CORRIGENDUM

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The mineral name scorzalite should be replaced by lazulite throughout the text and in Table 2.
In Table 1, replace Scorzalite–lazulite $(Fe^{2+},Mg)Al_2(PO_4)_2(OH)_2$ with Lazulite–scorzalite $(Mg,Fe^{2+})Al_2(PO_4)_2(OH)_2$.

PHOSPHATE MINERALS IN GRANITIC PEGMATITES FROM THE MOUNT WILLS DISTRICT, NORTH-EASTERN VICTORIA

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ABSTRACT: Tin- and tantalum-bearing LCT-type granitic pegmatites occur in a 45 km long belt between Eskdale and Mount Wills in north-eastern Victoria. Near Mount Wills, several compositionally zoned rare-element pegmatites contain complex assemblages of primary and secondary phosphate minerals, many of which are rare and previously unrecorded in Victoria. The phosphate assemblages can be divided into Al-rich and Fe–Mn-rich suites, in addition to ubiquitous fluorapatite. The Al-rich phosphate suite includes montebrasite, scorzalite, bertossaite and brazilianite. The Fe–Mn phosphate suite includes heterosite, phosphoferrite, wolfeite, alluaudite (sp.), arrojadite (sp.) and jahnsite (sp.), derived from the metasomatic alteration of primary triplite. Further hydrothermal alteration of this assemblage has resulted in a secondary suite of strengite, rockbridgeite, phosphosiderite, whiteite, jahnsite and whitmoreite forming in etch cavities and fractures. A Late Silurian age of 420±4 Ma was obtained from one of the dykes via CHIME radiometric dating of monazite, suggesting a similar age for the adjacent Mount Wills Granite, which has not been reliably dated. This highly fractionated, peraluminous granite is presumed to be the source of the rare-element pegmatites based on their close spatial relationship.

Keywords: granite pegmatite, phosphate minerals, tin, tantalum, geochronology, Mount Wills, Victoria

INTRODUCTION

Granitic intrusions dominate Victorian Palaeozoic geology (VandenBerg et al. 2000; Rossiter 2003) but associated pegmatite bodies containing economically significant mineralisation are relatively uncommon and generally poorly documented. Pegmatite-hosted tin and tantalum mineralisation has been mined sporadically in two fields in north-eastern Victoria: the Walwa–Koetong district and the belt extending for approximately 45 km northwards from Glen Wills along the Dorchap Range to Eskdale on the Mitta Mitta River (Cochrane & Bowen 1971). Recent field and mineralogical studies on tin-bearing granitic pegmatites near Glen Wills have revealed a considerable range in composition and mineralogy, which broadly

relate to distance from their presumed source, the Mount Wills Granite (Eagle 2009). Two of these pegmatite dykes, here named the Blue Jacket and the Knocker, also contain complex assemblages of rare Fe–Mn- and Al-rich phosphate minerals, most of which have not been recorded before in Victoria. The current paper provides an overview of the mineralogy of these two pegmatites and places their origin within a regional framework.

HISTORY, LOCATION AND GEOLOGY

Mining history

The Mount Wills tinfield is situated at the eastern edge of the Victorian High Plains plateau, between Omeo and Wodonga (Figure 1). Access is now via the Omeo Highway, on which the remains of the historic mining villages of Glen Wills, Glen Valley and Sunnyside are situated, at the base of Mount Wills. The topography of the landscape to the east of Mount Wills is one of rugged, dissected ridges and valleys that are heavily forested (Figure 2).

Tin in the form of cassiterite was first reported in the gold-bearing gravels of Wombat Creek, which drains the eastern flanks of the Mount Wills Granite, around 1886. The cassiterite was traced to numerous pegmatites on the slopes of Mount Wills by a government prospecting party in 1887, and claims were quickly staked over the most prominent pegmatite outcrops (Stirling 1889; Murray 1890, 1891; Lidgey 1895; Rosales 1897). The pegmatites are
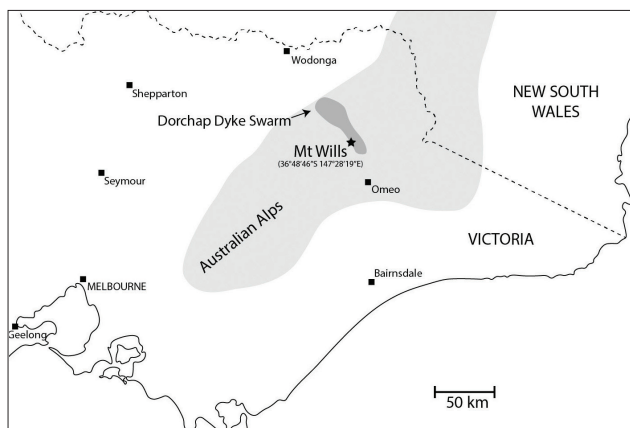

Figure 1: Locality map for the Mount Wills mining field.

Figure 2: View of the forested country encompassing part of the pegmatite field to the east of Mount Wills in 1997.

concentrated on several ridges forming the divides between Mount Wills Creek to the south and Wombat Creek and its tributaries flowing north-east. The earliest sketch map of the area, made by Stirling in 1889, shows a grid of leases over these ridges, but it is difficult to accurately position these based on modern topographic maps. A more detailed lease plan was published by the Mining Department in 1891 (Figure 3). Several companies established leases covering the larger tin-bearing pegmatites, including the Mount Wills Proprietary, the Mount Wills South and the Blue Jacket companies (see Figure 3). The most successful of these early mines was the Mount Wills South, which mined a rich 'soft lode', so named for the friable nature of the weathered feldspar that composed the bulk of the dyke. Initial excitement was soon dampened by the erratic nature of the high-grade tin mineralisation and severe difficulty in recovering most of the cassiterite. Because fine crushing of the lode material rendered the small particles of cassiterite impossible to separate from the abundant mica within the lode, much of the tin was washed down the creeks within the tailings. This factor, combined with depressed tin prices and the costs associated with working in such a rugged and remote area, resulted in the cessation of tin mining in the district by 1893. Nearby gold-bearing quartz reefs on the eastern slopes of Mount Wills near Sunnyside were instead opened up. Popular accounts of the early mining history of
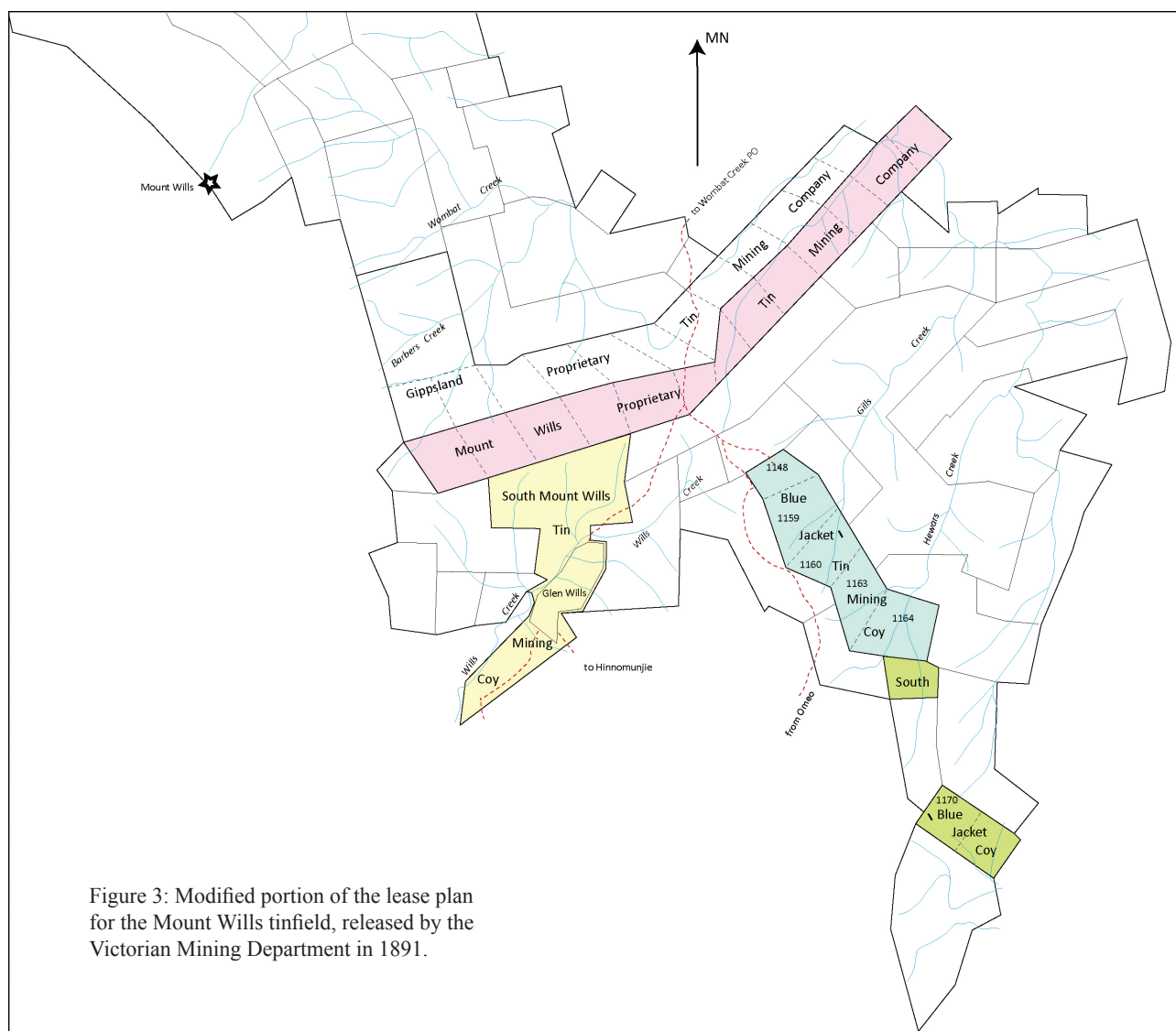

Figure 3: Modified portion of the lease plan for the Mount Wills tinfield, released by the Victorian Mining Department in 1891.

the district have been written by Fairweather (1983) and Christie (1993).

An increase in the price of tin in 1911 brought about the reopening of some of the old mines (Cochrane & Bowen 1971). However, the earlier issues of poor recoveries and sporadic grade brought an end to this second phase by 1914. Renewed exploration in the late 1960s through to the early 1980s investigated the tin lodes (e.g. Wright 1982), as well as prospecting for tantalum–niobium, which had been identified in the Dorchap Dyke Swarm (previously referred to as the Mitta Mitta Dyke Swarm) (Morand et al. 2004) to the north.

Geology

Mount Wills itself consists of a medium- to coarse-grained, S-type leucogranite, which is inferred to be Late Silurian, based on field relationships and compositional similarity to Omeo Metamorphic Complex migmatite (Morand et al. 2004). The Mount Wills Granite intruded Ordovician metasediments of the Omeo Metamorphic Complex, which consists of deformed schist and phyllite in the study area (Crohn 1958) (Figure 4). The pegmatite bodies of interest have also been emplaced into the metasediments, which have undergone contact metamorphism near the

granite, resulting in cordierite hornfels and schist. Quartz–andalusite veins and calc-silicate nodules containing grossular and vesuvianite have also been intersected in exploration drilling at Glen Wills. The Late Silurian – Early Devonian Anglers Rest Granite appears to post-date emplacement of the pegmatites and forms the eastern boundary of the study area.

The Mount Wills Granite consists mainly of quartz, oligoclase and K-rich feldspar. Magmatic muscovite is common and biotite is also present in the northern end of the pluton. Other accessory minerals include abundant tourmaline and garnet, with minor topaz, but opaque phases are absent. The granite hosts abundant cavity-bearing pegmatitic zones, suggesting a high level of intrusion (English 1988). This is at odds with the presence of magmatic muscovite, which generally indicates crystallisation at deeper levels in the crust. This anomaly may be explained by the presence of high levels of fluxing elements such as Li, B and P, which lower the granite solidus and enable primary muscovite to crystallise at shallower crustal levels (e.g. Clemens & Wall 1988). These elements may have migrated away from the pluton during the late stages of crystallisation and been incorporated into tin-bearing pegmatite bodies. The highly fractionated nature of the granite is suggested by high Sn and depressed Eu contents (Morand et al. 2004).

The pegmatite dykes

Numerous dykes and irregular masses with a granitic composition occur around the margins of the Mount Wills Granite. Many of these form prominent outcrops, particularly where they intrude the metasediments. Nevertheless, the rugged topography and thick vegetation make them difficult to revisit today. The six granitic dykes investigated by Eagle (2009) range from several with finer-grained aplite-like textures within the Mount Wills Granite to four coarser-grained, tin-bearing pegmatites intruding the metasediments at increasing distance from the granite margin. These pegmatites are here named the Proprietary, Knocker Track, Blue Jacket and Knocker respectively (see Figure 4).

Dykes close to, and within, the Mount Wills Granite have a simple mineralogy,
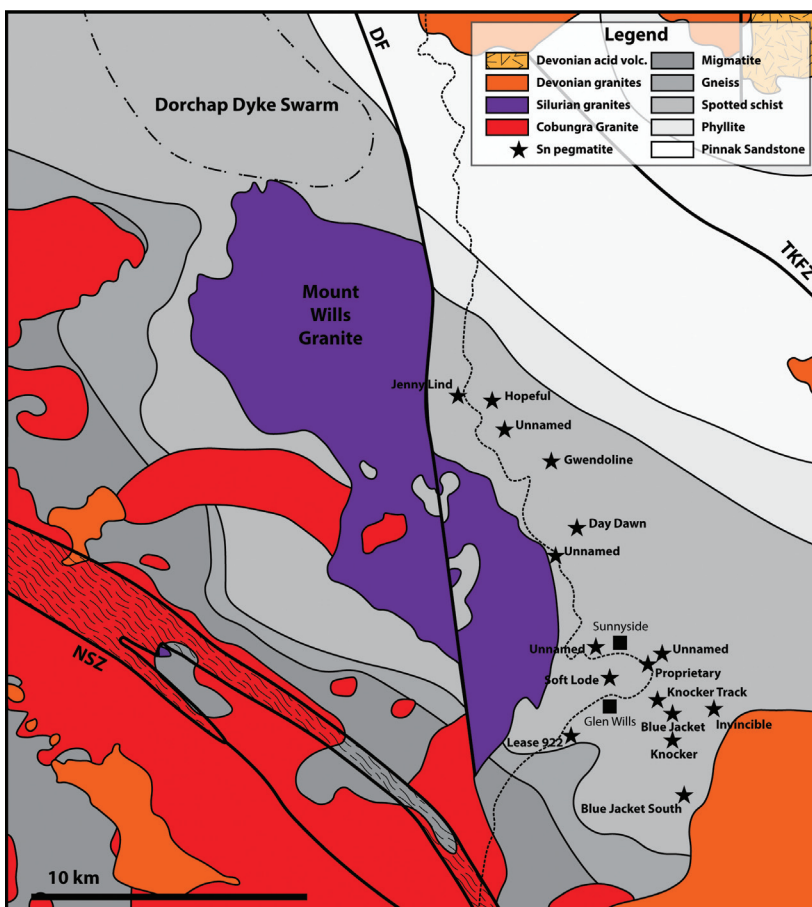

Figure 4: Simplified geological map of the pegmatite area east and south of Mount Wills, adapted from the Geological Survey of Victoria's Bogong 1:100,000 map area geological map sheets. Abbreviations used: DF - Dunstans Fault; NSZ - Nelse Shear Zone; TKFZ - Tokes Creek Fault Zone.
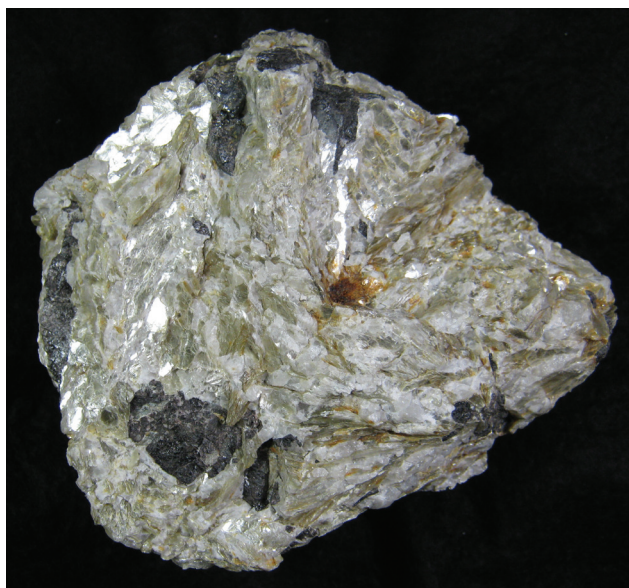
Figure 5: Typical specimen of the richest tin ore from the Mount Wills field, consisting of cassiterite (black) in plumose muscovite. Specimen is 13 cm across. Museum Victoria collection E12651. Photographer W. Birch.

Figure 6: Outcrop of the Blue Jacket pegmatite dyke, January 2011 (Dermot Henry for scale).

consisting of quartz, K-rich feldspar, muscovite, garnet and schorl, with minor fluorapatite, biotite, chlorite, rutile and trace amounts of uraninite. The tin-bearing pegmatite masses more distal to the granite consist mainly of coarse-grained quartz, K-rich feldspar and muscovite. According to early descriptions, these pegmatites contained masses and bunches of quartz and 'plumose' muscovite, resembling 'greisen' (Rosales 1897; Murray 1890), which carried the coarsest and richest grades of cassiterite (Figure 5). Perhaps because of the short period during which the mines were active and the remoteness of the operations, not many specimens from the earliest period of mining have been preserved in museum collections. However, Mr Oliver Rule at the Industrial and Technological Museum in Melbourne provided descriptions of a small selection of samples for Murray's 1890 report. In his assessment of the ultimate failure of the tinfield, Rosales (1897) noted the absence of minerals such as tourmaline, wolframite, fluorite, topaz and apatite, which normally accompanied higher grade tin ore in other fields.

Field collecting between 2009 and 2011 has revealed that two pegmatite dykes, the Blue Jacket and the Knocker, contain unusual phosphate-rich mineral assemblages that were overlooked at the time of earliest mining (perhaps a hint that these were observed comes from Murray's note that 'slight tinges of iron and manganese' occurred in the Proprietary mine ore). As this is the first record for Victoria of many of the minerals in these assemblages, an overview is provided in this paper.

Blue Jacket pegmatite

The Blue Jacket pegmatite dyke is located about 2.5 km east of the old Glen Wills township, in the headwaters of

Gills Creek. It was the main source of ore for the Blue Jacket Tin Mining Company, which was gazetted in May 1891 and had leases along the main spur between Mount Wills Creek and Gills Creek (Murray 1891). The pegmatite is up to 15 m wide and extends for about 200 m in a NW–SE direction from the summit of the spur to a northward-draining gully (Wright 1982). Coarse tin ore was visible in the surface pegmatite (Murray 1891; Rosales 1897). A shaft was sunk on the pegmatite and a tunnel driven from the gully, but mining had ceased by 1895. There are no accurate production records, although Rosales (1897) reported that 7 cwt (0.35 tonnes) of cassiterite had been obtained from the surface. Access to the pegmatite is now difficult, but it can be reached via a very overgrown track, about 400 m north of its intersection with the Knocker Track. The dyke outcrops strongly (Figure 6), with a sharp northern margin, and consists mainly of a wide zone of coarse-grained quartz, K-rich feldspar and muscovite, with sporadic pale tourmaline veins and cassiterite crystals, surrounding a thick core of massive quartz. Phosphate mineralisation is generally inconspicuous, represented by sporadic pale-blue scorzalite grains and by several zones of strongly sheared or brecciated quartz–albite–muscovite containing small irregular patches and veinlets of dark-brown material. Dumps adjacent to the lower adit contain rare pieces of fine-grained pegmatite consisting of quartz, pale purplish mica ('lepidolite') showing 'ball-peen' habit (Figure 7), and cassiterite; these are possibly from the innermost zone of the pegmatite.

Knocker dyke (South Blue Jacket)

Based on comparisons with the original leases over the tinfield, this pegmatite is almost certainly on the former leases of the South Blue Jacket Company, probably on lease block 1170. The pegmatite is about 500 m south-east of the Knocker trig station and was found during fieldwork by RE in 2009. It outcrops as a large mass of
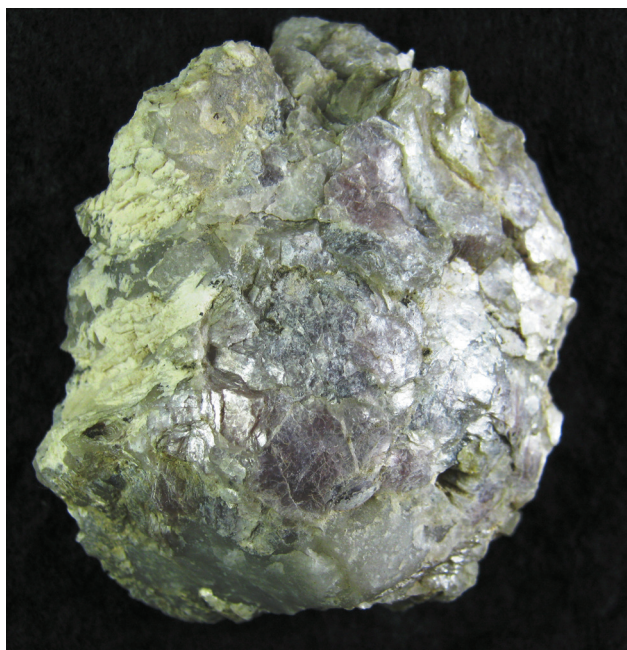
Figure 7: Pale-purplish mica ('lepidolite') showing ball-peen habit form the Blue Jacket pegmatite. Specimen is 6 x 5 cm. Museum Victoria collection M51488. Photographer W. Birch.

common granitic pegmatite with coarse pegmatite pods (Figure 8) about 40 m across. However, this does not fit the original description of the pegmatite being mined on the Blue Jacket South lease in the early 1890s. Murray (1891) noted a 'huge' outcrop of coarse pegmatite over 100 ft (30 m) wide and traceable for several hundred feet on a general bearing NW–SE. Coarse tin ore was visible in the outcrop and a shaft 23 ft (7 m) deep had been sunk. These observations suggest that the original pegmatite remains to be rediscovered further south in the old lease area.

The most prominent feature of the Knocker outcrop is a quartz 'blow', which appears to be the central zone of the dyke. Rare rafts of metasomatised country rock occur in the outer zone, either altered to a greenish material or to a banded schorl–muscovite–quartz assemblage. Float of fine-grained chlorite rock found adjacent to the dyke may be country rock that has been hydrothermally altered by late-stage fluids exiting the pegmatite. A zone of quartz–albite ±

Figure 8: Outcrop of the Knocker pegmatite.

montebrasite–tourmaline–muscovite pegmatite runs along the northern side of the quartz zone. A prospecting trench has been cut into the quartz–albite zone, where skeletal pseudomorphs of Fe-phosphates and sparse masses of cassiterite up to about 8 cm long can be found. Patches of blue scorzalite are distributed sporadically and greyish blue to green tourmaline is common.

MINERALOGY

Methods

Representative hand specimens were selected from both the Blue Jacket and Knocker pegmatites for examination. Polished thin sections and mineral grain mounts were prepared for petrographic study and mineral identification, with emphasis on the phosphate-bearing rock types. Minerals separated carefully by hand under the microscope were subjected to powder X-ray diffraction analysis (PANalytical unit at Museum Victoria), supplemented by scanning electron microscopy equipped with EDS systems (an FEI XL30 ESEM at the University of Melbourne and a JEOL 6300 instrument at Federation University). Quantitative analyses were obtained using a Cameca SX50 electron microprobe in the School of Earth Sciences at the University of Melbourne.

Monazite crystals in both pegmatites provided an opportunity to apply radiometric CHIME Th–U–Pb dating, using the method of Suzuki and Kato (2008). Dating was carried out at the Electron Microscopy and X-ray Microanalysis Facility at the University of Tasmania, using a polished thin section cut from the albite–montebrasite zone of the Knocker pegmatite.

Silicates (primary phases)

Quartz, albite and perthitic K-rich feldspar (orthoclase–microcline) are the dominant rock-forming minerals of the Mount Wills dykes, although their distribution, relative abundance and grain size are variable. The K-rich feldspar is usually perthitic, with lamellae commonly replaced by sericite. Graphic intergrowths of quartz and orthoclase–microcline occur in the Blue Jacket pegmatite (Figure 9). Albite is abundant as masses of bladed crystals varying from cream to pale pink and, rarely, pale bluish. In thin section, albite commonly appears to be mechanically deformed, with numerous blocky subgrains and kinked lamellae.

Micas

Muscovite is by far the most abundant mica found within the granite pegmatites, ranging from finely crystallised sericite to decimetre-sized books. Most of the mica is colourless to pale greenish but some books in the Blue Jacket pegmatite

are pale lilac, suggesting a gradation in composition towards lithium-bearing 'lepidolite'. This was confirmed by a fusion test on a small fragment that produced a bright red flame. Quantitative analysis for Li was not undertaken, so the proportion of dioctahedral lithian muscovite relative to trioctahedral 'lepidolite' (trilithionite–polylithionite) is unknown. Some muscovite contains elevated contents of Rb and Cs, with up to 2.4 wt % Rb_2O and 10 wt % Cs_2O detected (Eagle 2009), while most contains small amounts of fluorine.

Tourmaline

Published descriptions refer to the rarity of tourmaline in the tin-bearing pegmatites, with Rosales (1897) noting that the Blue Jacket pegmatite had yielded the only specimen he had observed in the entire field. Distinct crystals of black schorl are absent in the Blue Jacket and Knocker pegmatites; however, irregular prismatic crystals of bluish and greenish grey to pale-green tourmaline are present (Figure 10), commonly occupying fractures through the quartz–feldspar matrix. These have compositions in the schorl–elbaite series. Very small colourless to pale-pink crystals of presumed elbaite are associated with fine-grained 'lepidolite' in the Blue Jacket pegmatite. The banded schorl–quartz rock type from the contact zone around the Knocker pegmatite suggests interaction between late-stage fluids and the host rocks.

Figure 9: Graphic intergrowth of quartz and K-rich feldspar in the Blue Jacket pegmatite.

Oxides

An early account (Murray 1891) of the Blue Jacket pegmatite referred to 'coarse tin ore' being visible in the 'hard stone' all along the outcrop. Masses of cassiterite up to 27 kg (60 pounds) had been found on the surface of the spur. Recent inspection showed only a few cm-scale black cassiterite crystals in the lower portions of the dyke. Thin sections reveal that cassiterite occurs as tiny disseminated grains with a subhedral to skeletal morphology within the

Figure 10: Bluish-grey schorl–elbaite crystals up to 4 mm long from the Knocker pegmatite. Museum Victoria M51168. Photographer Simon Hinkley.

inner zone of the Knocker pegmatite and within samples of fine-grained lepidolite–quartz from the Blue Jacket.

Tabular black crystals of manganoan columbite-(Fe) up to 1 mm long occur in both pegmatite dykes, generally associated with iron phosphates and cassiterite (Figure 11).
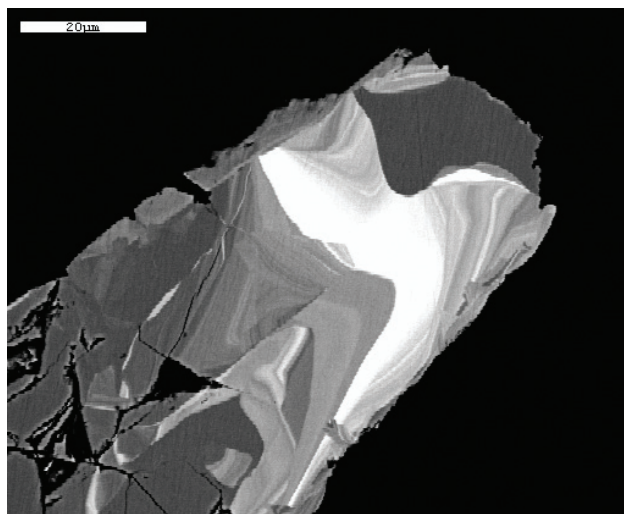

Figure 11(a): Prismatic crystal (2 mm long) of manganoan columbite-(Fe) from the Knocker pegmatite. Photographer R. Eagle. 11(b). Complex zonation in columbite-(Fe) crystal as shown by SEM back-scattered electron image. The bright areas are enriched in Ta relative to the bulk of the crystal.

Microprobe analysis indicates that compositions vary mainly in the series columbite-(Fe) – tantalite (Fe) with a smaller and relatively uniform columbite-(Mn) component. Crystals tend to show zonation with Nb/Ta increasing from core to rim.

Accessory minerals

Accessory monazite-(Ce) and zircon are present in both pegmatites, while xenotime, zircon and rutile occur in the Knocker pegmatite (Figure 12) and microlite and uranmicrolite in the Blue Jacket rock. The only sulfide mineral observed is arsenopyrite, forming irregular grains a few mm across in the Blue Jacket dyke.

Phosphate assemblages

Both pegmatites contain similar suites of phosphate minerals, which include Al- and Fe–Mn-dominant assemblages (Table 1). These two suites can be subdivided on the basis of their formation stage in the crystallisation of the pegmatites, in accordance with the scheme developed by Moore (1973).

Figure 12: Zircon crystals (to 0.8 mm) in montebrasite from the Knocker pegmatite. Photographer R. Eagle.

Primary stage

Fluorapatite can form at most stages of phosphate crystallisation in pegmatites. In the primary stage it is usually as anhedral grains which are greyish to blue and intergrown with other phosphates or silicates. In the Blue Jacket and Knocker pegmatites, fluorapatite shows these general characteristics, forming inconspicuous irregular

Table 1: Phosphate minerals in the Blue Jacket and Knocker pegmatites.

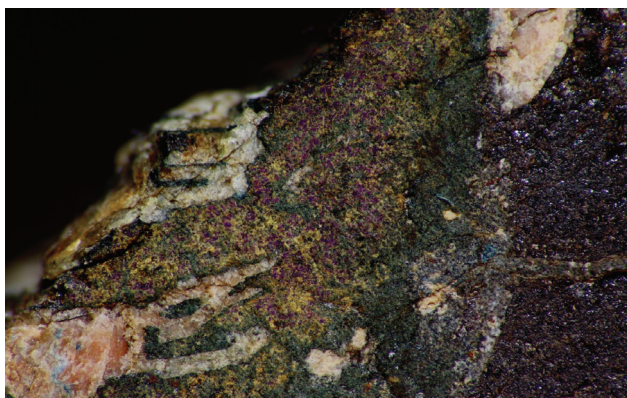| **Primary**	
Fluorapatite $(Ca,Mn)_5(PO_4)_3F$	
I: Subhedral to euhedral primary phases	
(Fe, Mn) ± Li assemblage	**(Al ± Li) assemblage**
Triplite–zwieselite $(Mn^{2+},Fe^{2+})_2(PO_4)F$	Montebrasite–amblygonite
Arrojadite-(KFe) $(KNa)Fe^{2+}(CaNa_2)Fe^{2+}_{13}Al(PO_4)_{11}(PO_3OH)(OH)_2$	$LiAlPO_4(OH,F)$
Arrojadite- (KNa) $KNa_3(CaNa_2)Fe^{2+}_{13}Al(PO_4)_{11}(PO_3OH)(OH)_2$	
II: Anhedral 'primary' phases (metasomatic exchange products)	
Alluaudite $(Na,Ca)(Mn,Mg,Fe^{2+})(Fe^{3+},Mn^{2+})_2(PO_4)_3$	Scorzalite–lazulite
Wolfeite $Fe^{2+}_2(PO_4)(OH)$	$(Fe^{2+},Mg)Al_2(PO_4)_2(OH)_2$
Heterosite–purpurite $(Fe^{3+}, Mn^{3+})(PO_4)$	
Secondary	
Ligand addition, alkali-leached and oxidised products, hydrothermal products	
Phosphoferrite–kryzhanovskite	Brazilianite
$Fe^{2+}_3(PO_4)_2·3H_2O – (Fe^{3+},Mn^{2+})_3(PO_4)_2(OH,H_2O)_3$	$NaAl_3(PO_4)_2(OH)_4$
	Bertossaite
	$(Li,Na)_2CaAl_4(PO_4)_4(OH,F)_4$
Jahnsite (sp.) $(Ca,Mn,Fe^{2+}, Mg,Na)_4 Fe^{3+}_2(PO_4)_4(OH)_2·8H_2O$	Whiteite (sp.)
Strengite $Fe^{3+}PO_4· 2H_2O$	
Phosphosiderite $Fe^{3+}PO_4· 2H_2O$	Goyazite?
Rockbridgeite $Fe^{2+}Fe_4^{3+}(PO_4)_3(OH)$	
Whitmoreite $Fe^{2+}Fe_2^{3+}(PO_4)_2(OH)_2 · 4H_2O$	
Strunzite? $Mn^{2+}Fe_2^{3+}(PO_4)_2(OH)_2 · 6H_2O$	
Supergene	
Autunite	
Phosphuranylite?	

Figure 13: Aggregates of purple heterosite and yellowish jahnsite replacing primary Fe phosphate in the Knocker pegmatite. Photographer R. Eagle.

grains up to a few mm across associated with tourmaline and secondary phosphates. Blue grains may be confused with scorzalite or tourmaline and contain significant amounts of Mn.

Fe–Mn phosphates are present as irregular dark to honey and purplish-brown aggregates and patches up to a few mm across associated with albite, tourmaline, quartz and muscovite (Figure 13). Thin sections examined under the microscope reveal these patches are complex aggregates of up to four or five minerals, with distinctive colours under plain polarised light, and with variable grain sizes mostly in the range of 5–50 microns. A combination of X-ray diffraction and scanning electron microscopy identified the main phases as heterosite, phosphoferrite, wolfeite, alluaudite (sp.), arrojadite (sp.) and jahnsite (sp.), all of which may be present within zones a few mm across (Figures 14, 15). Heterosite is the most easily distinguished of these phosphates in thin section due to its strong purple colour in plane polarised light. Phosphoferrite is reddish brown and wolfeite is near-opaque dark brown, both colours probably due to the presence of trivalent iron arising from oxidation. Jahnsite is pale yellowish, while alluaudite shows prominent pleochroism from darkish green to yellowish brown. Arrojadite is the only colourless phosphate mineral in this assemblage and can easily be overlooked in thin section; it was commonly encountered during electron microscopy. These minerals are the products of metasomatic reactions involving Na and Ca, as well as oxidation of Fe^{2+} to Fe^{3+}, as the pegmatites cooled in the presence of fluids. An aggregate of triplite grains enclosed in heterosite and arrojadite in a thin section of the Knocker pegmatite is probably a remnant of the main primary mineral for the Fe–Mn assemblage.

Secondary stage

With further hydrothermal alteration of this metasomatic assemblage, minerals such as strengite, rockbridgeite, phosphosiderite, whiteite, jahnsite, whitmoreite and
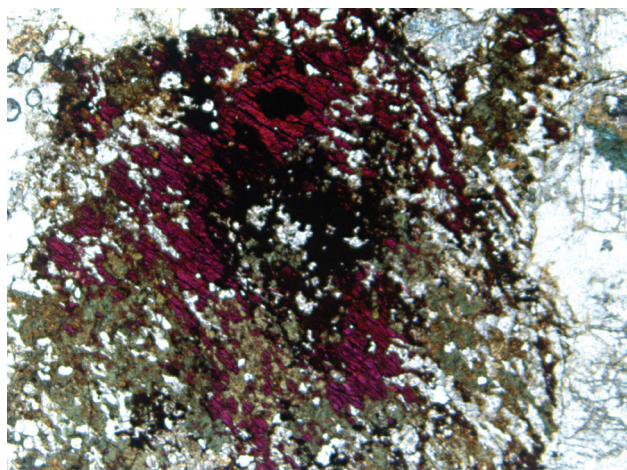

Figure 14: Transmitted light (plane polarised) image of phosphate aggregate from the Blue Jacket pegmatite showing assemblage of heterosite (purplish) with alluaudite (green), arrojadite (colourless) and minor jahnsite (yellowish) probably replacing primary triplite. Photographer W. Birch. Field of view is 2 mm across.
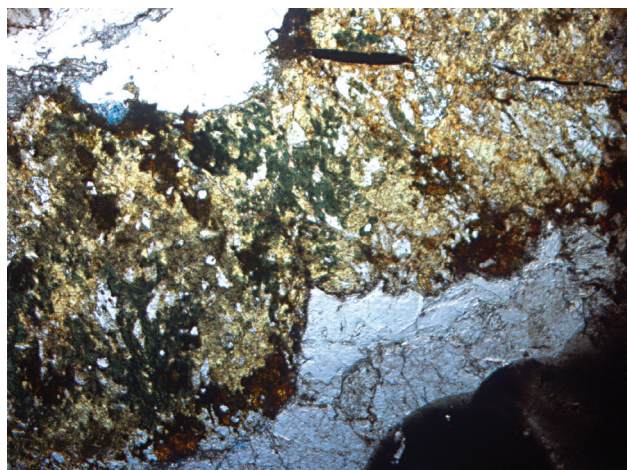

Figure 15: Transmitted light (plane polarised) image showing alluaudite (green), with jahnsite (sp.) (pale yellow), arrojadite (colourless) and minor phosphoferrite (reddish brown) from the Blue Jacket pegmatite. Field of view is 2 mm across.

possibly strunzite have crystallised (Table 1). There are slight differences in the assemblages present in the two pegmatites, but this may reflect sampling that is not representative. The secondary phases may occupy small cavities etched in primary silicates such as albite and tourmaline, form thin veinlets and films, or occur as flattened aggregates on fractures. In the Knocker pegmatite, strengite occurs as pale-pink transparent cavity linings (Figure 16), while jahnsite (sp.) forms granular yellowish-brown patches and veinlets which in places open out into small cavities lined with crystals up to 0.2 mm long (Figures 17, 18). Strunzite may be represented by tiny pale-yellow prisms, associated with jahnsite and honey-brown spheres of possible cacoxenite. Phosphosiderite forms irregular microcrystalline pale-purple aggregates
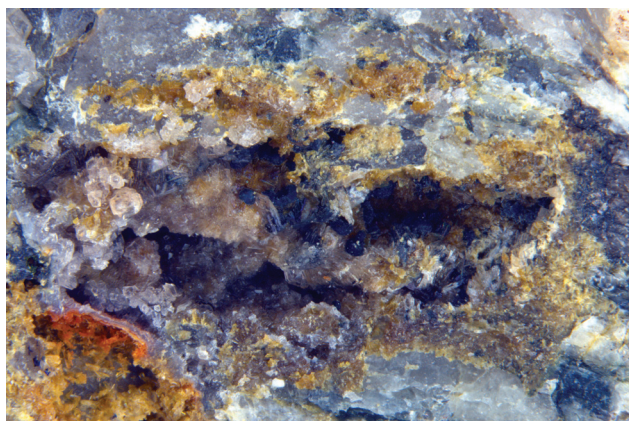
Figure 16: Cavity (4 mm across) in Knocker pegmatite lined with jahnsite (brownish) and pale pinkish grey strengite crystals. Museum Victoria collection M53359. Photographer S. Hinkley.
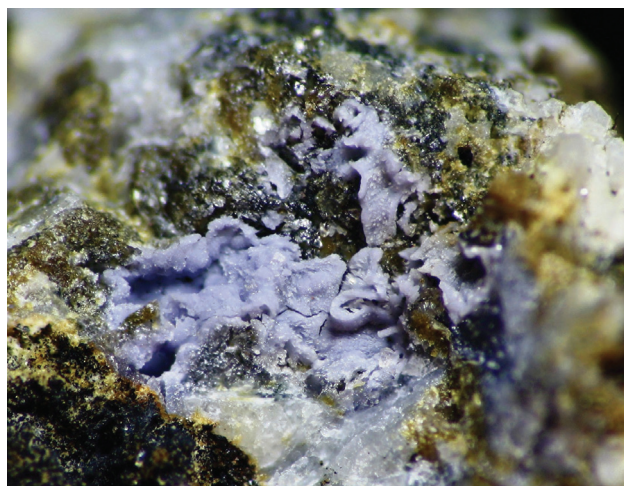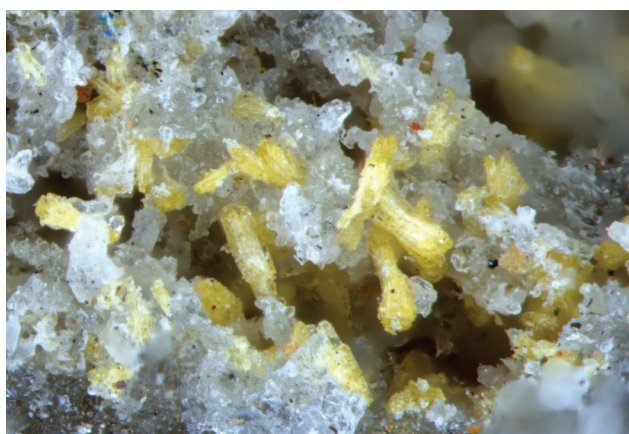

Figure 17: Pale-yellow jahnsite (sp.) crystals in cavity in Knocker pegmatite. Field of view is 1 mm across. Museum Victoria collection M53360. Photographer S. Hinkley.
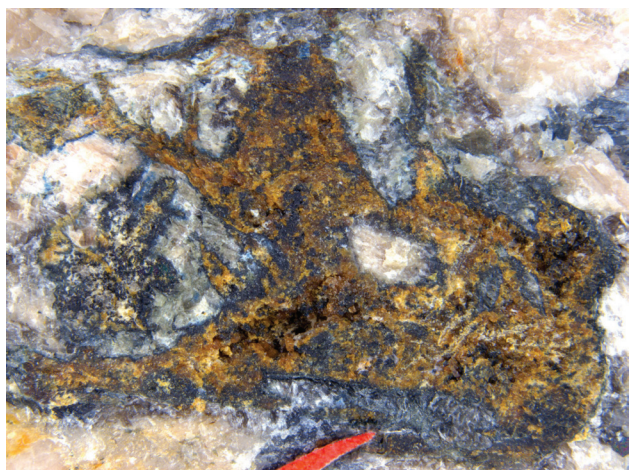

Figure 18: Jahnsite (sp.) as veinlets and open cavities in the Blue Jacket pegmatite. Field of view is 13 mm across. Museum Victoria collection M52576. Photographer S. Hinkley.

(Figure 19). Minerals occurring as radiating aggregates of crystals on fractures include pale-yellow jahnsite–whiteite, dark-green rockbridgeite and dark-brown whitmoreite.

Aluminium-rich phosphates are less obvious than the Fe–Mn minerals. In the Knocker pegmatite, montebrasite

Figure 19: Metastrengite patch (4 mm across) in Knocker pegmatite. Photographer R. Eagle.

is a rare primary phase occurring as pale-bluish crystals in graphic intergrowth with albite. Scorzalite is common to both pegmatites, as a primary 'metasomatic' mineral occurring as irregular pale to sky blue patches up to a few cm across. In places in the Knocker pegmatite, scorzalite grains are surrounded by a zone of microcrystalline greyish bertossaite, an exceedingly rare mineral known only from three pegmatite fields in Rwanda and China. Brazilianite has only been observed in the Knocker pegmatite, as aggregates of bladed greyish crystals intergrown with albite and associated with scorzalite.

Phosphate mineral chemistry

Representative microprobe analyses have been obtained for most phosphate minerals (Table 2), although there is scope for more analytical work to determine compositional limits in many of the species in the Fe–Mn assemblages. Manganese substitution for iron is significant in both primary and secondary species, including fluorapatite, where up to nearly 20% of the Ca may be replaced by Mn, coinciding with more intense blue colours. In heterosite from the Blue Jacket pegmatite, Fe:Mn is relatively uniform, ranging between about 72:28 to 67:33. This is similar to the range shown by wolfeite analyses.

Minerals identified as belonging to the alluaudite and arrojadite groups show considerable complexity and it is difficult to identify individual species based on composition alone. For the alluaudites *sensu stricto*, analyses show Fe dominant over Mn and high Na contents relative to Ca, suggesting compositions may involve the endmembers alluaudite, alluaudite-Na□ and ferroalluaudite. Arrojadite compositions are more uniform in terms of Fe relative to Mn and have significant K, suggesting they are probably arrojadite-(KFe) (Chopin et al. 2006; Chopin pers. comm. 2014).

Table 2: Representative electron microprobe analyses of phosphate minerals in the Blue Jacket and Knocker pegmatites.

Wt%	1	2	3	4	5	6	7	8	9
SiO_2	0.00	0.00	3.05	0.00	0.01	0.23	0.09	0.05	nd
Al_2O_3	2.34	0.01	3.27	0.04	0.05	0.15	32.39	2.39	10.76
Fe_2O_3				35.64		37.15			
Mn_2O_3						15.09			
FeO	26.57	22.58	1.76		40.21		7.79	20.78	10.02
MnO	14.52	35.62	10.93	13.45	17.37		0.05	14.19	16.46
MgO	3.71	3.37	0.04	0.36	4.56	0.36	9.24	3.16	1.89
CaO	1.27	1.69	39.89	0.02	0.13	0.04	0.00	3.22	3.31
Na_2O	6.49	0.01	0.02	5.58	0.00	0.00	0.02	0.72	0.35
K_2O	1.80	0.01	0.53	0.04	0.01	0.00	0.00	0.00	0.00
P_2O_5	39.23	30.64	37.51	44.41	31.56	46.20	45.10	31.84	33.53
As_2O_5	nd	nd	nd	nd	nd	nd	nd	nd	nd
F	1.12	6.05	3.58	1.02	1.11	1.10	0.79	0.82	nd
O=F	0.47	2.55	1.51	0.43	0.49	0.46	0.33	0.35	
Total	96.58	97.43	99.07	100.13	94.52	99.87	95.14	76.72	76.32
Formulae									
P	12.00	1.00	3.00	12.00	1.00	1.00	2.00	4.00	4.00
Si	0.00	0.00	0.29	0.00	0.00	0.01	0.00	0.01	
Al	1.00	0.00	0.36	0.04	0.00	0.01	2.00	0.42	1.79
Fe^{3+}				8.17		0.71			
Mn^{3+}						0.29			
Fe^{2+}	8.03	0.73	0.14		1.26		0.34	2.57	1.18
Mn^{2+}	4.45	1.20	0.88	3.48	0.55		0.00	1.78	1.97
Mg	2.00	0.12	0.01	0.17	0.25	0.01	0.72	0.69	0.40
$\sum M$	15.47			11.86					
Ca	0.50	0.07	4.04	0.00	0.00	0.00	0.00	0.51	0.50
Na	4.54	0.00	0.01	3.30	0.00	0.00	0.00	0.20	0.09
K	0.83	0.00	0.06	0.02	0.00	0.00	0.00	0.00	0.00
$\sum X^{1+}$	5.86								
F	1.28	0.73	1.07	0.99	0.13	0.09	0.13	0.38	
$\sum X + M$	21.33								
$\sum$cations		2.12	5.05	11.82	2.07	1.02	1.06	5.97	5.84

nd = not determined

Samples
1   Arrojadite, Blue Jacket pegmatite (26.1.2)
2   Triplite, Knocker pegmatite (K1-1-2, #33)
3   Fluorapatite, manganoan, Knocker pegmatite (K2-5, #27)
4   Alluaudite, Blue Jacket pegmatite (BJ1-2, #43)
5   Wolfeite, Blue Jacket pegmatite (BJP 26-9-4)
6   Heterosite, Blue Jacket pegmatite (BJ1-1, #37)
7   Scorzalite, Blue Jacket pegmatite (BJ2-3, #65)
8   Jahnsite-(CaMnFe), Blue Jacket pegmatite (BJ2-3-3 #19)
9   Whiteite-(CaMnFe)', Knocker pegmatite (KP-1 #4)

Minerals in the whiteite and jahnsite groups show even greater complexity, involving highly variable Al, Fe, Mn, Ca and Mg contents. This is complicated further by zonation within individual crystals, as observed by Grey et al. (2010) in crystals from the Hagendorf pegmatite in Germany. Allocation of elements into the four sites in the crystal structure is in the order of progressively smaller ionic radii (Moore & Ito 1978). Applying this principle to the analyses obtained for these minerals in the Knocker pegmatite yields species such as 'whiteite-(MnMnFe)' or rittmannite, whiteite-(CaMnFe), jahnsite-(CaMnFe) and jahnsite-(CaMnMn). Whiteite-(CaMnFe) represents a potential new mineral in the group but further investigation is required to fully characterise it.

DISCUSSION

Geochronology

The monazite-(Ce) crystals from the two pegmatites have unusually high Th and U contents and low U/Th ratios (Table 3) suggesting crystallisation from a highly fractionated magma with a pegmatitic origin (Gramaccioli & Segalstad 1978; Demartin et al. 1991; Foerster 1998), rather than being restite or carried over from a parent granite. The high U contents (5–10 wt % U) exceed those both in the standards used and for which the CHIME method was designed, leading to concern over possible systematic errors. However, the 24 analyses from 13 grains yielded similar ages, giving rise to an average of 420±4 Ma. This figure provides the best minimum age constraint to date for the Mount Wills Granite, the assumed parent granitic body for the pegmatites, due to their crosscutting relationship. Previous attempts to date the Mount Wills Granite directly via K–Ar muscovite dating have produced a wide, unreliable range of dates (Richards & Singleton 1981) indicating that the K–Ar system has been disturbed sometime after crystallisation of the muscovite.

Origin and classification

The age of the Knocker pegmatite places its intrusion in the Late Silurian, immediately following the Benambran Orogeny. This long-lived deformation event resulted in the regional metamorphism forming the Omeo Metamorphic Complex and gave rise to a range of syn- and post-tectonic granitic intrusions, including the Mount Wills Granite (VandenBerg et al. 2000). Morand et al. (2004) estimated that the regional metamorphism was 'low pressure – high temperature' in style, with maximum pressures of about 0.3 GPa and with heating due to magmatic activity rather than burial. The magmatism and regional metamorphism have been attributed by Fergusson (2014) to subduction-related

Table 3: Microprobe analyses of monazite.

	KPA2.2	KPA2.10	BJ02
SiO_2	0.25	0.09	0.00
CaO	4.08	3.88	3.51
FeO	0.00	0.11	0.22
Ce_2O_3	17.15	17.31	20.30
La_2O_3	7.65	7.98	8.94
Nd_2O_3	6.61	6.05	8.91
Sm_2O_3	5.72	6.12	2.26
Gd_2O_3	3.53	4.71	2.64
Pr_2O_3	1.65	1.25	1.57
ThO_2	11.65	9.08	7.08
UO_2	11.26	13.14	12.52
P_2O_5	28.50	28.68	29.90
Total	98.05	98.40	97.85

tectonism in the southernmost portion of the Wagga–Omeo Zone of the Lachlan Orogen in south-eastern Australia.

Using the classification system of Cerny and Ercit (2005), both the Blue Jacket and Knocker pegmatites are highly evolved rocks within the LCT (Li–Cs–Ta) family. This is unsurprising, given that LCT granitic pegmatites are typically associated with late tectonic peraluminous granites formed during anatexis of primarily sedimentary source rocks, a setting represented by the Wagga–Omeo Zone. Subdivided further in terms of their dominant Li-bearing mineral, the Blue Jacket is subclass REL-Li-Complex-lepidolite and the Knocker is subclass REL-Li-Complex-amblygonite. The absence of Li-bearing minerals such as spodumene and petalite can be explained in terms of the maximum pressure of 0.3 GPa attained during dyke intrusion being close to the lower stability limit of spodumene, while high P, Li and K activities would have suppressed petalite formation in favour of montebrasite in the Knocker and lepidolite in the Blue Jacket dykes (London & Burt 1982). The absence of beryl from these and other pegmatites in the region (Eagle 2009) may be related to the general abundance of cordierite, which can accommodate small amounts of Be in its structure (Evensen & London 2002), in granites and metamorphic rocks within the Victorian region of the Lachlan Fold Belt.

Pegmatite fields tend to be zoned in regard to degree of fractionation and complexity of internal zonation of the dykes (Trueman & Cerny 1982). The dykes most distal (vertically and horizontally) from the magma source typically are more highly fractionated, and have more complex internal zonation than dykes proximal to the parent

body. This model appears to be applicable at Mount Wills, where dykes within and close to the granite contain simple, unfractionated granitic mineral assemblages. The Blue Jacket and Knocker pegmatites are the two most distal from the Mount Wills Granite and have the highest elevation of those granitic dykes investigated by Eagle (2009) (Figure 20). Their more evolved Li-, Ta- and P-bearing mineral assemblages are consistent with advanced fractionation of a granitic melt, as exemplified by LCT pegmatites.

Chemical differences between the granite and regional pegmatites have been noted by Maher and Morand (2003) on the basis of Hf–Rb–Ta contents. Eagle (2009) pointed out that the Mount Wills Granite is undersaturated with respect to Zr, unlike the pegmatites, in which zircon is a common accessory. These geochemical distinctions may arise from the processes undergone by a late-stage pulse of magma, enriched in incompatible elements, during and following its expulsion from the upper regions of a pluton (London 2005; Simmons 2007). As discussed by London (2008), the expelled magma will have a different geochemical signature to the parent, and may also interact with wall rocks prior to its crystallisation.
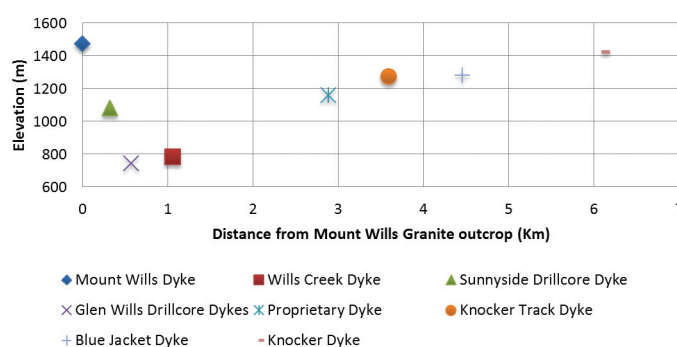

Figure 20: Plot showing the position of the pegmatite dykes studied by Eagle (2009) relative to the nearest outcrop of the Mount Wills Granite.

Comparison with other pegmatites

Due to the very small scale of the Mount Wills granite pegmatites, it is difficult to make reasonable comparisons in this paper with much larger, more complex pegmatites in overseas settings, such as Hagendorf in Germany (Mücke 1981) and Kobokobo in the Democratic Republic of Congo (Saffianikoff & Wambeke 1967). A field of LCT pegmatites in the Eurowie district, north of Broken Hill in New South Wales, may be the closest analogue in Australia. Here, tin-bearing pegmatites occupy andalusite-grade metasedimentary rocks of the Early Proterozoic Willyama Complex, with the most fractionated dykes containing cassiterite, tantalite, amblygonite, elbaite and possibly lepidolite-series micas (Lishmund 1982). The assemblage of secondary phosphates within the Mount

Wills pegmatites can be regarded as a small subset of the extraordinarily diverse mineralogy of the phosphate-rich Buranga pegmatite in central Rwanda. Daltry and Knorring (1998) recorded 55 phosphate minerals in this single dyke, which is also the type locality of bertossaite.

CONCLUSIONS

Strongly fractionated, cassiterite-bearing, granitic pegmatites classified in the LCT family outcrop in the Mount Wills district. The pegmatites contain a complex suite of secondary phosphate minerals, including both Al-rich and Fe–Mn-rich assemblages. Primary phosphate mineralisation probably consisted of fluorapatite, triplite and montebrasite, with subsequent metasomatic and hydrothermal alteration yielding secondary suites containing species such as scorzalite, bertossaite, brazilianite, heterosite, wolfeite, arrojadite, alluaudite, jahnsite and whiteite, most of which are new records for Victoria. Further work is in progress to establish paragenetic relationships and determine compositional ranges for some species, such as jahnsite and alluaudite.

CHIME Th/U/Pb dating of monazite from the Knocker pegmatite yielded an age of 420±4 Ma, which supports a genetic relationship with the nearby Mount Wills Granite. The granite formed during subduction-related tectonism affecting a thick sequence of marine Ordovician sediments within the southern Lachlan Fold Belt during the Benambran Orogeny. Elevation and distance relationships with respect to the pluton support the conclusion that those pegmatites containing phosphate assemblages represent the greatest degree of fractionation of the granitic magma, with the residual liquids enriched in Li, P, Sn and Ta. Similar granites and proximal pegmatite dykes are found in a corridor extending northwest for ~30 km towards Wodonga. It is likely that additional bodies with complex phosphate assemblages will be identified with further investigation.

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