



Greenbushes tin, tantalum and lithium deposit

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INTRODUCTION

The Greenbushes pegmatite contains one of the largest deposits of tin, tantalum and lithium in the world and has been in operation for more than 128 years. The deposit is located 350 km south of Perth, Western Australia (WA), at -33.86°, 116.06° in the Archean Western Gneiss Terrane. The Greenbushes deposit is receiving renewed interest due to increasing demand for lithium for battery production. Recently, Tianqi Lithium Australia formally approved the development of a A\$400 million lithium plant in Kwinana near port facilities, south of Perth. In conjunction with plant approval it is planned to expand Greenbushes' lithium production, already the largest hard rock lithium mine in the world, to supply more than 30% of the world's lithium. This will increase the importance of Greenbushes as a global source of lithium in particular, with potential future production of tin and tantalum.

EXPLORATION AND MINING HISTORY

Greenbushes is recognised as the longest continuously operated mining area in WA (Blockley, 1980). Tin was first mined at Greenbushes by the Bunbury Tin Mining Co in 1888, mainly from alluvial sources; however, there was a gradual decline in tin production between 1914 and 1930. Vultan Mines carried out sluicing operations of tin oxides from weathered pegmatite between 1935 and 1943, then modern earth-moving equipment was introduced and tin dredging was carried out between 1945 and 1956. Greenbushes Tin NL commenced open cut mining of the softer oxidised rock in 1969.

Tantalum hard-rock mining operations commenced in 1992 with an ore processing capacity of 800 000 t/a. By the late 1990s demand for tantalum peaked, and in order to meet this demand a decision was made to expand the mill capacity to 4 Mt/a and develop an underground mine, providing higher grade ore for blending with the lower grade ore from the Central Lode pits. The underground operation commenced at the base of the Cornwall Pit in April 2001 to access high-grade ore prior to the completion of the available open pit high-grade resource. In 2002, the tantalum market collapsed and subsequently the underground operation was placed on care and maintenance. The underground operation was restarted in 2004 due to increased demand, but again placed on care and maintenance the following year.

Initial development of the lithium orebody at Greenbushes commenced in 1983 and the first lithium processing plant was commissioned in 1985. Since that time, the lithium

processing plant has been expanded several times to produce a range of lithium concentrates. Lithium has been produced from the Greenbushes operations for over 25 years and Talison Lithium currently exports over 350 000 t of lithium products annually.

Current resources for lithium, which is the only commodity currently mined from the Greenbushes pegmatite, is summarised in Table 1. Tantalum and tin are recovered as by-products during lithium processing, with the tantalum grade averaging 127 ppm Ta and tin grade averaging 199 ppm Sn. Both tin and tantalum resources remain, particularly in the albite zones of the pegmatite, but these have not been estimated since the mining operations for these commodities were placed in care and maintenance in 2005.

PREVIOUSLY PUBLISHED WORK ON THE DEPOSIT

The main research carried out on the Greenbushes pegmatite was by a research group at the University of WA that included five Honours projects, a PhD thesis and a postdoctoral project; then follow-up research through an MSc project and three Honours projects at Curtin University, from which a number of research papers were generated (Bettenay, Partington and Groves, 1985; Partington, 1990; Partington, McNaughton and Williams, 1995). Other more general papers include work by the Geological Survey of WA and a number of summary papers produced by the various companies that have operated the mine at Greenbushes through its history (Blockley, 1980; Hatcher and Bolitho, 1982; Hatcher, and Clynick, 1990; Hatcher and Elliot, 1986). Other than an MSc project on the mining of spodumene and detailed studies on individual minerals in the pegmatite, there has been no new major research on the genesis of the pegmatite in recent times.

TABLE 1 – Greenbushes lithium Mineral Resources estimate at 30 September 2015.

Mineral Resources	Tonnage (Mt)	Grade LiO ₂ %	Metal Mt LCE
Inferred Resources	6.85	1.93	0.33
Indicated Resources	149.49	2.26	8.34
Measured Resources	0.73	2.95	0.05
Total Resources	157.06	2.25	8.72

Note that both tin and tantalum resource remain, but these have not been estimated since the mining operations for these commodities was placed in care and maintenance in 2004.

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The Greenbushes pegmatite intrudes rocks of the Balingup Metamorphic Belt and is part of the Greenbushes mineral field, which includes two major pegmatite groups at Ferndale and Greenbushes respectively (Partington, 1990). The Greenbushes pegmatite has been intruded into the Donnybrook-Bridgetown shear zone (Figure 1), which has a strike length of approximately 150 km (Partington, 1990). The shear zone is subparallel to the Darling fault in the north of the Balingup Metamorphic Belt and trends north-west to south-east, oblique to the Darling fault to the south. The main rock types in the pegmatite district include dioritic gneiss, which appears to be basement to Archean greenstone-like sequences of fine-grained amphibolite and associated banded iron formation, ultramafic schist, coarse-grained amphibolite and felsic massive to banded paragneiss (Figure 1; Partington, 1990). The gneiss has been intruded by quartz biotite-feldspar porphyry dykes, dolerite sills, dolerite dykes and granite, which predate the intrusion of the mineralised pegmatites at Greenbushes, and barren pegmatites and dolerite dykes that are later (Figure 1; Partington, 1990). The later dolerite dykes are oriented east-west and where they cut the Greenbushes pegmatite, are re-intruded by pegmatite veins. These veins are interpreted to have formed due to remelting of the pegmatite at the time of dolerite intrusion (Bettenay, Partington and Groves, 1985).

pegmatite at Greenbushes, and a younger suite that appears to be synchronous with intrusion of the mineralised pegmatite (Figure 1; Partington, 1990). The younger granitoids are aligned parallel to the Donnybrook–Bridgetown shear zone, believed to form part of the Wheatbelt Batholith (Wilde and Walker, 1979) and associated with linear belts of migmatite (Figure 1).

Four phases of non-coaxial deformation have been recognised in the pegmatite district (D1–D4), resulting from movements along the Donnybrook–Bridgetown shear zone (Partington, 1990). Fabric and structural analyses suggest that D1 predates pegmatite intrusion; D2 predates and is synchronous with pegmatite intrusion and crystallisation; D3 postdates pegmatite intrusion but predates intrusion of east–west dolerite dykes that cut the Greenbushes pegmatite; and D4 postdates east–west dolerite dyke intrusion. The structures associated with these deformation events and their relationship to pegmatite intrusion are described in more detail in Partington (1990) and Partington *et al* (1995).

The metamorphic history of the district is complex with structural and geochronological evidence for four metamorphic episodes closely associated with the deformation events. M2 metamorphism occurs synchronously with D2 deformation, and hence provides evidence for the environment of intrusion of the Greenbushes pegmatite (Partington, 1990; Partington *et al*, 1995). Temperatures and pressures attained during the various tectonic events were estimated from coexisting minerals within the various structural fabrics. The temperature estimates for the first three metamorphic events in the pegmatite district were in

the vicinity of 550° to 650°C (Partington, 1990; Partington, McNaughton and Williams, 1995). Additional constraints on the pressure and temperature of mineral growth for the second tectonic event were derived from the presence of spodumene in the pegmatite (compare London, 1984) and fluid inclusion studies. Pressures of >4–5 kb for the first three metamorphic events are suggested by the presence of almandine garnet, and further constrained for the M2 event by staurolite-kyanite assemblages (Partington, 1990; Partington, McNaughton and Williams, 1995).

ORE DEPOSIT FEATURES

The pegmatites that form the Greenbushes pegmatite group occur as a series of linear dykes, varying in length from 2 to 3 km and 10 to 300 m in thickness, to individual pods of a few metres across. The pegmatite dykes and *en echelon* pods extend from what appears to be an intrusive centre (Figure 2). The pegmatite and its subsidiary dykes and pods are concentrated within shear zones that mark the boundaries between major

sequences of granofels, ultramafic schist and amphibolite (Figure 2). Primary magmatic textures and structures in the Greenbushes pegmatite group have been modified to varying degrees by later deformation and metamorphism (Bettenay, Partington and Groves, 1985; Partington 1990). As the deformation is heterogeneous, some areas retain primary features, whereas other areas are completely recrystallised and mylonitised. Four major and four subsidiary compositional zones are recognised in the Greenbushes pegmatite group. As noted by Bettenay, Partington and Groves (1985), the macroscopic zonation in the Greenbushes pegmatite group is unusual and perhaps unique in that those zones (for example, lithium zones) normally expected to crystallise last and hence occur in the centre of the pegmatite (Černý, 1991a; London, 1996; London 2016), occur as footwall and hanging wall zones in the Greenbushes pegmatite group (Figures 2 and 3). Many smaller subzone variations occur within the broad zonal sequence; for example, muscovite-apatite beryl in the K feldspar zone, tourmaline-rich layers in the albite zone and quartz layers in the lithium zone (Bettenay, Partington and Groves, 1985; Partington, 1990).

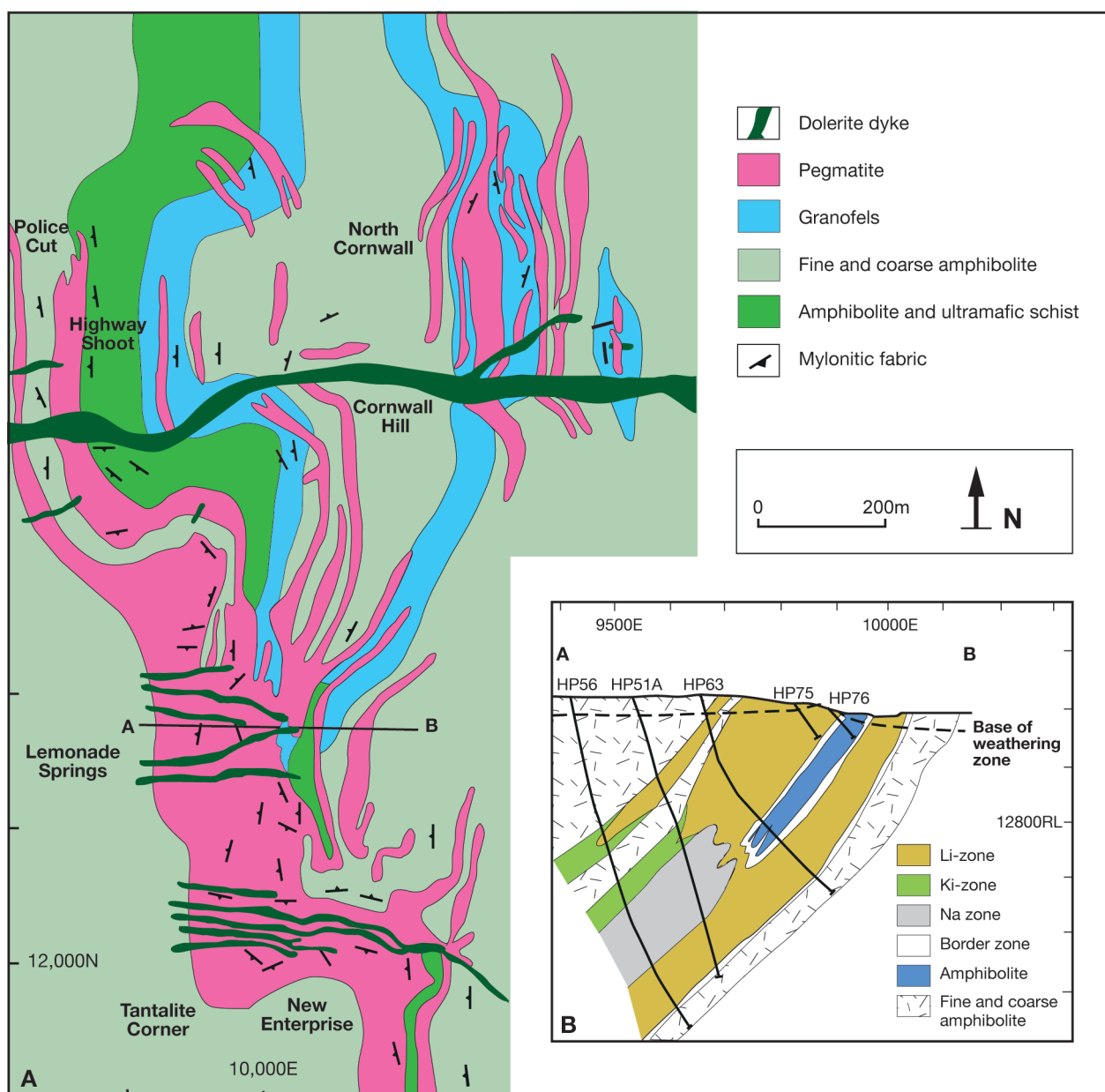


FIG 2 – Mine scale geology of the Greenbushes pegmatite showing pegmatite zonation and distribution of lithium, tin and tantalum mineralisation (from Partington, 1988).

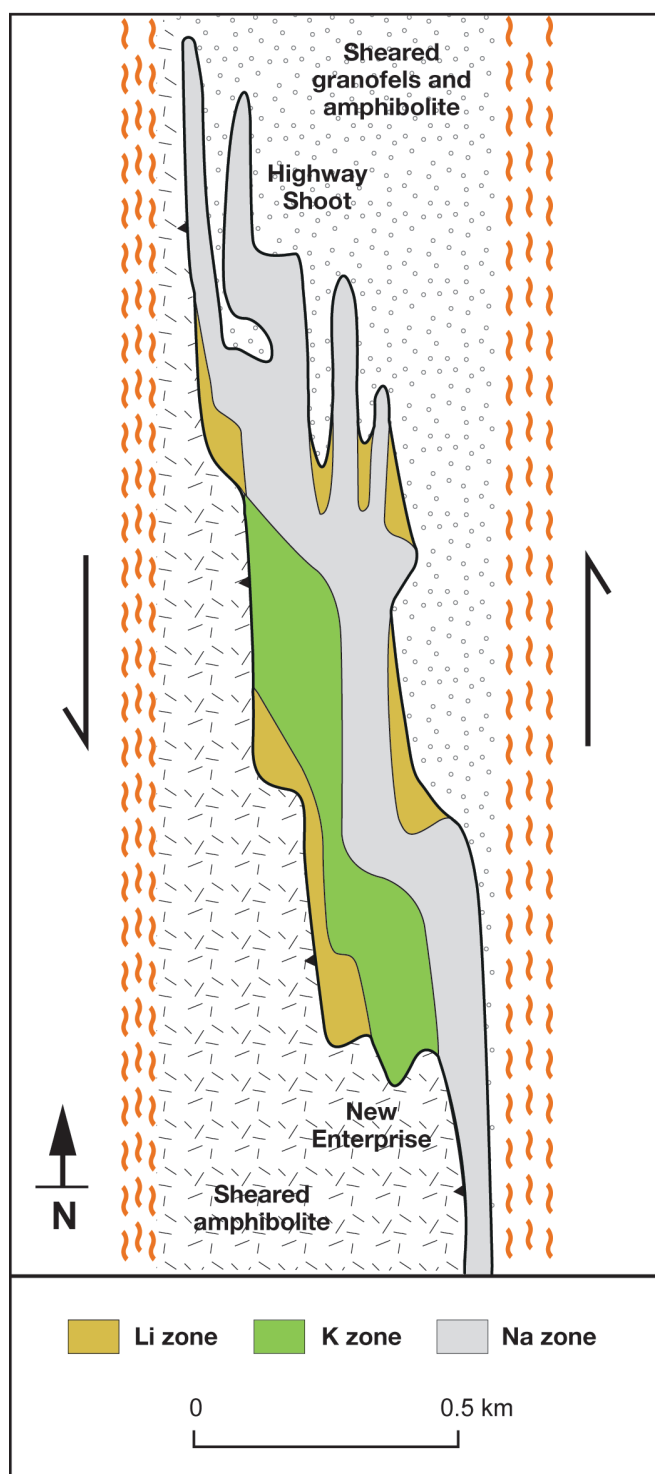


FIG 3 – Structural schematic model to explain the distribution of pegmatite zonation and mineralisation.

The highest grade tin and tantalum ore shoots occur exclusively in the albite zones in the pegmatite and generally within tourmaline-rich subzones. Tin and tantalum oxides are associated with uraninite and appear to have crystallised synchronously with tourmaline. Cassiterite is the main tin-bearing phase occurring as euhedral swallow-tailed crystals, which when deformed have pulled-apart and cataclastic textures. Early formed tantalum minerals occur as inclusions (mainly wodginite and ixiolite) within cassiterite crystals and tourmaline crystals. In contrast, the later coexisting tantalum phases (microlite, tantalite and tapiolite) in silicates are tin poor (Bettenay, Partington and Groves, 1985). Characteristic

ore zone accessories include zircon, monazite and uraninite. Preserved low-strain textures in the mineralised zones are typically magmatic and suggest that tin and tantalum minerals crystallised at an early stage (Bettenay, Partington and Groves, 1985) in association with tourmaline and other accessories (notably garnet, zircon and uraninite). The lithium ore zones comprise mainly primary spodumene, Mn apatite and quartz. Very high-grade lithium zones occur in the Greenbushes pegmatite group with some zones returning above 5% [Li2O2](#). The lithium zone is over 2 km long and enriched in the lithium-bearing mineral spodumene, which often makes up 50% of the rock and is particularly pure.

TEMPORAL AND STRUCTURAL CONTROLS ON MINERALISATION

The sequence of orthogneiss near Bridgetown appears to be the oldest crustal component in the Greenbushes pegmatite district (around 3100 Ma), and probably represents the earliest tectonothermal event in the area (Wilde and Walker, 1979). The supracrustal sequences in the Greenbushes pegmatite district formed parallel to the trend of the Donnybrook–Bridgetown shear zone between 2600 and 3100 Ma. An age of 2800 Ma derived from granofels elsewhere in the Western Gneiss Terrane suggests that these supracrustal sequences formed at a similar time (Wilde and Walker, 1979). The lack of D1 deformational structures and the presence of D2 mylonitic fabrics indicate that this sequence formed after the deformation of the dioritic gneiss but parallel to a similar crustal structure.

Regional D2 sinistral shearing, metamorphism and granitoid intrusion began by 2610 Ma with the initial intrusion of the Logue Brook Granite and possibly an early phase of the Millstream Dam Granite (Wilde and Walker, 1979). The intrusion of granites continued until at least 2577 Ma with intrusion of the Cowan Brook and Millstream Dam Granites, and ended with the intrusion of the Greenbushes pegmatite at 2527 Ma (Wilde and Walker, 1979; Partington *et al*, 1995). The intrusion of a regionally extensive east–west dolerite dyke suite then occurred across the Yilgarn at 2400 Ma. The dolerite dykes intruded the pegmatite causing contact metamorphism and local remelting of the pegmatite. The intrusion of these dykes may have also caused hydrothermal alteration of the pegmatite along D2 shear zones, and the consequential remobilisation of mainly tantalum mineralisation and the growth of the 2430 to 2440 Ma zircon population present in all pegmatite samples (Partington, McNaughton and Williams, 1995).

The resetting of the mineral Pb–Pb and zircon U–Pb data suggests that further deformation and metamorphism occurred between 1300 and 1100 Ma due to reactivation along the major structure encompassing the Greenbushes pegmatite district (Partington, McNaughton and Williams, 1995). These ages agree with ages derived for metamorphism, deformation and granite emplacement in the Albany–Fraser Province.

The last recognised metamorphic event in the district occurred at 700 to 500 Ma and is marked by reactivation of sinistral shearing, metamorphism and intrusion of the Ferndale pegmatite and Mullalyup pegmatite.

Preliminary conclusions of the crystallisation history of the pegmatite combine paragenetic and temperature data from Bettenay *et al* (1985) and structural and age data from Partington (1988). Crystallisation of the pegmatite commenced with tourmaline in the albite zone and tourmaline zone at 890°C, followed by albite, cassiterite and tantalite in the albite zones and tourmaline zones at 750°C. Zircon from these zones

and this phase of crystallisation gave the maximum recorded age of 2527 ± 2 Ma. This was followed by crystallisation of spodumene-quartz assemblages in the footwall lithium zone at a temperature of 770°C . Crystallisation of the hanging wall K-feldspar zone was coeval or transitional with the hanging wall lithium zone at 700 to 690°C .

Deformation and metamorphism were synchronous with the intrusion and crystallisation of the pegmatite. This deformation caused fracturing of early formed minerals, which then became suitable sites for the second phase of mineralisation and continuing crystallisation of tourmaline, albite, muscovite, spodumene and beryl at a temperature of 680°C . A second episode of zircon growth occurred at this time along with cassiterite and microlite. The younger zircon grains (2430 – 2400 Ma) can either be interpreted to have formed as a result of hydrothermal crystallisation of the pegmatite over a 90 Ma time interval, or as a result of significant remelting and/or hydrothermal remobilisation of the pegmatite during regional metamorphism or the intrusion of the east–west dolerite dyke suite (Partington *et al*, 1995). Finally, the third stage of mineralisation occurred at a temperature of 620°C associated with greisen-like zones within D3 shear zones, which can be related to later D3 deformation and metamorphism. This deformation and metamorphism affected the cross-cutting Proterozoic dolerite dykes and is interpreted to have occurred around 1100 Ma.

IMPLICATIONS FOR PEGMATITE EXPLORATION AND DEVELOPMENT

Rare metal pegmatites are part of the ore association related to granite magmatism. It is generally believed that those pegmatites that host most of the important mineralisation are found in a specific geologic environment (that is, within rocks subjected to low-pressure and medium-temperature Abukuma Facies metamorphism; Černý, 1982a, 1982b; Černý *et al*, 2005). These pegmatites are further subdivided into a series that emanates from a central granite source, with the most economically important pegmatites occurring a certain distance from their source granite. If these classifications are correct, these features should provide criteria for assessing the potential of prospects for rare element mineralisation during regional exploration (for example, Černý, 1982a, 1982b; Černý *et al*, 2005). That is to say, the most prospective areas for rare metal pegmatites should occur in low-pressure, medium-temperature Abukuma Facies metamorphic rocks that are adjacent to source granites showing evidence of fractionation.

The Greenbushes pegmatite group, however, occurs in a high-temperature and high-pressure metamorphic terrane, is not associated with nearby fractionated granites and was intruded some 50 million years after regional granite intrusion. According to most models it should be unmineralised, as is the younger Ferndale pegmatite group (Figure 1). It is clear from the tectonic environment and mechanisms of intrusion of the Greenbushes pegmatite group that the suggested models and exploration techniques need to be refined to include such significant pegmatite deposits as Greenbushes.

Giant rare metal pegmatites can occur in medium- to high-temperature and medium-pressure metamorphic terranes, and this type of pegmatite need not have obvious parental granites. Such pegmatites may contain mineralisation not usually associated with rare element pegmatites intruded at this depth, and are likely in the Archean to be associated with tectonism along crustal-scale fault systems. These data provide additional criteria to be used during regional

exploration for rare metal pegmatites in Precambrian terranes, and consequently should open new areas to exploration previously considered non-prospective.

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