range in many of the other metasedimentary samples selected from the Bowry Fm. (at the Savage River mine), yet is most similar to the dolerite sample (C109185) from South Pit. The intervening geology (mapped on the Livingston and Meredith 1:25,000 geological map sheets) shows a continuation of the Bowry Fm. to Rocky River, yet this area was not mapped in detail and there is some possibility that this sequence of rocks has been faulted.

*C109134 Albite-chlorite volcaniclastic*

Out of the 19 grains analysed from this sample, none were rejected. The grains used in the final age calculations exhibit minor discordance (Figure 10d.). Some zircons show moderate levels of zonation, and have young rims and older cores, and in these cases, the most concordant part of the analysis (the first ~10 seconds of ablation) was used.

The four youngest zircons yielded ages between 759 ± 14 Ma and 978 ± 4 Ma, providing a mean age of 777 ± 37 Ma (MSWD 1.2). The sample yields a complex age spectrum with numerous peak ages of grains in the 806–749 Ma, 971 Ma, 1117–1076 Ma age range as well as a complex set of peaks in the -1716–1344 Ma age range (Figure 15). There is a single 2290 Ma zircon. This sample exhibits similar peak age ranges to other samples analysed from the WWA in the Bowry Formation, namely the prominent peak around 1462 Ma.

*C108848a Amphibolite*

All of the 58 grains analysed from this sample were concordant, or nearly so. Grains from the sample showed variable iron levels. The two youngest zircons yielded ages of 818 ± 7 Ma and 788 ± 5 Ma (Figure 10e) and a weighted mean age of 1158 ± 14 Ma (MSWD 0.32) was calculated for the 4 next oldest grains. The sample also yields a multimodal age spectrum.

The largest portion of grains yield an age range between 1883 Ma and 1012 Ma with notable peaks at 1242–1219Ma, 1480–1438 Ma and 1770–1742 Ma age ranges (Figure 15). There are four zircon grains aged between 2538 and 2354 Ma, and single zircon with an age of 2707 Ma (although this age is slightly discordant).

This sample exhibits a similar detrital zircon age spectrum to other samples analysed) from the WWA (C109134 and C108898), all of which have large age peaks at ~1450 Ma.

*C108886 Albite-quartzite metasedimentary rock*

A total of 60 zircon grains from this sample showed fairly concordant ages. A weighted mean $^{207}Pb/^{206}Pb$ age of 1161 ± 15 Ma (Table 2) gives a conservative estimate for the maximum depositional age for this sample. The youngest zircon has a $^{207}Pb/^{206}Pb$ age of 1032 ± 14. The remaining zircons yielded scattered ages with prominent peaks at around 1767 and 1440 Ma (Figure 15).

*C108899 Albitite*

A total of 12 zircon grains from this sample of albitite were analysed in-situ owing to their small grain size. The sample contained three Cambrian zircons; one displayed a young rim and older core, another contained a rutile inclusion, and the third zircon was fine grained and euhedral. These three zircons have a weighted mean $^{207}Pb/^{206}Pb$ age of 510 ± 15 Ma (MSWD 0.99) but were interpreted to represent metamorphic grains (by Bottrill, pers comm.) based on the morphology of the zircons. However, Th/U ratios are 1.09-1.76, which are consistent with either metamorphic or igneous zircons (Peng et. al., 2012). The remaining nine zircons yielded scattered ages between 1748 Ma and 1099 Ma (Figures 10f and 15).

*C109185 Dolerite*

Eleven zircons from a dolerite sample C109185 were analysed in situ. Of the zircons analysed, only two were free of lead loss and common lead, and yielded ages of 760 Ma and a 780 Ma, producing a weighted mean age of 774 ± 12 (Table 2; Figure 10f). Older grains have $^{207}Pb$ corrected $^{206}Pb/^{238}U$ zircon age ages between 713 Ma and 684 Ma, but all of these have been compromised by either Pb loss and common lead contamination. The sample represents the only confirmed magmatic rock in the sample suite and the zircons with more robust ages can be compared to those analysed from the albitite analysed from Rocky River (sample C113322; see above).

### 5.4 Timbs Group – "Armstrong Creek Schist"

*G407288 Albite-chlorite-mica schist*

All of the "Armstrong Creek Schist" samples exhibit a similar range of zircon ages and few zircons show Pb loss and minor discordance. Ninety nine grains were analysed from G407288 and these yielded multiple large age populations between ca. 1000 Ma and 1800 Ma, with five older grains yielding $^{207}Pb/^{206}Pb$ ages between 3006 and 2287 Ma (Figure 16). The youngest grain is 988 ± 26 Ma (Figure 11a) with a mean age of 1063 ± 12 (MSWD 0.73).

*G407286 Quartz-muscovite chlorite schist*

Of the 97 zircons analysed from G407286, about twenty of the zircons show Pb loss (Figure 11b). Most zircon grains in the sample define a series of prominent age peaks between 1000 and 1867 Ma (Figure 16). The youngest grain is 1010 ± 20 Ma and a mean age of 1199 ± 13 (MSWD 0.27) has been calculated. There are eight older grains with a $^{207}Pb/^{206}Pb$ ages between 3293 and 2526 Ma (Figure 16).

*G407287 Quartz-chlorite schist*

About a third of the zircon grains from G407287 have Pb loss and minor discordance. Eighty-nine grains were analysed and most of these have ages between 977 Ma and 1882 Ma (Figure 11c). The youngest grain is 977 ± 20 Ma had a mean age of 993 ± 19 (MSWD: 2) calculated based on 5 concordant analyses. There are three older grains with a $^{207}Pb/^{206}Pb$ age between 2734 Ma and 2019 Ma. However, a complex series of peak ages are evident, with the most significant being around 1343, 1382 and 1765 Ma (Figure 16).

### 5.5 Timbs Group – "Fulfords Creek Schist"

*C110161A Quartz schist*

A total of 49 mostly concordant grains were analysed from C110161A (Figure 11d). The youngest grain is 801 ± 34 Ma and a weighted mean age of 1228 ± 25 Ma (MSWD 0.51) was calculated for the sample. There is a spread of age ranges between 1000 and 2500 Ma with a major age peak at ca.1490 to 1453Ma (as shown in Figure 17). The sample has a much younger minimum age compared to the Armstrong Creek Schist, however the sample has similar peak age ranges around 1400 Ma.

### *5.6 Keith Schist*

*G408151 Banded quartzite and phyllite*

The sample was collected about 2.5 km north of C109169 (see below) and shares a very similar detrital zircon age spectrum (Figure 12a). Ninety-one grains were analysed and many of the older grains exhibit Pb loss and inclusions. Most zircon ages define a series of age peaks between 1662 and 1182 Ma with the largest age peak at 1790 Ma. The youngest grain is 1066 ± 14 Ma (Table 2; Figure 12c) and a weighted mean age of 1196 ±15 (MSWD 0.91) was calculated. There are four older grains with a $^{207}Pb/^{206}Pb$ age between 2448 Ma and 2618 Ma (Figure 18).

*C109169 Quartz-muscovite schist*

Ninety-five grains were analysed from this sample. Of these grains, a little over a third showed some Pb loss or reverse discordance (Figure 12b). The youngest grain is 1034 ± 14 Ma and a weighted mean age of 1147 ± 8.5 has been calculated (Table 2). Most zircon ages in the sample define a complex series of age peaks between 1000 Ma and 1867 Ma with the largest age peak cantered on 1785 Ma (Figure 18). The seven oldest grains have $^{207}Pb/^{206}Pb$ ages between 2923 Ma and 2313 Ma.

*C110297 Laminated siltstone*

Eighty-five grains were analysed from sample C110297. Of these grains, a little under half have Pb loss or reverse discordance. The youngest grain is 1233 ± 16 Ma (Figure 12c) and a weighted mean age of 1419 ± 16 (MSWD 1.07) was calculated. The detrital zircon age spectrum is characterised by a series of age peaks between 1878 Ma and 1056 Ma with the largest age peak centred on 1785 Ma. There are seventeen older grains with $^{207}Pb/^{206}Pb$ ages between 2976 Ma and 2223 Ma (Figure 18).

## 6.0 Discussion

### *6.1 Ahrberg Group*

The youngest zircon ages from the Ahrberg Group come from a basaltic breccia (sample G408138) from the Bernafai Volcanics and yield an age population ranging up to ca. 580 Ma (Figure 14). Based on the dominance of this age population (4/17 grains analysed) and the compositionally and texturally immature nature of the host rock (Figure 4), the 580 Ma zircon grains may have been derived from syn-sedimentary volcanic sources, indicating an Ediacaran age for the Bernafai Volcanics. This ca. 580 Ma age supports a correlation by Holm et. al., (2003) between the Bernafai Volcanics and the Kanunnah Subgroup, which includes a rhyodacite dated (U-Pb on zircon) at 582 ± 4 Ma (Calver et. al., 2004; 2014). However, a sample of volcaniclastic sandstone from the Bernafai Volcanics (G408124) from within a fault bound block to the south lacks the interpreted syn-sedimentary volcanic ca. 580 Ma zircon population (Figure 14). However, the older zircon ages in sample G408124 show similar populations to those observed in G408138. Volcanism associated with the Kanunnah Subgroup in western Tasmania are overwhelmingly mafic and therefore zircon-poor, which likely limits the source of 580 Ma zircons. Alternatively, the lack of ca. 580 Ma zircon in sample G408124 may be an artefact of the low zircon yield (i.e. a sampling bias).

Detrital zircon data from the Donaldson Formation indicate that deposition of these units occurred after ~1247 Ma (Figure 13). The newly analysed samples of the Donaldson Formation lack minor (~1-2%) population of ~750 Ma detrital zircon observed in the Forest Conglomerate and Oonah Formation (Bottrill et al., 2017; Mulder et al. 2020) but are otherwise similar, supporting their correlation (Turner et al., 1998; Mulder et. al, 2018). Based on the current datasets it is not clear whether the lack of 750 Ma zircon in the Donaldson Formation samples is significant. This could be an artefact of the small zircon dataset presented here. Alternatively, the Donaldson Fm. could represent an older segment of the same siliciclastic depositional basin represented by the Oonah Formation.

### *6.2 Timbs Group (Bowry Fm.: "Western Wall Assemblage")*

The youngest reliable single detrital zircon age (with a weighted mean age of 733 ± 7 Ma.) from the eight samples, provides a late Tonian to early Cryogenian maximum depositional age for the Bowry Fm. Detrital zircon data from the WWA can be characterised into four main groups (also summarised in Figure 19):

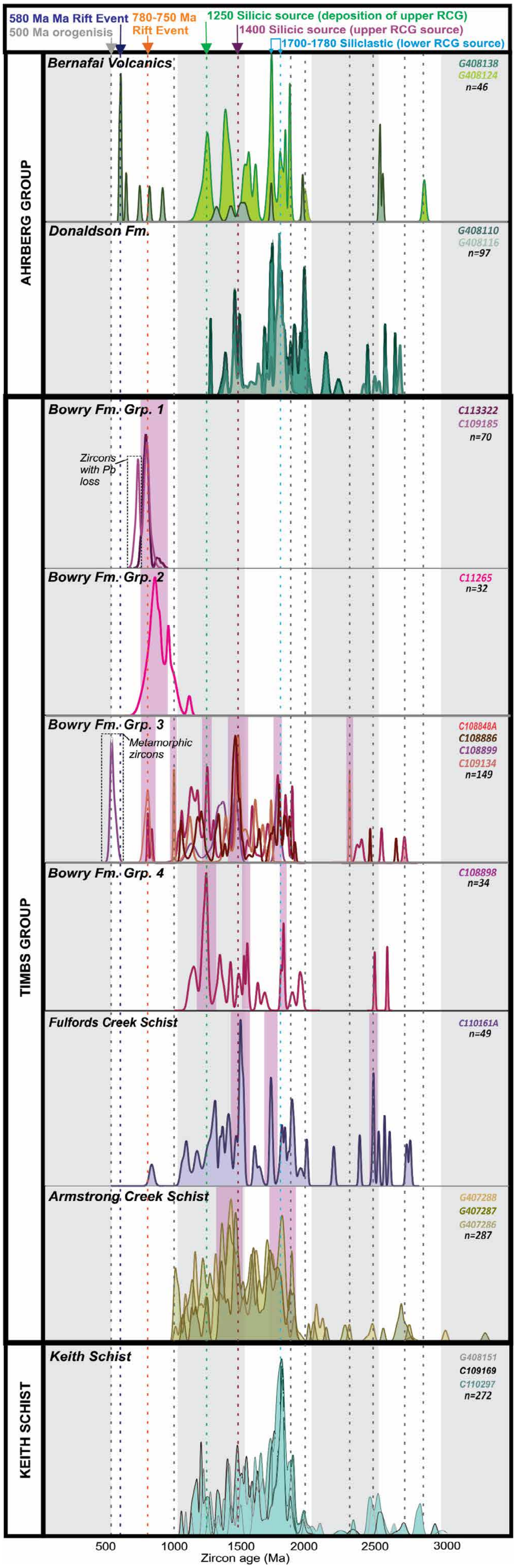
**Group 1:** Dolerite and albitite with strong peak age ranges between 780 and 750 Ma. No older zircons.

**Group 2:** Approximately unimodal age population at 840 Ma

**Group 3:** Youngest ages at 780–750 Ma, minor populations at 1250–1000 Ma and 1800–1700 Ma, and prominent populations at 1450 Ma.

**Group 4:** Prominent age population at ca.1250 Ma with lesser spread of ages extending to 2000 Ma.

The Armstrong Schist and "Fulfords Creek Schist" are considered separately below.




Group 1 consists of a sample of albitite (C113322) and dolerite (C109185). The samples show fairly concordant zircon ages between 1032 Ma and 717 Ma. Four zircons with age ranges between 713 and 684 Ma zircons are present in C109185, but these displayed lead loss and/or common lead throughout so are not considered reliable. The 717 ± 18 Ma age is from a quartz-albitite (C113322), which were previously interpreted to represent a granitoid by Turner et. al. (1998). Both samples show strong age peaks at 764 and 768 Ma (in Figure 15), which coincides with the onset of Neoproterozoic rifting in western Tasmania (Mulder et. al. 2020). The relatively restricted age distribution of this group, especially apparent in the single sample from the Rocky River (C113322) is consistent with a magmatic protolith, or a clastic rock derived from a restricted source area, such as a syn-eruptive volcaniclastic deposit. As discussed previously, Turner et. al., (1998) dated a similar rock considered to be a granitoid, as somewhat older, at 777 Ma. This age was used to provide a minimum age for the Bowry Formation. Bottrill (in prep.), however, found no indication of granitic rocks at Savage River and provides strong evidence in support of a metasomatic-metasedimentary origin for the albitites in the area, based on geological relationships, petrology and geochemistry. Moreover, albitites can often form in association with magnetite deposits (Sillitoe, 2003).

The implications for the interpretation of the albitites is significant: if the protolith of the albitites are magmatic then they provide a minimum age for the Bowry Fm. at 733 ± 7 Ma (weighted mean age). However, with a sedimentary interpretation it represents a maximum depositional age for the Bowry Fm., which is therefore younger than previously thought (ca. 780 Ma; Mulder et al., 2020) and is more comparable to the 711 Ma ages for the Tayatea dyke swarm (as documented by McGregor, 2016). Although these are somewhat younger. A sample of dolerite (C109185) revealed a slightly older magmatic age of 774 ± 12 Ma (based on two concordant analyses). This dolerite sample originated from a body that exhibited faulted contacts, and does not obviously cross-cut the sequence, so cannot be used to imply a minimum age for the Bowry Fm.

Group 2 sample C11265 (quartz-albititemeta-sedimentary rock) shows a strong peak age around ~840 Ma, which is otherwise absent in other samples from the WWA of the Bowry Fm.

Figure 19. Summary Probability plots of U-Pb ICPMS ages of detrital zircons of all samples. Samples are grouped with data from the same formation, except for the “Western Wall” Bowry Formation, samples, which are split into four different groups. The Fulfords Creek and “Armstrong Creek Schist”s are also displayed separately.

Group 3 samples (C108848A, C108886, C108899 and C109134) show age peaks at 787 – 784 Ma, 1233-1215 Ma, ~1450 Ma, 1760 Ma and smaller late Archean to early Paleoproterozoic age distributions (Figure 15; summarised in Figure 19). These age spectra are similar to samples of the "Armstrong Creek Schist", which may support correlation of these units. Sample C108899 also contains some fine, euhedral Cambrian zircons (510 ± 15 Ma), which may have originated from metamorphic or metasomatic fluids.

Group 4, characterised by a single sample (C108898), lacks the prominent 1450 Ma zircon population observed in Group 3 and does not contain zircon younger than 1090 Ma. However, as only 12 zircons were collected from this sample, there are insufficient data from this sample to explore relationships to other units.

The WWA includes both metasedimentary and igneous rocks. Group 1 and 2 samples are dominated by large populations of 780-750 Ma and 840 Ma zircon grains (Figure 19) which likely confirm both magmatic activity and erosion of restricted magmatic sources during the Neoproterozoic. In contrast, Group 3 and 4 samples have a more diverse provenance, with most age populations overlapping with those observed in other Mesoproterozoic and Neoproterozoic clastic rocks in western Tasmania (e.g., the Togari Group and upper and lower-middle Rocky Cape Group). Furthermore, the WWA cannot be related to the neighbouring Bernafai Volcanics samples, as all of the eight WWA samples lack any younger zircons with reliable ages.

### *6.3 Timbs Group ("Fulfords Creek Schist" and "Armstrong Creek Schist")*

The "Fulfords Creek Schist" has a single young 800 Ma zircon. The youngest zircon analysed in the "Armstrong Creek Schist" was 977 Ma, and three additional zircons are between 988 and 986 Ma. Both these units share a similar provenance. Therefore, it is plausible these two units are correlatives, although the "Fulfords Creek Schist" may contain a somewhat younger part of this sequence based on the presence of an 800 Ma zircon grain.

*Summary – Timbs Group Geochronology*

The samples of Bowry Formation and Timbs Group described here are far more diverse and complex when compared to data for a single sample of Bowry Formation presented in Mulder et al., (2020). Mulder et. al., (2020) suggested that the Bowry Formation was similar to the Keith Schist and could have been recycled from the "upper" Rocky Cape Group (i.e. Jacob Quartzite). However, the new age data presented here suggests that this provenance may only be applicable to parts of the Bowry Formation, the Keith Schist, and Timbs Group (i.e. the Fulfords Creek and "Armstrong Creek Schist"). Within the Bowry Fm., there are units that also show a restricted provenance (Group 1 and 2) or a more varied age profile (i.e. C11265 and C109134). The variety of zircon age distributions for closely spaced samples in the WWA indicates an evolving provenance for precursor basins of the Bowry Formation, or that the formation comprises a series of unrelated and structurally juxtaposed units

Previous workers (Holm and Berry, 2002) have suggested that the Ahrberg Group is a direct correlate of the Timbs Group, yet the age of the youngest zircon and the age spectra for the Bernafai Fm. and Donaldson Fm. cannot be correlated directly with any of the samples collected from the Timbs Group. The youngest zircon ages (ca. 500 Ma) from the Timbs Group were recovered from an albitite (C108899) and likely reflect metamorphic ages. No younger pre-Ediacaran zircons of detrital origin were obtained from the Timbs Group, so the possibility of a correlation between the Ahrberg Group and lithologically similar rocks in the Timbs Group, is not unambiguously supported by the new zircon data.

The predominance of the ca. 1450 Ma zircon population over Paleoproterozoic age populations in the "Armstrong Creek" and "Fulfords Creek Schist" is similar to the detrital zircon spectrum of parts of the late Mesoproterozoic "upper" Rocky Cape Group (Jacob Quartzite), suggesting the Timbs Group may in part have been recycled from these older strata (Mulder et. al., 2020).

### *6.4 Keith Schist*

The youngest zircons in the Keith Schist are two zircons (1066 and 1034 Ma), with maximum depositional ages calculated between 1233 and 1034 Ma but the provenance of this unit is otherwise characterized by abundant 1785-1790 zircons and minor peak ages between 1100 and 1400 Ma. Zircon age spectra from both the "Armstrong Creek Schist" and Keith Schist are quite similar, although the Keith Schist samples lack the dominance of 1400 Ma zircons evident in the "Armstrong Creek Schist".

The detrital provenance spectra for the "Fulfords Creek Schist", "Armstrong Creek Schist" and Keith Schist somewhat contrast with zircon spectra of the para-autochthonous Oonah Formation (Mulder et. al., 2020) in that they contain more abundant 1100-1200 Ma grains. It is plausible that the Fulfords and "Armstrong Creek Schist"s are fault slivers equivalent to the Keith Schist. These units may slightly pre-date the Oonah

Formation and have been largely recycled from the "upper" Rocky Cape Group, which provides suitable source for large 1100—1200 Ma, ca. 1450 Ma, and 1600—1800 Ma zircon age populations (Mulder et al., 2020).

The Keith Schist samples show comparable detrital age spectra to equivalent rock units in the northern part of the AMC, i.e. in the Keith River and Arthur River areas (documented in Mulder et. al., 2020).

The Bowry Fm. WWA samples contrast with the remaining samples of "Armstrong Creek Schist" (G407288, G407287 and G407286) and "Fulfords Creek Schist" (C110161A), which show age peaks at 1200 Ma, 1400 Ma, and 1790 Ma, and lack the abundant ages 780 Ma. The "Fulfords Creek Schist" shares a similar 1400 Ma age peak to Group 3 Bowry Fm. samples, but the youngest zircons are ca. 800 Ma.

**7.0 Summary**

Samples from the various fault bound units at Savage River have varied zircon age spectra. The age range and detrital zircon spectra for the Ahrberg Group do not support a direct correlation with the Timbs Group. The ca. 580 Ma age of the Bernafai Volcanics supports a correlation with the Kanunnah Subgroup (of the Togari Group in NW Tasmania). If the albitite units (in the Bowry Fm.) represent metasedimentary rocks, rather than magmatic rocks (as previously thought by Turner et al., 1998) a maximum age for the Timbs Group is somewhat younger than previously thought (~733 Ma). The Bowry Formation includes clastic rocks, dolerite and albitites. The albitites occur as replacement mineral assemblages that overprint and replace various lithologies with uncertain origins (such as dolerite, meta-volcaniclastic rocks (of Group 1 and 2) and are dominated by both magmatic and detrital zircons, which may be related to syn-rift magmatism during the onset of Neoproterozoic rifting in western Tasmania. The Bowry Formation also includes metasedimentary rocks with more diverse provenance (Group 2, 3 and 4) and may have been recycled from older Mesoproterozoic strata in western Tasmania. The "Armstrong Creek Schist", "Fulfords Creek Schist" and Keith Schist have a broadly similar provenance to Group 2 and 3 samples of the Bowry Formation and likely represent fault-disrupted blocks of the same sedimentary succession. Much of the Timbs Group probably formed in Neoproterozoic rift basins filled by siliciclastic and carbonate sediment and accompanied by mafic and minor felsic magmatism. These allochthonous rocks were strongly deformed, albitised, and faulted against the younger Ediacaran Bernafai Volcanics (Ahrberg Group) during the middle Cambrian Tyennan Orogeny.

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# APPENDIX 1

## La-ICPMS zircon U-Pb data

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