Geology and Geochronology of the Paleoproterozoic Hart Dolerite, Western Australia

¹ Ramsay, R.R., ¹ Eves A.E., ² Denyszyn, S.W., ^{2,3} Wingate, M.T.D., ² Fiorentini, M., ⁴ Gwalani, L.G. and ⁵ Rogers K.A.

¹ Trident Capital Ltd, Level 24, 44 St Georges Terrace, Perth, WA 6000, Australia

² School of Earth Sciences, Centre for Exploration Targeting, ARC Centre for Core to Crust Fluid Systems, University of Western Australia, Perth, WA 6009, Australia

³ Geological Survey of Western Australia, 100 Plain Street, East Perth, WA 6004, Australia

⁴ Deceased

⁵ King River Copper Ltd, 254 Adelaide Terrace, Perth, WA 6000, Australia

ABSTRACT

The Hart Dolerite is the intrusive component of the Hart–Carson Large Igneous Province, which extends over an area of >160,000 km² in the Speewah and Kimberley Basins in the western part of the North Australian Craton. In the core of the Speewah Dome, a ca. 500 m thick composite sill of Hart Dolerite comprising four discrete gabbroic units and two later-stage dyke and sill units of potassic granophyre, all intruded into metasedimentary rocks of the Speewah Group, which have a maximum depositional age of 1814 ± 10 Ma. Cross-cutting relationships between the intrusive units indicate a younging-upwards sequence. The gabbros locally contain platinum-group element enrichment and vanadiferous titanomagnetite mineralisation. New ID-TIMS U-Pb geochronology of baddeleyite from gabbro units in the Speewah Dome yield upper-intercept ages (all 2σ) of 1792.7 ± 1.3 Ma and 1791.7 ± 4.1 Ma, complemented by a SHRIMP age of 1792.1 ± 5.9 Ma (2σ) for baddeleyite in a late-stage pigeonite vein in Hart Dolerite 120 km south of the Speewah Dome. These results are consistent with regional historical data from late-stage potassic granohyres and a model of rapid emplacement of the Hart Dolerite at 1792.6 ± 1.2 Ma in an intracratonic extensional setting within a few million years of the recently revised maximum age of sedimentation at ca. 1814 Ma. In a global setting, the period around ca. 1793 Ma reports a number of Large Igneous Provinces indicating continental extension, high heat-flow in the mantle and the large-scale generation of mafic melts.

Keywords: baddeleyite, large igneous province, mafic igneous rocks, petrography, U-Pb geochronology

37 **INTRODUCTION**

38 Large igneous provinces (LIPs) are generated when large volumes of mantle-derived
39 magmas are emplaced in either less than 5 Ma or in multiple short pulses over a time-
40 span of 30-50 Ma and extend over an area greater than 100 000 km² (Ernst and
41 Buchan, 2001; Bryan and Ernst, 2008). Their inferred intraplate origins and settings are
42 commonly based on models of extension produced by the impingement of a mantle
43 plume at the base of the lithosphere, rather than plate-margin mechanisms (De Paolo
44 and Manga, 2003; Sleep, 2006). During ascent, the melts typically show evidence of a
45 complex evolutionary history reflecting staged intervals of fractionation and crustal
46 contamination (e.g. Neumann et al., 2011; Ernst et al., 2019).

47 In continental settings, the intrusive and extrusive components of LIPs represent
48 stratigraphic markers that can be used to correlate sequences at local, regional, and
49 global scales (e.g. Haggerty, 1996; Ernst and Bleeker, 2010; Gumsley et al., 2017).
50 Intrusive parts of some LIPs host globally significant accumulations of metals, such as
51 chromium, nickel, vanadium, titanium, iron, and platinum-group elements, in areas that
52 include the Bushveld Complex in South Africa, the Norilsk and Talnakh chonolith
53 intrusions and elongated sills in Russia, as well as the Jinchuan and Panzhihua
54 intrusions in China, all with markedly short emplacement histories (Zeh et al., 2015;
55 Kamo et al., 2003; Sluzhenikin, 2011; Li et al., 2005; Pang et al., 2010; Shellnutt et al.
56 2012; Mudd and Jowitt, 2014; Mudd et al., 2018). High-precision geochronology of LIPs
57 can be used effectively to constrain the timing of their development, evolution and
58 mineralisation events (Denyszyn et al., 2018).

59 The Hart–Carson LIP consists of intrusive and extrusive igneous rocks that are
60 correlated using geochemistry. Stratigraphic evidence is consistent with a widespread
61 Paleoproterozoic emplacement event across the Kimberley region in the western part
62 of the North Australian Craton (Fig 1; Griffin et al., 1993; Tyler et al., 2006; Sheppard et

al., 2012). Sills of Hart Dolerite intruded mainly siliciclastic rocks of the Speewah Group and lower parts of the greenschist-facies Kimberley Group up to the level of the Carson Volcanics (Table 1; Sheppard et al., 2012). There are also undated dolerite sills in the upper Kimberley Group that may be younger than the Hart Dolerite, in the absence of observed relationships (e.g. Sheppard et al., 2012). The Hart Dolerite proper comprises a suite of tholeiitic rocks that range from olivine-bearing gabbro to potassic-quartz granophyre, and are interpreted as having been produced by closed-system fractionation from a common magma source (Thorne et al., 1999).

The Hart Dolerite extends over an area of about 160,000 km² and has an estimated minimum volume of ca. 300,000 km³ (Griffin et al., 1993; Sheppard et al., 2012, Hollis et al., 2014; Orth et al., 2015), and therefore meets most criteria for a large igneous province (Ernst and Buchan, 2001; Bryan and Ernst, 2008). However, the criterion of either rapid emplacement (ca. 1–5 Ma) or multiple short pulses over a more extended period of 30 to 50 Ma (Bryan and Ernst, 2008) has not been demonstrated, because existing constraints on the age of the Hart Dolerite consist of imprecise SHRIMP ²⁰⁷Pb/²⁰⁶Pb ages (all mean ages are quoted with 2-sigma or 95% confidence intervals, unless noted otherwise) of 1799 ± 17 Ma for zircon and 1795 ± 15 Ma for baddeleyite in two separate outcrop samples of Hart Dolerite potassic quartz granophyre (Sheppard et al., 2012). Furthermore, there have been no reliable ages for the gabbroic phases of the sills.

We present new information from mapping and sampling of a ca. 500 m thick sill of Hart Dolerite that outcrops in the core of a doubly plunging, regional anticline, known locally as the 'Speewah Dome', that hosts two major mineral systems on the eastern margin of the Speewah Basin (Fig. 1). The gabbroic sequence in the sill within the dome host a JORC-compliant vanadiferous titanomagnetite resource of 4.7 billion tonnes @ 0.3% V₂O₅ + 2% Ti + 14.7% Fe with co-magmatic sulphide-poor, Stella-type platinum-group element (PGE) mineralisation (Eupene, 1970; Blockley, 1972; Rogers,

1998; Maier et al., 2003; Niplats, 2008; Speewah Metals, 2012). In addition, some major faults host a JORC-complaint resource of 27.2 Mt @ 9.5% CaF₂ in veins of coarse-grained massive fluorite that are perhaps genetically unrelated to the gabbro event (Eupene, 1970; Blockley, 1972; Alvin, 1993; Rogers, 1998; Alvin et al., 2004; Gwalani et al., 2010). Diamond drilling in the Hart Dolerite has established that the rocks rich in vanadiferous titanomagnetite and cogenetic PGE mineralisation are part of a tabular composite sill that can be divided into six discrete units based on their textures. These units are separated by sharp igneous contacts that can be mapped in outcrop and correlated between drillholes (Figs. 2 and 3). We describe the mineralogy, textures, and distribution of the rock types in the study area.

We also present new U-Pb ages by Sensitive High-Resolution Ion Microprobe (SHRIMP) and by Isotope Dilution-Thermal Ionisation Mass Spectrometry (ID-TIMS) for baddeleyite and zircon from samples of three different rock types from the sill of Hart Dolerite in the Speewah Dome, as well as from a sample from a vein of pigeonite gabbro that intrudes another sill of Hart Dolerite about 120 km to the south-southwest (Fig. 1). Our results provide the first precise dates for the emplacement age of mafic rocks from the Hart Dolerite and provide first indications for the timing of magmatism in the Kimberley region, the constraints on the timing of Speewah Basin development, and better establish the geodynamic environment of the Hart–Carson LIP and its relationship with development of the North Australian Craton. The observations presented in this study also indicates that the Hart–Carson LIP represent a voluminous magmatic event on the North Australian Craton that is yet to be correlated equivalent with igneous rocks elsewhere that might constrain paleogeographic reconstructions. However, the evidence for large-scale mafic igneous events in an intracontinental setting at ca. 1793 Ma from other cratonic regions suggests a period of widespread extensional activity with high heat-flwo and magma generation.

REGIONAL GEOLOGICAL SETTING

The Kimberley region consists of igneous and metamorphic basement rocks of the Western Zone of the Lamboo Province, overlain unconformably by mainly siliciclastic sedimentary rocks deposited in the Speewah and overlying Kimberley Basins before being metamorphosed to greenschist facies (Fig. 1 and Table 1; Griffin and Grey, 1990; Sheppard et al., 1999, 2012; Johnson, 2013; Phillips et al., 2017). Although the crystalline rocks of the Western Zone are exposed only at the margins of the Speewah Basin, deeper magnetic responses from the area covered by rocks in the Speewah and Kimberley Basins suggest that these crystalline rocks extend beneath the region (Gunn and Meixner, 1998). The oldest outcrops in the Western Zone are greenschist to granulite facies turbiditic metasedimentary rocks of the Marboo Formation (Tyler et al., 1999). The Marboo Formation has a maximum depositional age constrained by detrital zircon geochronology of ca. 1872 Ma (Tyler et al., 1999).

During the ca. 1870–1850 Ma Hooper Orogeny, the Marboo Formation was intruded, metamorphosed, and locally partially melted by mainly felsic magmas of the 1864–1852 Ma Paperbark Supersuite (Tyler et al., 1999; Griffin et al., 2000; Page et al., 2001). The Central Zone of the Lamboo Province, which represents a ca. 1865–1810 Ma island arc that developed above a west-dipping subduction zone, was accreted to the Western Zone during the ca. 1832–1808 Ma Halls Creek Orogeny (Kohanpour et al., 2017). The Western and Central Zones subsequently collided and accreted with the western passive margin of the proto-North Australian Craton, which is preserved as the Eastern Zone of the Lamboo Province (Fig. 1; Blake et al., 2000; Tyler et al., 2012). The peak of the accretion event included the emplacement of mainly felsic magmas of the ca. 1832–1808 Ma Sally Downs Supersuite, which outcrop along the suture between the Central and Western Zones (Blake et al., 2000; Page et al., 2001).

The Speewah Group overlies the Western Zone, and contains detrital zircons with a dominant ca. 1860 Ma age component that reflects derivation from the Paperbark

Supersuite (Hollis et al., 2014; Ramsay et al., 2017). Zircons in rhyodacitic volcanoclastic beds within the Valentine Siltstone in the middle of the Speewah Group are dated at 1835 ± 3 Ma (Table 1; Sheppard et al., 2012). This age was first correlated with the early stages of the Halls Creek Orogeny and interpreted as an indicator of synvolcanic deposition on the foreland of a back-arc basin (Page and Sun, 1994; Sheppard et al., 2012; Tyler et al., 2012). More recently, detrital zircons from the Tunganary Formation, near the base of the Speewah Group, yielded a detrital zircon age component at 1814 ± 10 Ma, including a youngest zircon at 1803 ± 12 Ma (Table 1; Ramsay et al., 2017). This ca. 1814 Ma component represents detritus from rocks that crystallised during the later stages of the Halls Creek Orogeny and indicates that the Speewah Group was deposited over the Western Zone of the Lamboo Province in an intracratonic setting after accretion of the Kimberley Craton to the North Australian Craton (Ramsay et al., 2017).

Numerous Hart Dolerite sills, with a combined thickness of about 3000 m, intrude the Speewah Group and lower parts of the overlying Kimberley Group, up to the basal part of the Carson Volcanics (Fig. 1 and Table 1; Sheppard et al., 2012; Hollis et al., 2014). Thicker sills with gabbroic and granophyric rock types separated by sharp contacts imply that these units were formed during more than one intrusive event (Plumb and Gemuts, 1976). The predominantly tholeiitic compositions are typical of intraplate mafic melts produced by decompression melting of the mantle (Campbell and Griffiths, 1990; Ganguly, 2005). However, xenolithic rocks, negative Ta and Nb anomalies, and Sm–Nd isotope data suggest that the magma was contaminated by crustal material upon ascent and emplacement (Plumb 1968; Thorne et al. 1999; Sheppard et al., 2012; Hollis et al., 2014). The xenolithic inclusions and flow textures are also interpreted to indicate that the magma was emplaced in a turbulent fashion (Morin and Corriveau, 1996; Ferreira et al., 2015). The overall change from an early olivine-bearing gabbro to

later-stage felsic granophyre has been attributed to closed-system fractionation of melts derived from a common magma source (Alvin, 1993; Thorne et al., 1999).

GEOLOGY OF THE STUDY AREA

The Speewah Dome is a doubly plunging, regional anticline about 20 km in diameter within metasedimentary rocks of the Speewah Group on the eastern margin of the Speewah Basin (Fig. 1; Dunnet and Plumb, 1964; Alvin, 1993; Thorne et al., 1999). The dome has a core of gabbroic to doleritic rocks surrounded by an annulus of potassic quartz granophyre from the Hart Dolerite. This pattern of igneous zonation and the low angle-intrusive contacts of potassic quartz granophyre against the gently dipping metasedimentary rocks have been used to suggest that the Hart Dolerite represents a differentiated lopolithic intrusion (Dunnet and Plumb, 1964; Eupene, 1970; Alvin, 1993; Thorne et al., 1999).

In the Speewah Dome, the Hart Dolerite and Speewah Group are cut by regional-scale north and northeast-trending faults (Fig. 2; Thorne et al., 1999). Locally, the faults have provided conduits for fluids which altered and replaced the wall rocks and precipitated veins that are variably rich in K-feldspar, quartz, carbonate, fluorite and barite (Eupene, 1970; Blockley, 1972; Alvin, 1993; Rogers, 1998; Alvin et al., 2004; Gwalani et al., 2010). These veins were initially considered to have crystallised from volatile components that evolved during the differentiation of the Hart Dolerite (Eupene, 1970; Blockley, 1972). Later geological and geochemical studies suggested that the veins were the products of fractionation from more localised, fault-hosted, brecciated carbonate-rich rocks that were described as carbonatites, with an implied igneous origin (Alvin, 1993; Alvin et al., 2004; Gwalani et al., 2010). Noble gas and C, O, and H isotope data from minerals in the veins and replaced wall rocks of Hart Dolerite indicate

a significant crustal component that supports a predominantly hydrothermal rather than a magmatic origin for these fluids (Czuppon et al., 2014).

REVISED GEOLOGY OF THE HART DOLERITE IN THE SPEEWAH DOME

Mapping over an area of about 200 km² and drilling of six vertical diamond holes up to 582 m deep in the core of Speewah Dome provided the geological framework for this study (Fig. 2). Each of the drillcores passed through the Hart Dolerite into a footwall of metasedimentary rocks. The subhorizontal basal contact of the dolerite indicates that the igneous rocks are part of a tabular sill with a total thickness of about 500 m (Fig. 3). However, rather than a single differentiated gabbroic to potassic granophyre sill emplaced during a single igneous event, the sill is a composite intrusion in which sharp igneous contacts separate six rock types that can be mapped and correlated between drillholes (Fig. 3). These are summarised in Table 2 and described in detail here, in order to provide a framework for the understanding of the history of igneous intrusion in a complex mafic magmatic system.

Coarse-grained gabbro

The gabbro at the base of the sill is approximately 100 m thick and has a lower contact against metasedimentary rocks of either Valentine Siltstone or Tunganary Formation. (Figs. 2 and 3). The gabbro has a 0.1 – 0.2 m thick aphanitic lower zone, and becomes coarse grained (up to 10 mm) in the 2–5 m above the contact (Fig. 4a). The coarse-grained minerals are dominated by variably chloritised, augitic pyroxene enclosing about equal amounts of mostly sericitised, finer-grained laths of plagioclase. The lower part also contains up to 5% chloritised olivine and 5% subhedral titanomagnetite, frequently enclosing silicate inclusions. Minor minerals include andraditic grossular, more common near the basal contact, and biotite, the abundance of which increases upward. There are also trace amounts of fine-grained pyrite, apatite, and baddeleyite. Within 10 m of the upper contact, the gabbro becomes medium-grained; this includes

an uppermost 1–5 m thick interval of chloritised pyroxene and sericitised plagioclase against a sharp contact marking the base of the overlying spotted magnetite gabbro. The contact between the gabbros can be correlated between drillholes as a subhorizontal surface (Fig. 3).

Spotted magnetite gabbro

Above this sharp subhorizontal lower contact, the spotted magnetite gabbro ranges in thickness from 150 to 250 m and outcrops extensively (Figs. 2 and 3). It is medium-grained, subophitic, and dominated by about equal amounts of partially sericitised plagioclase and augitic pyroxene, plus 1–2% of subhedral titanomagnetite. However, in the upper 15–20 m of this unit, the titanomagnetite consists of aggregates of fine subhedral grains that increase in size from 1–2 mm up to 5 mm. These aggregates create a distinctly spotted appearance in both drillcore and outcrop (Fig. 4b). In the 20–50 cm beneath the sharp upper contact that is mapped as another subhorizontal surface, plagioclase is sericitised and pyroxene is chloritised. Interstitial minerals throughout this unit include minor fine-grained quartz, K-feldspar, apatite, pyrite, and baddeleyite.

Disseminated magnetite gabbro

The ca. 100 m thick disseminated magnetite gabbro overlies the spotted magnetite gabbro and outcrops intermittently through thin soil cover (Figs. 2 and 3). Its basal contact is subhorizontal and sharp, but with broad 1–5 cm deep channels into the underlying unit. This gabbro is dominated by a dark, medium-grained, subophitic texture but shows upwards gradational changes in mineralogy and in the abundance of xenoliths. The lower 50 m interval contains subequal amounts of plagioclase and augite, the latter exhibiting abundant granular and lamellar pigeonite exsolution. Within this interval, the lower 20 m contains traces of olivine and up to 20% disseminated subhedral vanadiferous titanomagnetite that decreases in abundance upwards. The

medium-grained vanadiferous titanomagnetite overgrows finer-grained, subhedral ilmenite that contains abundant fine silicate inclusions. In a 1–5 m interval about 15–20 m above the basal contact, there is a marked increase in the trace abundance of chalcopyrite, which coincides with PGE enrichment.

In the upper 50 m, where the vanadiferous titanomagnetite abundance is reduced to trace amounts, the abundance and grain size of graphically intergrown K-feldspar and quartz both increase. In some localities, the uppermost 0.3 – 1.0 m is a dark reddish pink, coarse-grained felsic granophyre that has a subhorizontal upper contact either against the Valentine Siltstone or the pegmatitic gabbro. Finer-grained interstitial minerals in this gabbro include K-feldspar, quartz, apatite, zircon, baddeleyite, pyrite and chalcopyrite. A sample of this gabbro, collected over a 2 m interval (8–10 m depth) about 50 m above the base of the unit in drillhole SDH08-06, yielded baddeleyite for geochronology (sample GS11043-1, Figs. 2 and 3; Table 2).

The disseminated magnetite gabbro is also characterised by the abundance and distribution of xenoliths with 10 mm thick, lighter-coloured, altered outer margins that are mainly dispersed through the 20–30 m interval above the basal contact (Fig. 4c). The xenoliths and coarser-grained laths of plagioclase in the groundmass are typically oriented with their long axes parallel to the subhorizontal basal contact. Angular to rounded xenoliths are up to 30 cm in diameter, with larger examples more abundant near the basal contact. Smaller xenoliths above the contact are typically tabular or more irregular in shape with diffuse margins (Fig. 4c). Xenoliths include coarse-grained gabbro, fine-grained anorthosite, medium- to coarse-grained granitic gneiss, and fine-grained siltstone. Zircons were recovered for geochronology from a xenolith of granitic gneiss (sample GS11042-3), which was exposed in an outcrop immediately above the base of the magnetite gabbro (Fig. 2 and Table 2).

Pegmatitic gabbro

This coarse-grained to pegmatitic gabbro (grain size 20–30 mm) occurs as localised sills up to 50 m thick, which are better preserved above parts of the disseminated magnetite gabbro in the central and northern parts of the Speewah Dome where the sequence is less eroded (Figs. 2 and 3). Thinner sills have also been intersected in drillcores within the spotted magnetite gabbro and along the contact between the spotted magnetite and disseminated magnetite gabbros. The pegmatitic gabbro has a subophitic texture with subequal amounts of variably saussuritised plagioclase and partly chloritised augitic pyroxene, as well as up to 5% skeletal titanomagnetite, variable amounts of graphically intergrown quartz and K-feldspar, and minor baddeleyite in sills to about 20 m thick. In sills >20 m thick, the abundance of graphically intergrown quartz and K-feldspar increases upwards such that that this gabbro contains diffuse segregations, cross-cutting veinlets and thin dykes of potassic granophyre (Fig. 4d). Baddeleyite was recovered for geochronology from a surface outcrop as sample (GS12051-2) in a sill above the disseminated magnetite gabbro (Fig. 2 and Table 2).

Mafic and felsic granophyres

In addition to granophyric rocks in the upper parts of the disseminated magnetite and pegmatitic gabbros, there are two subordinate units that are characterised by a groundmass of potassium feldspar-rich, quartz granophyre. These typically outcrop as 1–2 m wide dykes that cut through the spotted magnetite and disseminated magnetite gabbros. Less commonly, they form 2–5 m thick sills overlying the gabbroic rocks described above. However, in drillhole SDH09-01, which was collared near a major northeast-trending fault, an intercalated sequence of mafic and potassic quartz granophyres were intersected over a vertical thickness of about 130 m (Figs. 2 and 3). The older of these rocks is a mafic granophyre consisting of fine- to medium-grained (0.5–2.0 mm) potassic groundmass supporting abundant (60–80%) saussuritised dolerite xenoliths up to 2 cm in diameter and sericitised plagioclase laths up to 2 mm

long (Fig. 4e). The younger coarse-grained potassic quartz granophyre locally cross-cuts dykes of mafic granophyre. In addition to K-feldspar–quartz intergrowths up to 5 cm in diameter, the felsic granophyre contains sparse, partially sericitised, plagioclase laths up to 2 mm long, and up to 20% of an acicular ferromagnesian mineral pseudomorphed by epidote and chlorite (Fig. 4f).

GEOCHRONOLOGY

Samples and mineral separation

As described above, samples for geochronology were collected from diamond drillcore for the disseminated magnetite gabbro (GS11043-1), whereas the sample of pegmatitic gabbro (GS12051-2) and the granitic xenolith (GS11042-3) in the disseminated magnetite gabbro were collected from surface outcrops. Sample coordinates are provided in Table 2 and locations are indicated on Fig. 2.

A fourth sample (GSWA 206156), a pegmatitic pigeonite gabbro vein, was collected for geochronology from a surface outcrop about 120 km south-southwest of the Speewah Dome (Fig. 2 and Table 2). The vein is about 6 cm wide and intruded into medium-grained dolerite (Fig. 4g) near the upper contact of a Hart Dolerite sill intruding the Lansdowne Arkose (Table 1). In some places these veins cut the dolerite sharply, but locally they grade into the host dolerite. The geochronology sample consisted of bladed, subhedral pigeonite up to 6 cm long enclosed by saussuritised calcic plagioclase, with interstitial granophyre, and minor chlorite, biotite, and ilmenite.

Selection of samples for geochronology was based on optical examination and/or scanning electron microscopy of polished thin-sections to identify dateable minerals. For four of the five samples, about 2 kg of either quartered drill-core or unweathered rock chips that had reported baddeleyite and zircon in the petrographic studies was sent to Geotrack Laboratories in Melbourne for mineral separation. About 3 kg of

sample GSWA 206156 was processed by the laboratory of the Geological Survey of Western Australia (GSWA). For all samples, zircons or baddeleyites were concentrated using a high-density liquid and magnetic techniques, then hand-picked under a binocular microscope.

Analytical methods

Baddeleyite crystals from the disseminated magnetite and pegmatitic gabbros, and zircons from the granitic gneiss xenolith, were dated by the ID-TIMS U-Pb method. Baddeleyite exhibited coatings of microcrystalline zircon, which gave the grains a frosted appearance. This coating is difficult to remove, so baddeleyite crystals with the least evident coatings were selected for analysis, although all were affected to some degree. No pre-treatment methods were used beyond cleaning the grains with concentrated distilled HNO₃ and HCl; due to their small size, no chemical separation methods were employed. The samples were spiked with an in-house ²⁰⁵Pb–²³⁵U tracer solution. Dissolution was by vapor transfer of HF, using Teflon microcapsules in a Parr pressure vessel placed in a 220°C oven for six days. The resulting residue was redissolved in HCl and H₃PO₄ and placed on an outgassed, zone-refined rhenium single filament with 5 µL of silicic acid gel. U-Pb analyses were carried out using a Thermo Triton Plus mass spectrometer at the John de Laeter Centre, Curtin University, in peak-jumping mode using an electron multiplier. Uranium was measured as an oxide (UO₂). Fractionation and deadtime were monitored using SRM981 and SRM982. Mass fractionation was 0.10 ± 0.09 ‰/amu. Uranium decay constants are from Jaffey et al. (1971). The weights of the grains were calculated from measurement of photomicrographs and estimates of the third dimension. The weight of the grains only provides information about absolute U concentration and does not contribute to the age calculation; an uncertainty of 50% may be attributed to this estimate. Data were reduced and plotted using the software packages Tripoli (from CIRDLES.org) and Isoplot 4.15 (Ludwig, 2012).

Grains for analysis by SHRIMP were mounted with appropriate standards in 25 mm diameter epoxy discs, which were then polished to section the crystals for analysis. Measurements of U, Th and Pb in zircon and baddeleyite were conducted using the instruments at the John de Laeter Centre, Curtin University, with operating procedures similar to those described by Wingate and Lu (2017). Reflected light, transmitted light and cathodoluminescence (CL) images (for zircon) were used to guide all analyses. Measurements consisted of five or six scans through the mass range using a spot size of ca. 20 μm diameter and a primary ion beam (O^{2-}) with an intensity between 2 and 4 nA. U/Pb ratios in zircon were determined relative to the Temora-2 zircon standard ($^{238}\text{U}/^{206}\text{Pb}$ age = 416.8 Ma; Black et al., 2003), and $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ ratios (Pb* refers to radiogenic Pb) were monitored during most sessions using the OG1 zircon standard ($^{207}\text{Pb}/^{206}\text{Pb}$ age = 3465.4 ± 0.6 Ma; Stern et al., 2009). Element concentrations were estimated by comparison with the SL13 zircon standard (238 ppm ^{238}U ; Claoué-Long et al., 1995). U/Pb ratios in baddeleyite were determined relative to the Phalaborwa standard ($^{206}\text{Pb}/^{238}\text{U}$ age = 2060 Ma; Heaman 2008), and element concentrations were estimated by comparison with the CZ3 zircon standard (551 ppm ^{238}U ; Pidgeon et al., 1994; Nasdala et al., 2008). Owing to bias of U/Pb ratios during SHRIMP analysis of baddeleyite (Wingate and Compston, 2000), these ratios were used only semi-quantitatively in assessing age concordance, and isotopic dates were based on $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. Analyses of standards were interspersed with those of unknown grains during each analytical session. Data were reduced using SQUID 2.50 and Isoplot 3.75 (Ludwig, 2009, 2012), using decay constants recommended by Jaffey et al. (1971). Correction for initial or common Pb was made using measured $^{204}\text{Pb}/^{206}\text{Pb}$ and contemporaneous common-Pb isotopic compositions determined according to the model of Stacey and Kramers (1975). SHRIMP analyses >5% discordant or indicating high common Pb ($f_{204} > 1\%$, where f_{204} is the proportion of common ^{206}Pb in total measured ^{206}Pb), are considered to be of low reliability and are candidates for rejection.

For both ID-TIMS and SHRIMP analyses, uncertainties for individual analyses in data tables (Supplementary Data Tables 1 and 2) and error bars and ellipses in concordia diagrams are at the 1σ level, whereas sample mean ages are quoted with 2-sigma or 95% uncertainties.

Results

Baddeleyite was recovered from the disseminated magnetite gabbro, pegmatitic gabbro, and the gabbro pegmatite vein, whereas zircons were recovered from the spotted magnetite gabbro and from the granitic gneiss xenolith hosted by the disseminated magnetite gabbro.

Disseminated magnetite gabbro (sample GS11043-1)

Four baddeleyite crystals were analysed by ID-TIMS (Supplementary Data Table 1; Fig. 5a). Calculated weights were between 0.2 and 0.4 μg , with U concentrations generally high, between 551 and 1682 ppm. Th/U ratios are typically low in baddeleyite; these analyses indicate ratios between 0.03 and 0.05. Likely due to the microcrystalline zircon coatings, each analysis exhibits signs of Pb loss and discordance, up to 2.5%. A free regression of all four analyses (MSWD = 2.2) yields an upper intercept of 1791.7 ± 4.1 Ma (Fig. 5a), and a lower intercept of 68 ± 200 Ma, which is within uncertainty of the origin. If the regression is anchored at the origin, the upper intercept is 1790.5 ± 1.4 Ma (MSWD = 1.6). We interpret the date of 1791.7 ± 4.1 Ma as the crystallisation age of the disseminated magnetite gabbro.

Pegmatitic gabbro (sample GS12051-2)

Four baddeleyite grains analysed by ID-TIMS had calculated weights between 0.1 and 0.3 μg , with U concentrations between 541 and 1075 ppm and Th/U ratios between 0.04 and 0.07 (Supplementary Data Table 1; Fig. 5b). Minor Pb loss is indicated by each analysis, resulting in 1–2% discordance and attributable to the presence of zircon

coatings. A regression through all data (MSWD = 1.3) yields an upper intercept of 1792.7 ± 1.3 Ma (Fig. 5b), and a lower intercept at -167 ± 210 Ma, which is within uncertainty of the origin. Anchored at the origin, the regression yields an upper intercept of 1793.4 ± 1.1 Ma (MSWD = 2.1). We interpret the date of 1792.7 ± 1.3 Ma as the crystallisation age of the pegmatitic gabbro.

Pigeonite gabbro vein (sample GSWA 206156)

This sample yielded about 200 baddeleyite crystals, which are pale to dark brown and pleochroic, subhedral to euhedral, and up to 200 μm long (Fig. 4h). Forty-two crystals were analysed by SHRIMP (Supplementary Data Table 2; Fig. 5c). Concentrations of ^{238}U range from 31 to 538 ppm, with a median of 98 ppm, and Th/U ratios from 0.01 to 0.14, with a median of 0.03. Two analyses indicate high common Pb ($f_{204} > 2\%$), whereas all others indicate low common Pb (median $f_{204} = 0.1\%$). Of the remaining 40 analyses, 37 yield a weighted mean $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ date of 1792.1 ± 5.9 Ma (MSWD = 1.4), and three analyses that are significantly ($>2\sigma$) younger are excluded. Although there is a correlation in these data ($R = 0.7$) between the $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ date and the common-Pb correction (f_{204}), the common-Pb corrections are very small and extend to both positive and negative values (negative values arise where background counts are similar to those for $^{204}\text{Pb}^+$). The main effect is to slightly increase dispersion in the data, rather than bias the weighted mean value significantly. The date of 1792.1 ± 5.9 Ma is interpreted as the magmatic crystallisation age of the pigeonite gabbro vein.

Granitic gneiss xenolith in disseminated magnetite gabbro (sample GS11042-3)

Zircons from the granitic xenolith are colourless to pale brown and prismatic. Forty grains were analysed by SHRIMP and 10 by ID-TIMS (Supplementary Data Tables 1 and 2; Fig. 5d). Of 40 SHRIMP analyses, 19 are $>5\%$ discordant, indicate high common Pb, or are very imprecise (probably implying an analytical problem) and are excluded from further consideration. The remaining 21 analyses yield $^{207}\text{Pb}^*/^{206}\text{Pb}^*$

dates of 2699–1805 Ma, and can be divided into three groups. The oldest three analyses yield $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ dates of 2699, 2514, and 2013 Ma, interpreted as the ages of xenocrysts within the granitic xenolith. Thirteen analyses yield a weighted mean $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ date of 1876 ± 8 Ma (MSWD = 1.4), whereas five analyses that yield $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ dates of 1840–1818 Ma are significantly younger.

Nine of ten ID-TIMS analyses are less than 5% discordant (one is 30% discordant), but the dates of 2379–1774 Ma are mostly dispersed beyond analytical precision (Supplementary Data Table 1; Fig. 5d). The oldest two analyses yield $^{207}\text{Pb}/^{206}\text{Pb}$ dates of 2379 and 2039 Ma, and may represent xenocrysts within the xenolith. The remaining seven analyses are all significantly younger than the mean date of 1876 ± 8 Ma for 13 SHRIMP analyses, and presumably reflect loss of radiogenic Pb.

Provided all the zircons are not inherited, the weighted mean $^{207}\text{Pb}^*/^{206}\text{Pb}^*$ date of 1873 ± 6 Ma for 13 SHRIMP analyses may represent the crystallisation age of the granite protolith. Accordingly, the 14 younger analyses (1851–1774 Ma) are interpreted to reflect minor ancient loss of radiogenic Pb.

DISCUSSION

The precise geochronological characterisation of selected units within the sill of Hart Dolerite in the Speewah Dome is the first evidence to support the interpretation that igneous activity at ca. 1793 Ma was of short duration, which would indicate that the Hart–Carson magmatic province comprises discrete pulses of mafic magmatism comprising a single LIP-forming event. Within this new context, we can evaluate the tectonic evolution of the westernmost component of the North Australian Craton as it relates to other parts of the Australian continent. This study also provides a comprehensive account of the mineralogical and petrographic features of the igneous units that comprise the composite sill of Hart Dolerite in the Speewah Dome and represent an essential framework for interpreting geochronological results. A

subsequent study on the geochemical and isotopic evolution of this magmatic system, based on mineral chemistry and whole-rock geochemical and isotopic analyses, will form the basis of a subsequent contribution.

Episodic emplacement of the sill of Hart Dolerite in the Speewah Dome

The sill of Hart Dolerite in the Speewah Dome is shown from surface and drillcore mapping to be subhorizontal and tabular in form, with a thickness of about 500 m (Fig. 3). This contrasts with the model of Eupene (1970), which proposed that the core of gabbroic rocks with an annulus of felsic granophyre against the country-rock represented the feeder and upper parts of a lopolithic intrusion. Within the sill, sharp contacts subdivide the igneous rocks into four gabbroic and two potassic quartz granophyric units with distinct petrological features, each of which represents at least one discrete pulse of magma.

The location of this sill in the Speewah Basin suggests that the rheological contrast between siltstone and sandstone units exerted significant control on the style of emplacement. The widespread preservation of the Valentine Siltstone on the upper surface of the igneous rocks and a lesser degree of preservation along the lower contact suggests that the siliciclastic Tunganary Formation and Lansdowne Arkose provided an important control for emplacement (Table 1; Sheppard et al., 1999). The subhorizontal upper and lower surfaces of the gabbro units suggest that they were emplaced under conditions in which the minimum stress was vertical (Kavanagh et al., 2006; Taisne and Jaupart, 2009; Cashman and Sparks, 2013).

Textural and mineralogical features in the igneous units indicate that they young upwards. The coarse-grained and spotted magnetite gabbros each have an uppermost interval of sericite and chlorite alteration consistent with heating from above. There are also small-scale channelised structures in the upper surface of the spotted magnetite gabbro that appear to reflect the effects of thermo-mechanical erosion during

483 emplacement of the overlying disseminated magnetite gabbro. The pegmatitic gabbro
484 locally overlies and also occurs as sills within the disseminated magnetite gabbro
485 showing that the pegmatitic gabbro is a late-stage phase. All the gabbroic rocks were
486 cross-cut by locally composite potassic quartz granophyre dykes where the mafic
487 granophyre is disrupted and cut by the coarse feldspar-rich granophyre.

488 Textural and mineralogical features in the igneous rocks also provide evidence of the
489 processes associated with emplacement and crystallisation. Abundant xenoliths in the
490 disseminated magnetite gabbro and mafic granophyre indicate rapid emplacement of a
491 turbulently flowing magma (Morin and Corriveau, 1996; Ferreira et al., 2015). The pale,
492 diffuse margins on xenoliths in the disseminated magnetite gabbro indicate that
493 assimilation, which typically increases the density of the xenolithic fragments, was in
494 progress (Leshner, 2017). This density increase potentially contributed to an increase in
495 the rate of settling during melt crystallisation and is reflected by the greater abundance
496 of xenoliths along the basal contact of the disseminated magnetite gabbro. Vertical
497 mineralogical changes within each gabbro unit imply that sufficient time elapsed for
498 fractional crystallisation to proceed. These include transitions from olivine-bearing
499 sections to biotite-bearing sections within the coarse-grained gabbro, the transition
500 from olivine-bearing to quartz-bearing potassic granophyre in the disseminated
501 magnetite, and the segregation of veinlets and dykes within the pegmatitic gabbro.

502 *Age of the Hart Dolerite and xenocrystic components*

503 Previous SHRIMP U-Pb zircon ages of 1799 ± 17 and 1795 ± 15 Ma were obtained
504 from samples of relatively small-volume, late-stage felsic granophyres (Page and Sun,
505 1994; Sheppard et al., 2012). Our new U-Pb baddeleyite ages for the gabbros provide
506 the first high-precision age constraints on their crystallisation. An ID-TIMS U-Pb upper-
507 intercept age of 1791.7 ± 4.1 Ma was obtained from the disseminated magnetite
508 gabbro and another of 1792.7 ± 1.3 Ma from the pegmatitic gabbro that cross-cuts the

disseminated magnetite gabbro. These are complemented by a SHRIMP U-Pb upper-intercept age of 1792.1 ± 5.9 Ma for a pigeonite gabbro vein in the Hart Dolerite about 120 km south of the Speewah Dome. The ages agree within analytical uncertainty at 1792.6 ± 1.2 Ma (2σ), which is consistent with a short duration (<3 Ma) for emplacement of the Hart Dolerite, and with typical durations reported for large igneous provinces of similar size (Ernst and Buchan, 2001; Bryan and Ernst, 2008).

Older ages for zircons from granitic gneiss inclusions hosted by the disseminated magnetite gabbro and for zircons from the spotted magnetite gabbro clearly indicate a xenolithic relationship with the Hart Dolerite. The results are also consistent with a SHRIMP U-Pb age of 1876 ± 4 Ma for 34 zircons from a pelitic migmatite in the Lamboo Province (Kirkland et al., 2014). There are also three SHRIMP and four ID-TIMS U-Pb analyses between ca. 2699 and 2013 Ma that are similar to late Archean to Paleoproterozoic zircon results from the Lamboo Province (Tyler et al., 1999; Kirkland et al., 2013; Kirkland et al., 2014; Lu et al., 2016).

Regional significance of the Hart–Carson LIP

Geochronology results presented here from the mafic phases of the sill in the core of the Speewah Dome, particularly the ID-TIMS U-Pb analyses, are the first precise ages for the mafic events in the study area and also the entire region of Hart Dolerite. The new ages that are within error of previously published ages from the potassic quartz granophyres, some 200 to 400 km from the Speewah Dome, provide additional constraints on the tectonic evolution of the western North Australian Craton. In the Kimberley region, predominantly siliciclastic metasedimentary rocks of the Speewah Group that host the composite Hart Dolerite sill in this study unconformably overlie the Western Zone of the Lamboo Province. The youngest detrital zircon age component in the Speewah Group from a sample in the Speewah Dome is dated at 1814 ± 10 Ma, and includes a youngest zircon at 1803 ± 12 Ma (1σ) (Ramsay et al., 2017). The

youngest SHRIMP U-Pb zircon ages indicate that sedimentation post-dated the Halls Creek Orogeny and implies that the Speewah Basin developed in an intracratonic setting during the later stages of the amalgamation of crustal blocks that formed the northern parts of the Australian continent. The abundance of zircons with ages recording events from the ca. 1870–1850 Ma Hooper Orogeny is consistent with siliciclastic sediments being derived from local sources (Hollis et al., 2014). Some zircons dated at ca. 1835 Ma in volcanoclastic and tuffaceous rocks of the Valentine Siltstone appear also to represent an inherited population in the Speewah Group, reflecting igneous activity that may be related to extension that accommodated the Speewah Basin (Sheppard et al., 2012; Ramsay et al., 2017).

The ca. 1793 Ma emplacement of the Hart Dolerite into the Speewah and lower Kimberley Groups is correlated with eruption of the Carson Volcanics within the Kimberley Basin and attributed to extension following amalgamation of the Kimberley and North Australian Cratons (Sheppard et al., 2012). In other regions, the abundance of vanadiferous titanomagnetite in these systems is attributed to mantle-derived melts undergoing an initial period of deep crustal fractionation at pressures in excess of 10 kbar followed by emplacement at shallower levels (Pang et al., 2007). Although field evidence indicates episodic emplacement and crystallisation within the composite Hart Dolerite sill in the Speewah Dome, the new SHRIMP and ID-TIMS U-Pb ages presented in this study indicate that these events occurred over an interval as short as 3 Ma.

The Hart–Carson LIP in a global context

If the Kimberley Craton at ca. 1793 Ma was significantly larger than it is today, and parts were subsequently rifted away during breakup of the Rodinia supercontinent, as suggested by Li et al. (1996) and Sheppard et al. (2012), then originally contiguous parts of the Hart Dolerite and its host rocks might be found on other continents.

Paleomagnetic data for the Hart Dolerite place the Kimberley Craton in low latitudes (ca. 5°S) at ca. 1793 Ma (McElhinny and Evans, 1976; Kirscher et al., 2018). A 'semi-stable' link between the North Australian Craton and Laurentia between ca. 1800 and 1730 Ma was suggested by Kirscher et al. (2018). However, there is no counterpart in Laurentia to the Hart–Carson LIP, and the relevant Laurentian paleopoles (all somewhat younger than the Hart Dolerite) are poorly constrained in age and/or reliability, and are only broadly permissive of a link between Laurentia and the North Australian Craton at that time.

A synthesis of paleomagnetic data by Pisarevsky et al. (2014) indicated that several cratons shared low latitude positions at ca. 1770 Ma, including Amazonia, Baltica, West Africa, North China, and the Australian cratons, whereas Laurentia occupied moderately high latitudes. Pisarevsky et al. (2014) suggested, based mainly on geological arguments, that Laurentia and Australia were separated by an ocean basin until at least 1650 Ma. The Kirscher et al. (2018) paleomagnetism-based reconstruction permits either a close fit between these paleocontinents or a significant separation by oceanic crust, although it does suggest that Laurentia and Australia shared a similar drift history in the Paleoproterozoic. Potentially correlative units include the Avanavero LIP of the Amazonian craton (Reis et al., 2013), the Pará de Minas dyke swarm in the Sao Francisco Craton (Cederberg et al., 2016), the Uruguayan dykes in the Rio de la Plata craton (Teixeira et al. 2013), the Tomashgorod dykes in Baltica (Bogdanova et al. 2012), and the Libiri dykes in West Africa (Ernst et al., 2014).

The Avanavero LIP extends over at least 300,000 km² in the Amazonian Craton, and the have geochemical features typical of an intraplate basalt province (Reis et al., 2013). The Avanavero Dolerite sills have baddeleyite and/or zircon U–Pb ages between about 1795 and 1780 Ma (Norcross et al., 2000; Santos et al., 2003; Reis et al., 2013), although the most precise results are ID-TIMS U–Pb baddeleyite ages of 1794.5 ± 1.6 and 1792.6 ± 1.3 Ma for sills in the Pakaraima and Urupi Blocks of the

Guiana Shield (Reis et al., 2013). These ages partially overlap with our new Hart Dolerite ages of 1791.7 ± 4.1 , 1792.7 ± 1.3 , and 1792.1 ± 5.9 Ma (average 1792.6 ± 1.2 Ma).

The tholeiitic Pará de Minas dyke swarm extends for about 1400 km in the southern Sao Francisco Craton (Chaves and Correia Neves, 2005). The dykes are potentially related to intracontinental rifting (Cederberg et al., 2016). Samples of three dykes yielded ID-TIMS U-Pb baddeleyite ages of ca. 1795 Ma (1798 ± 4 , 1791 ± 7 and 1793 ± 18 Ma, Cederberg et al., 2016). The Florida dyke swarm (a.k.a. Uruguayan or Piedra Alta dykes) extends through the Rio de la Plata craton with rocks classified as tholeiitic andesites and andesitic basalts and are thought to be related to intraplate magmatism in an extensional setting (Teixeira et al., 2013). One dyke yielded an ID-TIMS U-Pb baddeleyite and (metamorphic) zircon intercept age of 1790 ± 5 Ma (Halls et al., 2001). The ages for the Pará de Minas and Florida dyke swarm are within uncertainty of the new age for the Hart Dolerite.

Within the East European Craton, a.k.a. Baltica), there are widespread 1.80–1.75 Ga mafic dykes related to coeval anorthosite–mangerite–charnockite–granite (AMCG) plutonism (Shumlyanskyy et al., 2012). Zircons from a pegmatitic zone within one dyke yielded a combined SIMS and ID-TIMS U-Pb zircon age of 1787 ± 6 Ma (Shumlyanskyy et al., 2012). Furthermore, baddeleyite from a medium-grained dolerite sample of the same dyke provided an ID-TIMS age of 1791 ± 5 Ma (Bogdanova et al., 2013), which is again within uncertainty of the age of the Hart Dolerite. In the SAMBA (South America – Baltica) reconstruction, Johansson (2009) proposed that ca. 1790 Ma mafic magmatism in the Ukrainian Shield was linked to not only the Ananavero LIP in Amazonia, but also to the Libiri dykes in West Africa (Ernst et al., 2014), for which an ID-TIMS U-Pb baddeleyite age of ca. 1790 Ma was reported in an abstract (Baratoux et al., 2016).

Based on isotopic age and broad compatibility of paleomagnetic constraints with possible reconstructions, the mafic igneous provinces described above are possible matches with the newly defined ca. 1793 Ma Hart–Carson LIP. Further studies of precise dating, paleomagnetic determinations and perhaps studies of the host rocks and any components from the basement associated with ca. 1793 Ma events may provide additional support for a more definitive correlation.

CONCLUSIONS

Mapping of surface outcrops and drillcores shows that the Hart Dolerite in the Speewah Dome is a 500 m thick, composite, tabular sill that intrudes the Speewah Group at the level of the Valentine Siltstone. This composite sill, which is locally mineralised with sulphide-poor Stella-type PGE enrichment and vanadiferous titanomagnetite, comprises six discrete textural units separated by sharp igneous contacts, with cross-cutting relationships that indicate a younging-upwards sequence of four gabbroic sills which were then intruded by two granophyric dyke units. Abundant xenoliths in the disseminated magnetite gabbro and mafic granophyre indicates the mafic and potassic granophyre melts were emplaced rapidly and that magma flow was turbulent. However, the overall mineralogical change from olivine-bearing, through titanomagnetite-rich, to later-stage potassic granophyre across and within the sills suggests that successive melts were derived from a magma source undergoing closed-system fractional crystallisation.

Despite textural and mineralogical evidence for episodic emplacement and fractionation, ID-TIMS upper-intercept ages from baddeleyite in two successive gabbroic intrusive events are identical within uncertainty at 1792.7 ± 1.3 Ma and 1791.7 ± 4.1 Ma. This relatively short interval for mafic magmatism in the sill in the Speewah Dome is also supported regionally by a SHRIMP upper-intercept age of 1792.1 ± 5.9 Ma for baddeleyite from a mafic pegmatite vein within Hart Dolerite about 120 km to the

south, and in agreement with previous, less-precise SHRIMP U-Pb ages for late-stage potassic granophyres collected some 200 to 400 km from the Speewah Dome. Taken together, these results indicate that the Hart Dolerite was emplaced in multiple pulses and each crystallised within about 3 Ma at ca. 1793 Ma, and imply that the Hart-Carson represents an LIP.

During emplacement, the Hart Dolerite was contaminated with a variety of rock types that included a felsic granulite which contains a youngest zircon component at ca. 1872 Ma as well as older Paleoproterozoic zircons. These ages are typical of crystalline metasedimentary rocks in the Western Zone of the Lamboo Province, which is interpreted as the basement beneath most of the Kimberley region. The more precise age for the Hart Dolerite further constrains the timing of extensional events in the Speewah and Kimberley Basins when combined with the maximum depositional age represented by a youngest detrital zircon component of ca. 1814 Ma in the Speewah Group. The ca. 1793 Ma age of the Hart Dolerite indicates that within about 10 Ma of the Kimberley Craton being amalgamated with the North Australian Craton, extensional tectonics thinned the lithosphere, allowing the impingement of a mantle hotspot to drive decompression melting in the upper mantle.

There are several mafic igneous provinces globally that are similar in age to the ca. 1793 Ma Hart–Carson LIP, but further systematic studies of the palaeomagnetic responses, geochemistry and perhaps the associated host-rocks will be required before a clear counterpart to the Hart–Carson LIP can be identified in another continent. However, it does appear that the ca. 1793 Ma interval was a period of extensional tectonics and high-heat flow that produced extensive volumes of mafic melts in cratonic areas that are now widely separated cratonic blocks.

ACKNOWLEDGEMENTS

King River Copper Ltd (previously Niplats Australia Ltd) would like to thank the State Government of Western Australia for funding from the Exploration Incentive Scheme which contributed to the deep diamond drilling programme on the study area and provided the samples for this study. SHRIMP II U–Pb measurements were conducted at the John de Laeter Centre, Curtin University, operated with the financial support of the Australian Research Council and Auscope NCRIS. MTD Wingate publishes with permission of the Executive Director of the Geological Survey of Western Australia. This is Contribution XXXX from the Australian Research Council Centre of Excellence for Core to Crust Fluid Systems.

REFERENCES

- Alvin, M.P., 1993. The nature, depositional conditions and sources of ore fluids and solutes of the Speewah fluorite deposit, East Kimberley Region, Western Australia. BSc Honours Thesis, University of Western Australia (unpublished), 76p.
- Alvin, M.P., Dunphy, J.M., Groves, D.I., 2004. Nature and genesis of a carbonatite-associated fluorite deposit at Speewah, East Kimberley region, Western Australia. *Mineralogy and Petrology* 80, 127–153.
- Baratoux, L., Jessell, M., Söderlund, U., Ernst, R.E., Benoit, M., Naba, S., Cournede, C., Perrouy, S., Metelka, V., Yatte, D., Diallo, D.P., Ndiaye, P.M., Dioh, E., Baratoux, D., 2016. Geodynamic setting of Proterozoic dyke swarms of the Leo-Man Craton, West Africa, based on new U-Pb dating and geochemistry. *American Geophysical Union, Fall General Assembly 2016*, abstract V11B-2777.
- Barnes, S-J., Lightfoot, P.C., 2005. Formation of magmatic nickel sulfide deposits and processes affecting their copper and platinum group element content. In: Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., Richards, J.P. (Eds.), *Economic Geology—One hundredth anniversary volume 1905–2005*: Littleton, Colorado, Society of Economic Geologists. pp.179–213.
- Black, L.P., Kamo, S.L., Allen, C.M., Aleinikoff, J.N., Davis, D.W., Korsch, R.J., Foudoulis, C., 2003. TEMORA 1: A new zircon standard for Phanerozoic U–Pb geochronology. *Chemical Geology* 200, 155–170.
- Blake, D.H., Tyler, I.M., Page, R.W., 2000. Regional Geology of the Halls Creek Orogen. In: Hoatson, D.M., Blake, D.H. (Eds), *Geology and economic potential of the Palaeoproterozoic layered mafic–ultramafic intrusions in the East Kimberley, Western Australia*. Australian Geological Survey Organisation, Bulletin 246, pp. 35–62.
- Blockley, J.G. 1972. The Speewah fluorite deposit. Geological Survey of Western Australia, Mineral Resources Report 27 (unpublished).
- Bogdanova, V.S., Gintov, B.O., Kurlovich, M.D., Lubnina, V.N., Nilsson, M.K.M., Orlyuk, I.M., Pashkevich, K.I., Shumlyanskyy, V.L., Starostenko, I.V., 2013. Late Palaeoproterozoic mafic dyking in the Ukrainian Shield of Volgo-Sarmatia caused by

705 rotation during the assembly of supercontinent Columbia (Nuna). *Lithos* 174, 196–
706 216.

707 Bryan, S.E., Ernst, R.E., 2008. Revised definition of large igneous provinces (LIPs).
708 *Earth Science Reviews* 86, 175–202.

709 Campbell, I.H., Griffiths, R.W., 1990. Implications of mantle plume structure for the
710 evolution of flood basalts. *Earth and Planetary Science Letters* 99, 79–93.

711 Cashman, K.V., Sparks, R.S.J., 2013. How volcanoes work: a 25 year perspective.
712 *Geological Society of America Bulletin* 125, 664–690.

713 Cederberg, J., Söderlund, U., Oliveira, E.P., Ernst, R.E., Pisarevsky, S.A., 2016. U-Pb
714 baddeleyite dating of the Proterozoic Pará de Minas dyke swarm in the São
715 Francisco craton (Brazil) – implications for tectonic correlation with the Siberian,
716 Congo and North China cratons. *GFF* 138:1, 219–240.

717 Chaves, A.O., Correia Neves, J.M., 2005. Radiometric ages, aeromagnetic expression,
718 and geology of mafic dykes from southern Brazil and implications for African–South
719 American correlations. *Journal of South American Earth Sciences* 19: 387–397.

720 Chemale Jr., F., Dussin, I.A., Alkmim, F.F., Martins, M.S., Queiroga, G., Armstrong, R.,
721 Santos, M.N., 2012. Unravelling a Proterozoic basin history through detrital zircon
722 geochronology: the case of the Espinhaço Supergroup, Minas Gerais, Brazil.
723 *Gondwana Research* 22, 200–206.

724 Claoue-Long, J.C., Compston, W., Roberts, J., Fanning, C.M., 1995. Two
725 Carboniferous ages: A comparison of SHRIMP zircon ages with conventional zircon
726 ages and $^{40}\text{Ar}/^{39}\text{Ar}$ analysis. In: Berggren, W.A., Kent, D.V., Aubrey, M.P.,
727 Hardenbol, J. (Eds.), *Geochronology, time scales, and global stratigraphic*
728 *correlation*. SEPM Special Publication 54, pp. 3–21.

729 Czuppon, G., Ramsay, R.R., Özgenç, I., Demény, A., Gwalani, L.G., Rogers, K.A.,
730 Eves, A., Papp, L., Palcsu, L., Berkesi, M., Downes, P.J., 2014. Stable (H, O, C) and
731 noble-gas (He and Ar) isotopic compositions from calcite and fluorite in the
732 Speewah Dome, Kimberley Region, Western Australia: implications for the
733 conditions of crystallization and evidence for the influence of crustal-mantle fluid
734 mixing. *Mineralogy and Petrology* 108, 759–775.

735 De Paolo, D.J., Manga, M., 2003. Deep origin of hotspots – mantle plume model.
736 *Science* 300, 920–921.

737 Denyszyn, S.W., Fiorentini, M.L., Maas, R., Dering, G., 2018. A Bigger Tent for CAMP.
738 *Geology* 46, 823–826.

739 Dow, D.B., Gemuts, I., 1967. Dixon Range, WA Sheet SE 52-6, 1:250 000 Geological
740 Series Explanatory Notes, Bureau of Mineral Resources, Australia, 15p.

741 Dunnet, D., Plumb, K.A., 1964. Explanatory notes to accompany the Lissadell
742 1:250,000 Geological Sheet SE 52-2, Western Australia. Bureau of Mineral
743 Resources Australia, Record 1964/70.

744 Ernst, R.E., Bleeker, W., 2010. Large Igneous Provinces (LIPs), giant dyke swarms,
745 and mantle plumes: significance for breakup events within Canada and adjacent
746 regions from 2.5Ga to the Present. *Canadian Journal of Earth Sciences* 47, 695–
747 739.

748 Ernst, R.E., Buchan, K.L., 2001. Large mafic events through time and links with mantle
749 plume-heads. *Geological Society of America, Special Paper* 352, 483–576.

750 Ernst, R.E., Liikane, D.A., Jowitt, S.M., Buchan, K.L., Blanchard, J.A., 2019. A new
751 plumbing system framework for mantle-plume related continental Large Igneous

- 752 Provinces and their mafic-ultramafic intrusions. *Journal of Volcanology and*
753 *Geothermal Research* 384, 75–84.
- 754 Ernst, R.E., Söderlund, U., Baratoux, L., Jessell, M.W., Cournède, C., Bleeker, W.,
755 2014. 1790 Ma dyke swarm in southwest Niger (West African craton): part of a
756 regional LIP that extends into formerly attached Amazonia and Sarmatia. 25th
757 Colloquium of African Geology (CAG25), 11–14 August 2014, Dar Es Salaam,
758 Tanzania.
- 759 Eupene, G.S., 1970. Observations on the petrology of the igneous rocks, Speewah
760 Valley, Western Australia. Geological Survey of Western Australia, Open File Report
761 A060461.
- 762 Ferreira, V.P., Sial, A.N., Weinberg, R.F., Pimental, M.M. 2015. Deep-seated
763 fragmentation, transport of breccia dykes and emplacement: An example from the
764 Borborema province, northeastern Brazil. *Journal of South American Earth Sciences*
765 58, 300–308.
- 766 Ganguly, J., 2005. Adiabatic decompression and melting of mantle rocks: An
767 irreversible thermodynamic analysis. *Geophysical Research Letters* 32, L06312,
768 doi:10.1029/2005GL022363
- 769 Gellatly, G.C., Derrick, G.M., 1967. Lansdowne, WA Sheet SE 52-5, 1:250 000
770 Geological Series Explanatory Notes. Bureau of Mineral Resources, 28p.
- 771 Gellatly, D.C., Derrick, G.M., Halligan, R., Sofoulis, J., 1974. The geology of the
772 Charnley 1:250 000 Sheet area, Western Australia. Bureau of Mineral Resources,
773 Report 154.
- 774 Geological Survey of Western Australia, 2017. 1:500 000 Tectonic units of Western
775 Australia, 2017. Geological Survey of Western Australia, digital product.
- 776 Gladkochub, D.P., Pisarevsky, S.A., Donskaya, T.V., Ernst, R.E., Wingate, M.T.D.,
777 Söderlund, U., Mazukabzov, A.M., Sklyarov, E.V., Hamilton, M.A., Hanes, J.A.,
778 2010. Proterozoic mafic magmatism in Siberian craton: an overview and implications
779 for paleocontinental reconstruction. *Precambrian Research* 183, 660–668.
- 780 Griffin, T.J., Grey, K., 1990. Kimberley Basin. In: *Geology and Mineral Resources of*
781 *Western Australia*. Geological Survey of Western Australia, Memoir 3, pp. 293–304.
- 782 Griffin, T.J., Page, R.W., Sheppard, S., Tyler, I.M. 2000. Tectonic implications of
783 Palaeoproterozoic post-collisional, high-K felsic igneous rocks from the Kimberley
784 region of northwestern Australia. *Precambrian Research* 101, 1–23.
- 785 Griffin, T.J., Tyler, I.M., Playford, P.E., 1993. Lennard River, WA Sheet SE 51-8, 1:250
786 000 Geological Series Explanatory notes, third edition. Geological Survey of
787 Western Australia, 56p.
- 788 Gumsley, A.P., Chamberlain, K.R., Bleeker, W., Söderlund, U., de Kock, M.O.,
789 Larsson, E.R. Bekker, A., 2017. Timing and tempo of the Great Oxidation Event.
790 *Proceedings of the National Academy of Sciences* 114, p. 1811–1816.
- 791 Gunn, P.J., Meixner, A.J., 1998. The nature of the basement to the Kimberley Block,
792 northwestern Australia. *Exploration Geophysics* 29, 506–511.
- 793 Gwalani, L.G., Rogers, K.A., Demeny, A., Groves, D.I., Ramsay, R., Beard, A.,
794 Downes, P.J. Eves, A.E., 2010. The Yungul carbonatite dykes associated with the
795 epithermal fluorite deposit at Speewah, Kimberley, Australia: carbon and oxygen
796 isotopic constraints on their origin. *Mineralogy and Petrology* 98, 123–141.
- 797 Haggerty, B.M., 1996. Episodes of flood-basalt volcanism defined by $^{40}\text{Ar}/^{39}\text{Ar}$ age
798 distributions: Correlation with mass extinctions? *Journal of Undergraduate Sciences*
799 3, 155–164.

- Halls, H.C., Campal, N., Davis, D.W., Bossi, J., 2001. Magnetic studies and U–Pb geochronology of the Uruguayan dyke swarm, Rio de la Plata craton, Uruguay: petromagnetic and economic implications. *Journal of South American Earth Sciences* 14, 349–361.
- Heaman, L.M. 2008. The application of U–Pb geochronology to mafic, ultramafic and alkaline rocks: an evaluation of three mineral standards. *Chemical Geology* 261, 43–52.
- Hollis, J., Kemp, A., Tyler, I.M., Kirkland, C.L., Wingate, M.T.D., Phillips, C., Sheppard, S., Belousova, E., Greau, Y., 2014. Basin formation by orogenic collapse: zircon U–Pb and Lu–Hf isotope evidence from the Kimberley and Speewah Groups, Northern Australia. *Geological Survey of Western Australia, Report 137*, 46p.
- Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.T., Essling, A.M., 1971. Precision measurement of half-lives and specific activities of U235 and U238. *Physical Review C* 4(5), 1889.
- Johansson, A., 2009. Baltica, Amazonia and the SAMBA connection—1000 million years of neighbourhood during the Proterozoic? *Precambrian Research* 175:1–4, 221–234.
- Johnson, S.P., 2013. The birth of supercontinents and the Proterozoic assembly of Western Australia. *Geological Survey of Western Australia*, 78p.
- Jourdan, F., Hodges, K., Sell, B., Schaltegger, U., Wingate, M.T.D., Evins, L.Z., Söderlund, U., Haines, P.W., Philips, D., Blenkinsop, T., 2013. High-precision dating of the Kalkarindji large igneous province, Australia, and synchrony with the Early–Middle Cambrian (Stage 4–5) extinction. *Geology* 42, 543–546.
- Kamo, S.L., Czamanske, G.K., Amelin, Y., Fedorenko, V.A., Davis, D.W., Trofimov, V.R., 2003. Rapid eruption of Siberian flood-volcanic rocks and evidence for coincidence with the Permian–Triassic boundary and mass extinction at 251 Ma. *Earth and Planetary Science Letters* 214, 75–91.
- Kavanagh, J.L., Menand, T., Sparks, R.S.J., 2006. An experimental investigation of sill formation and propagation in layered elastic media. *Earth and Planetary Science Letters* 245, 799–813
- Kirscher U., Liu Y., Li Z.-X., Mitchell R. N., Pisarevsky S.A., Denyszyn S.W., Nordsvan A. (2019) Paleomagnetism of the Hart Dolerite (Kimberley, Western Australia) – A two-stage assembly of the supercontinent Nuna? *Precambrian Research*, 2018, doi: 10.1016/j.precamres.2018.12.026
- Kirkland, C.L., Wingate, M.T.D., Hollis, J., Phillips, C., 2014. 206154: pelitic migmatite, Paperbark Bore; Geochronology Record 1204: Geological Survey of Western Australia, 6p.
- Kirkland, C.L., Wingate, M.T.D., Tyler, I.M., Hollis, J., Bodorkos, S., 2013. 206102: sandstone, Richenda River; Geochronology Record 1135: Geological Survey of Western Australia, 5p.
- Kohanpour, F., Gorczyk, W., Lindsay, M.D., Occhipinti, S., 2017. Examining tectonic scenarios using geodynamic numerical modelling: Halls Creek Orogen, Australia. *Gondwana Research* 46, 95–113.
- Kroonenberg, S.B., de Roever, E.W.F., Fraga, L.M., Reis, N.J., Faraco, T., Lafon, J.-M., Cordani, U., Wong, T.E., 2016. Paleoproterozoic evolution of the Guiana Shield in Suriname: A revised model. *Geologie en Mijnbouw* 95-4, 491–522.

- 846 Leshner, C.M., 2017. Roles of xenomelts, xenoliths, xenocrysts, xenovolatiles, residues,
847 and skarns in the genesis, transport and localisation of magmatic Fe-Ni-Cu-PGE
848 sulphides and chromite. *Ore Geology Reviews* 90, 465–484.
- 849 Li, X.H., Su, L., Chung, S.L., Li, Z.X., Liu, Y., Song, B., Liu D.Y., 2005. Formation of the
850 Jinchuan ultramafic intrusion and the world's third largest Ni-Cu sulfide deposit:
851 Associated with the ~825 Ma south China mantle plume? *Geochemistry Geophysics*
852 *Geosystems* 6, 1–16.
- 853 Li, Z.-X., Zhang, L., Powell, McA.C., 1996. Positions of the East Asian cratons in the
854 Neoproterozoic supercontinent Rodinia: *Australian Journal of Earth Sciences* 43,
855 593–604.
- 856 Lu, Y., Wingate, M.T.D., Kirkland, C.L., Maidment, D.W., Phillips, C., Hollis, J.A., 2016.
857 212344: pelitic schist, Napier Creek; *Geochronology Record* 1348: Geological
858 Survey of Western Australia, 6p.
- 859 Ludwig, K.R., 2009. *Squid 2.50, a user's manual*. Berkeley Geochronology Centre,
860 95p.
- 861 Ludwig, K.R., 2012. User's manual for *Isoplot 3.75*, revised 30 January, 2012. Berkeley
862 Geochronology Centre, Special Publication 5, 75p.
- 863 Maier, W.D., Barnes, S.-J., Gartz, V., Andrews, G., 2003. Pt-Pd reefs in magnetitites of
864 the Stella layered intrusion, South Africa: A world of new exploration opportunities
865 for platinum group elements. *Geology* 31, 885–888.
- 866 McElhinny, M.W., Evans, M.E., 1976. Palaeomagnetic results from the Hart Dolerite of
867 the Kimberley Block, Australia. *Precambrian Research* 3, 231–241.
- 868 Morin, D., Corriveau, L., 1996. Fragmentation processes and xenolith transport in a
869 Proterozoic minette dyke, Grenville Province, Quebec. *Contributions to Mineralogy*
870 *and Petrology* 125, 319–331.
- 871 Mudd, G.M., Jowitt, S., 2014. A detailed assessment of global nickel resource trends
872 and analysis. *Economic Geology* 109, 1813–1841.
- 873 Mudd, G.M., Jowitt, S., Werner, T.T., 2018. Global platinum group element resources,
874 reserves and mining – A critical assessment. *Science of the Total Environment*, 622–
875 623, 614–625.
- 876 Nasdala, L., Hofmeister, W., Norberg, N., Mattinson, J.M., Corfu, F., Dörr, W., Kamo,
877 S.L., Kennedy, A.K., Kronz, A., Reiners, P.W., Frei, D., Kosler, J., Wan, Y., Götze,
878 J., Häger, T., Kröner, A., Valley, J.W., 2008. Zircon M257 — a homogeneous natural
879 reference material for the ion microprobe U–Pb analysis of zircon. *Geostandards*
880 *and Geoanalytical Research* 32, 247–265.
- 881 Neumann, E.-R., Svensen, H., Galerne, C.Y., Planke, S., 2011. Multistage evolution of
882 dolerites in the Karoo Large Igneous Province, central South Africa. *Journal of*
883 *Petrology* 52, 959–984.
- 884 Niplats, 2008. Two PGE+Au zones identified in the Speewah Dome, northern Western
885 Australia. Niplats Australia Ltd ASX Report, NIP 2008–08-23.
- 886 Norcross, C., Davis, D.W., Spooner, E.T.C., Rust, A., 2000. U–Pb and Pb–Pb age
887 constraints on Paleoproterozoic magmatism, deformation and gold mineralization in
888 the Omai area, Guyana Shield. *Precambrian Research* 102, 69–86.
- 889 Orth, K., Hollis, J., Phillips, C., Wingate, M.T.D., 2015. Regional potential for Ti–V–Fe
890 ore in the intrusive complex of the 1,795 Ma Hart–Carson Large Igneous Province,
891 northern Western Australia. *Society of Exploration Geologists*, Hobart.

- Oyhantçabal, P., Siegesmund, S., Wemmer, K., 2011. The Rio de la Plata Craton: a review of units, boundaries, ages and isotopic signature. *International Journal of Earth Sciences* 100, 201–220.
- Page, R.W., Griffin, T.J., Tyler, I.M., Sheppard, S., 2001. High- and low-K granites and adakites at a Palaeoproterozoic plate boundary in northwestern Australia. *Journal of the Geological Society* 158, 547–560.
- Page, R.W., Sun, S-S., 1994. Evolution of the Kimberley region, WA and adjacent Proterozoic inliers — new geochronological constraints. *Geoscience Australia — 1994 and Beyond*, Geological Society of Australia Abstracts 37, pp. 332–333.
- Pang, K.N., Zhou, M.F., Qi, L., Shellnutt, G., Wang, C.Y., Zhao, D., 2010. Flood basalt-related Fe–Ti oxide deposits in the Emeishan large igneous province, SW China. *Lithos* 119, 123–136.
- Peng, P., Zhai, M.G., Zhang, H., Guo, J.H., 2005. Geochronological Constraints on the Paleoproterozoic evolution of the North China Craton: SHRIMP zircon ages of different types of mafic dikes. *International Geology Review* 47, 492–508.
- Peng, P., Zhai, M.G., Guo, J.H., 2006. 1.80 – 1.75 Ga mafic dyke swarms in the central North China craton: implications for a plume-related break-up event. In: Hanski, E., Mertanen, S., Ramo, T., Vuollo, J. (Eds.), *Dyke Swarms – Time Markers of Crustal Evolution*, Taylor & Francis, London, pp. 99–112.
- Phillips, C., Maidment, D.W., Lu, Y., 2017. Revised tectono-stratigraphy of the Kimberley Basin, northern Western Australia. *Geological Survey of Western Australia, Record* 2017/2, pp. 33–37.
- Pidgeon, R.T., Furfaro, D., Kennedy, A.K., Nemchin, A.A., Van Bronswijk, W., 1994. Calibration of zircon standards for the Curtin SHRIMP II. Eighth International Conference on Geochronology, Cosmochronology, and Isotope Geology — Abstracts, United States Geological Survey, Circular 1107, p. 251.
- Plumb, K.A., 1968. Lissadell, WA Sheet SE 52-2, 1:250 000 Geological Series Explanatory Notes. Bureau of Mineral Resources, 31p.
- Plumb, K.A., Gemuts, I., 1976. Precambrian geology of the Kimberley region, Western Australia. 25th International Geological Congress, Excursion Guide 44C, 69p.
- Ramsay, R.R., Eves, A.E., Wingate, M.T.D., Fiorentini, M.L., Batt, G., Rogers, K., Gwalani L.G., Martin, S., 2017. Detrital zircon geochronology of the Speewah Group, Kimberley region, Western Australia: Evidence for intracratonic development of the Paleoproterozoic Speewah Basin. *Australian Journal of Earth Sciences* 64, 419–434.
- Reis, N.J., Teixeira, W., Hamilton, M.A., Bispo-Santos, F., Elmeida, M.E., D'Agrello-Filho, M.S., 2013. Avanavero mafic magmatism, a late Paleoproterozoic LIP in the Guiana Shield, Amazonian Craton: U–Pb ID-TIMS baddeleyite, geochemical and paleomagnetic evidence. *Lithos* 174, 175–195.
- Rogers, K.A., 1998. Speewah fluorite deposit. In: Berkman, D.A., Mackenzie, D.H. (Eds.), *Geology of Australian and Papua New Guinean mineral deposits*. Australasian Institute of Mining and Metallurgy, Monograph 22, 387–392.
- Santos, J.O.S., Potter, P.E., Reis, N.J., Hartmann, L.A., Fletcher, I.R., McNaughton, N.J., 2003. Age, source and regional stratigraphy of the Roraima Supergroup and Roraima-like outliers in northern South America based on U–Pb geochronology. *Geological Society of America Bulletin* 115, 331–348.

- 938 Shellnutt, J.G., Denyszyn, S.W., Mundil, R., 2012. Precise age determination of mafic
939 and felsic intrusive rocks from the Permian Emeishan large igneous province (SW
940 China). *Gondwana Research* 22, 118–126.
- 941 Sheppard, S., Griffin, T.J., Tyler, I.M., Page, R.W., 2001. High- and low-K granites and
942 adakites at a Palaeoproterozoic plate boundary in northwestern Australia. *Journal of*
943 *the Geological Society of London* 158, 547–560.
- 944 Sheppard, S., Page, R.W., Griffin, T.J., Rasmussen, B., Fletcher, I.R., Tyler, I.M.,
945 Kirkland, C.L., Wingate, M.T.D., Hollis, J.A., Thorne, A.M., 2012. Geochronological
946 and isotopic constraints on the tectonic setting of the c. 1800 Ma Hart Dolerite and
947 the Kimberley and Speewah Basins, northern Western Australia. *Geological Survey*
948 *of Western Australia, Record* 2012/7, 28p.
- 949 Sheppard, S., Thorne, A.M., Tyler, I.M., 1999. *Geology of the Bow 1:100 000 Sheet,*
950 *1:100 000 Geological Series Explanatory Notes*, Geological Survey of Western
951 Australia, 36p.
- 952 Shumlyanskyy, L., Billström, K., Hawkesworth, C., Elming, S.-A., 2012. U-Pb age and Hf
953 isotope compositions of zircons from the north-western region of the Ukrainian
954 shield: mantle melting in response to post-collision extension. *Terra Nova* 24:5,
955 373–379.
- 956 Sleep, N.H., 2006. Mantle plumes from top to bottom. *Earth Science Reviews* 77, 231–
957 271.
- 958 Sluzhenikin, S., 2011. Platinum-copper-nickel and platinum ores of Norilsk Region and
959 their ore mineralization. *Russian Journal of General Chemistry* 81, 1288–1301.
- 960 Speewah Metals Ltd., 2012. Significant resource upgrade for the Speewah titanium
961 vanadium deposit. Speewah Metals Ltd: ASX report - 2012-03-12.
- 962 Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by
963 a two-stage model. *Earth and Planetary Science Letters* 26, 207–221.
- 964 Stern, R.A., Bodorkos, S., Kamo, S.L., Hickman, A.H., Corfu, F., 2009. Measurement of
965 SIMS instrumental mass fractionation of Pb isotopes during zircon dating.
966 *Geostandards and Geoanalytical Research* 33, 145–168.
- 967 Taisne B., Jaupart, C. 2009. Dike propagation through layered rocks. *Journal of*
968 *Geophysical Research* 114, doi.org/10.1029/2008JB006228.
- 969 Teixeira, W., D'Agrella-Filho, S.M., Hamilton, A.M., Ernst, E.R., Girardi, V.A.V.,
970 Mazzucchelli, M., Bettencourt, S.J., 2013. U–Pb (ID-TIMS) baddeleyite ages and
971 paleomagnetism of 1.79 and 1.59 Ga tholeiitic dyke swarms, and position of the Rio
972 de la Plata Craton within the Columbia supercontinent. *Lithos* 174, 157–174.
- 973 Thorne, A.M., Sheppard, S., Tyler, I.M. 1998. Lissadell, WA Sheet SE52-2, 1:250 000
974 Geological Series Map, Second Edition, Geological Survey of Western Australia.
- 975 Thorne, A.M., Sheppard, S., Tyler, I.M. 1998. Lissadell, WA Sheet SE52-2, 1:250,000
976 Geological Series Explanatory Notes, Second Edition. Geological Survey of Western
977 Australia, 68p.
- 978 Traves, D.M., 1955. The geology of the Ord-Victoria region, northern Australia. Bureau
979 of Mineral Resources, Bulletin 27, 133p.
- 980 Tyler, I.M., Hocking, R.M., Haines, P.W., 2012. Geological evolution of the Kimberley
981 region, Western Australia. *Episodes* 35, 298–306.
- 982 Tyler, I.M., Pirajno, F., Bagas, L., Myers, J.S., Preston, W. 1998. The geology and
983 mineral deposits of the Proterozoic in Western Australia. *AGSO Journal of Geology*
984 *and Geophysics* 17, 223–244.

985 Tyler, I.M., Sheppard, S., Pirajno, F., Griffin, T.J., 2006. Hart-Carson LIP, Kimberley
 986 region, northern Western Australia. Event No. 143 in LIP record database.
 987 www.largeigneousprovinces.org/06aug
 988 Wingate, M.T.D., Compston, W., 2000. Crystal orientation effects during ion
 989 microprobe U–Pb analysis of baddeleyite. *Chemical Geology* 168, 75–97.
 990 Wingate, M.T.D., Lu, Y., 2017. Introduction to geochronology information 2017.
 991 Geological Survey of Western Australia, 5p.
 992 Worden, K.E., Carson, C.J., Close, D.F., Donnellan, N., Scrimgeour, I.R., 2008.
 993 Summary of results. Joint NTGS–GA geochronology: Tanami Region, Arunta
 994 Region, Pine Creek orogen and Halls Creek Orogen correlatives, January 2005–
 995 March 2007. Northern Territory Geological Survey, Record 2008-003, 180p.
 996 Zeh, A., Ovtacharova, M., Wilson, A.H., Schaltegger, U., 2015. The Bushveld Complex
 997 was emplaced and cooled in less than one million years – results of zirconology,
 998 and geotectonic implications. *Earth and Planetary Science Letters* 418, 103–114.
 999
 1000

Figure captions

Fig 1. Regional geological map showing the Hart Dolerite and Carson Volcanics (Hart–Carson large igneous province), major sedimentary basins, and basement units of the Lamboo Province (Geological Survey of Western Australia, 2015). Also shown are SHRIMP U–Pb sample locations in the felsic phase of the Hart Dolerite (from Sheppard et al., 2012) and new sample locations in gabbroic rocks.

Fig 2. Local geology of the Hart Dolerite within the Speewah Dome based on mapping during this study and by GSWA (Thorne et al., 1998), showing the locations of drillholes and geochronology samples (see also Table 2) .

Fig 3. Interpreted cross-section of the Hart Dolerite sill based on drillhole information, illustrating the distribution and thickness of the mafic and felsic rock types, and the schematic locations of three geochronology samples (Table 2). Datum is the basal contact of the sill (at 600 m depth) with underlying Speewah Group metasedimentary rocks.

Fig 4. Photomicrographs and outcrop images of: (a) coarse-grained gabbro showing minor olivine and more abundant plagioclase enclosed by coarse-grained augitic pyroxene (crossed-polars); (b) medium-grained gabbro with aggregates of magnetite in weathered outcrop from the upper interval of the spotted magnetite gabbro (pen is about 10 cm long); (c) outcrop of medium-grained disseminated magnetite gabbro showing blocky aligned xenoliths and amoeboid xenoliths with leucocratic margins (hammer is about 50 cm long); (d) coarser-grained to pegmatitic gabbro in outcrop containing granophyric segregations of quartz and K-feldspar (pouch is about 5 cm wide); (e) mafic granophyre in three polished sections of drillcore, showing the close-packed, greenish grey, altered, gabbroic xenoliths in pink potassic matrix (field of view is about 30 cm); (f) felsic granophyre in outcrop showing altered acicular ferromagnesian minerals in a potassic matrix. Scale is about 5 cm in length; (g) pegmatitic pigeonite gabbro vein (sample GSWA 206156) in outcrop of medium-grained dolerite – the vein is 6 cm wide; (h) baddeleyite crystals recovered from sample GSWA 206156.

Fig 5. Concordia diagrams showing U–Pb analytical data by IDTIMS for baddeleyite in (a) sample GS11043-1 (disseminated magnetite gabbro), and (b) sample GS12051-2 (pegmatitic gabbro); (c) by SHRIMP for baddeleyite in sample GSWA 206156 (pigeonite gabbro vein); and (d) by IDTIMS and SHRIMP for zircons in sample GS11042-3 (granitic gneiss xenolith). In (c) and (d), yellow squares indicate analyses

included in calculating igneous crystallisation or protolith age; red circles indicate analyses of inherited zircons; black squares indicate radiogenic-Pb loss; crossed squares indicate analyses with discordance >5% or high common Pb. In (d), two discordant analyses are not shown. Uncertainties in mean ages are 2-sigma confidence intervals; MSWD, mean square of weighted deviates; error ellipses and error bars are 1 sigma.

Supplementary Data Tables

Supplementary Data Table 1. ID-TIMS U–Pb analytical data

Supplementary Data Table 2. SHRIMP U–Pb analytical data

Table 1. Stratigraphic succession in the Speewah and Kimberley Basins

Group/ Supersuite	Stratigraphic Unit	Maximum thickness (m)	Description
Kalkarindji Supersuite	Antrim Plateau Volcanics	---	Massive and amygdaloidal tholeiitic basalt and basalt breccia; commonly capped by ferricrete. Agglomerate with brecciated flow tops. Minor sandstone and chert interbeds (Traves, 1955). Part of the c. 511 Ma Kalkarindji large igneous province (Jourdan et al., 2013).
Kimberley Group	Pentecost Sandstone	1400	Medium-grained quartz sandstone with interbeds of fine-grained to medium-grained feldspathic sandstone, micaceous and glauconitic sandstone, shale-pellet conglomerate (Gellatly and Derrick, 1967).
	Elgee Siltstone	250	Red-brown siltstone with thin interbeds of fine-grained micaceous, ferruginous and feldspathic sandstone. The basal interval includes beds of stromatolitic, sandy or oolitic dolomite (Gellatly and Derrick, 1967).
	Warton Sandstone	500	Cross-bedded, commonly white to purple, medium-grained quartz sandstone and minor feldspathic sandstone. Locally there is a 1–5 m thick siltstone between the volcanic rocks and sandstone with siliceous stromatolites (Gellatly, and Derrick, 1967).
	Carson Volcanics	1400	Green to black, locally amygdaloidal basalt and basaltic volcanoclastic rocks with interbeds of feldspathic or argillaceous quartz sandstone, laminated siltstone and mudstone (Gellatly, et al., 1967).
	Hart Dolerite	3000	Gabbro, dolerite, diorite, granophyre; pyroxene granophyre differentiate overlies the dolerite and gabbro in some thicker sills (Dow and Gemuts, 1967). Intrudes all units of the Speewah Group, the King Leopold Sandstone and lower Carson Volcanics.
	King Leopold Sandstone	1050	White, thick-bedded, medium-to coarse-grained quartz sandstone with trough cross-bedding and minor pebble bands (Dow and Gemuts, 1967).

Speewah Group	Bedford Sandstone	500	Argillaceous and feldspathic quartz sandstone containing minor quartz, chert and claystone pebbles and showing large-scale cross-beds; basal red-purple-brown medium-grained quartzite and thin interbeds of flaggy micaceous fine sandstone (Griffin et al., 1993).
	Luman Siltstone	75	Rippled red-brown to grey-green micaceous siltstone and phyllite interbedded with fine feldspathic sandstone (Dow and Gemuts, 1967).
	Lansdowne Arkose	400	Pink to red-brown, medium-grained feldspathic to arkosic sandstone with small cross-beds, less coarse poorly-sorted sandstone and green to brown micaceous siltstone, shale and phyllite (Dow and Gemuts, 1967).
	Valentine Siltstone	75	Dark grey-green tuff and tuffaceous siltstone with conchoidal fracture surfaces, grey-green flaggy laminated siltstone and fine feldspathic sandstone (Dow and Gemuts, 1967). Intruded by Hart Dolerite sill in the Speewah Dome area. Zircons dated at 1835 ± 3 Ma in volcanoclastic rock (Page and Sun, 1994; Sheppard et al., 2012) were proposed as reflecting a xenocrystic component by Ramsay et al. (2017).
	Tunganary Formation	290	Fine-grained feldspathic sandstone interbedded with micaceous or sericitic siltstone, phyllite and minor coarse quartz sandstone (Dow and Gemuts, 1967). Youngest detrital zircon age component at 1814 ± 10 Ma includes a youngest zircon at 1806 Ma (Ramsay et al., 2017)
	O'Donnell Formation	260	Rippled and graded massive poorly sorted coarse to granule quartz sandstone, locally lithic, ferruginous or glauconitic; olive green to fawn micaceous silty shale, and conglomerate mainly near the base (Dow and Gemuts, 1967)
Lamboo Province	Western Zone	---	Metagreywackes of the Marboo Formation with oldest zircons from the peak of metamorphism at c. 1872 (Worden et al., 2008). Intruded by granitic rocks of the Paperbark Supersuite and overlain by late-stage felsic volcanic rocks of the ca. 1855 Ma Whitewater Volcanics (Page et al., 2001).

Table 2. Geochronology samples in the Hart Dolerite sill

Northing (mN)	Easting (mE)	Sample ID	Rock type
8075529	350412	GSWA 206156	Pegmatitic pigeonite gabbro vein
8198709	385864	GS12051-2	Pegmatitic gabbro
8190784	387832	GS11043-1	Disseminated magnetite gabbro
8203010	387731	GS11042-3	Xenolith of felsic granulite in basal disseminated magnetite gabbro

UTM coordinates (Easting and Northing) are GDA94 Zone 52

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5