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Department of **Mines, Industry Regulation and Safety**

DIAMOND EXPLORATION AND PROSPECTIVITY OF WESTERN AUSTRALIA

by MT Hutchison

EXPLORATION
INCENTIVE
SCHEME

Geological Survey of Western Australia

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DIAMOND EXPLORATION AND PROSPECTIVITY OF WESTERN AUSTRALIA

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MT Hutchison

PERTH 2018

Geological Survey of Western Australia

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Cover photograph: Run of mine production from Ellendale 9 post-acid cleaning, showing the range of size, morphology and colour of production, 2008, Photograph by MT Hutchison

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Diamond exploration and prospectivity of Western Australia

by

MT Hutchison

Abstract

Pre-1.6 Ga rocks comprise approximately 45% of the onshore surface area of Western Australia, and form the West Australian Craton (including the Archean Yilgarn and Pilbara Cratons) and the western part of the North Australian Craton. As kimberlite and lamproite emplacement ages span close to 2500 million years, there are significant opportunities for diamond-affinity rocks being present near-surface also among the expansive sedimentary basins that overlie the thick mantle lithosphere. Most of the State is therefore prospective for diamonds and numerous diamondiferous lamproite and kimberlite fields are known to exist. At its peak in 2015, Australia produced approximately 11% of global rough diamond production by weight, exclusively due to Western Australia's production. Western Australia's size, terrain, infrastructure, and climate mean that many areas remain underexplored. However, continuous diamond exploration since the 1970s has resulted in abundant data.

In order to advance future exploration, Western Australia's diamond exploration database comprising 88 515 diamond exploration samples and data from 524 discrete in situ bodies with diamond potential (kimberlites, lamproites, ultramafic lamprophyres, and carbonatites) has been assessed. The most successful sampling methodologies employed by exploration programs have assessed mineral grains down to 0.2 or 0.3 mm in size that have been taken from high-energy trap sites. The large majority of nondiamond indicator minerals are spinels, which are relatively durable in the harsh weathering environment. Additionally, garnet, diopside, ilmenite, Cr-pseudobrookite, orthopyroxene, monticellite and olivine with indicator chemistries have been recovered. The Yilgarn and Pilbara Cratons and samples sourced further west to the coastline contain spinel indicators almost exclusively dominated by chromite (>90%). In contrast, (Mg,Fe,Ti)-bearing Al-chromites account for larger proportions of indicator spinels in North Australian Craton samples, with up to 50% in some samples bordering the Northern Territory. Increasing dominance of Al in chromites is interpreted as a sign of a shallower source than for Al-depleted Mg-chromites. Garnet compositions across the State also correlate with geographic subdivisions, with lherzolitic garnets showing more prospective compositions (Ca-depleted) in West Australian Craton samples compared with the North Australian Craton. West Australian Craton samples also show a much broader scatter into strongly diamond-prospective G10 and G10D compositions. Ilmenites from the North Australian Craton show Mg-enriched compositions (consistent with kimberlites) over and above those present in the Northern Territory data. However, again consistent with findings for other minerals, ilmenites from the West Australian Craton (particularly the Hamersley Basin and Eastern Goldfields) show the most diamond-prospective trends.

Prospectivity analysis has been carried out by subdividing the State into 67 tectonic units. A prospectivity map has been produced by analysing the extent and results of sampling, in conjunction with the age of surface rocks relative to ages of diamond-prospective rocks and the underlying mantle structure in each unit. The resulting map presents a 13-level ranking of attractiveness for future diamond exploration. Locations within the North Australian Craton and in proximity to Western Australia's diamond mines score well. However, results point to parts of the West Australian Craton being more prospective, which is consistent with mineral chemical data. Most notable of these are the Hamersley Basin, Eastern Goldfields Superterrane and the Goodin Inlier of the Yilgarn Craton.

Despite prolific diamond exploration, Western Australia is considerably underexplored and the ageing Argyle mine and recent closure of operations at Ellendale warrant a re-evaluation of the State's diamond potential. The results of this prospectivity analysis make a compelling case for renewed diamond exploration within Western Australia.

KEYWORDS: databases, diamonds, diamond exploration, mineral deposits, lamproite, kimberlite, lamprophyre, indicator minerals, chromite, chrome diopside, garnet, picroilmenite, microdiamonds

Introduction

Away from areas of thick cover, Western Australia hosts 696 000 km^2 of onshore, exclusively Archean rocks and 439 000 km^2 of Paleoproterozoic rocks (Fig. 1). Pre-1.6 Ga rocks comprise approximately 45% of the onshore area of the State, constituting the West Australian Craton (WAC), which includes the Yilgarn Craton (Wyche et al., 2012) and the Pilbara Craton (Hickman and Van Kranendonk, 2012), and the western part of the North Australian Craton (NAC). The NAC (Gun and Meixner, 1998; Tyler et al., 2012) extends into the Northern Territory. Seismic tomography has demonstrated that considerable remaining portions of the State are also underlain by thick mantle lithosphere (Kennett et al., 2013) that hosts the conditions under which diamonds form. Therefore, most of the State is prospective for diamonds and numerous diamondiferous lamproite and kimberlite fields are known to exist. Emplacement of diamond-bearing rocks spans much of geological time, from the c. 1868 Ma Brockman Creek kimberlite in the Pilbara (White, 2000) to the c. 17 Ma Walgidee Hills lamproite, Noonkanbah field, west Kimberley (Phillips et al., 2012). According to Kimberley Process Certification Scheme statistics, Australia is estimated to have produced approximately 11% of the global rough diamond production by weight in 2015, ranking it fourth in the world after the Russian Federation, Botswana and the Democratic Republic of Congo. These production figures are accounted for by two mines, both in Western Australia. However, due to the closure in 2015 of the Ellendale mine, which was responsible for a large proportion of the world's fancy yellow production, only one currently producing mine remains in Australia (the AK1 olivine lamproite at Argyle, NAC; Boxer and Jaques, 1990). In order to assess the effectiveness of prior exploration and draw attention to underexplored prospective areas, a thorough compilation (GSWA, 2018; Hutchison, 2018) and interpretation (this study) of Western Australian diamond exploration data has been conducted.

The purpose of this interpretation of the diamond exploration database (DED) for Western Australia (Hutchison, 2018) is to provide a general critique of the processes of diamond exploration in Western Australia and to scrutinize reported data. The DED provides a large, statewide dataset appropriate for assessing the characteristics to be expected during diamond exploration sampling. The core component of the DED comprises 88 515 database rows (records), each corresponding to a unique diamond exploration sample with a known sample location. The terms 'sample' and 'record' are therefore interchangeable. All figures in this interpretation document derive their data from the DED, unless otherwise stated. Furthermore, DED data shown in figures are the full datasets applicable as of September 2017, except where indicated otherwise. As the large majority of readily captured and statistically treated exploration data is geochemical rather than geophysical, focus on compiling and interpreting the database has been applied to results of mineral recovery and mineral chemical data, with a view principally to making statements on diamond potential in a regional context. As such, there is intentionally no deliberate focus on individual localities, but they are discussed in part where they provide insights into interpreting regional observations. Consequently, while the Argyle diamond mine places Western Australia high among rankings of world diamond production, there is little specific discussion of the wealth of published data on the pipe, and similarly for the recently mined Ellendale E4 and E9 pipes.

Jaques et al. (1986) provided an exhaustive account of the diamondiferous and diamond-prospective bodies of Western Australia known up until the date of publication, in addition to a thorough treatise on exploration history to that point. In particular, pre-1990s exploration largely identified diamondiferous bodies in northern Western Australia surrounding and within the NAC. The summaries from Jaques et al. (1986) have not been repeated in this report. However, it is recognized that significant and relevant diamond-prospective bodies have been identified in Western Australia since that time. The last 30 years have seen a considerable broadening of successful diamond exploration particularly into the WAC and beyond. While the academic literature and various publicly available company reports document these discoveries, no detailed summary document exists. Hence, while focusing on the regional perspective, the more recently discovered bodies are introduced and referenced in this report, thus assisting in the understanding of regional trends in the exploration data.

The ultimate aim of this interpretation is to lead explorers to areas of relatively high prospectivity and establish the criteria that have succeeded or failed in the past, in order to assist in future exploration. The establishment of a regional prospectivity model has taken two independent paths that lead to similar conclusions on diamond prospectivity in Western Australia. One path takes an observational approach whereby the density of sampling and success in visually identifying indicator minerals is married to knowledge of the ages of surface rocks relative to diamond-hosting rocks and the form of the current underlying lithosphere. Prospective areas follow a model where they are reasonably underexplored, but have yielded visually identified diamond indicators, have underlying thick lithosphere, and comprise rocks that are relatively old compared to diamond host rocks. The second path takes a different analytical approach. A wealth of mineral chemical data is available throughout much of Western Australia, although at a coarser spatial resolution than visual observations. Chemical data are associated both with known diamondiferous bodies and regional samples. Diamond indicator minerals (DIMs) provide a glimpse directly into the mantle, often uninfluenced by the chemistry of the host rocks that conveyed them to the surface. By scrutinizing mineral chemical characteristics of DIMs in terms of geographical location, conclusions can be reached on the relative prospectivity of different areas. More specifically, calculations may be performed to indicate their ranges of depth formation, hence allowing inferences on their origin in either the diamond or graphite stability field. This second approach has the advantage that it can be queried in a more sophisticated and varied manner and the window provided into the lithosphere relates to the time of emplacement rather than the present-day picture provided by geophysics. While the geochemical approach does not allow the same resolution of geographical subdivision as the observational approach, the two techniques complement each other.

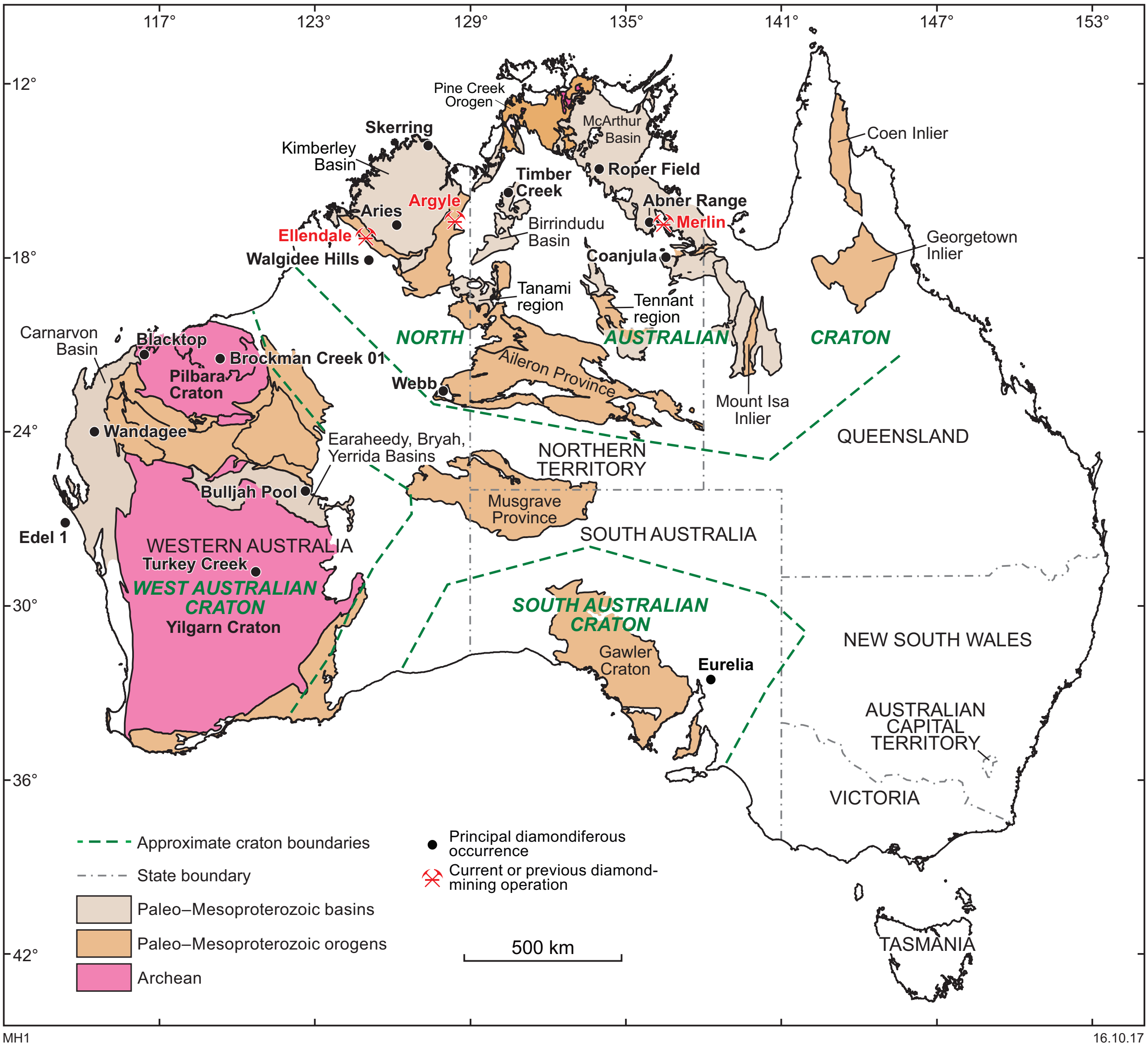

Figure 1. **Generalized map of Australia showing approximate craton boundaries, including under thick cover, and principal regions of Archean and Paleo–Mesoproterozoic rocks (modified from Hutchison, 2012). The boundaries of the North Australian Craton are adapted from Atkinson et al. (1990) and Kennett et al. (2011). Geological region boundaries follow current GeoScience Australia downloadable data and Kennett et al. (2011) and, for the Northern Territory, Ahmad and Scrimgeour (2013). The Ellendale lamproites reside within the King Leopold Mobile Zone and the Argyle pipe within the Halls Creek Mobile Zone. The Merlin kimberlite field lies within the McArthur Basin. All occurrences are in situ bodies with the exception of Coanjula, which is a microdiamond paleoplacer**

Terminology and key concepts in diamond exploration

Rock types

Primary magmatic sources of diamonds have traditionally been thought to be restricted to kimberlites. However, diamonds exist as xenocrysts, sometimes in economic concentrations, in lamproites (e.g. the AK1 pipe at Argyle; Jaques et al., 1986) and ultramafic lamprophyres such as aillikites (Hutchison and Frei, 2009). Australia provides many striking examples demonstrating the expansive range of rock types within which diamonds can be transported to the Earth's surface.

The term diamond-prospective rock is used here to describe a primary magmatic rock that has the potential, due to its chemical make-up and depth of origin, to host diamonds. Typically, the inference is by analogy to diamond-bearing rocks from elsewhere (kimberlites, lamproites and some ultramafic lamprophyres). However, in the case of carbonatites, which are included in this study, while the distinct possibility is there (Hutchison and Frei, 2009), no carbonatites according to the strict definition requiring over 50% carbonate minerals have actually been identified with diamonds. It is important to make the distinction between diamond-prospective and diamond-phyric rocks. While pathfinder minerals can allow an assessment of the likelihood that a particular rock contains diamonds, there exists a very wide variability in whether or not even closely similar rocks contain diamonds. Some types of lamproites contain diamonds, some do not or rarely do so (Jaques et al., 1986). Few lamprophyres contain diamonds, but some do (Tappe et al., 2005; Hutchison and Frei, 2009), and kimberlites show a strong variability in diamond occurrence, sometimes even within individual pipes (Kjarsgaard, 2007). Therefore, no implication is made that a diamond-prospective rock is diamondiferous and to any particular concentration, until it has proven to be so. That said, the purpose of this study is to assist in identifying primary deposits of diamonds; hence it should be assumed that mineral clues to the existence of diamond-prospective rocks contained in the DED have a real potential to be derived from diamondiferous rocks.

The distinctions between aillikite and some kimberlites are very subtle and can only be discerned by detailed petrology of fresh samples. Furthermore, the term kimberlite can be correctly subdivided into Type-I and Type-II kimberlites; the latter term being typically regarded as equivalent to the rock type 'orangeite' (Mitchell 1995b). Due to the complexity and often subtlety required to correctly identify diamond host rocks, a practical field term is useful rather than a true petrological classification. Except for lamproites, which when they are not strongly weathered can be separately identified, it is common to refer to primary igneous diamond-host rocks as kimberlites or kimberlitic rocks. Although using the same word as both a field term and a precise petrological term can cause confusion, particularly when rigorous classification can be important, this is accepted practice within the industry.

Field terms and even those terms used routinely in the academic literature for diamond-prospective rocks are numerous. Although robust attempts have been made to impose classification (Rock, 1987; Mitchell, 1995b; Tappe et al., 2005), the inherent characteristics of diamond-prospective rocks provide challenges both in the laboratory and in the field. Deeply sourced and explosively emplaced rocks, kimberlites, lamproites and other diamond-hosting rocks inherently have the potential to incorporate a wide spectrum of host rock material, sometimes quite intimately and to the extent that the primary magmatic component is present as a small minority of the emplaced rock. Hence, bulk chemical attempts to identify such rocks are fraught with pitfalls and even distinguishing important primary phases, such as olivine, between phenocrysts and xenocrysts can be challenging (Nielsen et al., 2009). Furthermore, diamond-prospective rocks host minerals and mineral assemblages that are often unstable at pressures and temperatures at the Earth's surface and hence they can be particularly susceptible to weathering. In areas such as northern Australia, which has a deep and pervasive weathering history (May et al., 2011; Anand and Butt, 2010; Maidment, 2015), diamond-prospective rocks often have little chance of surviving in any form other than as colourful mud at the surface. While there are rare cases of some bodies being remarkably fresh, such as Brooking Creek (Jaques et al., 1986), a particularly striking example of a heavily weathered body can be found at the Seppelt 1 kimberlite in the Kimberley Basin of Western Australia (Fig. 2). Little remains at Seppelt of the approximately 50 m of excavation other than mud and occasional rock fragments with a heavily replaced mineralogy. The general condition of diamond-hosting rocks in Western Australia challenges how they were identified in the first place, and it is a testament to the perseverance of explorers that they have been and continue to be found.

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Figure 2. Exposure of terminally weathered kimberlite at Seppelt 1, Kimberley Basin, Western Australia. The scale bar shows centimetre increments. Photo: TH Reddicliffe (2002)

It is no surprise therefore that with challenges as they are in the laboratory, the identification and classification of rocks in the field is extremely difficult and has naturally given rise to some creative and sometimes disingenuous terms. Those interested in Western Australia diamond exploration should be aware that rock terms used are not necessarily substantiated and are occasionally simply made up. Examples include the term kimberlitic lamproite (Marx, 1999), which has no petrological basis. Geach (1991) used the term kimberlatoid. The De Beers group of companies, including Stockdale Prospecting Ltd, routinely uses their own field term para-kimberlite (Fried, 1995). Based at least on mineralogy, texture and bulk chemistry, the term leukimite has also been used to refer to rocks that appeared to be transitional between kimberlite and leucitite. However, there is no known genetic association between the two rock types that would justify a transitional terminology (Mitchell, 1986).

Field observations demonstrate the dangers of using superficial characteristics like colour and the presence or absence of an accessory mineral like diamond to argue petrological terminology. In the case of lamproites, Hissink (2003) noted: 'Another unusual observation is that none of the four drilled lamproites showed the same lithological characteristics and if Mt Noreen is described as a leucite lamproite then the others on the basis of colour alone the other lamproites cannot be. Yet the BHPN2 lamproite was described as a leucite lamproite, bore no resemblance at all to Mt Noreen and in the exploration reported here produced a single diamond while Mt Noreen did not.' Colour cannot reliably be used as a sole attribute for petrological classification.

Sometimes a rock name can refer to the fashion in which it happens to have been weathered, such as the Western Australian-specific term lennardite, commonly used in older literature. An example of this usage is as follows: 'I have called the rock in which CRA discovered diamond in the Lennard River area – Lennardite (after the nearby Lennard River). Lennardite differs from conventional kimberlite in as much as picroilmenite and pyrope garnet are rare or absent, a brecciated texture is not common and priderite is present. Lennardite differs from leucite lamproite in that the near-surface rock is partially decomposed whereas lamproites are fresh. As a result, lennardites form topographic lows and lamproite forms topographic highs' (Gregory, 1981).

Occasionally, bona fide petrological terms are routinely confused where many authors use the terms lamproite, lamprophyre and kimberlite interchangeably as if they were equivalent (Merrillees, 2003).

For consistency and in the absence of a suitably accepted field term, in this report the term kimberlitic is used where appropriate. Otherwise, more conservatively, the term diamond-prospective rock, as defined previously, is employed.

Diamond size classification

Another topic that causes a degree of miscommunication in diamond exploration is the classification of the size of microdiamonds. The distinction between a micro- and macrodiamond, aside from being instructive to indicate how large any recovered diamond actually is, also has an important bearing on whether a recovered diamond has the potential to have been wind transported. In the Northern Territory, wind-blown microdiamonds, particularly in the east, create significant limitations for the use of diamond as an indicator mineral. There is neither a single Australian nor an international standard for the definition of a macrodiamond. The closest concept to a relevant standard would perhaps be the requirement that in order to be termed 'macrodiamond' all three axial dimensions of a diamond have to be >0.5 mm, but this requires that each stone has to be physically measured. Despite numerous company reports documenting microdiamond or macrodiamond recovery, almost none of them define these terms. Where such information is given, examples include 'one dimension greater than 0.5 mm', 'captured on the 0.5 mm sieve', or simply '0.5 mm'. De Beers and its subsidiary Stockdale Prospecting Ltd (Mitchell, 1999) and Striker Resources (Garton, 2003) use a diameter of 0.4 mm as the cutoff size for macrodiamonds. In the earlier years of exploration in Australia Ashton Mining N.L. often quoted a 0.4 mm diameter cutoff, which in fact related to whether or not a stone would pass through a US 40 mesh sieve (425 µm square mesh). Such a mesh could readily pass a 0.6 × 0.4 × 0.4 mm diamond, which would then be classed as a microdiamond. Carnegie Minerals used a cutoff of 0.6 mm diameter to capture macrodiamonds (Geach, 1997). In the Northern Territory, Lee et al. (1997) reported Merlin microdiamonds within the size range 0.1 to 0.8 mm. For populations of diamonds that fall significantly outside the definition boundary, such as those extracted during trial mining, the details of how these boundaries are defined are academic. However, a threshold cutoff diameter of 0.5 mm falls comfortably within the upper size ranges that may be expected from an exploration sample that was collected within several kilometres of a primary diamond source.

Some clues are apparent in various reports of exploration activities where a definition is not provided. Occasionally, diamond recovery has been reported in terms of weight. Assuming a specific gravity of 3.51 and a square sieve, a perfect octahedra passing through a 0.5 mm sieve would weigh 0.00103 metric carat (mct;1 mct equals 0.2 g), whereas a cube would weigh 0.00219 mct. Hence, in order to apply a consistency to Western Australian exploration data, an average macro–micro cutoff weight of 0.0016 mct (0.0003 g) is assumed for the purposes of assigning such diamonds to a size classification in the DED (Hutchison, 2018). Similarly a macrodiamond or microdiamond classification (irrespective of the reporting company's assigned classification) has been applied on the basis of the physical properties of each diamond reported. To be classed as a macrodiamond, a stone must weigh over or equal to 0.0016 mct, or have been captured on a sieve with a diameter greater than or equal to 0.5 mm, or else the largest dimension reported is greater than or equal to 0.5 mm. Application of this test has resulted in some reported microdiamonds being reclassified as macrodiamonds and vice versa, and provides a path to a consistent interpretation of Western Australian diamond recovery as discussed later.

Indicator minerals

Mineral phases used in the course of diamond exploration have been variously called diamond pathfinders, diamond indicators, kimberlite indicators, and sometimes mantle indicators, and databases incorporating corresponding data are consequently often referred to by similar names. The chemistry of some phases, such as some garnets, can be directly attributed to a likely syngenetic association with diamond (Grütter et al., 2004). However, some other phases, such as ilmenites, provide information on a likely association with kimberlite (Wyatt et al., 2004), but no direct information on diamond potential. Other phases, such as olivines with particular compositions, are evidence of a mantle origin, but reveal little of the likely association with the types of magmatism usually associated with diamond deposits (Nielsen et al., 2009). However, all relevant phases, with the various pieces of information they provide, usefully contribute to a picture of the diamond potential of a particular area. It is notable that the terms spinel and the spinel subgroup of chromites are often used interchangeably by diamond explorers. Hutchison (2018) has described at length the mineral chemical classifications of spinels and other minerals in terms most relevant to diamond exploration. Generally, spinels considered to be of use for exploration are chromites, often with elevated Mg and Cr contents. However, not all indicator spinels are correctly termed chromite and not all chromites are considered indicators. It is this fact that gives rise to the occasionally confusing and non-standardized use of the terms in exploration.

The DED of Western Australia diamond exploration (GSWA, 2018) focuses on a core group of five traditional indicator minerals (diamond, chromite, garnet, ilmenite and diopside). In addition to spinel and chromite subdivisions, other nondiamond indicators are often described following their chemical classifications most applicable to an association with diamond as discussed in Hutchison (2018). Garnets are usually pyrope in composition, ilmenites are referred to as pircoilmenites (MgO >5 wt%; whether confirmed chemically or not) and diopsides are often elevated in chromium (Cr-diopside; Cr_2O_3 >1 wt%). These five traditional minerals have been focused on because they have been the ones laboratories processing diamond exploration samples have typically paid closest attention to and for which statistics are typically provided. However, given the diversity of diamond host rocks, a much wider gambit of exploration-relevant minerals exists. Where these are encountered they are also referred to as indicators, although the fashion in which they are used may differ from the core group of minerals where major and minor element chemistry, or simply appearance, are the key determinants.

Diamond itself is one of the range of minerals indicative of the diamond potential of a prospect. Hence, diamond is generally implied where the term indicator mineral is used. However, in some cases it is useful to distinguish between diamond and nondiamond indicator minerals, in which case the rather unwieldy term nondiamond indicator is used.

Geographic areas

For the purpose of making general statements relating to the various parts of Western Australia, the State has been subdivided into six parts (Fig. 3). These are the NAC, the WAC (further subdivided into the Yilgarn Craton 'WAC Yilgarn,' the Pilbara Craton 'WAC Pilbara' and elsewhere within the WAC), the western part of the State west of the WAC (WA West), and the eastern part of the State (WA East). Table 1 lists which of the tectonic subdivisions from the 1:10 000 000 tectonic units map of Western Australia (Martin et al., 2016) are assigned to each geographic region. As shown in Figure 3, the WA East zone lies between the WAC and NAC. It extends from the Canning Basin south and east to the Western Australia border and includes the Eucla Basin and a thin arm to the east of the NAC bordering the Northern Territory.

Diamond-affinity rocks of Western Australia

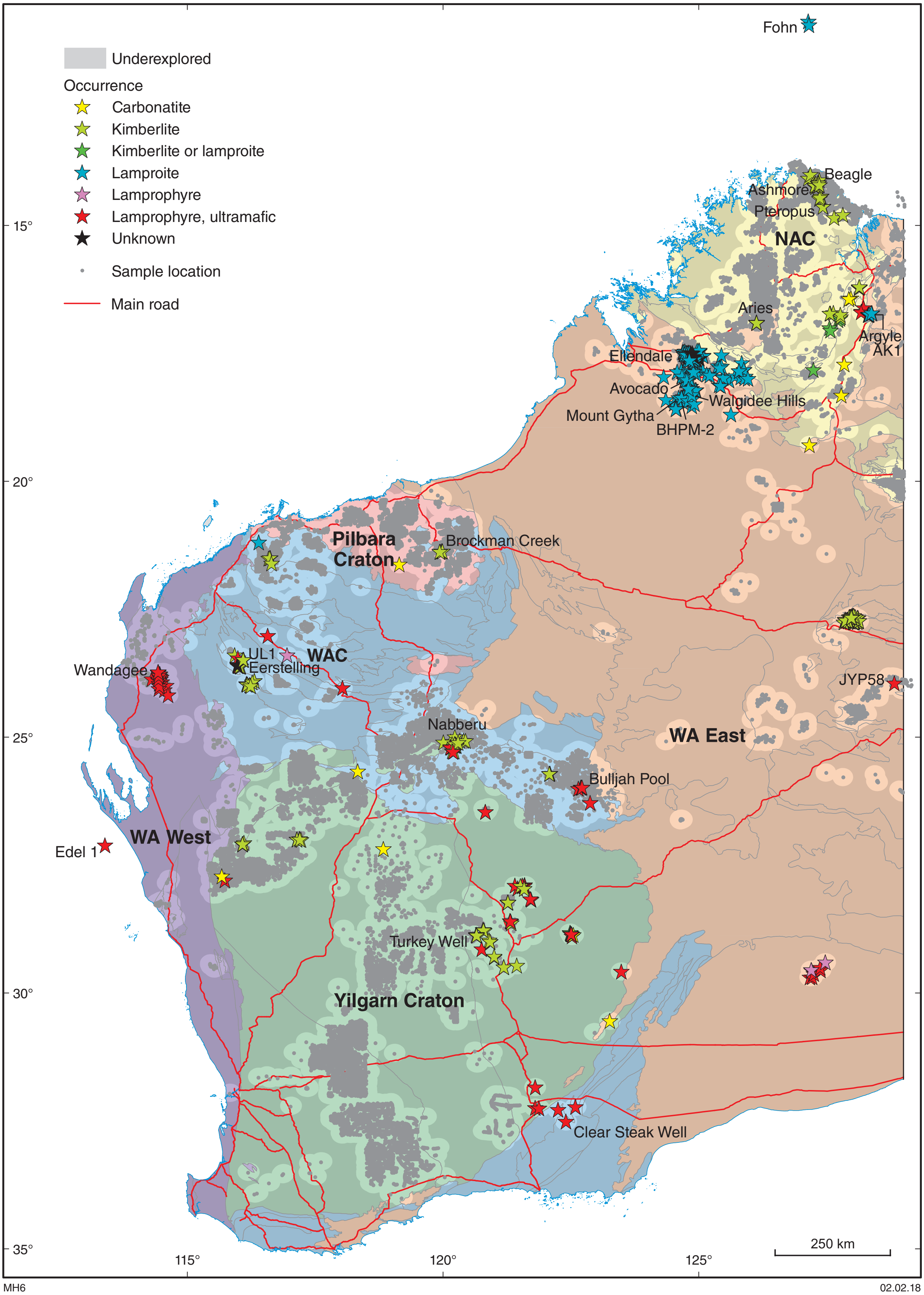
Jaques et al. (1986) have described much of the early work of exploration for diamond in Western Australia and included considerable petrological and mineralogical detail on Western Australian diamond-prospective and diamondiferous bodies. Some more recent findings have been summarized in Jaques (1998, 2006).

Minerals of interest to diamond explorers have been described in the Nullagine region of the WAC since the 1950s (Sofoulis, 1958; Carter, 1974). However, for a long time, the WAC experienced an hiatus in activity that has only recently revived in the 1990s. The early search for diamonds was focused on Lennard River in the west Kimberley. Investigations in 1970 by the Australian Minerals Development Laboratories of Adelaide, using methods developed in South Africa, found diamonds in river sands (Australian Mineral Development Laboratories, 1970). Much of the early work in the west Kimberley and Carnarvon Basin was conducted by Tanganyika Holdings Ltd, the Kalumburu, and subsequently Ashton Joint Ventures, the Australian Diamond Exploration Joint Venture, and Seltrust Mining Corporation Pty Ltd, and has been described in various publications and company reports such as Gregory (1981) and Tyler (1987). Investigations and discoveries continue to this day, with newly identified kimberlites hosted by the Aileron Province and Amadeus Basin in the Webb area (Fig 1) in the eastern central part of the State (Reddy, 2011; Reddicliffe, 2015).

The first diamonds reported in situ in an igneous rock in Western Australia were recovered from the Big Spring pipes in 1976 (Hughes and Smith, 1977). This discovery was particularly significant because the rock type is olivine lamproite, rather than the expected kimberlite hosts typical of other diamond fields worldwide. Lamproite has no genetic association with kimberlite (Mitchell, 1986) and its establishment as a genuine host rock for diamonds created a worldwide impact on where and how to look for diamonds. The expansion of the diamond search into lamproites ultimately led to the discovery of the Argyle AK1 pipe. The Argyle mine, according to Kimberley Process Certification Scheme statistics, was responsible for placing Australia as the second-largest producer of diamonds in the world by volume in 2005.

A total of 524 definitively identified in situ occurrences of diamond-prospective rocks have now been compiled for Western Australia (Hutchison, 2018; Figs 1, 3). These considerably expand on earlier compilations such as that by Jaques (2006). Age determinations are available for 63 of these occurrences (compiled in GSWA, 2018). The geographical extent of lamproites, kimberlites, carbonatites and ultramafic lamprophyres covers much of the State. Occurrences range from 11.0ºS at the Fohn-01 lamproite offshore in the Bonaparte Basin to a southerly extension of 32.5ºS at Clear Streak Well (Biranup Zone). East–west occurrences extend from 113.4ºE at the offshore Edel 1 ultramafic lamprophyre (Southern Carnarvon Basin) to the JYP58 ultramafic lamprophyre at 128.8ºE (Mu Hills; Amadeus Basin – Phase 1). The geographic range of known diamondiferous rocks is only slightly more restricted. There are 114 known bodies, extending from the Beagle kimberlite in the Kimberley Basin (14.2ºS) to the Bulljah Pool 1 ultramafic lamprophyre (Earaheedy

Figure 3. (page 7) Overview map of Western Australia showing identified diamond-prospective occurrences and exploration sample sites. The State is divided into tectonic units modified from the 1:10 million tectonic map of Western Australia (Martin et al., 2016). These units are further condensed into geographic regions, being the North Australian Craton (NAC), the West Australian Craton (WAC), the Pilbara Craton (Pilbara), the Yilgarn Craton and its outliers (Yilgarn), western WA (WA West; west of the WAC) and eastern WA (WA East; between the NAC and WAC). Sample sites constituting the diamond exploration database (DED) are shown with areas underexplored (greater than 20 km from onshore sample sites) being indicated with a grey overprint. This buffer is generous as diamonds may survive this distance from source depending on their initial size and quality, but most other indicator minerals would not. It is evident that many underexplored areas lie far from principal roads, indicating that accessibility has been a factor in the extent of exploration. All known diamond-prospective in situ occurrences of rocks (whether tested for diamonds or not) are indicated according to the key. Those referred to as 'kimberlite or lamproite' have indistinct petrological characteristics or have been studied only in a cursory fashion. The association between lamproites and the edge of the NAC is evident. More central parts of the NAC and other cratonic areas of Western Australia are more typified by kimberlites. Ultramafic lamprophyres more typically reside on craton edges around the WAC or off-craton



Underexplored
Occurrence
Carbonatite
Kimberlite
Kimberlite or lamproite
Lamproite
Lamprophyre
Lamprophyre, ultramafic
Unknown
Sample location
Main road
Fohn
Beagle
Ashmore
Pteropus
NAC
Aries
Argyle
AK1
Ellendale
Avocado
Walgidee Hills
Mount Gytha
BHPM-2
Pilbara Craton
Brockman Creek
UL1
WAC
Eerstelling
Wandagee
JYP58
Nabberu
WA East
Bulljah Pool
Edel 1
WA West
Turkey Well
Yilgarn Craton
Clear Steak Well
250 km
15°
20°
25°
30°
35°
115°
120°
125°
MH6
02.02.18

Table 1. Assignment of 1:10 million tectonic regions to broad geographical areas

East Western Australia (WA East)	Aileron Province	Louisa Basin	Roebuck Basin
	Amadeus Basin (Phases 1 and 2)	Murraba Basin	Rudall Province
	Bonaparte Basin (Northern and Southern)	Musgrave Province	Texas Downs Basin
	Canning Basin	Officer Basin (Phases 1 and 2)	Victoria Basin
	Carr Boyd Basin	Ord Basin	Wolfe Basin
	Eucla Basin	Osmond Basin	Woodline Sub-basin
	Gunbarrel Basin	Red Rock Basin	Yeneena Basin
North Australian Craton (NAC)	Bastion Basin	Kimberley Basin	Speewah Basin
	Birrindudu Basin	Lamboo Province	Tanami Basin
	Granites–Tanami Orogen		
West Australian Craton (WAC)	Arid Basin	Fraser Zone	Turee Creek Basin
	Ashburton Basin	Gascoyne Province	Yerrida Basin
	Barren Zone	Hamersley Basin	Pilbara Craton[(a)]
	Biranup Zone	Nornalup Zone	Eastern Goldfields Superterrane[(b)]
	Bresnahan Basin	Northern Foreland, Albany–Fraser Orogen	Narryer Terrane[(b)]
	Bryah Basin	Ragged Basin	South West Terrane[(b)]
	Collier Basin	Recherche Supersuite	Goodin Inlier[(b)]
	Earaheedy Basin	Salvation Basin	Marymia Inlier[(b)]
	Edmund Basin	Scorpion Basin	Youanmi Terrane[(b)]
	Fortescue Basin	Tropicana Zone	
West Western Australia (WA West)	Badgeradda Basin	Moora Basin	Pinjarra Orogen
	Carnarvon Basin (Northern and Southern)	Perth Basin	Yandanooka Basin

NOTES: (a) Pilbara Craton (WAC_Pilbara); (b) Yilgarn Craton (WAC_Yilgarn)

Basin; 26.0ºS) and from the Eerstelling 2 ultramafic lamprophyres (116.0ºE; Edmund Basin) to the Argyle AK1 lamproite pipe (128.4ºE; Lamboo Province). Furthermore, with emplacement ages of diamondiferous rocks ranging from c. 1868 Ma at the Brockman Creek kimberlite in the Pilbara (White, 2000) to c. 17 Ma at Walgidee Hills (Phillips et al., 2012) and Mount Gytha (Jaques et al., 1984) in the west Kimberley, a considerable portion of the geological history of the State is represented.

The principle fields of diamond-prospective rocks are as follows. In and around the NAC are the North Kimberley kimberlite field, including Seppelt (Fried, 1993; Garton, 2001), Pteropus (Fried, 1993) and Ashmore (Robins, 2002). The Aries pipe (Fazakerley, 1987; Towie et al. 1994) is notable as a largely isolated kimberlite pipe in the southern Kimberley Basin. The Ellendale lamproite field lies on the southern periphery of the exposed NAC and hosts the Ellendale 4 and Ellendale 9 openpit mines that closed in 2015. Other clusters such as the Calwynyardah and Noonkanbah fields (Jaques et al., 1986) are located south of Ellendale. The Argyle AK1 pipe (Skinner et al., 1985) lies off the eastern part of the NAC as a largely isolated body, with a few minor nearby lamproite dykes. In the WAC, diamondiferous and diamond-prospective bodies are apparently more sporadic and are more typically represented by kimberlites and ultramafic lamprophyres than are evident around the peripheries of the NAC. Kimberlites are present at Turkey Creek (van Kann, 1998) in the central Yilgarn Craton and both kimberlite and ultramafic lamprophyres are present in the Marymia Inlier of the Yilgarn Craton at Nabberu (Mitchell, 1995a). The Bulljah Pool (Clifford, 1994; Western Mining Corporation Ltd, 1988) ultramafic lamprophyres lie in the eastern WAC and the Blacktop kimberlite dykes (Goldsmith, 2004) are situated in the northwest WAC within the Fortescue Basin. The Brockman Creek kimberlite dykes (Booth, 2001) are located in the Pilbara Craton. Outliers are present in the Webb area kimberlites (Reddy, 2011; Reddicliffe, 2015) in central eastern Western Australia and the Wandagee ultramafic lamprophyres (Kerr, 1983) in Western Australia near Carnarvon. There are two definitively identified occurrences offshore, namely the Edel 1 ultramafic lamprophyre offshore from the west coast to the south of Carnarvon (Killar, 1972) and the Fohn 1 olivine–leucite lamproite offshore to the north (Gorter and Glikson, 2002). Of note also are numerous apparently isolated bodies of potential and realised diamond interest.

Lamproite/kimberlite pipes were discovered throughout the 1990s and 2000s, and to this day geophysical anomalies continue to be identified as kimberlite intrusives in the Webb area (Fig. 1) in eastern central Western Australia (Reddy, 2011; Reddicliffe, 2015). Chronologically, Stockdale discovered the Ullawarra 1 dyke in 1990 (Muggeridge, 2009) and in the same year a small lamproite pipe (Avocado) was discovered near Laymans Bore and west of Metters Bore 3 at Calwynyardah (Turley, 1990). The Lara melnoite was identified in 1991 by drilling under a joint venture between Stockdale and Western Mining Corporation (WMC; Reynolds, 1991). The Wandagee cluster at Minilya (Allen 1993a) and the Eerstelling cluster in the Edmund Basin (Rohde, 1993) were both identified in 1993. The Seppelt 2 kimberlite was discovered in the same year by Stockdale Prospecting Ltd (Fried, 1993). The Nabberu cluster (also known as Miss Fairbairn Hills) at Marymia was discovered by Stockdale Prospecting Ltd in 1995 (Mitchell, 1995a). The O'Grady Creek so-called lamproite pipes were reported in the mid-1990s, but cannot be substantiated as their original reporting was of such poor quality (Munster, 1995, 1996, 1997). Here a total of 22 lamproites were reported. Of these, five have further information associated with them. AK2 (also referred to as the Suzuki Flat Diatreme) has been reported to be 450 m wide (i.e. about 16 ha, if spherical in shape), AK3 has been reported to be a 145-m ellipsoid body and its satellite AK6 has been reported as a 210-m ellipsoid. AK10 has been reported to be a lamproite sill and K10 has been referred to as the Birthday Pipe. Only K10 has a known location (in this case, on a map at 117.009ºE, 23.1084ºS). However, subsequent field visits by the Geological Survey of Western Australia (GSWA) have failed to find any outcrops of interest. The Leonora–Menzies field (Melita) was discovered by Stockdale Prospecting Ltd in 1997 (Mitchell, 1998). In the later 1990s, the Brockman Creek dyke system in the Pilbara Craton garnered sufficient interest for Stockdale Prospecting Ltd to ship four 24-t mini bulk samples and considerable core to South Africa for processing (Mitchell, 1999). However, diamond recovery at 1–8 mm was disappointing, with two samples yielding no diamond. The Brockman Creek 01 locality yielded a grade of only 0.12 metric carats per hundred tons (cpht), and a location about 2 km to the east yielded a more respectable, but still non-commercial, 1.74 cpht (Zuvela, 2001). The Marsink lamproite pipe and nearby Hisshall dyke (named by the discoverer after himself and his colleague) were discovered in 2003 (Hissink, 2003). Although the Hisshall dyke coincides with BHP's description of the BHPM-2 dyke, this latter dyke would appear to be located farther to the south. The UKD1 pipe was identified in 2006, coincident with new and highly detailed airborne geophysics and a very thorough review and re-interpretation of the west Kimberley region by Coxhell (2006). More recently in the Yilgarn Craton, and of academic rather than economic interest, diamond has been reported in inclusions in zircon from the Jack Hills (Menneken et al., 2007). Additional bodies and extensions of known bodies at Cue were discovered in 2008 (Williams, 2008). The Barlee Range Kimberlite Province, Ullawarra (Muggeridge, 2009) was identified in the following year located approximately 15 km northeast of the Eerstelling ultramafic lamprophyres.

The sizes of diamond-prospective bodies in Western Australia vary considerably and the Walgidee Hills leucite lamproite is the largest known lamproite in the world, with an area of 461 ha. Sizes are documented, where constrained, in GSWA (2018) and Figure 4 shows the at- or near-surface morphologies of 138 lamproites, 24 kimberlites and 8 ultramafic lamprophyres, each sharing their own common scale. It is evident from Figure 4 that lamproites are usually considerably larger than the ultramafic lamprophyres, which are larger than the known kimberlites. In addition to the very large Walgidee Hills lamproite, it is apparent that the Fohn South lamproite, although its size has only been imprecisely determined by geophysical methods (Gorter and Glikson, 2002), is also extremely large. Little is known about Fohn South aside from a single drillcore and it is unknown whether it is diamondiferous. The dominant shape for all the bodies is circular, but irregular shapes are very common and are likely to be a consequence of particular crustal structures exploited during emplacement or due to multiple intrusions.

Review and analysis of past exploration methods and data

Exploration sampling

The collection and inspection of physical samples from the field lies at the core of historical diamond exploration in Western Australia. Methods have evolved over time; however, the principal goal remains the identification of minerals that can be attributed to diamondiferous, or at least diamond-prospective, rocks.

Evolving methodologies

Diamond exploration in Western Australia focusing on indicator minerals has been an evolving process (Jaques et al., 1986; Pidgeon et al., 1989). Techniques have been based on those developed earlier in South Africa and some of these methodologies persist, such as a reliance on kimberlite- rather than lamproite-prospective minerals. Due to the expectation in the late 1970s that economic kimberlites in Australia would mirror discoveries in southern Africa, what would be considered by today's standards as fairly sizeable bodies were occasionally ignored. As an example of this approach, the Amaz Iron Ore Corporation (Gellatly, 1980) considered an inferred kimberlite dyke, which a drill-pattern grid confirmed to be less than 20 m was 'considered too small to warrant further drilling.' The neighbouring pipe, which was drill tested and found to span 300 × 100 m (up to 4.5 ha in size), was determined to require 'unusually high grades… for the deposit to be economic' (Gellatly, 1980). The size of this body is not unlike those commercially exploited at Merlin in the Northern Territory (Reddicliffe, 1999).

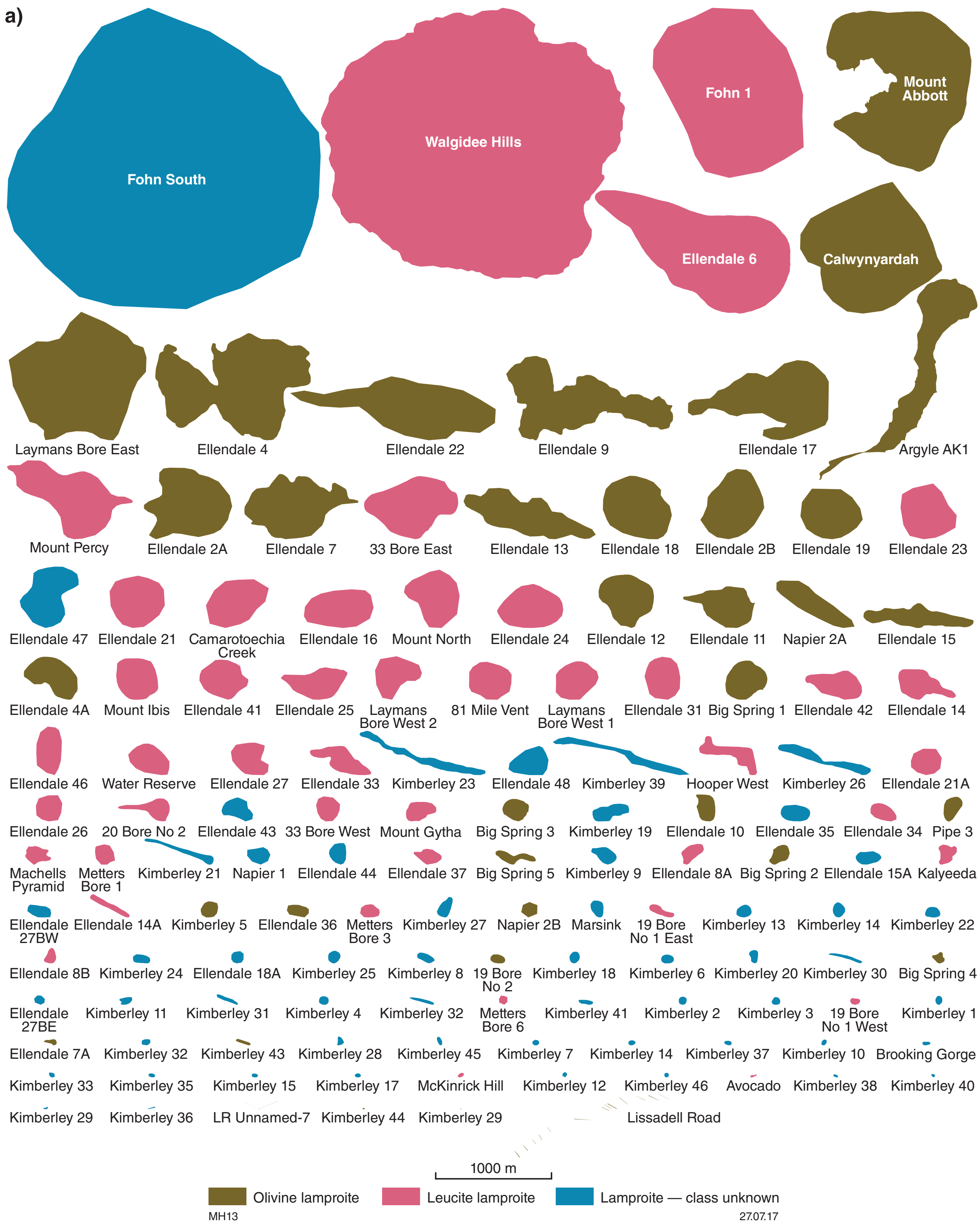


Figure 4. **Morphologies at or near surface of selected in situ diamond-prospective rocks of Western Australia: a) lamproite occurrences; b) kimberlite occurrences; c) ultramafic lamprophyre occurrences. Lamproites distinguish themselves as being very large in comparison with ultramafic lamprophyres and, in turn, with kimberlites**

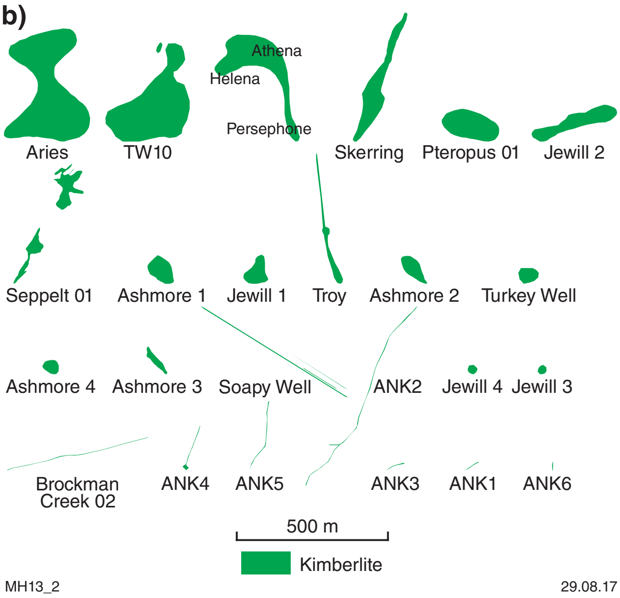


Figure 4b.

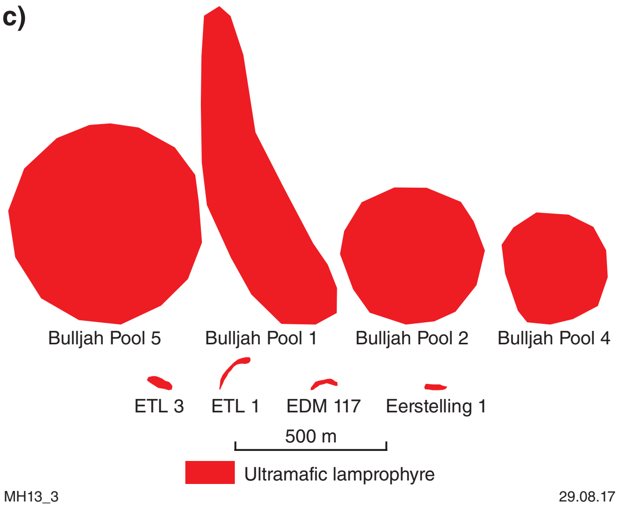


Figure 4c.

However, to different extents and depending largely on the particular explorer, techniques developed to account for the nuances of Western Australian diamond-prospective rocks. The detrimental effect of the weathering profile on almost all traditional indicator minerals aside from chromite led Garlick (1981) to state that '...any primary kimberlite source within the areas in question are likely to be shedding only chromite grains rather than the normal kimberlite indicator mineral assemblage.'

Figure 5 shows two examples of the evolving methodologies for diamond exploration in Western Australia. While the manual work of upgrading alluvial trap sites in the field remains a necessary exploration tool that requires care and skill, novel approaches to exploration in challenging environments continue to develop. Figure 5a shows Maureen Muggeridge and Vince Vincello hand sampling at Pteropus Creek in the north Kimberley in 1976. In addition to the jigs and pans used in sample collection, the field camp set up to service this work incorporated binocular microscopes so that indicator mineral assessment could be conducted as the program progressed. This 'on-the-fly' approach allowed for modifications to be made to the sampling program during the field season in a similar fashion to the early discoveries of kimberlites in Canada's Northwest Territories. While field conditions for sample processing are not optimum, and would be best considered to produce only preliminary results, the technique contrasts with the more commonly used modern methodology where samples are sent directly to the controlled conditions of laboratories. In the latter case, results are not known until after the field season is complete. Figure 5b shows the tracked drilling vehicle employed for drill testing of anomalies in the Webb area, in the Aileron Province of eastern central Western Australia (Fig. 1) in 2013. The ubiquitous sand in this part of the Gibson Desert makes access by wheeled vehicles next to impossible in places. In addition to the track-mounted drill providing opportunities for sampling in otherwise inaccessible locations, the vehicle is used for hauling support vehicles and other equipment around the field.

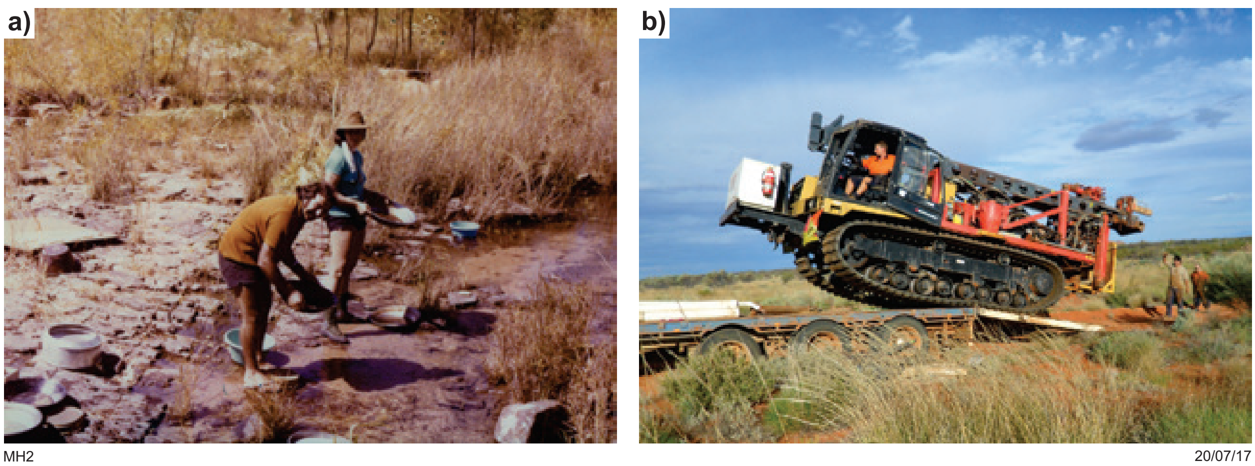


Figure 5. Examples of sampling methodologies used in Western Australian diamond exploration: a) Maureen Muggeridge and Vince Vincello taking alluvial samples at Pteropus Creek, North Kimberley in 1976. The pans and sieves used to screen the samples are evident in the photograph, which also shows the low-energy drainage that often provides challenges to identifying well-sorted trap sites. Photo: DC Lee (digital enhancement: S Dowling); b) tracked drilling vehicle being offloaded in 2013 into the field in the North Gibson Desert west of Lake Mackay (Webb kimberlite project). The vehicle is capable of conducting drilling operations in areas of heavy sand cover and hauling support equipment. Photo: TH Reddicliffe

Location and density of sampling

The parts of Western Australia explored for diamonds are identifiable by the locations of samples compiled in the DED (Fig. 3) and the locations of tenements assigned to the De Beers group of companies, including Stockdale Prospecting Ltd (Fig. 6). The De Beers group has been a major explorer in Western Australia; however, much of their sample-location data has not been reported. As their activities focused almost exclusively on diamond exploration, mapping their historical tenement boundaries (Fig. 6) provides a useful small-scale overview of their exploration coverage. Similar tenement maps for other explorers do not provide the same level of confidence in diamond exploration areas because most other companies searched for a wider range of commodities. Figure 6 shows that the De Beers group activities have very largely fallen within the same areas identified by sample locations in the DED (which does include a subset of the De Beers group samples). There are a few exceptions. The De Beers group has extended activities slightly farther south of the Ellendale field and far into the Canning Basin. They have operated in parts of the Officer Basin (Phase 1) not explored by other companies. Furthermore, they have had a significant presence beyond reported work by other companies in the Yilgarn Craton, particularly in the western Youanmi Terrane, the South West Terrane and sporadic parts of the Eastern Goldfields Superterrane.

Off-tenement (or open range) sampling that was conducted by numerous early explorers is not reflected in the sample sites (Fig. 3) nor the De Beers tenement data (Fig. 6). However, sampling results are generally not available for off-tenement samples in any case.

Figure 3 includes a 20-km buffer surrounding all compiled sample locations. Twenty kilometres is a large distance to expect most diamond indicators to survive from their source in Western Australia, except perhaps diamonds (Towie et al., 1994). However, the generous distance serves to identify the areas that are very much completely unexplored for diamonds using indicator methods. Despite the generous buffer, it is apparent that Western Australia is significantly underexplored. The eastern half of the State is almost completely unsampled, apart from a small number of particular areas and the same description can be applied to the western coastline. There are robust geological reasons for neglecting much of this territory. However, in the NAC it is apparent from Figure 3 that while the southern and eastern peripheries and a central corridor have been significantly sampled, there are notable unsampled areas. These lie in particular around the western and northern coastline. Probably due to its small size, the Pilbara Craton has a reasonably high-density coverage, but the remaining parts of the WAC and Yilgarn Craton contain only sporadic dense pockets of exploration, with prominent gaps.

In addition to small-scale sampling, it is important to consider the fact that indicator minerals do not travel far. Therefore, although a wide area may be unexplored, any new work must be carried out at a scale appropriate to capturing at least one anomalous sample. Local-scale sampling density is important, as exemplified by the drop in abundance of spinels recovered away from the Aries pipe (Fazakerley, 1987).

Materials sampled

Of the 72 627 exploration samples where the sample material has been noted, the target material has more or less been evenly split between two dominant types of alluvial samples (43%) and loam samples (39%). The balance is made up of soil samples (13%) and rocks (4%). A total of 473 biogenic and 51 lacustrine and marine samples make up less than 1% of the exploration samples. Of the alluvial samples where a distinction has been made between current and paleodrainage sites, only 0.29% were associated with buried channels.

In the context of almost equal numbers of loam and alluvial samples, loam sampling is considered best suited for areas of poor drainage, whereas alluvial sampling is better suited to areas of high-relief and high-energy drainage (Muggeridge, 1995). At Aries, a particular sample 10 km from the pipe provided considerably more (about 1500) spinel indicator grains than a much closer sample of the same weight, which contained only 37 spinels (Towie et al., 1994). It was concluded that the single most important factor in explaining this observation was that the distal trap site was of a much higher quality (better able to concentrate minerals based on density) than the proximal ones. Therefore, even for reasonably high-energy environments where alluvial sampling may be appropriate, the specifics of sample selection can make the difference between a positive and a negative result.

Sample sizes

An indication of sample sizes can be gleaned from the reported collection method, with hand samples assumed to be relatively small compared to, for example, excavator samples. Among the Western Australian diamond prospecting samples compiled in the DED where the collection method was documented (69 195 samples; 78% of the total) 90% are hand samples. A further 8% were drill samples, and bulk samples (variously termed barrage, costean, excavator, openpit, or trench) made up 1.6%. The remainder consisted of 32 marine dredge samples.

Stockdale Prospecting Ltd has provided a typical example of stream sampling methodology at Ullawarra (Muggeridge, 2009). Here they initially acquired 20 litres (quoted at approximately 50 kg) of material, and follow-up samples varied in volume up to 150 litres.

A total of 29 298 samples (33% of DED records) have been documented with sample weights. The average (4.3 tonnes) is skewed by the relatively small number of large bulk samples. The mode (165 kg) is still higher than expected based on the described methodologies. However, a subsample where the most comprehensive sample processing data was provided gives a mode of 45 kg for 4406 alluvial samples and a mode also of 45 kg for 4387 loam samples. Separately, an average of 1.65 kg/l of loam sample on a volumetric basis has been calculated (Hutchison, 2018). Hence, the recorded mode of 45 kg for loam samples is estimated to be equivalent to 75 litres.

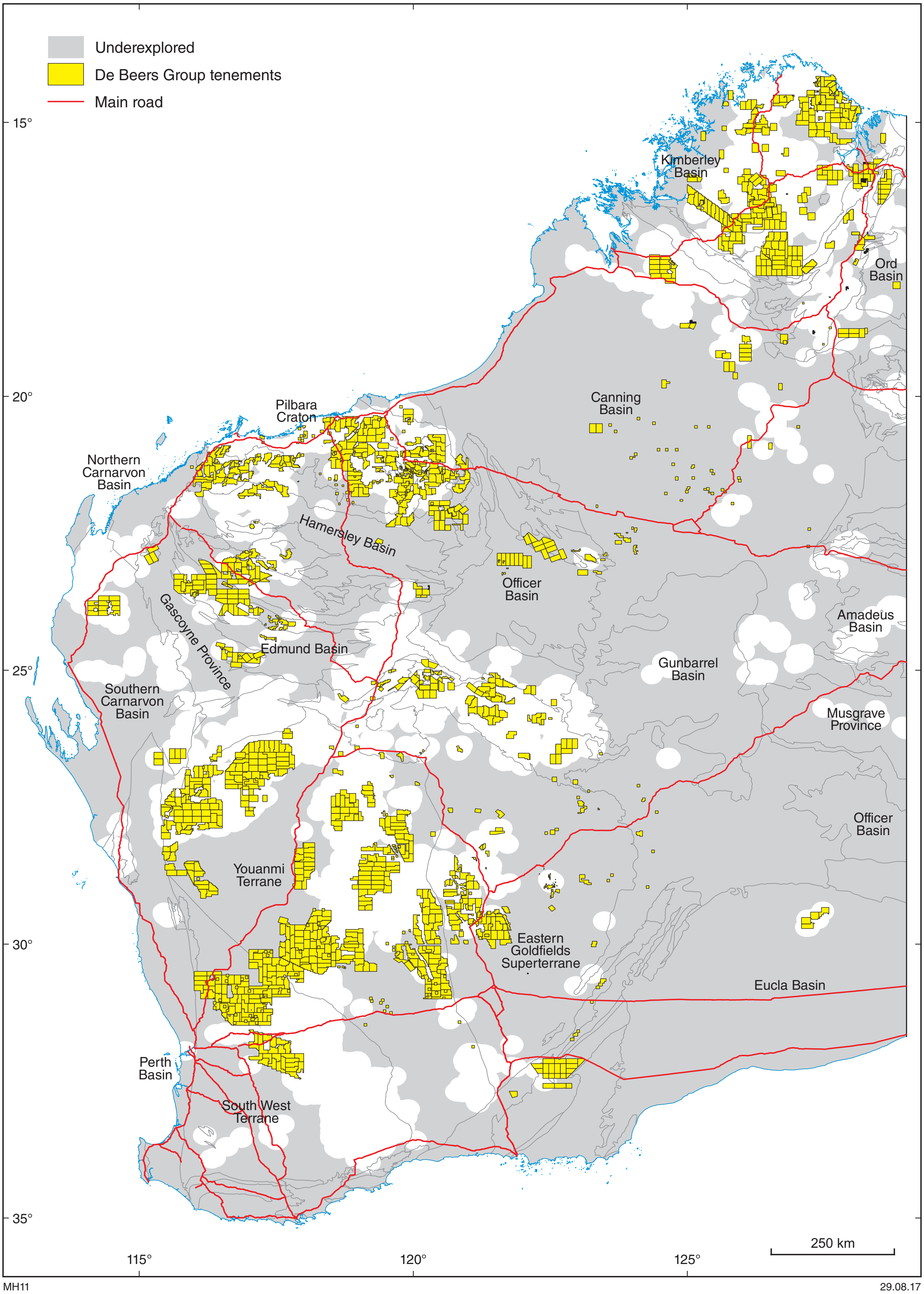


Figure 6. Map of the De Beers group tenements. The De Beers group of companies' (including Stockdale Prospecting Ltd) tenements are shown by yellow polygons. White parts of the State represent areas within 20 km of the locations of diamond-exploration sample sites from the DED. De Beers group activities have largely been undertaken in areas represented in the DED. There are a few exceptions, particularly in the Canning and Officer (Phase 1) Basins and in parts of the Yilgarn Craton

Sieve sizes

The range of grain sizes recovered in the field and subsequently inspected for minerals, whether diamond alone or in combination with indicator minerals, depends on a variety of factors. Ninety percent of all compiled samples have been taken for the purpose of heavy mineral and/or diamond separation and the sieve ranges reflect this purpose. Size fractions are dependent on whether samples are reconnaissance in nature or designed to test diamond grade. However, the DED only reports 1.6% of samples as being bulk samples, with 90% of the remainder being hand samples and 8% being drill samples (mostly small diameter). Hence, reported size ranges are more a reflection of reconnaissance rather than bulk sampling.

Maximum sieve sizes

The maximum grain size inspected for indicator minerals has been reported for 33 671 samples (38% of the DED records). Instances of the use of different maximum mesh sizes are shown graphically in Figure 7, which includes a smoothed distribution (red line) derived from grouping mesh sizes, and comparison data from the Northern Territory (grey line; Hutchison, 2012). Maximum inspected grain sizes of 1, 2, and 4 mm dominate the Northern Territory sampling and Western Australian methods favour similar values, with 61% of samples (20 650) quoting a maximum sieve size of 1.5 or 2 mm. The near-Gaussian distribution of the data suggests that there is an optimal typical mesh size, where additional factors may have prompted explorers to equally increase or decrease the maximum threshold for picking. The slightly anomalous peak in popularity of the 4 mm sieve may be artificially high. Occasionally, explorers have recorded having sieved to 4 mm in the field but inspected only <2 mm grains. Furthermore, it is often more practical to conduct final sieving to 2 mm in the laboratory rather than in the field (Smith et al., 1990). Some <4 mm samples are therefore suspected to have been observed only at <2 mm.

Minimum sieve sizes

A smaller (22 441; 25% of DED records) but still substantial number of records report the minimum mesh size inspected. The proportion where each mesh size has been selected is shown in Figure 8, which includes a smoothed distribution and comparison with Northern Territory data (Hutchison, 2012). Only 4.5% of Western Australian samples for which data are available have a minimum sieve size above 0.3 mm and only 2.7% of samples discarded grains below 0.425 mm diameter or more. This methodology contrasts strongly with the Northern Territory where Hutchison (2012) has reported that 17% of samples, where data were available, were inspected in the >0.425 mm fraction. The distribution of the minimum mesh size reflects a heavily skewed shape favouring the smaller sieve sizes. This is because the minimum size is naturally constrained by the maximum sieve size. In addition, there would be only few circumstances during exploration where an exploration sample would be targeting grains significantly over 0.5 mm. This would almost only happen where the purpose was to recover macrodiamonds either during large sample reconnaissance or trial pitting.

Size ranges

Size ranges can be inferred from the relative abundance of maximum and minimum sizes. However, a total of 20 587 records in the DED include both upper and lower mesh sizes ostensibly from which indicator minerals have been picked. Consistent with upper and lower mesh sizes being assessed separately, the most common ranges of sizes inspected for minerals have been 0.3 – 1.5 mm (45%), 0.2 – 1.5 mm (15%), and 0.3 – 1 mm (7%). Sizes ranges have an important bearing on the likelihood of recovering specific target minerals, as will be discussed later in the report.

Muggeridge (2009) considered Stockdale Prospecting Ltd's sampling at Ullawarra to be typical of historical diamond exploration in the State. They reported screening within the range 0.3 to 1 mm. Sometimes a 2 or 4 mm upper cutoff was used with wet material (Muggeridge, 2009; the symbology '-' is often used by explorers to denote 'less than,' so '-2 mm' means under 2 mm).

Heavy mineral concentrate recovery

The large majority of minerals considered useful in diamond exploration are of high density (specific gravity >2.96). The total weight of any sample is therefore less important than the weight of its heavy mineral component. Sampling and processing methods aim to maximize the recovery of high-density minerals.

Processing methods

Various methods for the extraction of heavy minerals have been implemented during the course of Western Australian diamond exploration (Smith et al., 1990; Muggeridge, 1995). Techniques can be classified according to the target mineral, the size of the sample and the location of the processing, whether in the field or laboratory.

Transportation of geological materials is expensive, particularly for fieldwork in remote areas that rely on helicopter access. Hence, all forms of sample beneficiation aim to reduce weight as rapidly as possible while maintaining recovery efficiency. For hand sampling, most samples are screened to a certain extent in the field, which usually refers to hand sieving to <4 mm or <2 mm. This can be labour intensive, particularly for soils or clay-rich samples where the sieving process creates clumps of adhered grains. Screening to <2 mm can readily reduce the sample weight by 50%. However, for dry samples that are subsequently screened wet, unless samples are dried the weight savings can be offset by the addition of water. There are centrifugal hand-screening tools available to prospectors, which produce a fairly efficient density concentrate, particularly for alluvial samples. However, their use in diamond exploration has not been reported in Western Australia. Hand samples are therefore transferred to the laboratory for further screening and final picking. For bulk samples, most projects establish infrastructure in the field in order to conduct beneficiation. A notable exception has been Stockdale Prospecting Ltd (De Beers group) where samples from the Pilbara, each weighing 25 t, were shipped to South Africa for processing (Mitchell, 1999). For other operators, and where the target mineral is diamond,

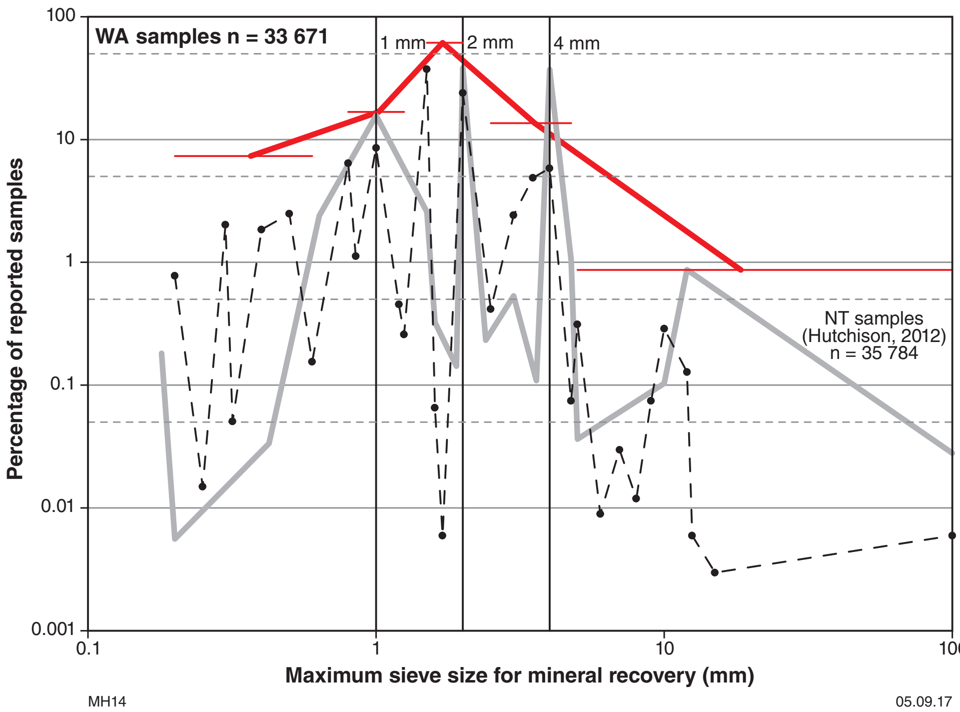


Figure 7. Exploration sample upper sieve sizes reported as a percentage of total samples. Black dots represent the percentage abundance of individual maximum grain sizes inspected for indicator minerals. Instances of different sizes are grouped in batches (0.2 – 0.6 mm, 0.8 – 1.25 mm, 1.5 – 2 mm, 2.5 – 4.75 mm and 5–100 mm) as represented by horizontal red lines to create the smoothed distribution shown by the heavy red line. Data from a similar number of Northern Territory samples (Hutchison, 2012) is shown in grey. The data show an even distribution of maximum sieve sizes, with a peak at 1.5 and 2 mm, largely similar to Northern Territory sampling methods

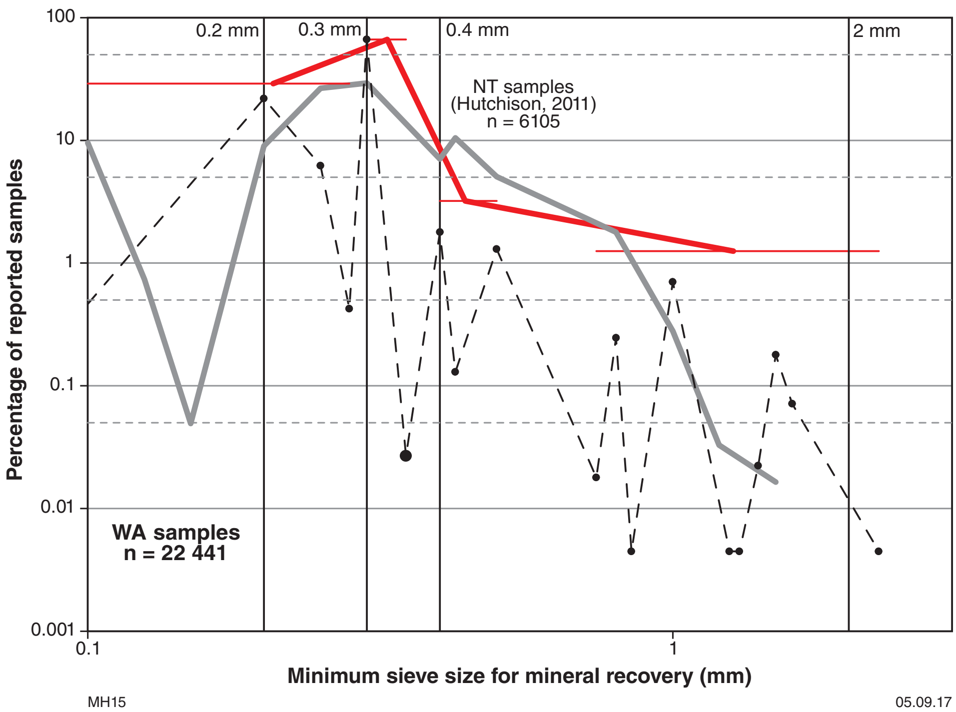


Figure 8. Exploration sample lower sieve sizes reported as a percentage of total samples. Black dots represent the percentage abundance of individual minimum grain sizes inspected. Sizes are grouped in batches (0.1 – 0.28 mm, 0.3 – 0.35 mm, 0.4 – 0.5 mm, 0.74 – 2.25 mm and 5–100 mm) as represented by horizontal red lines to create the smoothed distribution shown by the heavy red line. Data from a smaller number of Northern Territory samples (Hutchison, 2011) are shown in grey. The data show a skewed distribution favouring smaller sieve sizes, where 0.3 mm is the most common grain size cutoff. While 0.3 mm is common in the Northern Territory, there is a significant proportion of Northern Territory samples taken at much coarser sizes of up to 0.8 mm, which is not apparent in the Western Australian data.

this form of field processing may reach its conclusion without recourse to further laboratory work. However, for mineral-indicator processing almost all field-processed bulk sample concentrates have been sent to established, and often independent, laboratories for final processing and mineral picking under carefully controlled conditions.

Flow sheets for mineral processing vary depending on size and the target mineral. Examples of 14 flow sheets used in the Northern Territory and Western Australia have been provided in the appendix of Hutchison (2012). However, as a supplement and because the company was not represented in Hutchison (2012), a De Beers flow sheet is provided in Figure 9. In general, all processing commences with sample cleaning and size fractionation, with the smallest grain sizes (fines) removed. If this component goes to waste, as it usually does, the process is termed de-sliming. The sieving process may also involve a degree of jaw or rotary crushing or attrition milling, depending on the cohesion of the sample. Samples then undergo one or more of the following processes usually in the following order: gravity separation using a Wilfley table, or Pleitz jig for larger size fractions, and then magnetic separation. Nondiamond indicator samples are subsequently treated with heavy liquids using gravity or cyclone assistance in one or more stages. The ubiquitous first or single-stage liquid separation is with tetrabromoethane (TBE) with a specific gravity (S.G.) of 2.96 or a similar-density liquid. Further separation, if implemented, would typically use methylene iodide (MI) with an S.G. of 3.32. Diamond-focused samples often omit the heavy liquid stages and proceed directly to chemical dissolution techniques. Normally, this involves caustic fusion in a strongly alkali bath, which is heated and sometimes also pressurized. Caustic fusion may proceed after an initial acid-leaching process. However, because of the particularly hazardous acids required, the acid stage is often omitted. For reconnaissance samples, and because diamonds are expected to be present in a smaller size fraction than indicator minerals, it is common for samples to be split with finer fractions processed for diamonds and coarser fractions for nondiamond indicators. In programs where samples are expected to be distant (>1 km) from the source, or if the purpose is to identify whether a small rock sample (about 20 kg) is diamond-bearing, an optimum microdiamond prospecting program would involve diamond investigation down to 0.075 mm. Cost considerations often place the cutoff at 0.1 mm or 0.125 mm (Price, 1996), but it is worthwhile making a calculation of the additional cost of a larger sample that a coarser size fraction may demand.

The particularly severe extent of weathering in Western Australia has led some explorers to improve sample recovery by developing techniques in addition to the traditional flow sheet. Laterite digest (Fe-digest) was found to be useful in dealing with indicator mineral-bearing grains in the Hamersley Basin (Towie, 2004). In some examples, indicator-negative samples revealed abundant indicator minerals when subsequently subjected to an Fe-digest. It was noted by Towie (2004) that this necessary sample treatment, in his view, was not conducted in the area by their predecessors (Rio Tinto and Prenti Exploration), thus leading them to relinquish control of their projects. In a similar way, Archer (1986) reported using a reduction roasting technique to deal with high laterite content in samples in the Northern Territory.

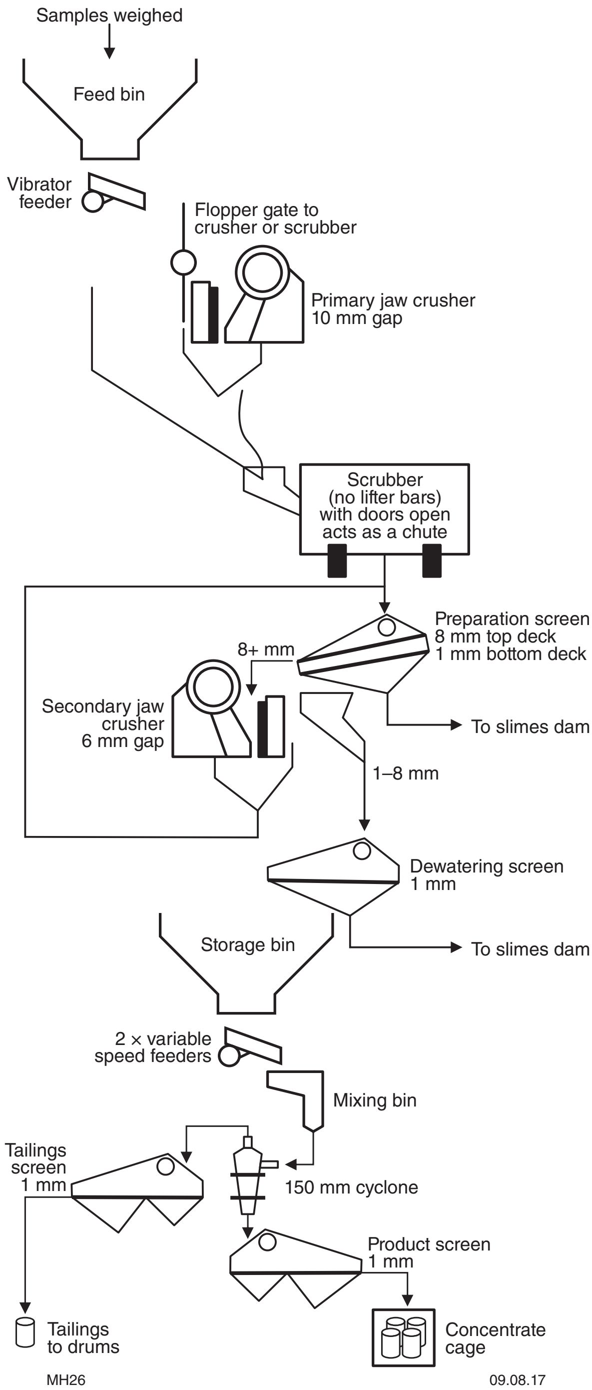


Figure 9. **Flow sheet for medium-scale diamond processing. This flow sheet illustrates the processing of bulk samples for diamond during the 1990s by Stockdale Prospecting Ltd (Mitchell, 1999). The processing plant was located in Kimberley, South Africa and used for processing 25 t bulk samples from Stockdale's Brockman Creek project in the Pilbara**

Proportions of heavy minerals

Within the DED (GSWA, 2018) a total of 9931 samples have had their sample weights and concentrate weights recorded. Among those, the large majority also report sample type and grain size. Recovery distributions are shown graphically in Figure 10. Medium-grained samples, defined as having an upper size limit below 2 mm and down to 0.8 mm (inclusive), show the distribution with the highest heavy mineral concentrations (median of approximately 0.045% by weight) followed by coarse-grained (maximum grain sizes of 2 mm and above) and then fine-grained samples (maximum grain size under 0.8 mm). However, the coarse samples show a bimodal distribution with a minor maximum at around 0.5% recovery by weight. It is the coarse samples that are more likely to be distributed between bulk and reconnaissance-style processing, with bulk processing favouring diamonds over indicators and diamonds, and hence a smaller recovery. Taking this into account, a similar trend from increasing heavy mineral recovery from fine- to medium- to coarse-grained samples is evident, which is also seen in other datasets such as in the Northern Territory (Hutchison, 2012).

Based on sample type (blue lines in Figure 10), loam samples followed by rock samples and then alluvial samples have increasingly higher heavy-mineral recovery distributions. However, as for coarse samples, rock-sample recovery efficiency has a shoulder at around 1% recovery. Samples with greater than 1% recovery are on average 29 kg in weight and are regional samples. Rock samples with poorer than 1% recovery average 870 kg and are bulk or mining-style samples. Bulk samples, particularly of rock, are like coarse samples more likely to have been targeting diamond recovery. Thus they have a narrower target density than indicator mineral samples, and hence it is expected that such samples would have poorer recovery percentage than reconnaissance samples. Therefore, by not accounting for the larger samples, on average heavy-mineral recovery percentages are incrementally higher from loam, through alluvial to rock samples. This observation is also consistent with samples from the Northern Territory (Hutchison, 2012). However, Figure 10 shows a striking difference between Western Australian and Northern Territory heavy mineral recovery. For all sample types, average Northern Territory heavy mineral concentrations have been higher. The differences are borne out in statistics, as shown in Table 2. Based on values in Table 2, a typical (median) 25 kg Western Australian alluvial sample yields 18 g of heavy minerals. For other sample types, loam yields 4 g and rock samples yield 15 g. Coarse-grained samples yield 3 g; medium-grained samples yield 11 g, and fine-grained samples yield 0.7 g. The full dataset provides a median of 0.03%, which is equivalent to 8 g of heavy minerals for 25 kg of sample. The equivalent value from the Northern Territory (Hutchison, 2012) is almost four times this amount at 30 g per 25 kg sample.

Of the less common sample types that have not been plotted or tabulated, anthill or termite mound samples (n = 22) ranged from 0.001 to 4% recovery, with a median value of 0.004%, with no discernible difference between anthills or termite mounds. Although the number of samples is small, given the reputation for ants and termites to upgrade heavy minerals, anthill and termite mound recovery is surprisingly low. Northern Territory bioturbation samples have almost exclusively been collected for bulk chemistry analysis (Hutchison, 2012), in which case only a small amount of fine-grained material may be expected to be recovered. However, all the Western Australian samples for which heavy mineral concentration data has been provided have been sampled for diamonds and indicator minerals. Low recovery cannot be explained by sample purpose and is likely therefore to be inherent in the particular mounds sampled.

Soil sample (n = 178) recoveries ranged from 0.001 to 23% heavy minerals, with a high median value of 1.73% (equivalent to 432 g in a 25 kg sample). However, given that the most extensive leaching takes place in the upper levels of weathering profiles (i.e. the soil horizon), the high median value is to be expected.

Nondiamond indicator recovery

Diamond is the target mineral in diamond exploration, so it is natural that in most cases diamond is the most desirable indicator mineral in exploration samples. However, even in economic deposits, diamond is an accessory mineral xenocryst within its host rock and so, at source, other indicator minerals are considerably more abundant. Increasingly away from source, diamond's durability compared to other minerals alters the balance in favour of diamond abundance relative to other minerals. However, it is the same durability that can give rise to diamond travelling extremely long distances and providing what are in effect false positives in exploration programs. Therefore, both at and near to source (in the range of kilometres) nondiamond indicators remain an indispensable tool to either substantiate or replace diamond recovery.

Mineral species recovered

The principle nondiamond indicator minerals recovered, and those to which most attention has been paid during picking, are chromite (and other spinels), pyrope–almandine garnet, ilmenite (particularly picroilmenite), and Cr-rich diopside, which exhibits an intense apple-green colouration. However, of those indicators documented, the very large majority are chromites that have been identified visually. A total of 1.6 million chromites have been documented, compared to almost 39 000 garnets and 30 000 picroilmenites. A further 10 231 Cr-diopsides have been identified. These large numbers are estimates only, due to the fact that for the indicator-abundant samples individual grains have been estimated rather than counted. Furthermore, a very large number of false positives contribute to these figures because visual criteria cannot definitively discriminate genuine indicators from those derived from other sources. This is particularly true for chromites compared to ilmenites and garnets. For garnet 39 000 grains, even if the majority are false positives, is a large number. However, only 48 samples have reported more than 100 garnet grains, thus emphasizing the large gap between chromite (spinel) occurrence and that of garnet. In the Northern Territory (Hutchison, 2012), genuine garnet indicator minerals are extremely rare and are situated only within or directly on top of primary bodies. A similar rarity is expected in Western Australia and is supported by the mineral chemistry determinations that are discussed later in this report.

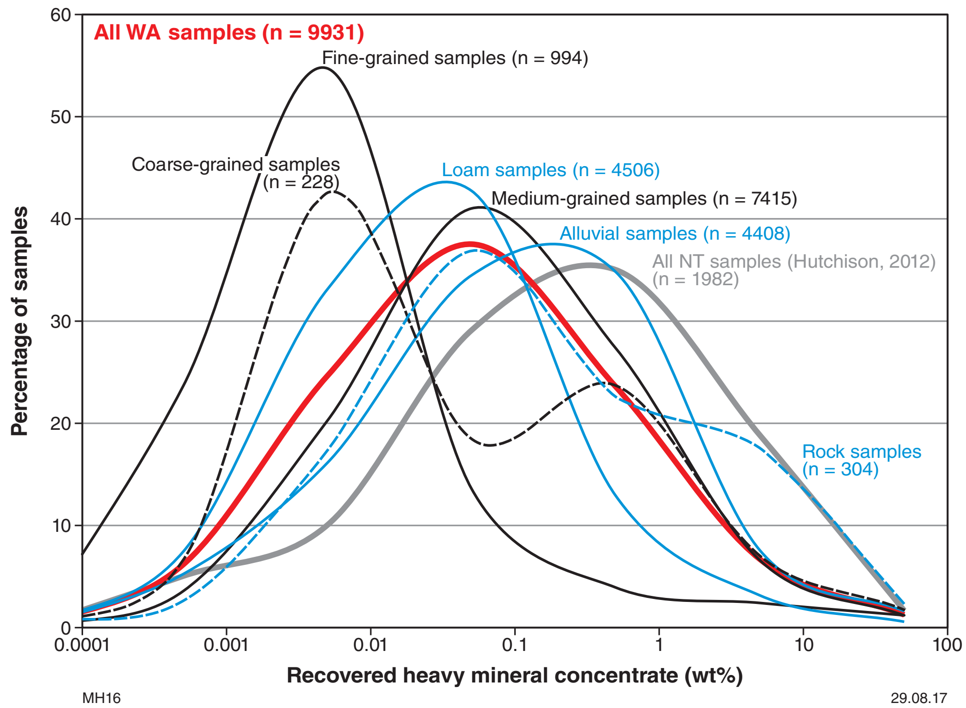


Figure 10. Western Australian exploration sample heavy-mineral concentrate percentage attributed to sample type and sample coarseness. All Western Australian data are derived from the DED (Hutchison, 2018; this study), are shown in red and are also shown subdivided according to sample coarseness (black lines) and sample type (blue lines). Coarse samples are defined as those using an upper mesh of 2 mm and above, medium samples have an upper mesh of 0.8 mm to <2 mm and fine samples have an upper mesh <0.8 mm. Recovery concentration distributions from the Northern Territory are shown in grey (Hutchison, 2012). Coarse samples and rock samples both show bimodal distributions, with a smaller peak at higher recovery percentages. These are interpreted to reflect a small proportion of bulk samples of in situ bodies that employ different recovery techniques. In general, loam and fine-grained samples have the smallest proportions of heavy minerals, thus reflecting poorer sorting, leaching and distance from the primary source

Table 2. Statistics for heavy-mineral concentrate weight as a percentage of sample weight

	All	*Coarse*	*Medium*	*Fine*	*Alluvial*	*Rock*	*Loam*
n	9931 *1982*	228 *252*	7415 *1644*	994 *78*	4408 *1687*	304 *42*	4506 *120*
Median	0.03 *0.15*	0.01 *0.15*	0.04 *0.15*	0.003 *0.10*	0.07 *0.16*	0.06 *1.24*	0.02 *0.05*
Mean	0.55 *1.06*	0.57 *1.23*	0.54 *1.05*	0.32 *0.20*	0.65 *1.00*	1.12 *7.32*	0.29 *0.24*
Maximum	52.92 *56.74*	21.20 *25.69*	52.92 *56.74*	25.07 *1.24*	52.92 *44.31*	23.58 *56.74*	51.72 *9.50*
Minimum	0.00001 *0.00003*	0.00018 *0.00008*	0.00008 *0.00003*	0.00004 *0.0038*	0.00004 *0.00008*	0.00003 *0.021*	0.00001 *0.00024*
Stdev	2.44 *3.54*	2.07 *2.51*	2.39 *3.74*	2.04 *0.33*	2.51 *2.77*	2.93 *15.43*	2.12 *0.89*

NOTES: Data from the Northern Territory (Hutchison, 2011) are included for comparison and are shown in italics. n – number of samples. Stdev – standard deviation. Upper mesh sizes: coarse – 2 mm and above, medium – 0.8 to < 2 mm, fine below 0.8 mm.

Indicator mineral sizes

Understanding the sizes of indicator minerals present in host rocks and their rate of attrition over transported distances is critically important in designing exploration sampling programs. As Hutchison (2012) has discussed, Northern Territory regional reconnaissance has often focused on size fractions that are too coarse to maximize the chances of recovering the most dominant indicator mineral spinel. Numerous studies, including in Western Australia, have looked at designing programs specific to northern Australian conditions of weathering (Muggeridge 1989, 1995). Some studies have been locality or process flow-sheet specific. For example, Towie and Brennan (1994, appendix F) conducted a detailed analysis of chromite recovery based on size fraction recovered from cone-crushed kimberlite from the Aries pipe. They showed that chromites were approximately four times more abundant in the 0.3 to 0.4 mm size fraction than in the 0.4 to 0.5 mm range. Where information is available, local knowledge from nearby pipes can allow the prospector to modify regional programs to target analogous bodies in local areas.

Data for sizes (or recovered size fractions) are much more numerous for spinels than any other Australian indicator mineral, most likely due to its high relative abundance. Hutchison (2011) has recorded for example that among the Elkedra Diamonds NL samples an average of over three times the number of spinels was observed in mineral separates with grain sizes under 0.4 mm compared to those with grains over 0.4 mm. It was also documented (Hutchison, 2012) that a concerningly high proportion (17%) of Northern Territory samples were inspected only in size fractions above 0.425 mm, thus leading to the conclusion that almost a fifth of Northern Territory exploration samples were too coarse and thus inappropriate for indicator mineral recovery. Hence, false negatives are to be expected frequently in the Northern Territory. Counts of spinel grains (the most commonly encountered indicator mineral) in different size ranges have been acquired from the references contributing to GSWA (2018) in relation to a considerable number (4205) of Western Australian exploration samples. The data have been examined to determine the ratio of spinels recovered for over and under different size cutoffs. Results for the ratios of spinels over and under 0.5 mm are shown in Figure 11a and for a 0.4 mm cutoff in Figure 11b. For samples where the spinels are abundant, an equal number of spinels were sometimes picked from each size fraction. The numbers of picked grains therefore reflect the picking procedure rather than the proportions of spinels actually present in the sample. In cases where distributions deviate from a Gaussian distribution, the picking procedure is the likely reason for this. However, deviations from smooth histograms are minor and do not affect the general conclusions.

The large majority (about 80%) of samples have more spinels under 0.5 mm compared to over this size fraction. The median value, in other words what one can expect in a typical sample, is almost three times more spinels below 0.5 mm than above. Few diamond explorers in Western Australia have used such a coarse minimum cutoff of 0.5 mm. However, for those that do (572 samples in the DED), 75% of their spinels will have been discarded. Bearing in mind that almost a fifth of Northern Territory explorers only inspected indicator minerals above 0.425 mm, to the detriment of mineral recovery, looking at the Western Australian statistics for a cutoff of 0.4 mm is also instructive. The DED records a small but significant number (1002 out of a total of 22 441) of Western Australian samples where grains below 0.4 mm or coarser were discarded and for which lower mesh sizes were recorded. Figure 11b demonstrates that samples with more spinels under 0.4 mm compared to over this size are more common. In this case, the median ratio is 2.0 indicating that one would expect double the number of spinels under 0.4 mm than over. A 0.4 mm cutoff could be used, but 20% of the samples reported more or less even numbers of spinels above and below 0.4 mm, so at least half of the potential spinel grains would be discarded. Comparing Northern Territory data with Western Australia, the median ratio for a 0.4 mm cutoff is larger, so that there are proportionally more <0.4 mm spinels reported in the Northern Territory than in Western Australia. It is therefore ironic that it has been in the Northern Territory that explorers have typically discarded <0.425 mm grains. Western Australian explorers have typically not adopted this coarse cutoff. Even if they had, it would have caused fewer lost spinels than in the Northern Territory.

Other established and potential indicator minerals

In addition to chromite, picroilmenite, Cr-diopside and pyrope–almandine garnet, less common minerals have been identified by explorers as, in their view, genuine indicators. Examples of these are olivine, perovskite, phlogopite, priderite and wadeite. Such minerals may have sources other than diamond-prospective rocks. However, on a case-by-case basis, commonly because of an association with other minerals or derivation from a particular rock type or particular locality, prospectors have been confident in defining them as indicator minerals. In such cases, they contribute to the total numbers of indicators attributed to a particular DED sample and thus contribute to sampling statistics. Minerals of these types are often not present in exploration samples because they are not durable and do not survive transportation well. For this reason they are referred to as rare indicators.

Rocks with diamond potential, particularly lamproites, also contain mineral species that are common rock-forming minerals in crustal rocks (Fipke, 1994; McInnes et al., 2009). Examples of these include zircon, tourmaline, rutile, kyanite, andradite, kimzeyite, corundum and pseudobrookite, and additionally alteration products such as leucoxene. In contrast to the rare indicators, many of these types of minerals are characterized by being relatively resistant to physical and chemical erosion and are reported to have potential for use in exploration for diamonds. Zircon and rutile exist as phenocrysts in some kimberlites (Mitchell 1986) and zircon is particularly important in exploration for lamproites (Fipke et al., 1995). Zr-bearing garnet (kimzeyite) has also been reported from some orangeites (Mitchell, 1995b) and carbonatites (Lupini et al., 1992). Corundum (Hutchison et al. 2004), zircon (Meyer and Svizero, 1973), rutile and kyanite (Prinz et al., 1975) are known as inclusions in diamonds.

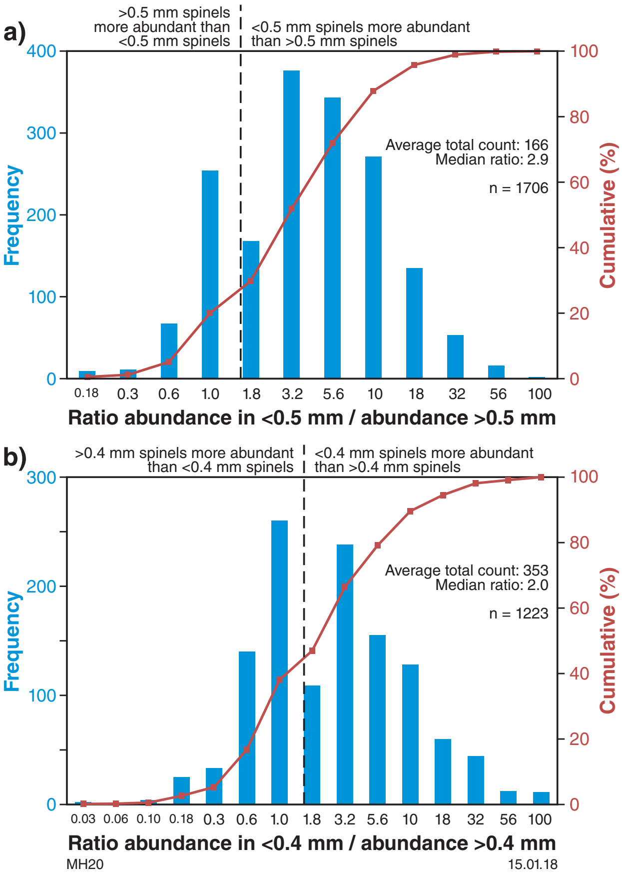


Figure 11. Frequencies of ratios of spinel counts above and below various size thresholds: a) a size threshold of 0.5 mm shows that the large majority of Western Australian spinel-bearing samples yield more <0.5 mm grains than larger sizes. The median sample has almost three times more <0.5 mm grains; b) reducing the cutoff to 0.4 mm shows that <0.4 mm spinels dominate in most samples, with a median ratio of 2:1 over coarser grains

Tourmalines have been recovered from lamproites, kimberlites and lamprophyres (Fipke et al., 1995). The particular chemical characteristics of such mineral species can be attributed to diamond-prospective rocks. However, in terms of appearance alone, it is difficult to utilize them as indicator minerals in the same way that, for example, Cr-diopside can be used. For these more challenging minerals, which are termed non-traditional indicators, it is likely that in surface sediment samples the number of grains derived from diamond-prospective rock are likely to be outnumbered by similar grains from crustal sources. Despite this shortcoming, explorers and mineral separation laboratories often make note of such mineral species and abundant data are available regarding locations of such samples. Paying attention to their distribution can be useful as a regional prospecting tool and for identifying sources of such minerals for further study when they are derived from known diamond-prospective areas.

The majority of non-traditional indicator mineral species that have been reported are corundum, tourmaline, and rutile (Fig. 12). It is likely in almost all cases that these occurrences are derived from crustal rocks. Particular concentrations are evident in the central Kimberley Basin, to the east in the Halls Creek Orogen, and in the WAC, particularly south of the Fortescue Basin. Localized clusters of other minerals are also apparent (Fig. 12). Of the rare indicators, phlogopite and perovskite show localized clusters in the NAC and in the vicinity of the Jewill kimberlites (WAC) respectively.

Andradite garnet

Andradite has been reported from five areas (Fig. 12). It is present in a cluster of seven samples from 11–16 km south of the Aries kimberlite pipes (Sackers, 1998; Louisa and Kimberley Basins); one sample in the Fortescue Basin (Barnes, 1995); a locality 350 m southeast of the Bulljah Pool 5 ultramafic lamprophyre in the Earaheedy Basin, one isolated sample with chromite, tourmaline and rutile in the Southern Carnarvon Basin (sampleID 730284) and in a sample not associated with other minerals of interest in the Hamersley Basin (sampleID 4801).

The Aries area yielded 18 andradite grains from four 40-kg samples taken from poor trap sites within current drainages. Samples were sieved to >0.3 mm. Accompanying andradite, indicators visually identified as chromites with morphologies classified as diamond-prospective (termed Types A, B, and C) were recovered from the 0.3 – 0.5 mm fraction.

The most andradite-rich sample (sampleID 9513) was derived from the Fortescue Basin, 140 km north of Newman (Barnes, 1995). A 76-kg sample of stream sediment from a low-quality trap site in a current drainage was taken and concentrated to 521 g by bromoform density segregation at the Independent Diamond Laboratories Ltd (IDL). Andradite was recovered with chromite from the >0.3 and <0.3 mm size fractions. Limonite, amphibole and garnet dominated the heavy minerals.

The Bulljah Pool andradites were recovered from a 30-kg sample (148901) of stream sediment (Purkait, 1997). The sample has been derived from the Paleoproterozoic Earaheedy Basin in an area of poor exposure very close to or within the extent of the 600-m diameter Bulljah 5 melnoite pipe (Clifford, 1994). The sample was observed in the 0.3 – 2 mm grain size fraction and was dominated by unidentified rock fragments and baryte. Andradite was accompanied by pyrope–almandine garnet, chromite, Cr-diopside, and phlogopite (Purkait, 1997).

Correct identification of andradite can be complex and while the grains discussed previously are genuine andradites, some other grains from three areas of Western Australia have been misidentified by visual inspection as other minerals, such as Cr-diopside. Their correct identities were revealed only by mineral chemical analysis. Consequently, these occurrences are discussed further in the Mineral chemistry section.

Leucoxene

Leucoxene can occur in kimberlites with sphene as a breakdown product of perovskite (Barron, 2005). Perovskite associated with leucoxene is also seen as a common alteration product of picroilmenite or chromite (Nguno, 2004). However, it is far from being ubiquitous in diamond-prospective rocks. Leucoxene has been reported in diamond exploration samples at discrete locations in

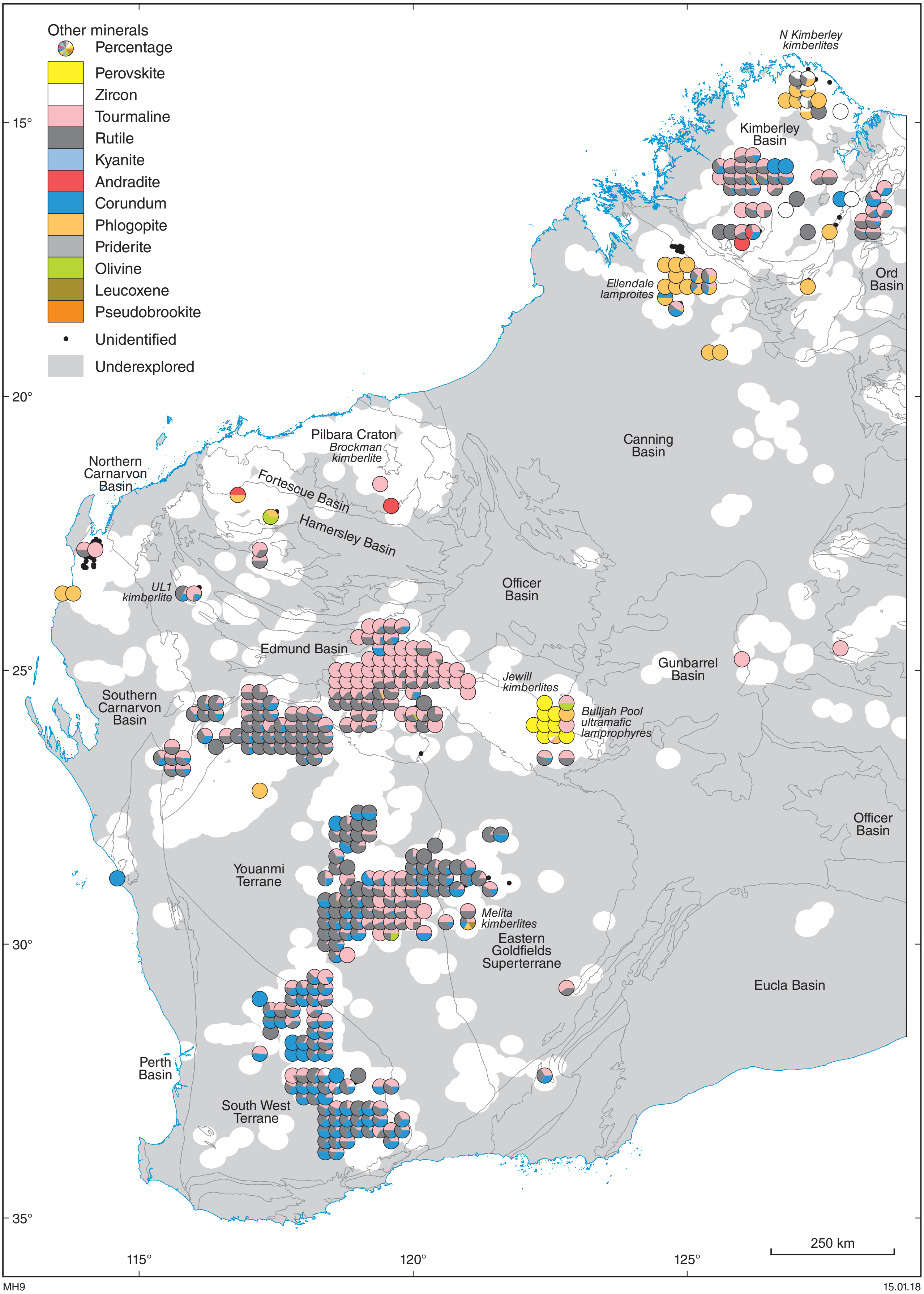


Figure 12. **Map of the distribution of minor and non-traditional indicator minerals. Western Australia is divided into major tectonic terranes shown by solid lines following Martin et al. (2016). Grey shading represents areas in excess of 20 km away from a diamond exploration sample, thus illustrating the difference between explored and unexplored areas. Olivine occurrences include instances of both olivine and monticellite**

the Ord Basin (with chromite; about 20 km from Argyle) and the South West Terrane of the Yilgarn Craton, with picroilmenite, and in the Youanmi Terrane. A single grain was also recovered from the Eastern Goldfields Superterrane (Fig. 12) at a location 200 m east of the Mae West 2 kimberlite, referred to as the Ballard Pipe (sampleID 728783). This occurrence is accompanied by garnet, chromite and picroilmenite. Furthermore, leucoxene grains appear in three samples from the Marymia Inlier approximately 7 km from the Methwin 01 and Methwin 02 kimberlites, as well as in two samples from the Kimberley Basin where they coexist with chromite and picroilmenite.

Olivine and monticellite

Olivine has been reported in 26 samples, with mineral chemistry reported for grains from six samples. The olivine-group mineral monticellite, which can exist as a primary kimberlite phase (Mitchell, 1986), was not identified visually in any sample, but appears in mineral chemical data from six samples. Some of the olivines were recovered from diamond-prospective rock samples. However, 10 olivine occurrences with no known source were identified in the Hamersley Basin (Fig. 12) and, with abundant chromite, pyrope and picroilmenite grains, the area was considered to be highly prospective (Towie, 2004). Monticellite grains were all derived from surface sediment samples from the Kimberley Basin (sampleID 706914; with chromite), Collier Basin (sampleID 715015) and Earaheedy Basin (sampleIDs 715421 and 715505; with Cr-diopside). Of particular note is a loam sample (sampleID 705600) from the Edmund Basin taken from 100 m south-southwest of the UL1 kimberlite (Fig. 12). This sample yielded a single monticellite grain in association with chromite and G3, G9 and G10D garnets.

Perovskite

All perovskite grains were derived from the Earaheedy Basin, where the Jewill kimberlites and the Bulljah Pool ultramafic lamprophyres (UML) are located (Fig. 12). Three perovskite-bearing surface sediment samples also containing chromite and zircon (Purkait, 2001) are closely associated with the Bulljah Pool UMLs. Other samples have been found within a 30-km radius of the nearest known diamond-prospective rocks at Bulljah (Hamilton, 1988; Clifford, 1994).

Phlogopite

Phlogopite exists as a primary phase in diamond-hosting rocks. While it is also present in other source rocks, it is readily discriminated from other micas that are more typical of crustal rocks. It is therefore not surprising that phlogopite is present in mineral concentrates from mantle-derived crustally emplaced bodies in Western Australia. However, phlogopite is a friable mineral that is easily destroyed during transportation. Therefore it is particularly notable on the occasions where it is present in surface sediment samples. The presence of phlogopite in surface sediment samples indicates a nearby rock source, whether as loose clasts or in situ occurrences. In examples where it is present with other DIMs, a stronger case can be made for a genuine diamond-prospective host being nearby. Hence, the identification of phlogopite in headless placers is a particular justification for further exploration.

Numerous phlogopite grains have been recovered from surface samples in the Ellendale lamproite field (Fig. 12). Most of these were derived from lamproite samples. Nearby (50 km south of the Brutens Hill lamproite) phlogopite has been reported in stream sediment samples with pyrope and chromite (Christie and Ryan 1993). In the Speewah Basin, Ransted (1995) reported phlogopite with pyrope, chromite and picroilmenite in a stream sediment sample about 1.5 km from the Devil's Elbow kimberlites. Possible phlogopite was reported from various samples in the central Kimberley Basin (Sackers, 1991). Phlogopite is also abundant in surface sediment samples in the north Kimberley Basin, sometimes with zircon (M Kammermann, 2014, written comm., May–June; e.g. DED sampleID 800282) and sometimes with chromite (Muggeridge, 2000). In the WAC, phlogopite has also been derived from in situ rock samples, but also appears in surface sediment samples, in some cases with olivine (Hamersley Basin; Towie and Field, 2000) and also with chromite and picroilmenite (about 20 km from the Bulljah UMLs, just within the Canning Basin; Purkait, 1998). Examples from alluvial samples also appear farther west in the Southern Carnarvon Basin, 75 km northwest of the Wandagee UML field (Askins, 1993).

All phlogopites with unknown sources, particularly in association with other indicator minerals, support cases for further exploration.

Priderite

Priderite (a hollandite group mineral) shares the distinction with wadeite of having the Walgidee Hills lamproite as its type locality. More Ba-rich hollandites are present in orangeites and carbonatites, and occur very rarely also in Type-I kimberlites (Mitchell, 1995b). However priderite is the most useful hollandite group indicator mineral for diamond exploration as it is typomorphic with lamproites (Mitchell, 1995b).

All five priderite-bearing samples reported in the DED compilation were discovered in the Canning Basin. Four were from samples of Walgidee Hills lamproites (with chromite and Cr-diopside; Astro Mining NL samples, e.g. sampleID 716630). However, one sample was present with chromite in a surface sediment sample from Brooking Springs (Turley, 1989) which, combined with other samples with abundant indicator minerals, led Turley (1989) to conclude that a source was nearby. The Big Spring West olivine–leucite lamproite was later discovered approximately 600 m to the north of the priderite-bearing sample, establishing its importance as a reconnaissance indicator mineral.

Pseudobrookite

Cr-pseudobrookite (>0.2 wt% Cr_2O_3) has been reported from three surface sediment samples; one from the Bulljah UML field (with chromite, pyrope and picroilmenite; Purkait 1997), one from Walgidee Hills (Astro Mining NL, sampleID 716818) and one from 9 km southeast of the Lissadell Road dykes (Astro Mining NL, sampleID 707314).

Wadeite

The Walgidee Hills lamproite is the type locality for wadeite (Prider, 1939) and while the mineral is not ubiquitous with lamproites it is common (Mitchell, 1995b) and is present in other lamproites from Western Australia, such as in the Ellendale field. Despite its association with Western Australian diamondiferous bodies, wadeite has only been reported in two exploration samples in the DED. Grains were recovered by Astro Mining NL (sampleID 707769 and two subsamples of sampleID 707747), both from approximately 14 km northwest of the Nabberu 20 kimberlite in the Marymia Inlier of the Yilgarn Craton.

Gold and other economic minerals

Gold is rarely present in kimberlites, and only in small quantities, and is more likely to be derived from subsequent metasomatic activity than from the mantle (Rozhkov et al., 1973). Gold is not considered to be a useful mineral for diamond exploration, nor is it known to be present in commercial quantities in diamond-hosting rocks. However, in a similar fashion to the documentation of the less traditional indicator-mineral species and because of its value in economic mineral exploration, laboratories often take note of the presence of gold grains when searching for DIMs. Consequently 297 distinct samples from the DED report gold grains and a further 13 company reports in the Department of Mines, Industry Regulation and Safety's (DMIRS) EXACT database refer to gold grains among some of their samples (totalling 493 records). Records of gold in the DED serve to demonstrate the usefulness of data compilation in stimulating parallel activity for commodities not of immediate initial interest. Figure 13 shows the distribution of reported gold grains compared with established Western Australian gold-bearing areas (indicated by locations from GSWA's MINEDEX database where the target commodity is gold). Although gold grains are present in regions where they would normally be expected, such as the Lamboo Province of the Halls Creek Orogen, the Eastern Goldfields Superterrane of the Yilgarn Craton, the Pilbara Craton and the Fortescue Basin, other occurrences of gold have been reported in areas with less well-established gold prospectivity. These are the northern and central Kimberley Basin (Muggeridge, 2000), a small number of samples within the Ellendale lamproite field immediately to the south, and the Collier Basin within the Capricorn Orogen (south of the Fortescue Basin). Outliers are also present within the Southern Carnarvon Basin, the central Canning Basin and the Amadeus Basin.

The median reported sample weight collected in Western Australia (29 298 samples; irrespective of sample type or collection method) is 45 kg. For gold samples with recorded weights (80 samples), the median sample weight is also 45 kg. Hence, gold recovery cannot be attributed to unusually large samples.

Other minerals of interest to the economic geologist have been reported from a wide distribution in the State and are included in the comments and other minerals fields of the DED. Examples include chalcopyrite (17 unique samples), bornite (6 unique samples), Cu-carbonates (23 unique samples, specifically two samples with azurite and eight with malachite), cuprite (1 sample), pyrite (87 unique samples), galena (4 unique samples), moissanite (71 unique samples), molybdenite (at least 27 unique samples), fluorite (16 unique samples), cassiterite (at least 34 unique samples) and monazite (4 unique samples).

Diamond recovery

Diamond survives chemical and physical degradation better than any other mineral derived from diamond-hosting rocks. Consequently, with increasing distance from host rocks, diamond increasingly becomes the most likely diamond-associated mineral to be recovered from exploration samples. The distance at which this takes place depends on various factors and, because the concentration and size distribution of host rocks is not known during exploration, it is not possible to quantify at what distance diamond will become the dominant mineral. It is important to take into account the fact that even in mined diamond deposits, the mineral is only present in concentrations around one part per million (Kjarsgaard 2007). Hence, the starting ratio of nondiamond indicators to diamonds in the host rock is very high. If the dominant diamond sizes are in the microdiamond category, it can be impractical to expect to target diamond as an indicator mineral despite its durability. This is particularly true in areas such as the eastern Northern Territory (Hutchison, 2012), where there is a ubiquitous background presence of windborne microdiamonds. Diamonds slowly degrade with transportation and considerable information on the likely distance from source can be ascertained from their surface characteristics (Sutherland, 1982). Hence, in terms of presence of and distance to a potential source, when diamonds are present it is worthwhile taking their presence seriously.

Diamond distribution

A total of 2523 samples with positive diamond recovery have been reported for Western Australia, as compiled in the DED. The number includes 720 samples from the EXACT database, where diamond recovery is attributed to groups of samples rather than known individual samples. Of the total diamond-positive samples, 1730 include macrodiamonds. Hence, quite a large proportion of samples contain macrodiamonds in contrast to parts of the Northern Territory (Hutchison, 2012). Unsurprisingly, diamonds are present in surface sediment samples near to most of the known primary diamond deposits in Western Australia, and are particularly common around the larger clusters of kimberlites in the northern Kimberley Basin and lamproites in the Ellendale field, and in nearby fields at the southwestern extent of the NAC (Fig. 14a, principally microdiamonds; Fig. 14b, macrodiamonds). Of more strategic interest for further exploration are the occurrences of diamonds whose host rocks are unknown ('headless' occurrences). To this end, locations of positive diamond recovery are useful and macrodiamond counts in particular express such unknown sources. However, data solely for counts can be skewed by sample size, making the significance of anomalies unclear. The DED contains 1269 samples where both diamond counts and sample weight are recorded (in this case, only 129 samples are derived from the EXACT database). Diamond concentration (counts of diamonds per kilogram of sample) can thus be

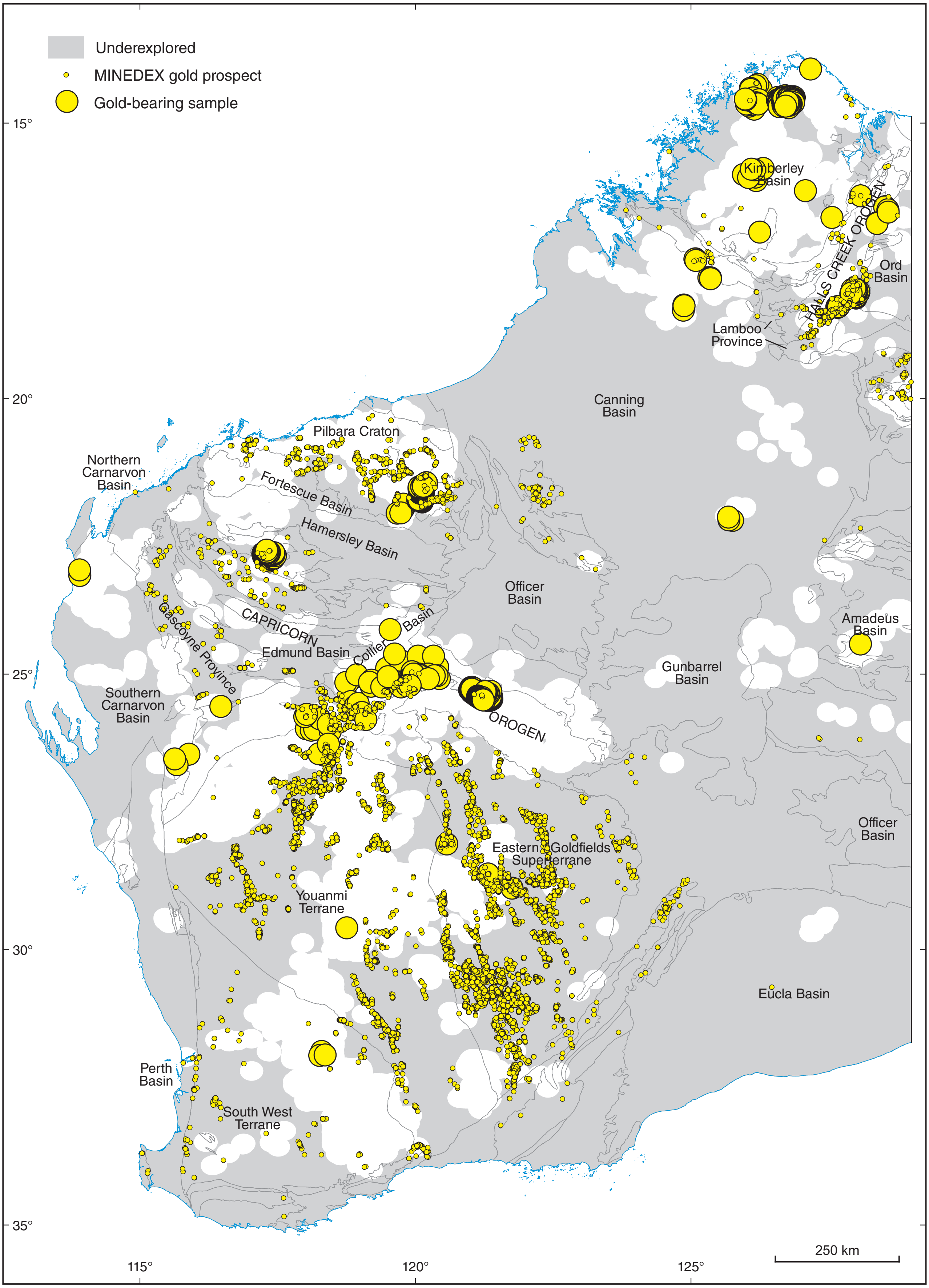


Figure 13. Map of the distribution of gold grains recovered from diamond exploration samples. The State is divided into major tectonic terranes shown by solid lines (Martin et al. 2016). Grey shading represents areas in excess of 20 km away from a diamond exploration sample, thus drawing attention to the difference between gold-negative and unexplored areas

calculated and mapped, and the distribution for the NAC of Western Australia is shown in Figure 14a. Figure 14b reproduces the same map with counts of macrodiamonds overlain in order to emphasize the relative importance of headless locations. EXACT database data, where diamond counts are assigned to all of the sample locations derived from each source report, are not shown on the map. Such sample locations would detract from the confidence level provided by definitive locations for diamond concentrations. Fewer data points are available to produce a comprehensive map of diamond distribution for the whole State. However, Figure 15 shows that where data exist, the same combination of headless and explained diamond anomalies is present.

In the NAC, diamond locations (including macrodiamonds) with unknown sources are present in the central Kimberley Basin north of the Aries kimberlite cluster and to the east (Fig. 14b). A particularly strong anomaly exists on the boundary with the Speewah Basin as a result of eight microdiamonds from two relatively small samples (seven diamonds in 43.2 kg and one diamond in 15 kg, sampleIDs 616356 and 616358; Paradigm North Pty Ltd, 2004). In eastern Western Australia anomalous diamonds occur in the Amadeus Basin (Phase 1), Northern and Southern Bonaparte, Carr Boyd, Ord and Yeneena Basins (Figs 14b and 15). To the west, unexplained occurrences have been reported in the Pilbara Craton, Yilgarn Craton (Eastern Goldfields Superterrane and Youanmi Terrane) and elsewhere in the WAC (Earaheedy, Fortescue and Hamersley Basins; Figure 15). Anomalies are particularly pronounced in the Hamersley Basin (sampleID 5193; Towie, 2004) and the Yerrida Basin (10 microdiamonds in 20 kg; sampleID 902341; Hamilton, 1984).

Physical characteristics of diamond

Detailed descriptions of 790 diamonds recovered from exploration samples have been compiled in the DED. In some cases, diamond colour, morphology, surface features and breakage have been documented. Abundances of different characteristics are provided in Table 3. Of particular note is that yellow and pink diamonds contribute 5% and 1% of the statewide regional sampling populations respectively. Of original growth forms, octahedral forms are most abundant (45%), in contrast to the Northern Territory where cubes dominate (Hutchison, 2013). However, 41% are dodecahedral or tetrahexahedral and 53% of octahedral stones show surface etching and resorption.

Western Australia has been prominent in worldwide diamond production in terms of highly valued fancy yellow-coloured diamonds (Downes et al., 2012) and continues to be so for the pink diamonds produced by the Argyle mine (Boxer and Jaques, 1990; King et al., 2014). Hence the presence of coloured diamonds is of particular significance among exploration samples. Diamonds described as yellow were reported from six localities, all associated with the NAC. Five descriptions were from samples in the Kimberley Basin and one was from nearby to the south, in the Ellendale field. Only two diamonds described as pink are in the database. A pink octahedral stone was from a sample acquired approximately 11 km northwest of the Aries kimberlite cluster (sampleID 916146; Muskett and Sackers, 1996), and notably, a yellow stone was recovered nearby (sampleID 916141; Muskett and Sackers, 1996). The other pink stone, described as clear pale pinkish-brown, was recovered from a sample taken in the Fortescue Basin (sampleID 7090; Barley and Blake, 1991) approximately 50 km south-southeast of the Brockman Creek kimberlites. This latter stone is particularly significant because coloured diamonds are not typically reported from the WAC.

Relationships between diamond and indicator recovery

Techniques for separating diamonds compared to other heavy minerals are normally different from each other. Whereas diamonds are usually picked from chemically reduced concentrates of small size fractions, nondiamond indicators are recovered from coarser fractions without wholescale sample dissolution. Consequently there are relatively few (568) subsample records that report both successful diamond and indicator mineral recovery. These records have been scrutinized to investigate the relationship between the numbers of visually determined nondiamond indicators and diamond recovery. These results are shown in Figure 16. Western Australian data show a strong coincidence with those from the Canadian Northwest Territories (Cranfield and Diprose, 2008) and from Queensland (Armstrong and Chatman, 2001), locations chosen because regional data are available. Queensland has a similar weathering environment to Western Australia, whereas the Northwest Territories are quite different in that regard. Compared to Western Australia, the proportions of nondiamond indicators to diamond are similar, but the absolute numbers of diamonds recovered from Western Australia are occasionally greater. Northern Territory data (Hutchison, 2012) are also included for comparison and are discriminated according to sample type. Both Western Australian and Northern Territory samples show a relative increase in abundance of nondiamond indicators compared to diamonds from alluvial to loam and rock samples. Comparing loam and alluvial samples from Western Australia, the absolute numbers of grains (both diamond and nondiamond indicators) are typically larger for alluvial samples. However, although Western Australian samples are consistent with Queensland and Northwest Territories data, the Northern Territory data are anomalous (Fig. 16). They differ both in terms of the abundance of diamonds recovered (in this case microdiamonds) and, particularly for alluvial samples, the high ratio of diamonds to nondiamond indicators.

For the 568 samples considered, due to scatter in the data, averages of ratios of nondiamond indicators to diamonds are not statistically robust. However, it can be confidently stated that for diamond-bearing rock samples, one would expect to recover between 10 to 1000 times more indicators than diamonds. The range for loams is larger (three orders of magnitude, 1 to 1000 times), as there are some samples where diamonds and nondiamonds occur in equal numbers. For alluvial samples there may be rare occurrences of samples with more diamonds than indicators, but typically ratios are expected to be similar to loams although with more absolute numbers of each.

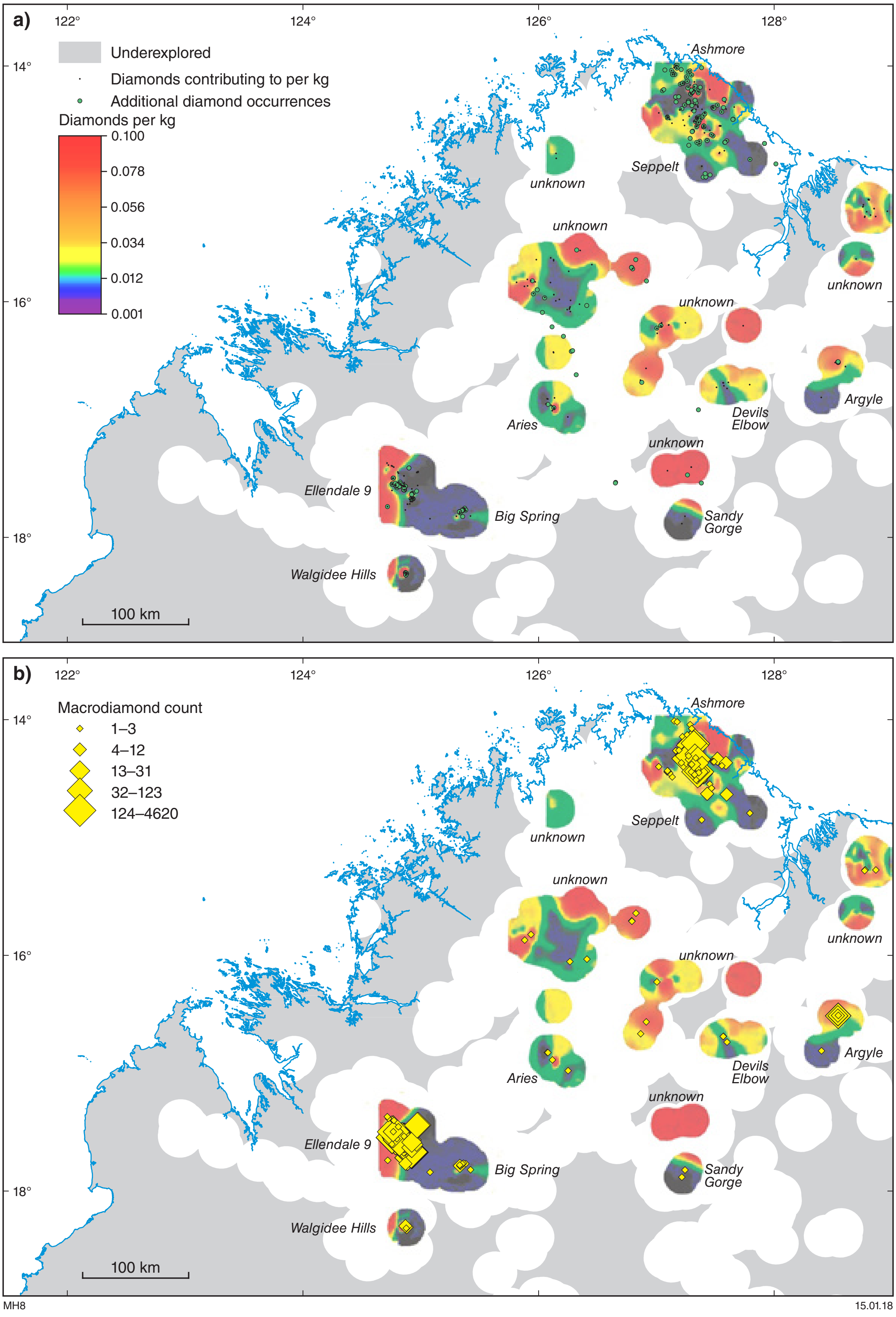


Figure 14. Distribution of diamond concentration in the North Australian Craton of Western Australia: a) diamond concentration (diamond counts per kg) is contoured following the key, with locations contributing to the map shown by small black dots. Additional occurrences of diamonds where the sample weight is unknown are shown by green circles. All areas in excess of 20 km from a diamond exploration sample are shown in grey shading, thus providing an indication of where the diamond concentration map is limited by no data. Diamond concentrations often can be associated with known diamondiferous rocks. However, some locations, annotated as 'unknown', have no known source rocks; b) the same diamond concentration is reproduced with counts of macrodiamonds indicated with a symbol size based on numbers of counts. While diamond counts are biased towards large sample sizes, the distribution emphasises the significance of the presence and absence of known sources

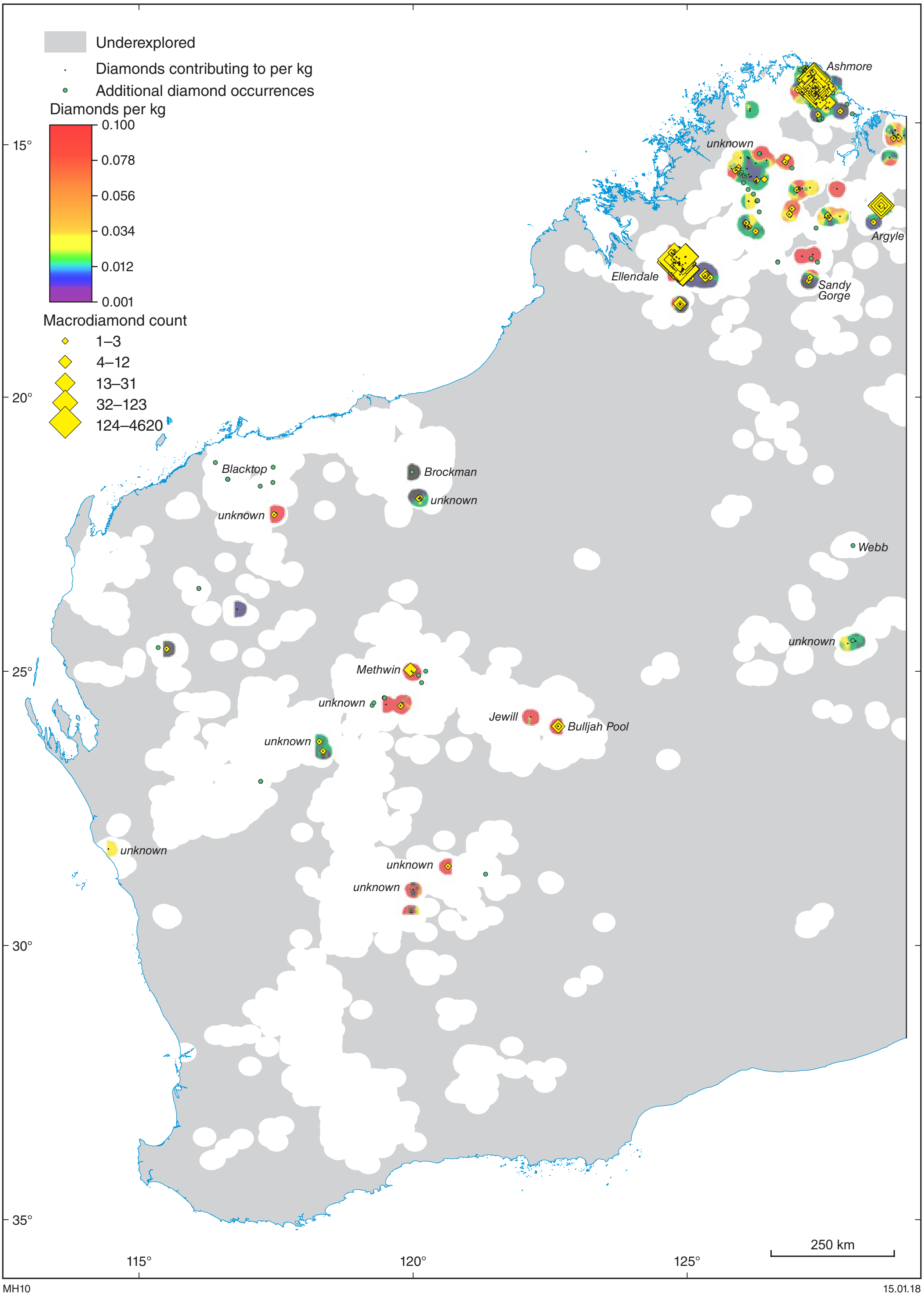


Figure 15. Distribution of diamond concentration across Western Australia. Diamond concentration (diamond counts per kg) is contoured following the key, with locations contributing to the map shown by small black dots. Additional occurrences of diamonds where the sample weight is unknown are shown by green circles. All areas in excess of 20 km from a diamond exploration sample are shown in shading, thus providing an indication of where the diamond concentration map is limited by no data. Diamond concentrations can be often associated with known diamondiferous rocks. However, some locations, annotated as 'unknown', have no known source rocks

Table 3. Physical properties of exploration sample-derived diamonds

Colour (n=292)	*Pink*	*Brown*	*Yellow*	*Colourless*	*Green*	*Grey*
Percentage	1	8	5	54	8	12
Shape (n=217)	*Irregular*	*Cube*	*Octahedron*	*Dodecahedron*	*Macle*	*Tetrahexahedron*
Percentage	56	1 (3)	21 (45)	7 (16)	4 (8)	12 (25)

NOTES: n – number of descriptions contributing to percentages. Figures in parentheses are percentages of different shapes amongst stones with identifiable morphologies (non-irregular).

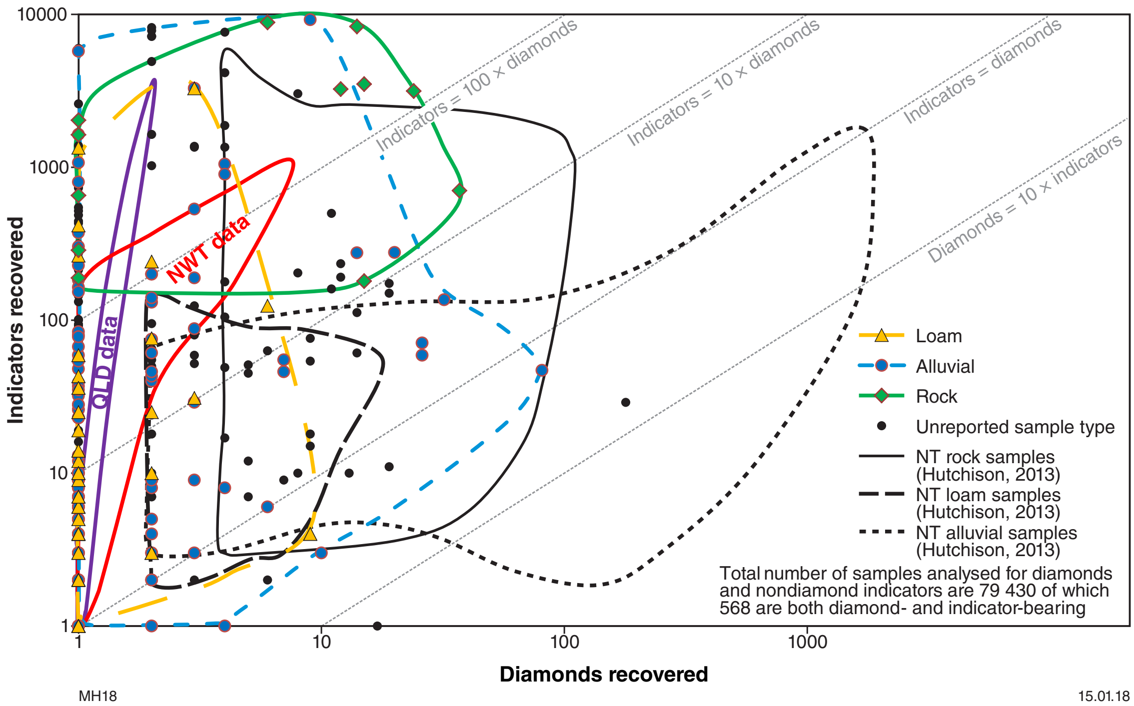


Figure 16. Relative abundance of nondiamond indicators to diamonds. Fields from Northern Territory samples (Hutchison, 2013) are shown as open polygons for comparison. Fields from Queensland (Cranfield and Diprose, 2008) and Canadian North West Territories (Armstrong and Chatman, 2001) samples are also indicated

The larger counts of all indicators (including diamond) in alluvial samples compared to loams are interpreted to be due to the sorting efficiency of alluvial processes compared to the formation of loams, with the former naturally concentrating heavy minerals such as diamonds and nondiamond indicators. The general trend in increasing abundance of nondiamond indicators compared to diamond for alluvial to loam to rock samples is derived from the relative amount of natural sample reworking. High ratios in the hundreds and thousands of nondiamond indicators to diamond in rock samples reflect the original ratios in the host rocks where diamond is present in small concentrations of parts per million or below. However, where sorting and grain degradation takes place increasingly from loam to alluvial settings, durable diamonds remain where more readily degraded indicators are destroyed or ground to sizes too small to be captured during sample processing.

The anomalous behaviour of Northern Territory alluvial samples is explained by a combination of the effects of weathering compounded by the presence of a distinct microdiamond anomaly in the eastern Northern Territory (Tyler, 1987; Hutchison, 2012). Microdiamonds are interpreted as being derived from a paleoplacer source at Coanjula (Smith et al., 1990) and have been very extensively wind-transported throughout the eastern Northern Territory. The ubiquity of microdiamonds in surface sediment samples in the eastern Northern Territory has led to the conclusion that the presence of microdiamonds is not a reliable indicator of a proximal source in this region (Hutchison, 2013). Fortunately, the masking effect of background microdiamonds does not apply to the western Northern Territory and, as the similarity with the Canadian Northwest Territories and Queensland data in Figure 16 implies, nor is there a regional microdiamond anomaly present in Western Australia.

Mineral chemistry

Acquisition of mineral chemical data is costly and time consuming. However, the process of fieldwork, sampling, transporting, processing and picking indicator minerals is extremely costly. Hence, acquiring mineral chemical data is proportionally not a large part of an exploration budget. This is particularly true because increasingly automated techniques are being employed to simplify and reduce the cost of the identification and analysis of mounted indicator grains (e.g. Keulen et al., 2009). Furthermore, as evidenced by the uncertainties encountered in correctly identifying phases (such as andradite and discriminating ilmenite from chromite) and further subdividing genuine from non-genuine indicators visually (such as garnets), mineral chemical data have a critical role to play in traditional indicator-mineral diamond prospecting. Nonetheless, in Western Australian diamond exploration, there are cases where mineral chemical techniques have been neglected. Excluding samples from the EXACT database where indicators have been attributed fractionally to multiple samples, a total of 13 659 subsamples have been reported to contain indicator minerals based on visual inspection. However, only 3 411 of these subsamples have any mineral chemical data attributed to them. Therefore, 75% of samples reported as indicator-positive have not been checked for mineral chemistry. In the Northern Territory (Hutchison, 2011) the equivalent figure is 81%.

Notwithstanding this shortcoming, abundant mineral chemical data do exist for Western Australia and scrutiny of this data provides useful insights into where mineral chemical techniques yield exploration dividends.

Chromite and other spinels

Spinels have been classified according to major and minor elements adapted from Ramsay (1992), and have been described in Hutchison (2011, 2018). Attribution as indicator minerals follows this classification where Mg, Al-spinel ± Ti, Cr and Fe, gahnite, and all chromites apart from Al-chromite are all classed as indicators and other compositions are excluded. The presence of Zn is not taken as a reason to preclude some chromites as indicators. Zn-chromites have been found in nondiamond-prospective rocks such as metamorphosed komatiites (Krishnakanta Singh and Bikramaditya Singh, 2011). However, Zn overprints to chromites have also been described as a consequence of low-grade metamorphism of kimberlites (Hutchison, 2013) and in some cases have an intrinsic association with diamond as evidenced by Zn-chromite inclusions in diamonds (Meyer and Boyd, 1972).

Among the indicator spinels, the majority are chromites (20 685 grains). A total of 2994 (Mg,Fe,Ti)-bearing Al-chromite indicator grains (Cr/(Cr+Al) cations are between 0.2 and 0.6; Hutchison, 2018) are not included in this number. Only 31 Al-spinels with indicator chemistry (as defined in Hutchison, 2018) and nine gahnites were reported. Statewide, some 3258 chromites are zincian (Zn-chromite, Zn, Mg-chromite and Zn, Ti-chromite) and almost all of these (83%) have been derived from the Yilgarn Craton. The large majority of the remainder are from elsewhere in the WAC, but not from within the Pilbara Craton. Seventeen zincian chromites are associated with chlorite-amphibolite schists (Astro Mining NL sample YNL0008, sampleID 728761) and one is from a dolerite (Astro Mining NL sample YS10447, sampleID 729490). However, one grain was recovered from a sample described as a micaceous kimberlite (most likely the Nabberu 2 ultramafic lamprophyre; Astro Mining NL sample YOR0003, sampleID 728778). Evidently there are a mix of diamond-related and nondiamond-related host rocks for zincian chromites in Western Australia. However, clusters occur closely around other bodies in the Nabberu (Marymia Inlier of the Yilgarn Craton), Bulljah Pool (Earaheedy Basin) and Turkey Well (Eastern Goldfields) fields and are present 40 km south of the Brockman Creek kimberlites. Elsewhere in Western Australia, examples of zincian chromite are found in the vicinity of the Big Spring lamproites and the Lower Bulgurri kimberlite dyke. Therefore, while regional zincian chromites may have crustal and nondiamond-prospective derivations, in some cases they likely act as pathfinders to diamond-prospective rocks. Gahnites (identified by mineral chemical analysis) have been found in two samples from the Ord Basin (Astro Mining NL sample KS1153, sampleID 707343; sampleID 617987, Roffey and Bishop, 2005); one sample from the Lamboo Province (about 10 km from the Argyle AK1 pipe and the Lissadell lamproite dykes; Astro Mining NL sample KS1125, sampleID 707315); and in two samples from the Youanmi Terrane (Astro Mining NL samples YL18253 and YS14360).

For the more abundant spinel indicators, comparison of absolute numbers of grains between regions may be misleading because the numbers of grains chosen for chemical analysis are somewhat arbitrary. However, it is useful to compare the proportion of different chemical classes within each region. Table 4 summarizes these data. Three areas have spinel indicators that are almost exclusively dominated by chromite (over 90%). These are the Yilgarn and Pilbara Cratons, and west Western Australia where some chromites derive from near the Wandagee ultramafic lamprophyres and others do not. In the WAC outside the Yilgarn and Pilbara Cratons, there is a similar dominance of chromite (88%), with the shortfall being made up mostly by (Mg,Fe,Ti)-bearing Al-chromites that are slightly more prolific than in the Yilgarn and Pilbara Cratons. (Mg,Fe,Ti)-bearing Al-chromites are most prevalent in the NAC and, in particular, in east off-craton Western Australia (bordering the Northern Territory), where they constitute almost 50% of the indicator spinels.

Indicator spinels have been further subdivided according to the methodology of Grütter and Apter (1998). A total of 345 chromites with compositions consistent with chromite inclusions in diamond (designated SP-CID or CID in the database) have been identified. All are Mg-chromites apart from three zincian Mg-chromites. One zincian CID chromite is from 400 m north of the Lower Bulgurri kimberlite (Kimberley Basin, NAC; AXIS database, M Kammermann, 2014, written comm., 18 May; sampleID 800294), one is from the Fortescue Basin (55 km SSE of the Brockman Creek kimberlites; Barley and Blake, 1991) and the third was recovered from the immediate vicinity of the Nabberu 1 kimberlite pipe (Astro Mining NL sample NAB1, sampleID 707696). The numbers of CID chromite grains identified are fairly evenly distributed across the cratonic regions with 110 from the NAC, 77 from the Pilbara Craton, 59 from the Yilgarn Craton and 62 from elsewhere in the WAC. Off-craton CID chromites are rarer and account for 37 samples, with 24

Table 4. Distribution of indicator spinel classes within Western Australian regions

	NAC	*WA East*	*WA West*	*WAC*	*Pilbara*	*Yilgarn*
Chromite	64.6	50.1	93.0	88.0	91.7	91.78
(Zn-chromite)	0.84	0.64	1.59	13.8	0.45	23.0
Al-chromite	35.4	47.4	6.87	11.8	8.29	8.16
Al-spinel	nul	2.0	0.12	0.11	nul	0.03
Gahnite	nul	0.46	nul	nul	nul	0.03
n	(1910)	(1087)	(1703)	(3487)	(3762)	(11 770)

NOTES: Numbers are expressed as percentages of the total number of grains (n) identified for each area, provided in parentheses. nul – not identified . Zn-chromite grains are considered as a subset of chromites, whereas Al-chromites are counted separately.

of these coming from the Walgidee Hills lamproite. For the more common compositions consistent with garnet peridotite chromites, relative abundances are similar with 1385 grains derived from the NAC, 3685 from the Pilbara Craton, 11 496 from the Yilgarn Craton, 3350 from elsewhere in the WAC, and 2708 regional off-craton samples. It must be emphasized that the number of grains chosen for mineral chemical analysis varies considerably from project to project. However, the ratios of CID to garnet peridotite compositions is useful because this is not influenced by sampling bias. In this regard, ratios are as follows: NAC 0.079, Pilbara Craton 0.021, Yilgarn Craton 0.005, other WAC locations 0.019, and off-craton regional samples 0.023. These data show that CID chromites are relatively uncommon in both off-craton settings, as might be expected, but also in the Yilgarn Craton, although the absolute numbers of indicator spinels are four times higher in the Yilgarn Craton compared to off-craton. CID chromites are particularly well represented among indicators from the NAC, followed by the Pilbara Craton and other WAC locations.

Further chemical discrimination using only spinels that were determined to be indicator minerals has the potential to provide a more specific attribution to host rocks. Figure 17 shows Cr relative to Cr + Al cations plotted against Fe^{2+} relative to Fe^{2+} + Mg cations where Fe has been attributed to both ferric and ferrous oxidations states based on cation calculations and charge balance (i.e. projected onto the oxidized prism of Mitchell, 1986). The numbers of chromites consistent with inclusions in diamond according to both this criteria (the labelled field in Figure 17) and Grütter and Apter's (1998) separate methodology is small. Examples came from the NAC, WAC and Yilgarn Craton and one sample was from the Pilbara Craton. All areas have generated spinel indicators with compositions consistent with both xenocrysts and phenocrysts in kimberlites. The western part of Western Australia, the Pilbara and Yilgarn Cratons and elsewhere in the WAC reveal abundant kimberlite phenocryst-consistent spinels. The Yilgarn and Pilbara Craton clusters are dominated by high Cr-chromites (mostly with Cr/(Cr+Al) cations over 0.6), whereas elsewhere on the WAC there is also a distinct trend in compositions towards Mg-rich and Cr-depleted (and Al-enriched) spinels (Fig. 17a). This same trend is evident among NAC samples, but slanted toward more Fe-rich (Mg-depleted) compositions (Fig. 17b). These are the same trends (Cr-enriched spinels in the Yilgarn and Pilbara Cratons, more so than elsewhere in the WAC; relative Al-enrichment in the NAC spinels) as seen in the comparison of CID with garnet peridotite spinels between areas.

Mitchell (1986) has described compositional trends, designated Magmatic Trend 1 (T1) and Magmatic Trend 2 (T2), in terms of the ratio of Ti cations to Ti + Cr + Al against Fe number ($Fe^{2+}/(Fe^{2+}$+Mg), where all Fe has been recast as ferrous (the 'reduced prism'). Based on worldwide samples, Mitchell (1986) concluded that T1 spinels are unique to kimberlites, whereas a T2 composition, due to a coincidence with spinels from lamproites, is not in itself diagnostic of a kimberlite or lamproite derivation. In order to identify a lamproite association definitively, an association with Ti–K richterite must be identified. Figure 18 presents indicator mineral compositions from Western Australia, with the T1 and T2 fields indicated, and the Northern Territory Kalkarindji Province (mostly basalt-derived) spinels (Hutchison, 2011) included for context. All Western Australian areas yield some spinel indicators with sufficiently elevated Ti to distinguish them from Kalkarindji and thus basaltic spinels. However, only a few Mg-rich outliers can be definitively placed as consistent with kimberlites (T1 trend). The chromite most convincingly within the T1 field is a Mg–Cr–Al-spinel grain from Ruby Bore in the WAC (Astro Mining NL sample PK3350, sampleID 715105). A handful of Yilgarn Craton grains (Mg, Al-chromite from Astro Mining NL sample YL19022, sampleID 727857 and Ti–Mg-chromite from Astro Mining NL sample PK0264, sampleID 713016) and a single Mg–Al-chromite grain from the NAC (AXIS database, M Kammermann, 2014, written comm., 18 May; sampleID 801863) lie within T1, along with a few off-craton eastern Western Australia grains. The NAC grain from 10 km south of the Ashmore kimberlite pipes (and north of Seppelt) is a chemical outlier. The WAC Ruby Bore T1 spinel was not accompanied by any other indicator phases and aside from the Nabberu kimberlite field 95 km to the northeast, no diamond-prospective rocks are known from the vicinity. However, PK0264 is closer (20 km northwest of the Nabberu field) and YL19022 was from 175 m south of the Turkey Well TW10 kimberlite pipe.

Aside from the few T1 outliers, Figure 18 demonstrates that the majority of recovered exploration spinel indicators cannot be attributed to specifically kimberlite or lamproite origins. As Mitchell (1986) has pointed out, a further association with Ti–K richterite is necessary to conclude a lamproite source. A total of 20 acceptable amphibole analyses have been acquired for the DED. With a maximum value of 0.95 wt% K_2O none are K-richterites, although with up to 1.92 wt% TiO_2 some are quite Ti-enriched. Richterite was identified visually in 13 samples and eight of these samples also had visually identified chromite

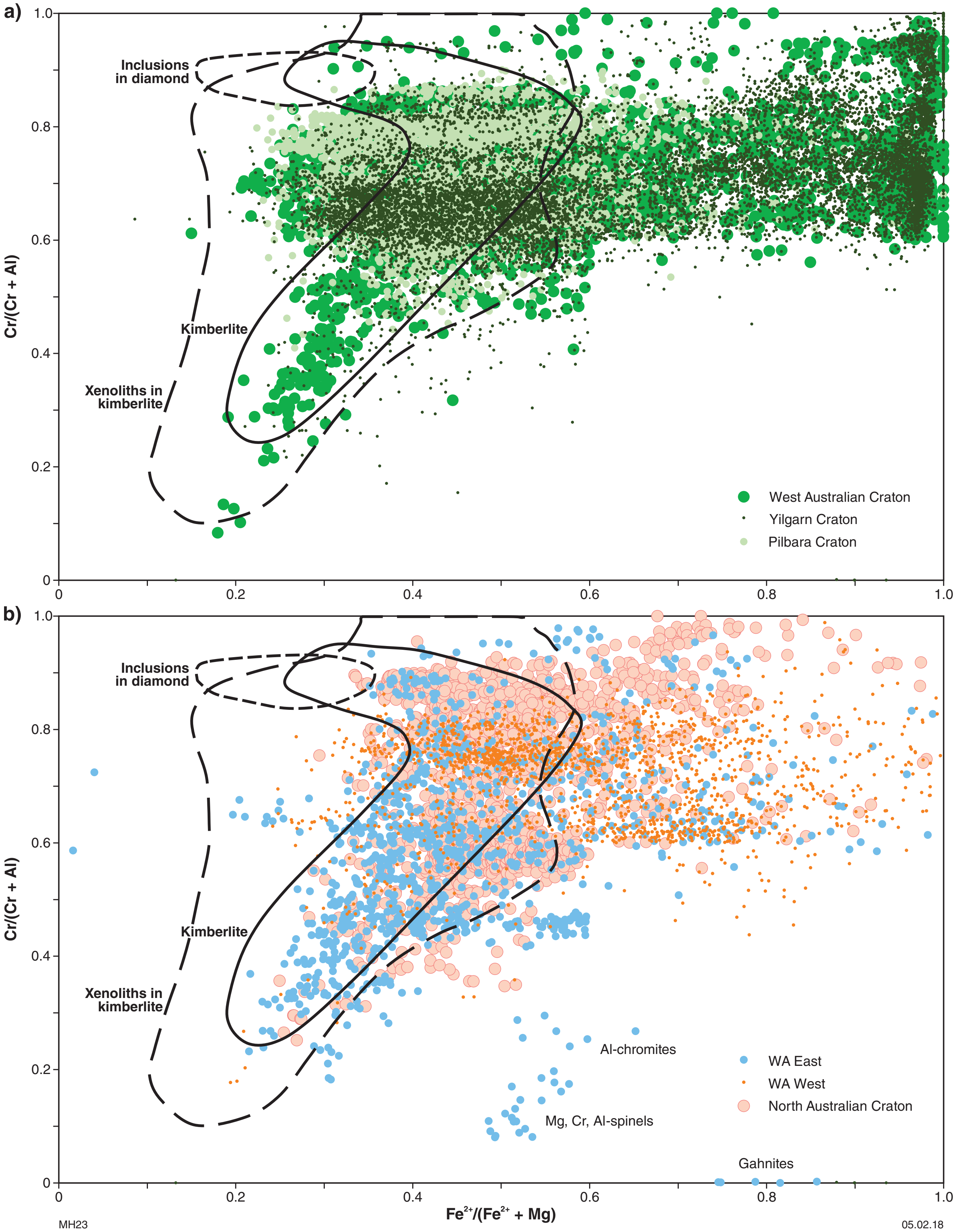


Figure 17. Chemical composition of indicator spinels projected from the oxidized prism in terms of Cr:Al ratio and Fe^{2+}:Mg ratio. Compositional fields coincident with chromite inclusions in diamonds, kimberlite groundmass grains and xenocrysts in kimberlites have been derived from Mitchell (1986). Projection onto the oxidized prism requires iron to be calculated as ferrous and ferric: a) West Australian Craton samples (subdivided amongst the Yilgarn and Pilbara Cratons and elsewhere in the WAC); b) other Western Australian locations. Few chromites have compositions consistent with inclusions in diamond. However, examples were found distributed over each geographic region. The large spread in compositional data for chromites derived from all parts of Western Australia reflects derivation from a variety of sources that are not necessarily diamond prospective. Outlier clusters of gahnite from eastern Western Australian regional samples and the Youanmi Terrane, and eastern Western Australian grains of Mg–Cr–Al-spinel and Al-chromite with elevated Mg or Ti are indicated

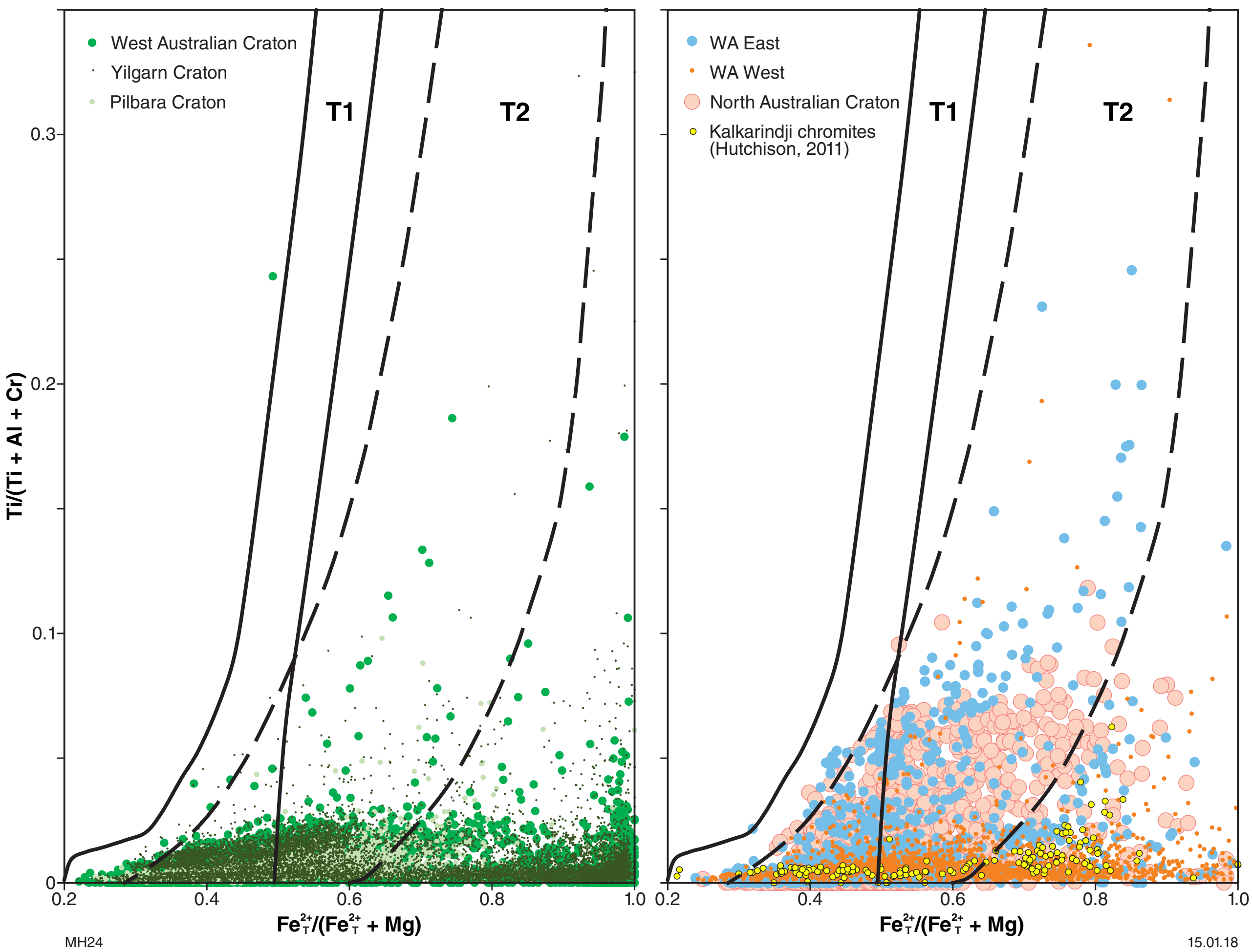


Figure 18. Chemical composition of indicator spinels in terms of Ti/(Ti+Cr+Al) against Fe-number projected from the reduced prism where all Fe is calculated to be ferrous (Fe^{2+}_T). Compositional fields following Magmatic Trends 1 (T1) and 2 (T2) are from Mitchell (1986): a) West Australian Craton samples (subdivided amongst the Yilgarn and Pilbara Cratons and elsewhere in the WAC); b) other Western Australian locations. Kalkarindji (Northern Territory) chromite compositions are shown for comparison (Hutchison, 2011). Only a few outliers can be attributed definitively to the T1 trend, hence making attribution to kimberlite or lamproite source rocks impossible based on these criteria

indicators. Five richterite-bearing samples have been derived directly from the Walgidee Hills lamproite, and one is from the Methwin 02 kimberlite (Astro Mining NL sample BS002, sampleID 703074). However, there is no data to tie Ti–K richterite to T2 spinels from exploration samples.

It is unfortunate that while spinel is by far the most abundant indicator mineral, major and minor element chemistry does not allow for a discrimination between a diamond-prospective and nondiamond-prospective source as well as for other indicator minerals. Methods based on trace element compositions (such as Co, Cu, Ga, Mn, Nb, Ni, Sc, Ti, V and Zr; Yaxley, 2008) yield much more definitive diamond-prospective associations. Although this method has been used with success in the Northern Territory (Hutchison, 2013) and is considered to be a fairly standard procedure for the larger companies (e.g. Roffey and Bishop, 2005), trace element compositions of spinels have rarely been determined by smaller diamond exploration companies in Western Australia.

Clinopyroxene

There is a significant overlap among clinopyroxene compositions from different geographic areas. Therefore, regional compositional extents are best shown by fields (Fig. 19a). The majority of WAC clinopyroxenes fall within the relatively Al-poor garnet peridotite field (after Ramsay and Tompkins, 1994). Al-depletion is particularly evident among Pilbara and Yilgarn Craton samples, although the latter show concurrent Cr-depletion such that much of the compositional range is consistent with an association with eclogites. Similar Al-depletion (in exchange for Cr) is seen in Yilgarn and Pilbara Craton spinels in comparison with elsewhere in the WAC. The Yilgarn Craton clinopyroxenes also show a separate Al-enriched field consistent with derivation from spinel peridotite. Off-craton eastern Western Australian samples show a wide compositional field in garnet peridotite and eclogite compositions, overlapping both the neighbouring western Northern Territory samples and the more Cr-enriched eastern Northern Territory samples, all from the NAC.

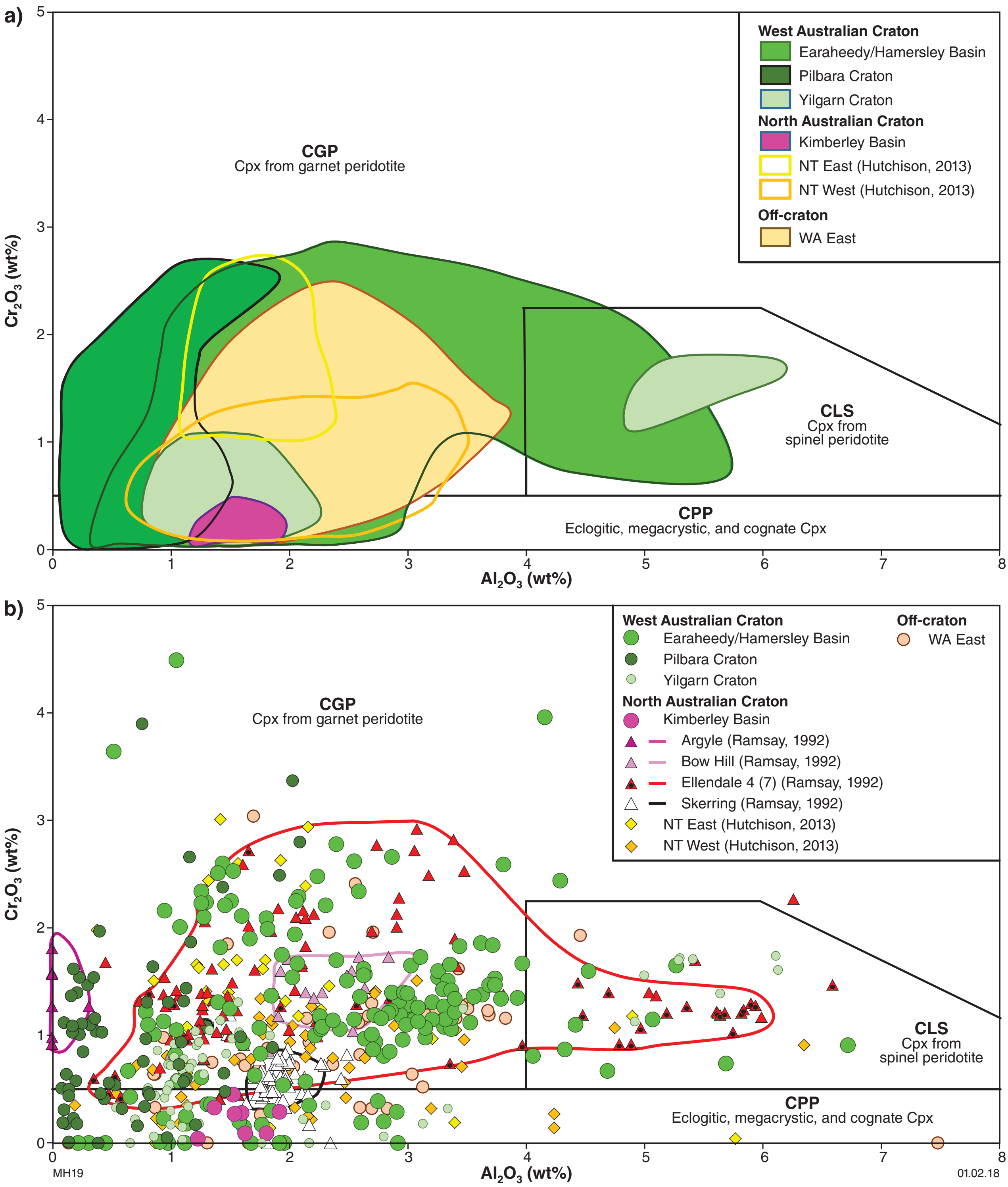


Figure 19. Chemical composition of clinopyroxenes in terms of Cr_2O_3 and Al_2O_3: a) compositional fields CGP, CLS and CPP with acronyms defined are from Ramsay and Tompkins (1994). Hand-drawn fields for regional samples from Western Australia and the Northern Territory (Hutchison, 2013) reflect 90% of the compositional data ranges omitting outliers. Eastern Western Australian samples show an overlap into lower Cr compositions (under 1.5 wt% Cr_2O_3) similar to samples immediately across the border in the Northern Territory. They also coincide with Cr-diopside compositions to the eastern extent of the NAC (also in the Northern Territory); b) individual data points contributing to the fields in a). Locality-specific clinopyroxene data from Ramsay (1992) are included with their extents emphasised by solid lines. Ellendale 7 samples are discriminated from Ellendale 4 samples by the addition of a black dot within the red triangle symbol. An incremental decrease in Al-content, reflecting greater depth and an association with garnet instead of spinel, is evident in samples from Ellendale 7 to Ellendale 4 and Bow Hill to Argyle lamproites. Elsewhere in the NAC, samples from the Skerring kimberlite are relatively Cr-poor and overlap with regional samples of eclogitic composition

The particularly Cr-depleted part of the compositional field for the western Northern Territory (which includes the Timber Creek kimberlite) samples coincides with the compositional range found in surface sediment samples from the Kimberley Basin in the vicinity of the Aries kimberlite cluster, the Pteropus Creek kimberlite and one regional sample with no known nearby source.

All data points contributing to the fields in Figure 19a are shown in Figure 19b, which includes locality-specific compositional clusters in the NAC from Ramsay (1992; also emphasized by polygons). Clinopyroxenes from the Ellendale lamproites show a wide compositional variation, particularly in the Al-content, which extends into the spinel peridotite field. Ellendale 7 clinopyroxenes are particularly Al-enriched compared with Ellendale 4 samples. Bow Hill lamproites show a tighter cluster within the garnet peridotite field at lower Al. Argyle lamproite-hosted clinopyroxenes show the strongest Al-depletion, placing their compositions firmly within the garnet peridotite field. For NAC kimberlites, samples from Skerring in the northern Kimberley Basin are poorer in Cr (some being consistent with eclogitic clinopyroxenes) than NAC lamproites. The Skerring compositional field clinopyroxenes have similar Cr contents to regional Kimberley Basin samples from this study.

Garnet

Garnet is considered a particularly useful mineral for diamond exploration because its large compositional variability can often allow attribution to very specific geological environments associated with high pressures within the mantle lithosphere (Grütter et al., 2004). Pyrope–almandine solid solution series garnets are associated with both mantle-derived eclogites and peridotites. Furthermore, other compositions such as kimzeyites and andradites are also known to be derived from diamond-hosting rocks (Mitchell, 1995b).

Pyrope–almandine garnet

Garnet does not survive well far from its host rocks, particularly in the heavily weathered environments of northern Australia (Hutchison, 2012; almost all indicator garnets in the Northern Territory have been derived directly from kimberlites). However, a total of 457 indicator mineral garnets associated with the DED have mineral chemical data reported and this supplements the extensive database from the known bodies of Ramsay (1992). The distribution of exploration samples among geographic areas is as follows: NAC – 119, WA East – 16, WA West – 2, Yilgarn Craton – 12, and WAC – 308. No indicator garnets with reported chemical compositions were recovered from the Pilbara Craton. However, statewide the numbers of grains chosen for analysis vary and, while not chemically classified, some indicator garnets have been identified visually from Pilbara Craton samples. All Pilbara Craton garnet indicators are associated with chromite indicators and some are derived directly from known kimberlites (Booth, 2001; Brockman Creek 01 West 5 kimberlite, Mitchell, 1999).

For the DED, all pyrope–almandine garnets have been classified following the methodology of Grütter et al. (2004). Inspection of the resulting mineral determinations reveals discrepancies between reported and recalculated classifications, emphasizing the importance of consistent reinterpretation of mineral chemistry data. For example, a garnet identified in surface sediment samples at Marymia (Davie-Smythe, 1992) was classified as a G3 (Grütter et al., 2004), whereas reclassification identifies it as a G4, but with a crustal derivation based on its high (0.51 wt%) MnO content.

Pyrope–almandine garnets with indicator mineral chemistry are shown in Figure 20 where they are plotted according to CaO and Cr_2O_3 content. Figure 20 also shows the compositional fields such as G9 and G10 following Grütter et al.'s (2004) classification. It is apparent, particularly when the distribution of data are expressed as fields (Fig. 20b), that the broad geographical subdivisions of Western Australia reveal different distributions of garnet chemistry. The NAC and in particular the WA East samples are characterized by compositions in the CaO-rich portion of the G9 field (Grütter et al., 2004). Only one garnet (from LD03736; Roffey and Bishop, 2005) falls into the G10 field (Grütter et al., 2004), although this is reported with an anomalously low CaO content even for G10 garnets. Many mineral chemical analysis reported by Rio Tinto, like this one, are based on SEM and many are of a poor quality. Most of the 3760 analyses reported as garnet from the Northern Territory and found to be unusable were provided by Rio Tinto (Hutchison, 2012).

In contrast to the WA East and NAC garnets, WAC samples distinguish themselves by trending in the mid- to low-CaO extent of the G9 field. Garnets from the Northern Territory's Merlin kimberlites (Reddicliffe, 1999) describe a well-constrained compositional field at yet lower CaO and straddling the boundary between G9 and G10. However, in further contrast to the Merlin garnets, WAC garnets also exhibit a considerably wider range of garnet chemistries, with a significant proportion plotting within the G10 field. These garnets are from the Edmund, Earaheedy and Hamersley Basins (e.g. Astro Mining NL sample GR10009, sampleID 705631; Astro Mining sample 149788, sampleID 700974; Towie, 2004).

Andradite garnet and kirschsteinite

As will be demonstrated in the case of andradites, determination of mineral chemistry has proven to be important over simple visual inspection. While andradite garnets are reported from five areas in Western Australia, mineral chemistry has been determined for samples from only three areas (Table 5). In the NAC, 18 analyses were determined from six samples from the Louisa and Kimberley Basins. One sample from the WAC (Fortescue Basin) yielded 89 grains (including Cr- and Ti-bearing examples) and another sample (from the Earaheedy Basin) contained a single grain. The bias towards andradite garnets being recovered from samples from the western Louisa Basin of the NAC is consistent with the bias towards lamproites compared to kimberlites in this part of Western Australia.

The most andradite-abundant sample (sampleID 9513) for which mineral chemistry has been obtained was reported with 90 Cr-diopsides and 15 chromites (Barnes, 1995). The Cr-diopside visual identification implies a greenish colour, but based on mineral chemical analysis all were subsequently classified as garnets. Analyses show

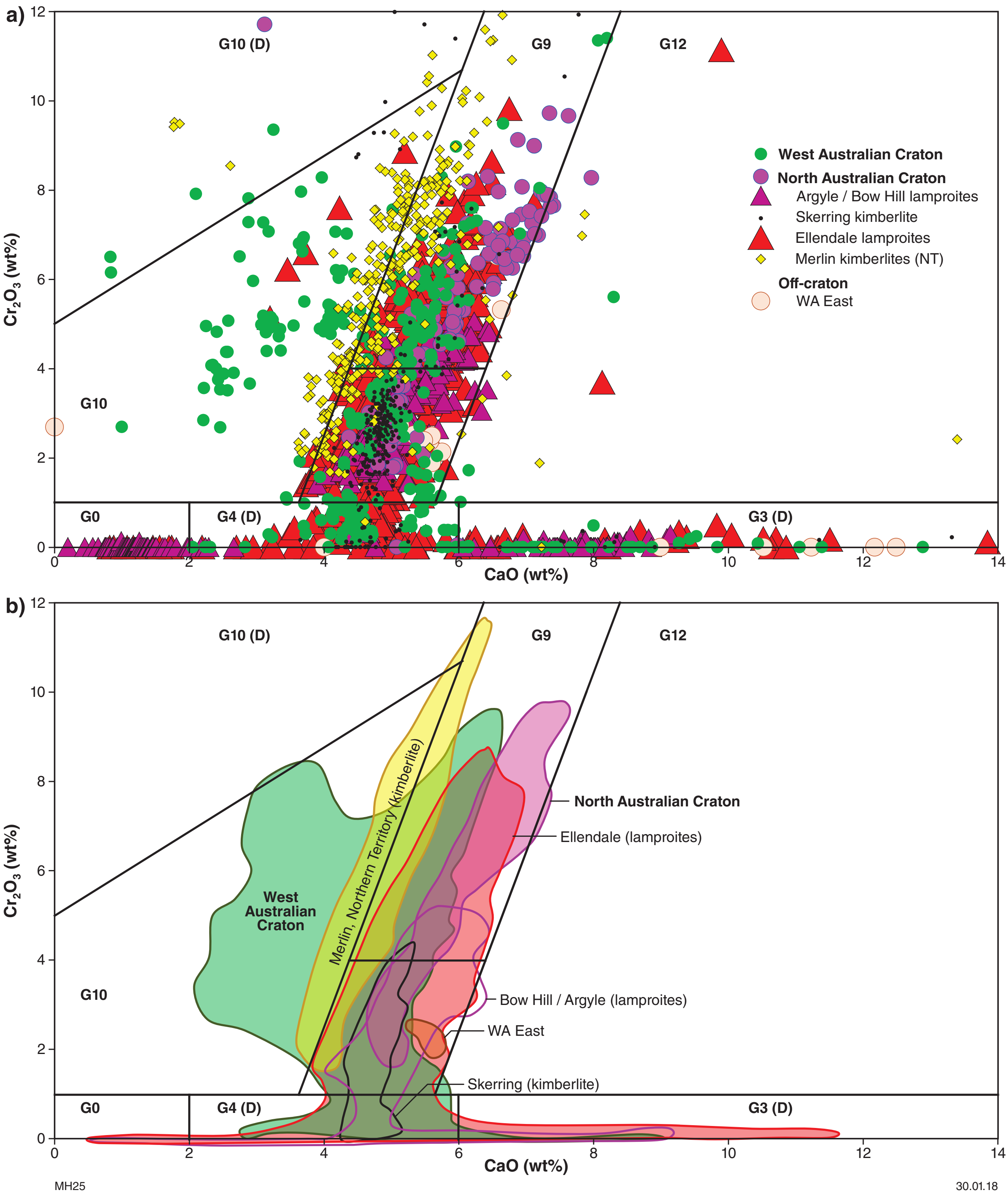


Figure 20. Chemical composition of pyrope–almandine–grossular garnets in terms of CaO and Cr_2O_3: a) point data from all Western Australian and Northern Territory samples, with Argyle, Bow Hill and Skerring data from Ramsay (1992) and Merlin (Northern Territory) data from Reddicliffe (1999). Argyle, Bow Hill and Ellendale all contain abundant G0 composition garnets not considered to be mantle derived according to standard criteria (Grütter et al., 2004); b) simplified diagram showing representative compositional fields encompassing about 90% of analyses from each location. Solid green — West Australian Craton; solid pink — North Australian Craton; solid orange — Eastern Western Australia; solid / lined red — Ellendale garnets (Ramsay, 1992); pink line — Argyle and Bow Hill garnets (Ramsay, 1992); black line — Skerring garnets (Ramsay, 1992); solid yellow — Merlin garnets (Northern Territory; Reddicliffe, 1999). The lherzolite trends are increasingly Ca-depleted from the North Australian Craton of Western Australia (including Ellendale, Argyle and Bow River) through the West Australian Craton to the Merlin field (Northern Territory) samples. However, the West Australian Craton samples also show a much higher proportion of G10 (Grütter et al., 2004) garnets also with an intermediate Ca-lherzolite trend

Table 5. Mineral chemical analyses of andradites and grains previously identified as kirschsteinite

Analyses with iron expressed as ferrous (Fe^{2+})						
Sample	AA758782	AA761370	AA761370	Ks-3[(a)]	Ks-6[(a)]	148901
Grain	4660206	7210101	7210102			15A
Source	1	1	1	2	2	3
SiO_2	33.55	35.93	35.6	36	35.6	36.52
TiO_2	0.42	0	0.34	0.2	0.7	0
Al_2O_3	0.65	0	0	0.4	2.4	2.94
Cr_2O_3	0.33	0	0.19		nd	0
FeO	28.72	28.4	27.91	28.6	24.8	24.39
MnO	0	0.5	0.21		0.1	0
MgO	0.63	0	0.3	0.4	2	0.25
CaO	33.67	34.45	34.2	33.9	33.9	35.53
TOTAL	98.74	99.28	98.89	99.5	99.5	99.63
Cations per 4 oxygen anions, with ferrous iron[(b)]						
Si	1.030	1.081	1.074	1.076	1.042	1.066
Ti	0.010	0.000	0.008	0.004	0.015	0.000
Al	0.024	0.000	0.000	0.014	0.083	0.101
Cr	0.008	0.000	0.005	0.000	0.000	0.000
Fe^{2+}	0.737	0.715	0.704	0.715	0.607	0.595
Mn	0.000	0.013	0.005	0.000	0.002	0.000
Mg	0.029	0.000	0.013	0.018	0.087	0.011
Ca	1.107	1.111	1.106	1.085	1.063	1.111
TOTAL	2.945	2.919	2.916	2.913	2.901	2.884
Analyses with iron expressed as ferric (Fe^{3+})						
Sample	AA761370	Ks-3[(a)]	Ks-6[(a)]	148901	8467	PDY-18
Grain	7210101			15A	76	GNT_15
Source	1	2	2	3	4	5
SiO2	35.93	36	35.6	36.52	34.25	33.49
TiO2	0	0.2	0.7	0	0	0.04
Al_2O_3	0	0.4	2.4	2.94	0.63	1.92
Cr_2O_3	0	nd	0	0	0.5	0
Fe_2O_3	31.56[(c)]	31.78[(c)]	27.56[(c)]	27.10	29.12	29.27
MnO	0.5	nd	0.1	0	0	0.47
MgO	0	0.4	2	0.25	0	0
CaO	34.45	33.9	33.9	35.53	33.43	33.05
Total	102.44	102.68	102.26	102.34	97.93	98.24
Cations per 12 oxygen anions, with ferric iron						
Si	2.977	2.963	2.906	2.976	2.959	2.885
Ti	0.000	0.012	0.043	0.000	0.000	0.003
Al	0.000	0.039	0.231	0.282	0.064	0.195
Cr	0.000	0.000	0.000	0.000	0.034	0.000
Fe^{3+}	1.968	1.968	1.693	1.662	1.893	1.898
Mn	0.035	0.000	0.007	0.000	0.000	0.034
Mg	0.000	0.049	0.243	0.030	0.000	0.000
Ca	3.058	2.989	2.965	3.102	3.095	3.051
Total	8.039	8.021	8.089	8.052	8.045	8.066

NOTES: Source 1 – Hutchison (2011), 2 – Chalapathi Rao et al. (1996), 3 – Purkait (1997), 4 – Barnes (1995), 5 – Sackers (1998).
(a) Grains originally published as kirschsteinite.
(b) Cations are calculated based on an olivine-like molecule $ABSiO_4$ and give unsatisfactory stoichiometry.
(c) Analyses have been recalculated from electron microprobe data to present iron as ferric as would be appropriate for andradite. High analysis totals are typical of garnet. Cation assignments based on $Ca_3(Fe^{3+},Al)_2Si_3O_{12}$ andradite give good stoichiometry supporting the contention that analyses published as kirschsteinite are andradites.

approximately 34% SiO_2, 32% Fe_2O_3, 34% CaO and low Al_2O_3 (<4 wt%). Chromium contents are up to 7.6 wt% Cr_2O_3. Such analyses are indistinguishable from the very rare mineral kirschsteinite (Table 5). Kirschsteinite is known from meteorites (Folco and Mellini, 1997), man-made slags and laboratory synthesis, and is referred to here because it has been attributed to the Kotakonda kimberlite in India as a groundmass mineral (Chalapathi Rao et al., 1996). However, in the absence of structural data, it is concluded that andradite has almost certainly been misidentified as kirschsteinite in this case, and no other terrestrial occurrences have been described. The analytical method for andradites from sampleID 9513 was not reported, but in other cases where grains were recovered by the same laboratory (IDL) they were analysed by electron microprobe. With electron microprobe as the likely analytical method coupled with good analysis totals and stoichiometries, it can be assumed that the mineral chemical data in this case are reliable. Combined with grains from a second mineral separation, 25 garnet peridotite-field chromite indicators accompany the andradite grains. No kimberlite or similar in situ rock was identified associated with these grains. The nearest known rocks of such type, the Brockman Creek kimberlites, lie 70 km to the north-northeast and the Mundine Well carbonatite lies 70 km to the northwest.

A second Western Australian chemically-identified andradite occurrence lies on the southern edge of the Phillips Range in the southern Kimberley, some 10 km from the 815 Ma (Downes et al., 2006) Aries kimberlite pipe (Sackers, 1998). This is a Group II kimberlite, although it shares a trace element signature with the similar-aged Maude Creek kimberlite and Bow Hill UML, which reflects their shared and distinctive mantle source (Towie et al., 1994). Eighteen andradite grains accompanied indicators visually identified as chromites with indicator morphologies (termed Types A, B and C). Heavy minerals from the Carson Volcanics basalts dominate the samples and visually identified ilmenites and garnets proved not to be mantle derived. However, among the analyses termed 'garnet' provided by Sackers (1998) are 18 analyses with low Al and with mineral chemistry consistent with identification as andradite. Andradites were accompanied by garnet peridotite-field chromite indicators in two samples in excess of 100 grains. The grains were not described individually. No definitive kimberlites have been described from the immediate vicinity of the samples.

Mineral chemical data for andradite from the vicinity of the Bulljah 5 melnoite pipe (Purkait, 1997) were determined in Dr Greg Pooley's UWA laboratory using electron probe microanalysis. The andradite was recorded as an unidentified mineral. However, with an analysis total of 99.6% and good stoichiometry (2.9 cations per 4 oxygens), the mineral chemical data are considered to be reliable. The andradite was accompanied by 35 garnet peridotite-field chromites, one mantle-derived G3 and three G4 garnets, two G9 garnets, five garnet peridotite and one eclogite/megacryst/cognate-field (CPP) Cr-diopside; a very respectable mantle-derived and diamond-indicating heavy mineral suite. The andradite grain was designated 15A, closely similar to a phlogopite grain termed 15B. This suggests that the two were attached composite grains that could not travel far without disaggregating. This constitutes further evidence that the samples derive from a near-situ source, almost certainly the Bulljah Pool 5 melnoite. An independent study of the chromite surface features led to the conclusion that corrosion cracks were consistent with a source less than 1 km away and most likely 'on-source' (Purkait, 1997).

Three Northern Territory andradites have been reported from regional diamond exploration (Hutchison, 2011) and were obtained from two 20-kg current drainage stream-sediment samples within the Kalkarindji Province, which is dominated by flood basalts. The samples were from a part of the Riveren East prospect (Archer, 1986) targeting diamonds and their source rocks. Grains were picked from the 0.2 – 0.8 mm bromoform-concentrated size fraction. The samples were laterite-rich and were subjected to a reduction roast technique. Mineral chemistry was determined by the ANU's precision energy-dispersive X-ray spectroscopy (EDS) method (Jeol T200 SEM with Kevex 7000 EDS using PIBS deconvolution), which is considered to be reliable. In addition to andradite, one sample also contained an intermediate-field composition picroilmenite and the other contained two garnet peridotite-field chromites and a garnet megacryst-field orthopyroxene. None of the indicators, including andradite, were identified as such visually, thus supporting the conclusions that visual inspection is no substitute for rigorous chemical analysis, and the diamond exploration history of northern Australia is almost certainly subject to false negatives. Although having good analytical totals (99%) and good stoichiometry, the significance of the andradites was not noted (Archer, 1986) and the grains were incorrectly classified as monticellite (Hutchison, 2012). Despite prospective indicator chemistries from the Kalkarindji locality, it lies in an area of the Northern Territory where kimberlites or similar rocks are not known, and while the Riveren East project aimed to identify the source of other possible kimberlite indicator minerals discovered, such a source was not found. To date, the nearest known similar body is the diamond-producing Argyle diamond mine, which lies approximately 200 km northwest in Western Australia.

Given the potential ambiguity for andradite mineral chemical identification, further inspection of the relevant data is merited. The first part of Table 5 presents Chalapathi Rao et al.'s (1996) data for kirschsteinite and grains from the Northern Territory (Hutchison, 2011) and Western Australia (Purkait, 1997) with iron calculated as the ferrous form. Analyses of kirschsteinite are indistinguishable within the range shown for Northern Territory and Western Australian andradites. Cations calculated based on 4 oxygen anions (of the form $(A,B)_2SiO_4$) show an excess of Ca over Fe^{2+} and low totals of divalent cations. The second half of Table 5 shows these same analyses recast with iron as the ferric form, and adding further data from Western Australian samples from Barnes (1995) and Sackers (1998), thus emphasizing that the 'kirschsteinite' analyses fall within the range of andradite analyses. Recast oxide data give high totals, although these are typical for garnet analyses. Calculations of cations with ferric iron are consistent with all analyses (including the Indian kirschsteinites) being andradite.

Ilmenite

Acceptable mineral chemical data have been obtained for 1614 ilmenite grains from Western Australian samples. A total of 642 have indicator mineral compositions following Wyatt et al. (2004). Ilmenite chemical compositions shown in Figure 21 are plotted according to TiO_2 and MgO. This diagram aims to discriminate ilmenites with a potential kimberlitic association from so-called intermediary compositions and those not consistent with a kimberlite source. It is evident that ilmenites from different geographical locations reveal different mineral chemical trends. Western Australian samples have been subdivided in Figure 21a such that the kimberlite and intermediary field grains are colour-coded according to their source region. The NAC regional samples shown extend the compositional trend of samples from across the border to the east within the Northern Territory (Hutchison 2012; identified by the open-dashed field) to considerably more Mg- and Ti-rich compositions and well into the kimberlite field. Non-kimberlite indicator ilmenites define a cluster largely at very low Mg contents (<1 wt%).

When ilmenites from known host rocks are plotted, the trend of increasing kimberlite association from the Northern Territory into the NAC of Western Australia is mirrored (Fig. 21b). Perhaps unsurprisingly, the kimberlite-derived ilmenites (Skerring pipe; Ramsay, 1992) fall more firmly in the kimberlite field than the lamproite-derived ilmenites (Ellendale 4; Ramsay, 1992), which dominantly lie within the intermediary field. In fact, the examples of compositions provided by Ramsay (1992) for Argyle-hosted ilmenites show them to be Mg-poor. Argyle lamproite ilmenites would not be classed as indicators following Wyatt et al.'s (2004) scheme. Western Australian NAC samples do not exhibit the high-Ti trend shown for NAC samples derived from the eastern Northern Territory (Fig. 21b; including from the Merlin kimberlites; Hutchison, 2013). Furthermore, the compositional ranges of Western Australian NAC ilmenites emphasize the conclusion of Hutchison (2013) that the eastern Northern Territory distinguishes itself from other parts of the NAC in having a pervasive Ti-enrichment in ilmenites from diamond exploration samples. A much higher proportion of Western Australian ilmenites overlap with kimberlitic ilmenite chemistry than ilmenites from the Northern Territory (i.e. approximately 50% compared with approximately 5%).

Ilmenites from the WAC show similar compositional variations for indicator composition grains as the Western Australian samples from the NAC (Fig. 21a). However, samples from the Eastern Goldfields Superterrane of the Yilgarn Craton distinguish themselves as having the most abundant high Ti- and high Mg- kimberlite field ilmenites of any Western Australian samples. Incrementally, the Hamersley Basin, Marymia Inlier and South West Terrane ilmenites, followed by off-craton examples to the west, are increasingly Mg-depleted. However, even past the western flanks of the WAC in the Southern Carnarvon Basin ilmenites are more Mg-rich than on-craton samples from the NAC in the Northern Territory.

A concern on considering ilmenite mineral chemistry is the influence of alteration. Ilmenites can show elevated MnO as a result of weathering where Mn replaces Mg. Significant numbers of Western Australian ilmenites have elevated Mn, with 38% having more than 1 wt% MnO. However, among those with indicator compositions, the proportion of ilmenites with over 1 wt% MnO is only 3%. The highest MnO value (10.03 wt%) was recorded from a sample of talc schist from the Eastern Goldfields Superterrane that was considered to be a candidate for a metamorphosed kimberlitic rock (Astro Mining NL sample YOR0301, sampleID 728794). Among the non-indicator ilmenites, if all of the MnO is assigned to MgO, few grains would be reclassified as indicators (4% would be reclassified as kimberlitic and 3% would be reclassified as intermediary). Hence, Mn introduced through weathering has apparently little effect on the abundance of ilmenites with indicator mineral chemistry.

Orthopyroxene

Orthopyroxene is not a common phase that survives in diamond exploration samples and hence only a relatively small number (95) of good-quality mineral chemical analyses for orthopyroxene are available in the DED. Of those, 36 are regarded as mantle derived following the classification scheme of Ramsay and Tompkins (1994). However, four of these analyses have chemistries reflecting sources derived from spinel lherzolites or pyroxenite xenoliths, too shallow for them to be considered as indicator minerals. Supplementing the regional data are locality-specific compositions from the Argyle, Bow Hill, Ellendale 4 and Ellendale 7 lamproites (Ramsay, 1992). Compositional variations are shown in Figure 22 where the ratio of Al_2O_3 to SiO_2 is plotted against Mg/(MgO + FeO).

As for other phases, analyses show distinct trends based on sample location. From the WAC, there are two clear groups. One group comprises garnet peridotite / on-craton megacryst (OGM) compositions from various regions. The other group comprises compositions consistent with associations with diamondiferous lherzolite (ODL) and harzburgite (ODH) that originate specifically from the Hamersley Basin. All Hamersley Basin indicator orthopyroxenes have been derived from a single sample (PRE006; Towie, 2004) that has the distinction of being associated with six G9 and two G10D garnets and a kimberlitic ilmenite. This sample has been described as coming from an in situ rock chip, but a diamond-prospective body has not been described at this locality. Samples (e.g. Davie-Smythe, 1994) that come from the Earaheedy Basin and Marymia Inlier of the Yilgarn Craton lie close (within 20 km) to the Nabberu field kimberlites. However, given the poor survival rates of diamond-associated enstatites, their presence in surface sediment samples is still enigmatic. More enigmatic are the indicator orthopyroxenes reported from the Collier Basin, which reside far from any known diamond-prospective rocks. No Collier Basin orthopyroxene-bearing samples had any other reported indicator minerals, with the exception of one (Astro Mining NL sample PK4201, sampleID 715668), making their association with diamond-prospective rocks questionable.

There are too few NAC indicator orthopyroxene samples from this study to reach conclusions on their compositional trends. However, some analysed grains have compositions either within or close to the OGM field at its Mg-depleted extent. One example came from approximately 20 km

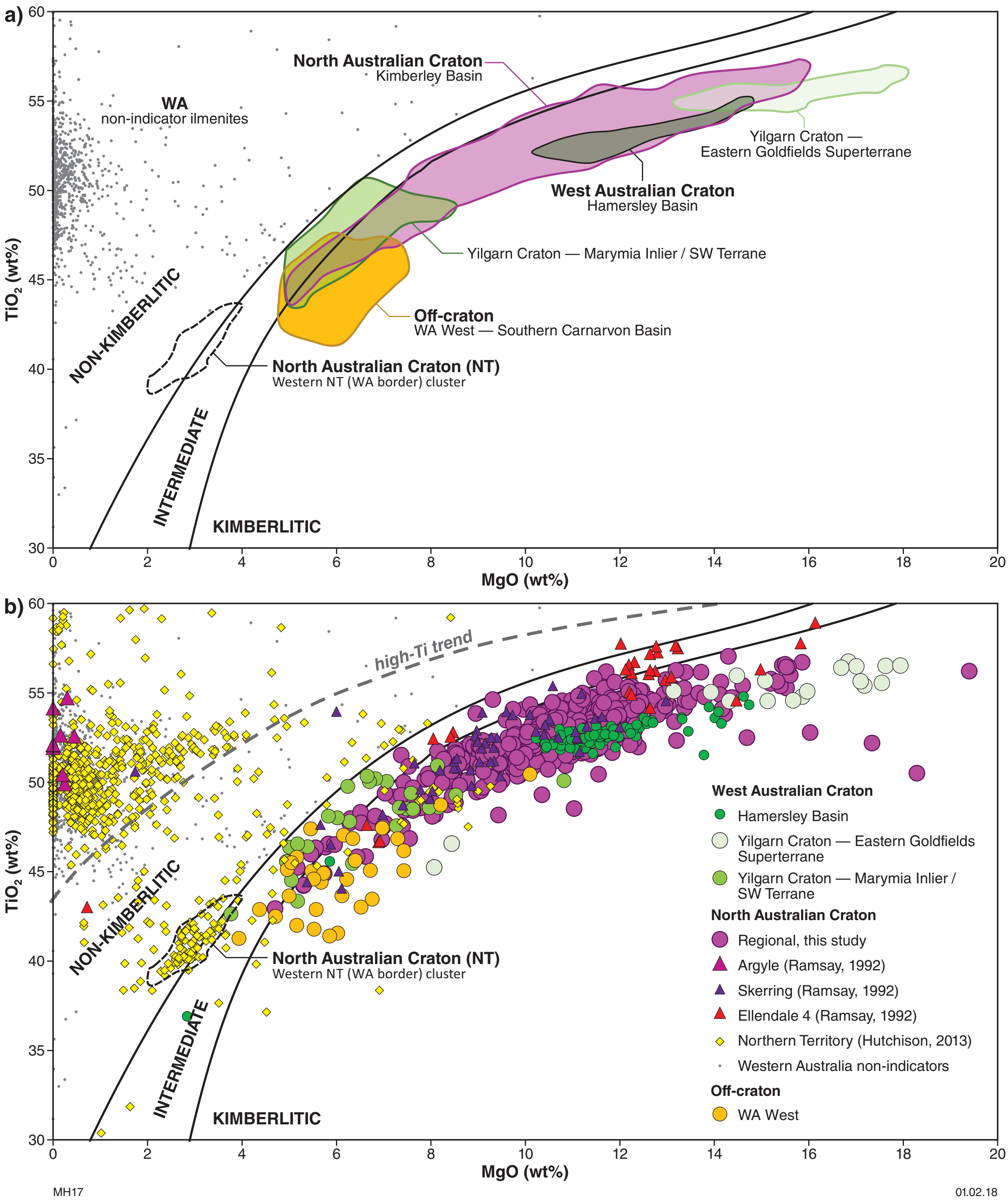


Figure 21. **Chemical composition of ilmenites in terms of TiO_2 and MgO: a) source locations are identified following the key. Indicator-composition ilmenites are indicated by hand-drawn fields encompassing 90% of data excluding outliers. Non-indicator composition ilmenites following Wyatt et al. (2004) are shown by blue dots. Amongst the Northern Territory ilmenites, a cluster of Northern Territory–Western Australian-border ilmenite compositions are labelled; b) all the data points from the DED (GSWA, 2018) are shown for Western Australian indicator ilmenites in the context of Northern Territory compositions (Hutchison, 2013) and locality-specific compositions from the NAC (Ramsay, 1992). Different regions show distinct compositional trends where generally speaking kimberlite-derived samples (Skerring kimberlite pipe; Ramsay, 1992) fall more firmly within the kimberlite compositional field than lamproite samples (Ellendale 4 and Argyle; Ramsay, 1992). Argyle ilmenites would not be classed as having indicator mineral compositions at all. Furthermore, the eastern Yilgarn samples (derived only from the Marymia Inlier and South West Terrane) distinguish themselves as more kimberlitic than samples from the western flanks of the WAC, just as the western NAC samples are more kimberlitic than those across the border to the east in the Northern Territory (Hutchison, 2013)**

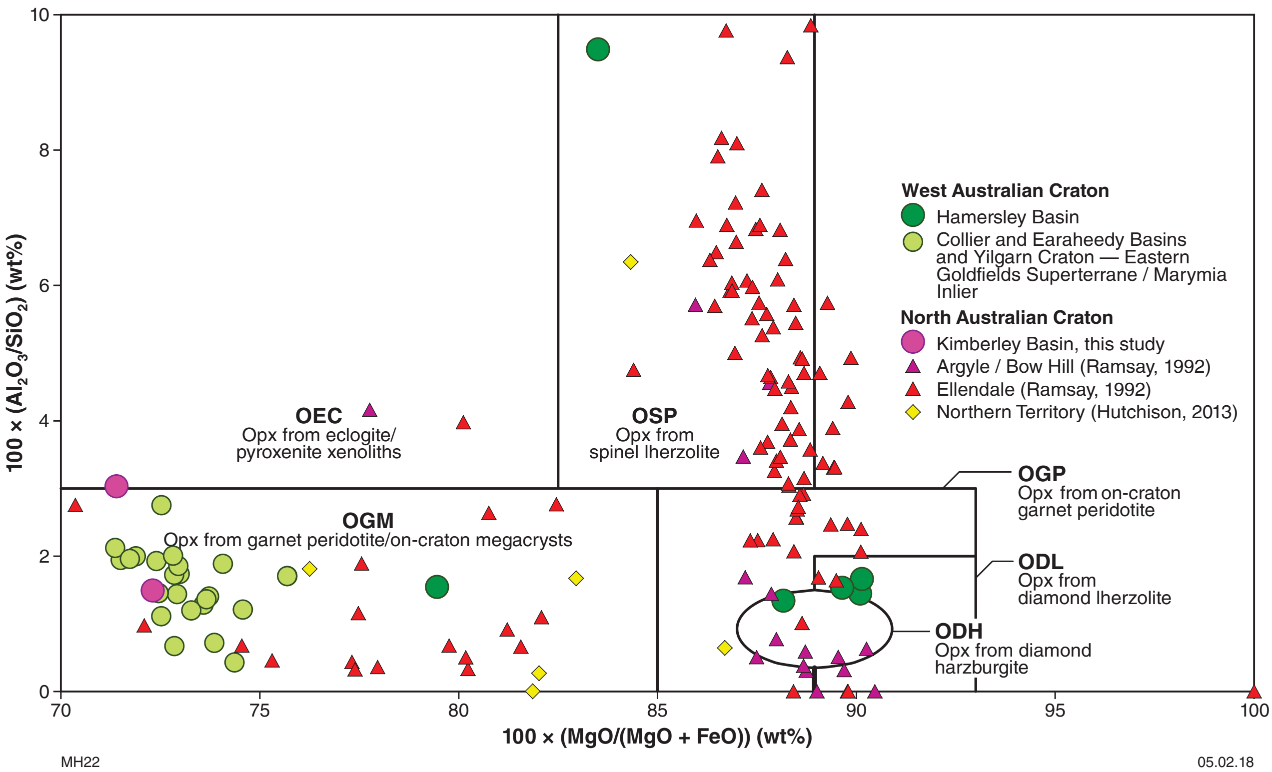


Figure 22. Chemical composition of orthopyroxenes in terms of Al_2O_3:SiO_2 and MgO:FeO ratios. Orthopyroxene grains are small in number, making generalizations on location-specific compositional trends less clear than for the more abundant phases. Note that WAC samples tend to cluster in deep-sourced peridotitic compositions, whereas NAC orthopyroxenes show a wider compositional trend reflecting a range of depth origins into the shallower spinel-stability field

southeast of the Aries kimberlite (Cooper, 1999) and contained 63 non-kimberlitic spinels and two non-kimberlitic garnets. With NAC analyses supplemented by data from Ramsay (1992), some trends become evident. Ellendale lamproite-hosted orthopyroxenes (Ramsay, 1992) show a distinct compositional trend with a more or less constant Mg/Fe ratio and with a varying Al-content spanning the spinel lherzolite (OSP), garnet peridotite (OGP) and diamond-association fields (ODL and ODH). Orthopyroxenes from Bow Hill and Argyle (Ramsay, 1992) show the same trend and particularly dominate the Al-poor diamond associations.

Alternative exploration methods

While the large bulk of readily compatible and queriable diamond-exploration data for the State has been derived from sampling for indicator minerals, numerous other techniques have been routinely used by diamond explorers. The successful identification of primary diamond deposits is routinely a consequence of a multidisciplinary approach (e.g. Kaminsky et al., 1995). Previous sections have discussed non-traditional and potential indicator minerals. The following section briefly discusses some of the other techniques employed.

Whole-rock techniques

A total of 9625 samples have been reported in the DED as being collected for the purpose of bulk chemical determination (11% of those for which a sample purpose has been reported). These samples have been collected either for the sole purpose of bulk chemical determination or in conjunction with other techniques applied to splits of the sample (normally indicator mineral picking). Routinely, the bulk chemical component of a sample will be the finer grain-size fraction, which gives rise to more representative data. In cases where coarser fractions are inspected for indicators or diamonds, the bulk chemical component will be of grains smaller than the minimum sieve size for indicator picking, typically 0.2 or 0.3 mm.

While the interpretation of whole-rock analyses of diamondiferous rocks is fraught with difficulties when used for petrological classification (Mitchell, 1995c), as a method for regional sampling it has benefits. Typically, concentrations of elements favoured by ultramafic rocks, particularly mantle-derived rocks (e.g. Co, Cu, Cr, Ni) or rocks formed from small-scale melting of metasomatized host rocks (e.g. Ba, K, Nb, Ti and rare earth elements), are contoured. Cornelius et al. (2005) used bulk chemical methods to good effect in the Yilgarn Craton near Lake Brown. Their data were compared against a baseline study in the vicinity of the Aries pipe in the Kimberley Basin that was further developed by Singh and Cornelius (2006). Elemental abundances of Cr, Ni, Cu and Co, and particularly multivariate statistical treatments of their variations, precisely described the extent of the lateritized outcrop of the Aries pipe. Similar geochemical signatures were identified at the 46 Gat Road anomaly at Lake Brown, which is interpreted to be due to a previously discovered ultramafic lamprophyre.

Despite a large number of samples, bulk chemistry exploration for diamond is under-reported. This suggests that the technique is generally most useful as an aside to diamond exploration (targeting other commodities), or where applied to known bodies (Singh and Cornelius, 2006) or to very specific cases.

Vegetation

The contrasting bulk chemistry of diamond-hosting rocks compared to the country rocks within which they are emplaced, and particularly the alkali component of that chemistry, can promote the growth of contrasting and sometimes luxuriant vegetation. Alexander and Shrivastava (1984) demonstrated this to be case in Central India, where trees of certain species are taller and considerably denser above the Hinota kimberlite pipe, such that the pipe can readily be identified from aerial photographs. Vegetation sampling exploration in Australia has attracted considerable interest, but it is still a technique that has only seen sporadic application in diamond exploration in Western Australia. In the Northern Territory in the Merlin kimberlite field, Reddicliffe (1999) favoured this approach. Clear positive anomalies of Ba, Ni, Pb, Ce, La, Pr and Nb contents accurately defined the locations and extents of the pipes studied, in contrast to the sandstone country rock. However, because there is no dispersal, surveys are best suited to very local areas. Anomalous samples would be present only if they were collected over underlying pipes. Hence, vegetation surveying may have a use for delineating the boundaries of in situ diamondiferous bodies to augment geophysical investigations. In Western Australia, the Ullawarra 1 dyke is well marked by a line of Gidgee trees (Muggeridge, 2009). It is inferred that where clusters occur, they may represent small pipes or blows. However, this has not been tested. The association between the Gidgee trees and the kimberlite is explained by either water retention caused by the clay-weathered kimberlite, or the trace elements that the kimberlite introduces into the soil. Child (1996) observed that vegetation anomalies comprised flat-lying treeless grassed areas with sharp boundaries against the ubiquitous thick scrub in the Yilgarn Craton. These were termed 'cricket-pitch' or 'cricket-field' anomalies by Stockdale Prospecting Ltd. The argument was that certain species of plant are more susceptible to fire burn than others, for example *Ruglinga craurophylla*. Hence the soil geochemistry that these plants favour, such as kimberlitic rocks, will be identifiable not so much by the plants themselves as by conspicuous fire-derived scars in the vegetation cover.

Fauna

Exploration by bioturbation usually refers to disturbance by ants, or preferably termites who dig to bedrock rather than the watertable. The technique whereby bedrock mineralogy can be gleaned under cover as a consequence of sampling the materials with which ants and termites build their nests has been used to effect in southern Africa (Lock, 1985). Hutchison (2012) concluded that the technique has been only very rarely utilized in the Northern Territory. Termite mound surveying has been put to good use and in part led to the recent discovery by United Kimberley Diamonds NL of the UKD1 pipe (Coxhell, 2006). However, in Western Australia termite mound and anthill surveying has been sporadic and largely anecdotal.

A more novel approach has been described by Hissink (2000), who referred to a rabbit warren 100 m south of the Rainbow kimberlite dyke. Hissink (2000) stated that 'such features are coincident with kimberlite', but provided no further evidence.

Remote geophysical sensing

A plethora of geophysical methods are available to the diamond explorer to augment the indicator mineral approach and should be considered as an integral part of any exploration strategy. Some useful reviews have been provided by Erinchek et al. (1997), Macnae (1995) and Smith (1985). The diversity of approaches and the subjectivity of their interpretation makes an assessment of their efficacy in Western Australian exploration hard to quantify. Various case histories of methodologies applied in Western Australia appear in the statutory company reports referenced in association with in situ occurrences throughout this report. With respect to mined deposits, the geophysical signature of the Argyle lamproite has been discussed in Drew and Cowan (1994) and the Ellendale lamproites have been discussed by Jenke and Cowan (1994). Ellendale lamproites stand out very prominently in magnetic surveying as is illustrated in Figure 23. In addition to the more commonly used magnetic response, other approaches have been taken. The Brockman Creek dyke has a well-defined magnetic expression (Wyatt et al., 2004), but it has also been reported to show a clearly defined $Mg(OH)_2$ carbonate multispectral anomaly (Wyatt et al., 2004).

The Fohn 1 lamproite is the only lamproite body known in Western Australia to have been discovered as a result of seismic surveying. In this case, the body lies offshore to the north of the State and distinguishes itself as being among the largest of known Western Australian lamproites (141 ha), and consequently in the world. It has been drill tested, and this and neighbouring inferred bodies have been described by Gorter and Glikson (2002). Various onshore kimberlite and lamproite fields in Western Australia coincide with Phanerozoic basins surveyed due to petroleum prospectivity, most notably the Ellendale field. A review of seismic line locations available through the Western Australian Petroleum and Geothermal Information Management System (WAPIMS <https://wapims.dmp.wa.gov.au/wapims>) shows that 18 two-dimensional seismic surveys have intersected either the interpreted outlines of diamond-relevant bodies or a 300-m radius buffer around bodies compiled as point locations. These intersecting surveys are compiled in Table 6. The shallower extents of seismic reflection surveys are difficult to interpret due to noise. Kimberlites, due to their relatively small size are not likely to be imaged well except on specifically designed surveys. However, as data from the Fohn lamproite field demonstrates, there is potential for identifying larger bodies if they are sufficiently wide below about 100 m in depth. Such techniques may have applications in the Hamersley Basin, where country rocks have strong negative effects on other geophysical techniques and where in situ bodies have country-rock caps (Ceplecha, 2007).

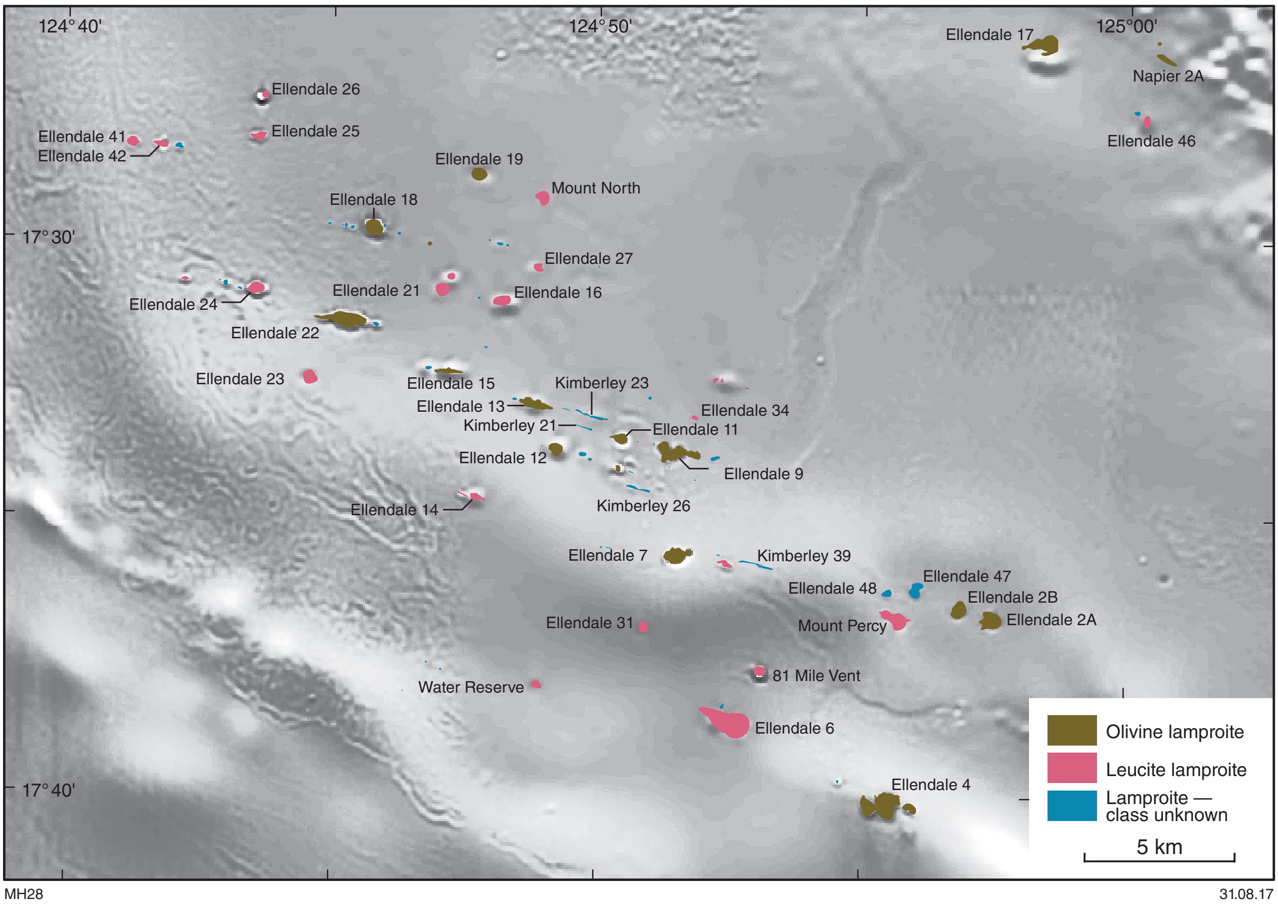


Figure 23. Lamproite occurrences of the Ellendale field in the context of magnetic surveying. The outlines of the near-surface expression of lamproite bodies in the Ellendale field are colour coded according to petrological classification. Outlines coincide closely with prominent magnetic anomalies evident in the first vertical derivative of the total magnetic intensity map of the area

Table 6. Seismic lines crossing within 300 m of known diamond-prospective bodies

Title	*Classification*	*Seismic line*	*Survey ID*
33 Bore West	Lamproite_Leucite	BAD12-08	S002700
Calwynyardah	Lamproite_Olivine	ED89-20	S001249
Ellendale 15	Lamproite_Olivine	L70-C	S000339
Ellendale 18	Lamproite_Olivine	ED84-348	S000932
Ellendale 18A	Lamproite	BMR88-03	S001499
Ellendale 19	Lamproite_Olivine	ED85-446	S000977
Ellendale 22	Lamproite_Olivine	BMR88-03	S001499
Ellendale 31	Lamproite_Leucite	ED81-10	S000759
Ellendale 40	Lamproite_Olivine	ED85-533	S000977
Fohn South	Lamproite	TS-17	S000174
Kimberley 41	Lamproite	ED81-10	S000759
Laymans Bore East	Lamproite_Olivine	P71-CH	S000387
Laymans Bore East	Lamproite_Olivine	P71-CG	S000387
Laymans Bore West 1	Lamproite_Leucite	ED83-220	S000880
Laymans Bore West 2	Lamproite_Leucite	AP07-16	S001959
Mount Weld	Carbonatite	01AGSNY2	S001800
Prima 2	Unknown	ED85-449	S000977
Walgidee Hills	Lamproite_Leucite	A-78-06	S000635

Ranking of Western Australian regions for diamond prospectivity

Methodology for determination of regional prospectivity

Theory and precedent support Western Australia being considered to be a world-class diamond prospective area, particularly as a consequence of undersampling due to its large size. However, Western Australia experienced a sharp decline in diamond exploration activities from 2008 as a consequence of stresses on raising investment. Diamond as a commodity represents high risk and presents opportunities only for long-term yields on exploration projects. It has taken almost ten years to experience an upturn in exploration activities in the State, driven in part by the closure of the Ellendale mine and the ageing of the Argyle mine. Activities have continued in the Webb area in the central eastern part of the State (GeoCrystal Ltd) and the Aries kimberlite pipes are being reassessed (Jindalee Resources Ltd). Recent projects have also commenced in the northern Kimberley Basin near the Ashmore kimberlites (Lithoquest Diamonds Inc.), in the east Kimberley Basin at Mad Gap, on the LANSDOWNE map sheet (Derrick et al., 1967; Prenti Exploration Pty Ltd), in the vicinity of the Big Spring lamproites east of the Ellendale field (Lucapa Diamond Company Ltd) and in the alluvials of the Ellendale field itself (India Bore Diamond Holdings Pty. Ltd and POZ Minerals Ltd). The WAC has also seen a commencement in activities at Nabberu (Diamond Resources Ltd).

The DED provides a very large abundance of diamond exploration data in support of future diamond exploration and, as has been introduced previously in this report, the mineral chemical components of the database draw attention to both large geographic areas and local occurrences. However, considerable value can also be gained from a rigorous and internally consistent approach to diamond prospectivity at an intermediate scale. Such as scale would draw attention away from known occurrences and yet be suitable for identifying realistically-sized exploration tenements. The DED data provide the opportunity to do so following the methodology described below.

Geological and geographic subdivisions of Western Australia

In order to rank different parts of Western Australia in terms of diamond prospectivity, a geographical subdivision must be employed. The subdivision needs to create a number of discrete geographical regions that are small enough to constrain the explorer to reasonably small areas, but not so long a list as to be statistically questionable. The geographical areas should be based also on distinct geological settings and identified age ranges as small as practical. GSWA's 1:2.5 million bedrock geology map subdivides the State, but comprises a total of 350 distinct units. This large number would necessarily include a large subset that only had a handful of diamond exploration samples. Conclusions deriving from the results of sampling in these units would be statistically questionable. As an alternative, GSWA's 1:10 million tectonic map sheet (Martin et al., 2016) was employed as the basis for subdivision. This required modification because the published map has numerous overlapping polygons reflecting a hierarchy of geological events. Hence, a single point may be represented by a number of geological regions. In order to be most applicable, a geological region should be assigned to a point at ground level that best reflects the rocks that are present at the surface at this location. On the 1:10 million map (Martin et al., 2016), GSWA identified 83 distinct geological regions made up of orogens, basins, cratons and igneous provinces. Five of these, the Browse Basin, the Forrest Zone, the Madura Province, the Mentelle Basin and the Wallaby Plateau, are completely confined to offshore Western Australia, and are neither subject to offshore sampling nor host suspected diamond-hosting intrusives. These five regions have therefore been removed from the prospectivity analysis. The Centralian Superbasin, because it is subdivided by better age-constrained sub-basins, has also been removed. Furthermore, among the regions GSWA has mapped orogens, namely the Albany–Fraser, Arunta, Capricorn, Granites–Tanami, Halls Creek, King Leopold, Paterson and Pinjarra Orogens. In general terms, orogenic zones spanning considerable geological time are represented more by deformation than specific rocks. They have all therefore been removed as discrete regions from the prospectivity analysis with two exceptions. A small part of the Pinjarra Orogen is not represented by any other geological region and hence is retained. The Granite–Tanami Orogen is also retained as a region because the event is tightly constrained in geological time and is reflected in contemporaneous and abundant new rocks. Finally, the NAC, WAC and Yilgarn Cratons (with the exception of the Marymia and Goodin Inliers) are not represented as discrete regions in the prospectivity analysis because better age-constrained subsets of these cratons have been used instead.

What remains are 67 non-overlapping geological regions covering the whole of onshore Western Australia. Each region constitutes a reasonably tight span of geological time with a consistent geology. It is notable that the Canning Basin is very large and consists of contrasting areas of abundant diamondiferous rocks (at and near to the Ellendale field) with apparently completely barren areas. Additionally, there are arguments to further subdivide the Yilgarn Craton beyond the current regional subdivisions (H Smithies, 2017, written comm., 11 May) However, in large part, the 67 regions serve the purpose of prioritizing diamond exploration and constitute the discrete geographic areas on which the prospectivity analysis is based. Of these, 47 regions have seen sampling for diamond exploration and each sample location recorded in the DED has been assigned a unique geological region.

Handling of marine samples

Some 44 marine samples have been compiled in the DED. These have all been assigned a geological region. However, because the geological environment and methods of exploration and sampling are distinctly different from the very large majority of samples taken onshore, the marine samples are excluded from the statistical treatments of the prospectivity analysed and are dealt with separately.

Prospectivity based on sampling history

The sampling history has been treated quantitatively and is described below. The number of onshore samples taken for the purpose of diamond indicator testing (including diamond-only samples) was counted for each prospectivity region. Samples that contained DIMs were also counted. For some regions, numerous samples taken from GSWA's historical exploration activity EXACT database contributed to the DED. The EXACT database structure as pertains to incorporation into the DED has been described in detail in Hutchison (2018). Therefore, groups of samples from single submitted statutory reports in EXACT do not always identify which individual samples are nondiamond-indicator positive and which are not. Hence, for such samples, recovered indicator counts were attributed fractionally in the DED to all samples. This process ensured that recovered indicator numbers are correctly reflected in the database and are not attributed to arbitrary samples. However, for the purpose of counting indicator-positive samples, the result is the appearance of false positives. Therefore for counting positive samples, the EXACT data have been handled as follows. Where the number of positive samples is documented in the comments fields, this number is used; otherwise only a single sample from each indicator-positive report is counted. The drawback of this approach is that false negatives result. However, the proportion of EXACT records to total samples for each prospectivity region is low and it has been concluded that the overall influence of false negatives in the final rankings is small.

The criteria used to score each region based on sampling history are described in Table 7. The method is based on the principle that undersampled areas provide more opportunity for new discoveries and are therefore favoured over heavily sampled regions. However, regions that have seen no diamond exploration sampling whatsoever score least because it is assumed that there are good geological reasons for a region to have been completely discounted. Furthermore, regions where a high proportion of samples return positive visually identified indicator minerals are favoured over those with low recovery success. As described in Table 7, the cutoffs are as follows (after McMartin and McClenaghan, 2001). The most underexplored regions (reconnaissance sampling) have an average of fewer than one sample per 100 km^2, regional samples have a sampling density between one sample per 4 to 100 km^2. Regions with local-scale sampling have more than one sample per 4 km^2. Regarding sample success, the most prospective regions have over one-third of samples with positive indicator recovery, and the least have under one positive sample in 20.

Prospectivity based on geological age

In order to be exploited economically, diamondiferous bodies must be close to or at surface. Float provides impediments to discovery, but it is the overlying solid geology that provides the biggest impediment to economic extraction. Hence, in order to assess the likelihood that diamondiferous rocks will be present at or near the surface, it is important to understand both the likely age of intrusion, based on the known ages of diamondiferous rocks elsewhere, and the ages of the country rocks in the area of interest. If, for example, the age range of rocks in a region is younger than any known diamondiferous rock, then it would be expected that any diamondiferous bodies present would be covered, possibly with kilometres of rock. The age ranges of Western Australian geological regions have been documented (Martin et al., 2016). The ages of 63 diamond-prospective intrusions have also been determined and have been compiled in the DED. Therefore, attribution of Western Australian regions with relative prospectivity scores based on age can be achieved. The criteria used to assign a score to each region based on the age of rocks exposed are described in Table 8. The important cutoff points are the ages of the oldest and youngest kimberlites, oldest and youngest lamproites, the ages of mined diamondiferous bodies, and the age of the oldest diamond-prospective rocks.

Prospectivity based on underlying lithospheric mantle

The thickness of the mantle lithosphere provides the strongest control on the formation of diamonds (Haggerty, 1994), and its morphology and associated crustal features impose the strongest controls on diamond emplacement at surface (Helmstaedt and Gurney, 1995; White et al., 1995; Haggerty, 1999). Cratonic regions of the Earth are typically characterized by thick, cold and old mantle lithosphere that provides the conditions required for diamond formation (Haggerty, 1994). Consequently, diamond explorers favour cratonic regions. More specifically, they favour the edges of cratonic regions or within-craton terrane boundaries that can provide mechanisms where diamond-hosting rocks can reach the surface more readily (Helmstaedt and Gurney, 1995; Kaminsky et al., 1995; Jaques and Milligan, 2004; O'Neill et al., 2005). Australia benefits from an extensive array of seismological recording stations that provide data suitable for modelling lithospheric mantle thickness and structure at a relatively fine scale (Fishwick et al., 2006; Kennett et al., 2011, 2013). Figure 24 shows two such models reflecting current mantle lithosphere thickness under Western Australia. Figure 24a shows the measured shear-wave velocity at a depth of 200 km (Fishwick et al., 2006). This is the model used to establish lithosphere zones for the determination of diamond prospectivity in the Northern Territory (Hutchison, 2012). Fast s-wave velocity is interpreted to reflect dense, cool and old mantle lithosphere. Figure 24b shows the calculated current mantle thickness or lithosphere–asthenosphere boundary (Kennett et al., 2013). Both the models expressed in Figures 24a and b have been used to subdivide the State based on lithospheric characteristics. Ranking follows a methodology favouring thick lithospheric mantle and, in particular, the edges of thick blocks of lithospheric mantle where the likelihood of the transport of diamonds to the surface may be greatest. Jaques and Milligan (2004) noted that many Australian diamondiferous bodies lie at the margins of lithospheric domains. Specific criteria for ranking based on lithospheric characteristics have been described in Table 9. Comparison of lithosphere-ranked polygons (Fig. 24) with the locations of the 67 geological regions for the prospectivity analysis (Fig. 25) allows a lithosphere score to be assigned to each region. In cases where a region lies within more than one lithosphere polygon, the average score by area is used. For example, in a region where approximately 50% lies above an area of lithosphere scoring 2 and 50% lies over an area scoring 4, then this particular region would be assigned a score of 3.

Table 7. Prospectivity scoring criteria based on sampling history

Ranking	*Description*	*n*	*Ranking*	*Description*	*n*
1	Reconaissance-scale sampling (< 1 sample per 100 km^2) with good recovery (> 1/3 of samples are indicator positive)	8	4	Local-scale sampling with reasonable recovery or reconaissance-scale with poor recovery (< 1/20 of samples are indicator positive)	7
2	Regional-scale sampling (between 1 sample per 4 km^2 and 1 sample per 100 km^2) with good recovery, or reconaissance-scale with reasonable recovery (1/20 to 1/3 of samples are indicator positive)	10	5	Poor recovery from regional or local sampling density	4
3	Local-scale sampling (> 1 sample per 4 km^2) with good recovery or regional with reasonable recovery	18	6	No sampling conducted	20

NOTE: n – Number of regions assigned to each ranking

Table 8. Prospectivity scoring criteria based on the age of exposed rocks

Ranking	*Description*	*n*	*Ranking*	*Description*	*n*
1	All rocks pre-date oldest kimberlite (Turkey Creek; 2128 Ma)	10	4	At least some rocks are older than the youngest kimberlite (Skerring; 800 Ma) but are not all older than Argyle (1177 Ma)	19
2	All rocks pre-date oldest lamproite (Yanyare-02; 1724 Ma)	7	5	All rocks are younger than the youngest kimberlite (Skerring; 800 Ma), but are also older than SW Kimberley lamproites (Ellendale 11; 25.2 Ma)	4
3	All rocks pre-date mined diamondiferous bodies (Argyle; 1177 Ma and Ellendale 9; 24 Ma)	19	6	Some rocks are younger than the youngest of the SW Kimberley lamproites (Mt Gytha; 17 Ma)	8

NOTE: n – Number of regions assigned to each ranking

Ranking of geological regions

For each geological region, the scores from 1 to 6 for each of the three criteria of age, sampling history, and underlying lithosphere thickness were added. The regions were ordered or ranked 1st, 2nd equal, 4th equal, 13th equal and so on, resulting in 13 equally ranked groups. Each group was subsequently assigned a category with 1 being the most prospective and 13 being the least prospective. Results for individual criteria and total rankings are discussed below. Scores and further treatments are shown in Table 10.

Results of sample success ranking

The results for sampling success are illustrated in Figure 26, with the criteria described in Table 7 applied in order to subdivide the samples. As Table 7 demonstrates, apart from regions with no sampling (scoring 6), the numbers of regions falling within each category describe a roughly bell-shaped distribution. This implies that the model truly represents the range of sampling density and success conducted in Western Australia. The modes for average success and average sampling density coincide with each other.

The Biranup Zone distinguishes itself by having a 100% sampling success rate (Table 10). This is due to the region only reporting one sample (sampleID 728775) from which 100 picroilmenites were recovered. On populating the DED, numerous examples of sample locations incorrectly reported at source were identified (e.g. typographic errors and wrongly reported UTM zones). Particular care was therefore applied to ensure that the Biranup Zone sample location is indeed correct, because similar-named samples are found in the Akbar pipes, some 500 km to the north. However, with the sample reported as being associated with the same magnetic anomaly (AN01) attributed to the Norseman 2 ultramafic lamprophyre, and with locations within 250 m of each other, the sample is concluded to be genuine. Furthermore, while the perfect success rate is not statistically robust, given the numerous ultramafic lamprophyres in the vicinity, it is fitting that the Biranup Zone scores well in this criterion.

The most statistically significant top score (value of 1) was found in the Canning Basin from which 3420 samples were taken with a success rate of 58%. The remaining top-scoring regions are the Aileron, Musgrave and Rudall Provinces, and the Ord, Roebuck and Wolfe Basins, all containing fewer than 150 samples.

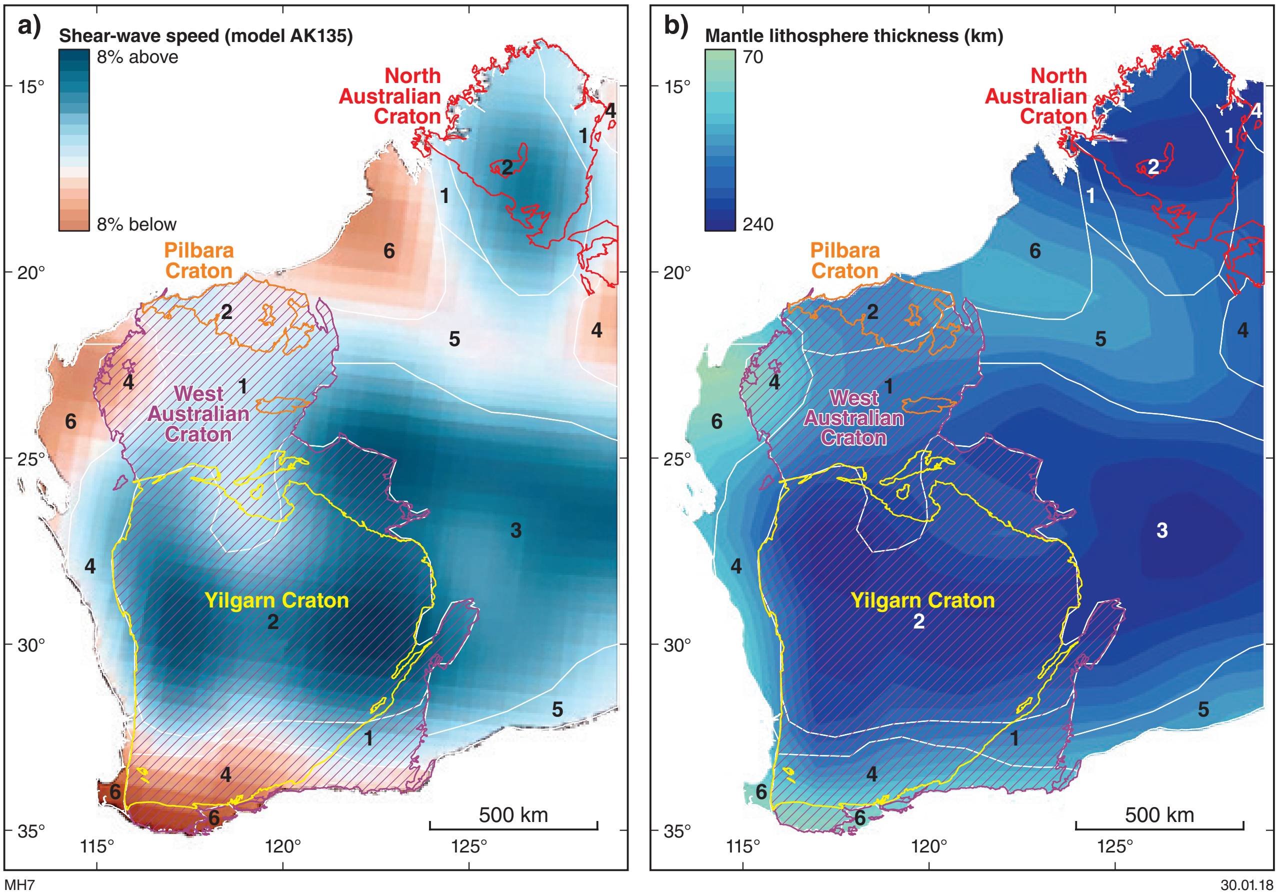
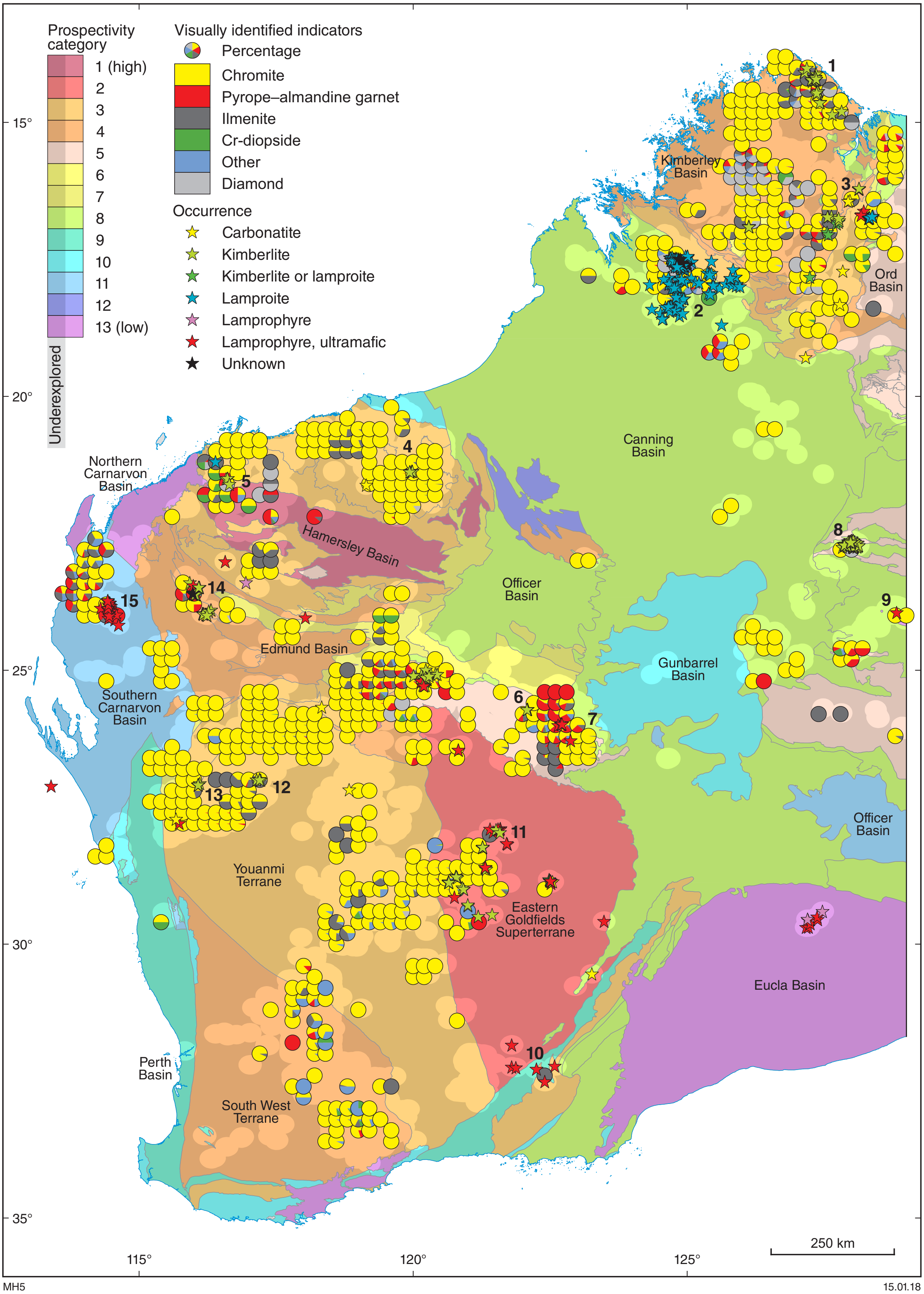


Figure 24. Map of lithosphere thickness of Western Australia: a) tomographic s-wave velocity model of Western Australia at 200 km depth (Fishwick et al., 2006). Colouration displays the relative perturbation of shear-wave speed from the global reference model AK135, ranging from 8% above (deep blue) to 8% below (deep brown). Areas of fast velocity are interpreted to be derived from relatively cold, dry and refractory lithospheric mantle, and be favourable for diamond formation (Haggerty, 1994). Areas of slow velocity are less favourable. Boundaries of Western Australian cratonic regions at surface, following Martin et al. (2016), are indicated on the map. White-bordered polygons describe areas of differing diamond prospectivity based on lithosphere characteristics, with 1 being most favourable and 6 being the least favourable. Prospectivity polygons are based on the s-wave model at 200 km; b) estimated depth to the lithosphere–asthenosphere boundary (adapted from Kennett et al., 2013)

Figure 25. (page 47) Prospectivity map of Western Australia. Geological subdivisions are ranked for prospectivity, following the detailed methodology described in the text, in the context of mantle structure, the age of surface rocks, the extent of sample coverage and recovery of visually determined indicators. Ranking follows the key, with 1 being the most prospective area and 13 the least prospective. In situ bodies with diamond potential (tested or otherwise) are shown by stars colour-coded according to the key. Notable localities are as follows: 1 — Ashmore, 2 — Ellendale field, 3 — Argyle, 4 — Brockman Creek, 5 — Blacktop, 6 — Jewill, 7 — Bulljah Pool, 8 — Webb, 9 — JYP58, 10 — Norseman, 11 — Akbar, 12 — Cue, 13 — Mileura, 14 — Barlee, 15 — Wandagee. Sample site areas are indicated by shading where unshaded areas lie within 20 km from an exploration sample location as in Figure 3. Pie chart symbols indicate sites of recovery of visually determined indicator minerals. For clarity, indicator mineral recoveries from all samples within blocks of 0.2 degrees of longitude and latitude are summed, and contribute proportionally to each pie chart symbol. This method of displaying the data results in the artificial regularity of sampling locations displayed in the figure. Diamond and chromite distinguish themselves as the most robust and hence commonly recovered indicator minerals. Much of Western Australia is underexplored, with prospective areas evident in the NAC and particularly the WAC


Prospectivity category
1 (high)
2
3
4
5
6
7
8
9
10
11
12
13 (low)
Underexplored
Visually identified indicators
Percentage
Chromite
Pyrope–almandine garnet
Ilmenite
Cr-diopside
Other
Diamond
Occurrence
Carbonatite
Kimberlite
Kimberlite or lamproite
Lamproite
Lamprophyre
Lamprophyre, ultramafic
Unknown
Kimberley Basin
Ord Basin
Canning Basin
Northern Carnarvon Basin
Hamersley Basin
Officer Basin
Edmund Basin
Gunbarrel Basin
Southern Carnarvon Basin
Youanmi Terrane
Eastern Goldfields Superterrane
Eucla Basin
Perth Basin
South West Terrane
15°
20°
25°
30°
35°
115°
120°
125°
250 km
MH5
15.01.18

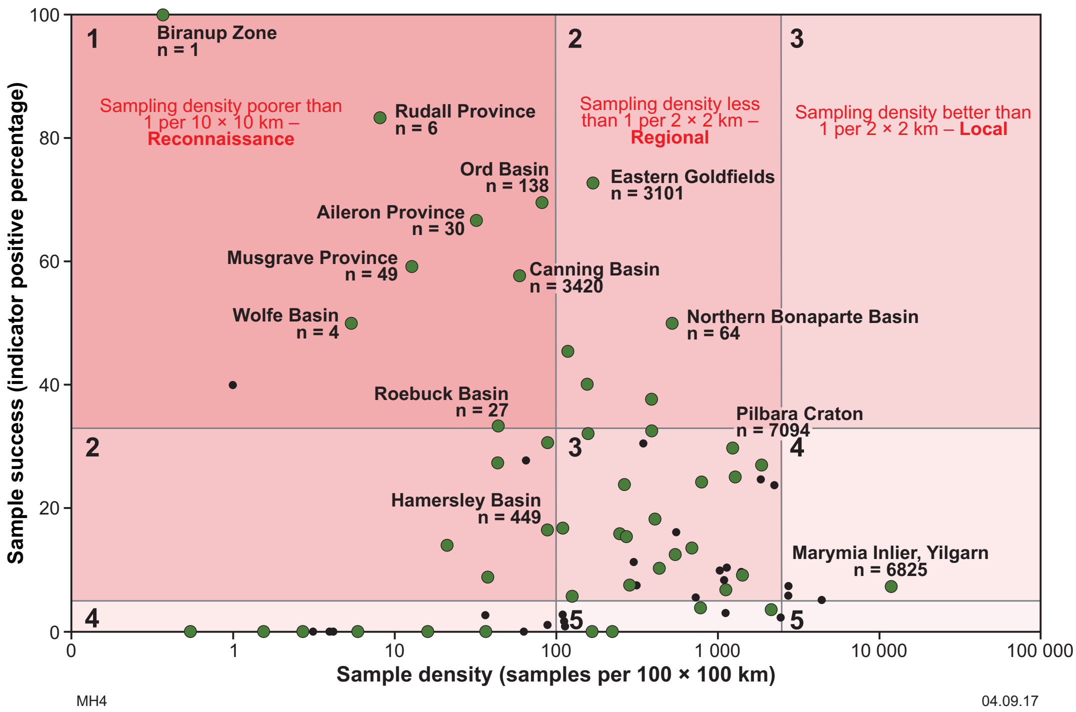


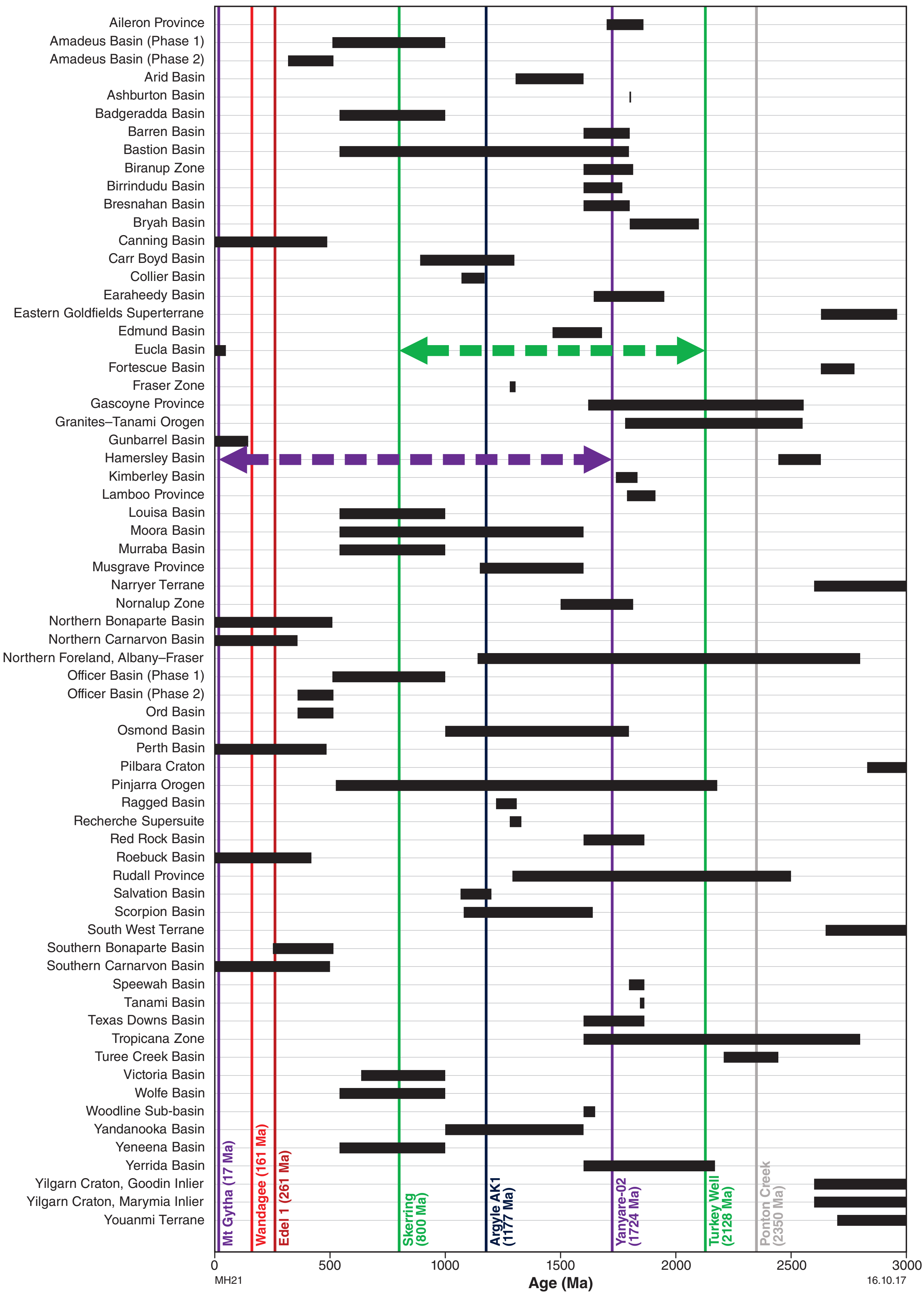
Figure 26. Sampling success versus sampling density for diamond exploration samples from Western Australian geological regions. The data is derived from calculations based on the DED data (GSWA, 2018). Selected regions are labelled. Sampling success is measured as the percentage of samples collected for diamond indicator minerals that returned a positive recovery (i.e. at least one visually determined indicator mineral, including diamond). Sampling density is the number of samples (n) taken per 10 000 km² area within each region. Black numbers represent prospectivity scores assigned to regions plotting within shaded areas of the chart. Regions with good indicator recovery (over 1/3 of samples being positive) but explored only at reconnaissance scale (< 1 sample per 100 km²) are favoured. Regions with poor recovery (under 1/20 of samples being positive) that have been sampled with average sampling density better than 1 sample per 100 km² are less favoured (scoring 5). Completely unsampled areas, not represented in the figure, score lowest (6) based on the assumption that they have been neglected for sound geological reasons. Northern Territory data (black dots) are provided for comparison (Hutchison, 2012), showing that Northern Territory diamond exploration has covered a similar sampling density range, but with fewer high-success regions

Results of age-dependent ranking

Figure 27 presents the age ranges of rocks present within each of the 67 Western Australian geological regions. For context, the range of ages of kimberlites from 2128 Ma at Turkey Well (Jourdan et al., 2012) to the 800 Ma Skerring pipe (Pidgeon et al., 1989) and for lamproites from the 1724 Ma Yanyare-02 lamproite (Matchan et al., 2009) to the southwest Kimberley lamproites are displayed. The oldest diamond-prospective rock (the Ponton Creek carbonatite; Graham et al., 2004), the Argyle AK1 lamproite (1177 Ma; Pidgeon et al., 1989), the Wandagee M142 ultramafic lamprophyre (161 Ma; Pidgeon et al., 1989) and the offshore Edel 1 (261 Ma; Killar, 1972) are also shown for context.

Based on the criteria described in Table 8, the Yilgarn Craton scored particularly well with all six Yilgarn Craton regions receiving a top score (Table 10). The Pilbara Craton also received a score of 1 in addition to the Fortescue, Hamersley and Turee Creek Basins elsewhere in the WAC. No NAC regions received top scores for prospectivity based on age.

Figure 27. (page 49) Ranges of ages of rocks present in geological regions of Western Australia in the context of diamond-prospective rocks. Kimberlite ages are shown in green from the Paleoproterozoic Turkey Well bodies (Jourdan et al., 2012) to the Neoproterozoic Skerring pipe (Pidgeon et al., 1989). Lamproites are shown in purple from the Paleoproterozoic Yanyare-02 dyke (Matchan et al., 2009) to the Oligocene and Miocene lamproites of the southwest Kimberley (17 Ma, Mt Gytha, Jaques et al., 1984; 25.2 Ma, Ellendale 11, Phillips et al., 2010). The Paleoproterozoic Ponton Creek carbonatite (Graham et al., 2004) is shown in grey. The Mesoproterozoic Argyle AK1 lamproite (Pidgeon et al., 1989) is represented by a black line. The Permian ultramafic lamprophyres at Edel 1 (Killar, 1972) are represented by a brown line and the Jurassic Wandagee M142 ultramafic lamprophyre (Pidgeon et al., 1989) is shown by a red line


Aileron Province
Amadeus Basin (Phase 1)
Amadeus Basin (Phase 2)
Arid Basin
Ashburton Basin
Badgeradda Basin
Barren Basin
Bastion Basin
Biranup Zone
Birrindudu Basin
Bresnahan Basin
Bryah Basin
Canning Basin
Carr Boyd Basin
Collier Basin
Earaheedy Basin
Eastern Goldfields Superterrane
Edmund Basin
Eucla Basin
Fortescue Basin
Fraser Zone
Gascoyne Province
Granites–Tanami Orogen
Gunbarrel Basin
Hamersley Basin
Kimberley Basin
Lamboo Province
Louisa Basin
Moora Basin
Murraba Basin
Musgrave Province
Narryer Terrane
Nornalup Zone
Northern Bonaparte Basin
Northern Carnarvon Basin
Northern Foreland, Albany–Fraser
Officer Basin (Phase 1)
Officer Basin (Phase 2)
Ord Basin
Osmond Basin
Perth Basin
Pilbara Craton
Pinjarra Orogen
Ragged Basin
Recherche Supersuite
Red Rock Basin
Roebuck Basin
Rudall Province
Salvation Basin
Scorpion Basin
South West Terrane
Southern Bonaparte Basin
Southern Carnarvon Basin
Speewah Basin
Tanami Basin
Texas Downs Basin
Tropicana Zone
Turee Creek Basin
Victoria Basin
Wolfe Basin
Woodline Sub-basin
Yandanooka Basin
Yeneena Basin
Yerrida Basin
Yilgarn Craton, Goodin Inlier
Yilgarn Craton, Marymia Inlier
Youanmi Terrane
Mt Gytha (17 Ma)
Wandagee (161 Ma)
Edel 1 (261 Ma)
Skerring (800 Ma)
Argyle AK1 (1177 Ma)
Yanyare-02 (1724 Ma)
Turkey Well (2128 Ma)
Ponton Creek (2350 Ma)
0
500
1000
1500
2000
2500
3000
Age (Ma)
MH21
16.10.17

Results of lithosphere thickness ranking

The results of ranking based on current underlying lithosphere are presented in Table 10. Regions in eastern Western Australia received numerous top scores (Osmond, Red Rock, Texas Downs and Victoria Basins) as a consequence of the NAC and its margins extending into the Northern Territory (Kennett et al., 2013). Both of the regions at the margins of the Yilgarn Craton (Goodin and Marymia Inliers) received top scores, as did four regions in the NAC (Bastion, Birrindudu and Tanami Basins and the Granites–Tanami Orogen) and six regions in the WAC (Bresnahan, Bryah, Collier, Hamersley, Turee Creek and Yerida Basins).

Overall ranking

The distribution of numbers of regions assigned to each of the six levels in the three prospectivity categories (summarized from Tables 7, 8 and 9 in Table 10) has been examined (Table 11). The age scores describe a broadly bell-shaped distribution. Sampling success scores are reasonably evenly distributed, although there is a small bias towards undersampled regions or regions of poor recovery. Regions are also biased so that the more prospective lithospheric settings are most represented. Western Australian rocks are typically old, although some of the older regions are still younger than the oldest diamond-bearing rocks. Historically, there has been a full spectrum of sampling activity and sampling success.

Table 9. Prospectivity scoring criteria based on mantle lithosphere characteristics

Ranking	*Description*	*n*	*Ranking*	*Description*	*n*
1	On- or near-craton, edge of thickest lithosphere	16	4	On- or near- craton, thinnest lithosphere	11
2	On-craton, thickest lithosphere	24	5	Far off-craton, medium lithosphere thickness	4
3	Off-craton, thickest lithosphere	10	6	Off-craton, thinnest lithosphere	2

NOTE: n – Number of regions assigned to each ranking

Table 10. Prospectivity scores and rankings of Western Australian geological regions

Region	*Sampling score*	*Age score*	*Lithosphere score*	*Total score*	*Ranking*	*Category*
Aileron Province	1	3	4	8	23	**5**
Amadeus Basin (Phase 1)	3	4	4	11	38	**8**
Amadeus Basin (Phase 2)	6	5	5	16	65	**13**
Arid Basin	6	3	2	11	38	**8**
Ashburton Basin	2	2	2	6	4	**3**
Badgeradda Basin	3	4	3	10	33	**7**
Barren Basin	6	3	4	13	53	**10**
Bastion Basin	6	4	1	11	38	**8**
Biranup Zone	1	3	2	6	4	**3**
Birrindudu Basin	4	3	1	8	23	**5**
Bresnahan Basin	6	3	1	10	33	**7**
Bryah Basin	3	2	1	6	4	**3**
Canning Basin	1	6	4	11	38	**8**
Carr Boyd Basin	3	4	4	11	38	**8**
Collier Basin	5	4	1	10	33	**7**
Earaheedy Basin	3	3	2	8	23	**5**
Eastern Goldfields Superterrane	2	1	2	5	2	**2**
Edmund Basin	2	3	2	7	13	**4**
Eucla Basin	6	6	4	16	65	**13**
Fortescue Basin	3	1	2	6	4	**3**
Fraser Zone	6	3	2	11	38	**8**
Gascoyne Province	2	3	2	7	13	**4**
Granites–Tanami Orogen	5	2	1	8	23	**5**
Gunbarrel Basin	4	6	3	13	53	**10**
Hamersley Basin	2	1	1	4	1	**1**

Table 10. continued

Region	*Sampling score*	*Age score*	*Lithosphere score*	*Total score*	*Ranking*	*Category*
Kimberley Basin	3	2	2	7	13	**4**
Lamboo Province	2	2	2	6	4	**3**
Louisa Basin	3	4	2	9	31	**6**
Moora Basin	6	4	3	13	53	**10**
Murraba Basin	4	4	3	11	38	**8**
Musgrave Province	1	4	3	8	23	**5**
Narryer Terrane	3	1	2	6	4	**3**
Nornalup Zone	6	3	4	13	53	**10**
Northern Bonaparte Basin	2	6	4	12	51	**9**
Northern Carnarvon Basin	4	6	6	16	65	**13**
Northern Foreland, Albany–Fraser Orogen	6	4	2	12	51	**9**
Officer Basin (Phase 1)	4	4	3	11	38	**8**
Officer Basin (Phase 2)	6	5	3	14	61	**11**
Ord Basin	1	5	2	8	23	**5**
Osmond Basin	6	4	1	11	38	**8**
Perth Basin	2	6	4	12	51	**9**
Pilbara Craton	3	1	2	6	4	**3**
Pinjarra Orogen	4	4	5	13	53	**10**
Ragged Basin	6	3	4	13	53	**10**
Recherche Supersuite	6	3	2	11	38	**8**
Red Rock Basin	3	3	1	7	13	**4**
Roebuck Basin	1	6	6	13	53	**10**
Rudall Province	1	3	3	7	13	**4**
Salvation Basin	3	4	2	9	31	**6**
Scorpion Basin	5	4	2	11	38	**8**
South West Terrane	3	1	3	7	13	**4**
Southern Bonaparte Basin	2	5	3	10	33	**7**
Southern Carnarvon Basin	3	6	5	14	61	**11**
Speewah Basin	3	2	2	7	13	**4**
Tanami Basin	5	2	1	8	23	**5**
Texas Downs Basin	6	3	1	10	33	**7**
Tropicana Zone	6	3	2	11	38	**8**
Turee Creek Basin	6	1	1	8	23	**5**
Victoria Basin	2	4	1	7	13	**4**
Wolfe Basin	1	4	2	7	13	**4**
Woodline Sub-basin	6	3	2	11	38	**8**
Yandanooka Basin	6	4	4	14	61	**11**
Yeneena Basin	6	4	5	15	64	**12**
Yerrida Basin	3	3	1	7	13	**4**
Yilgarn Craton, Goodin Inlier	3	1	1	5	2	**2**
Yilgarn Craton, Marymia Inlier	4	1	1	6	4	**3**
Youanmi Terrane	3	1	2	6	4	**3**

Table 11. Numbers of regions assigned to prospectivity categories

Sampling score	*Number of regions*	*Age score*	*Number of regions*	*Lithosphere score*	*Number of regions*
1	8	1	10	1	16
2	10	2	7	2	24
3	18	3	19	3	10
4	7	4	19	4	11
5	4	5	4	5	4
6	20	6	8	6	2

Western Australia is dominated by cratonic regions with thick underlying lithosphere, making few parts of the State unprospective. The distribution of scores therefore matches with empirical expectations and provides a level of satisfaction that the prospectivity model does not unrealistically skew any one criteria. The prospectivity model does not, for example, overly subdivide prospective lithosphere such that few prospective regions would actually score well for this criterion.

In Table 10 a minimum possible value for the sum of the three propsectivity scores is 3 denoting highly prospective and a maximum possible value is 18 for highly unprospective. No region achieved a perfect score. However, the single most prospective region scored 4. All 67 regions ranked from 1st to equal 65th place give the 13 discrete ranking categories previously described and these are used to colour-code the prospectivity map of the State (Fig. 25).

The WAC dominates the highly prospective regions. Parts of these regions are underexplored, and yet exhibit extremely attractive indicator mineral recoveries and mantle architecture. The lowest score and thus most prospective region is the Hamersley Basin of the WAC. Equal-second ranked regions are the Eastern Goldfields Superterrane and Goodin Inlier, both parts of the Yilgarn Craton. Category-three ranked regions are the WAC's Ashburton Basin, Biranup Zone, Bryah Basin and Fortescue Basin, which is host to the Blacktop kimberlites (Fig. 25). Among category-three regions also within the WAC is the Pilbara Craton, which contains the Brockman kimberlite dykes. Elsewhere in the WAC, the Yilgarn Craton's Marymia Inlier is host to the Nabberu bodies (Fig. 3), the Narryer Terrane contains the Mileura kimberlites and the Youanmi Terrane is host to the Cue kimberlite dykes, all of which are category-three regions. The most prospective NAC region is the Lamboo Province as the remaining category-three region. The Lamboo Province hosts the Big Spring lamproites, and the Ellendale lamproite field including the prior mines at E4 and E9 that lie within 25 km of its southwestern edge. The Argyle mine also outcrops within a kilometre from the edge of the Lamboo Province and is situated within the overlying Southern Bonaparte Basin. Poorest scoring areas lie the farthest from craton margins and are associated with the youngest rocks, such as the Eucla Basin.

Discussion

Sampling methods

Indicator minerals do not typically survive transportation and weathering well and their numbers in off-site exploration samples can be expected to be very small in most cases. Therefore, suitable sampling methods are critical to ensuring that any indicator minerals present are captured. The efficacy of historical sampling in Western Australia is discussed below.

Sample size

The lower percentage abundance of heavy minerals recovered, largely irrespective of grain size and sample type compared with Northern Territory samples (Fig. 10; Table 2), can be interpreted in various ways. Heavy mineral recovery depends on inherent qualities of the sample itself, the efficiency of the sampling methodology and the capabilities of the processing laboratory. There have been few processing laboratories operating in the Northern Territory and hence most samples from both the Northern Territory and Western Australia have historically been processed in Western Australian laboratories. Flow charts of processing methodologies have been provided in the appendix of Hutchison (2012). Western Australian samples have been attributed to 28 laboratories (not including on-site processing) and Northern Territory samples (Hutchison, 2011) have been attributed to 19 laboratories. However, 14 laboratories are reported to have handled both Northern Territory and Western Australian samples. Hence, processing methods are not likely to be a significant factor in explaining why Northern Territory samples have more abundant heavy minerals. Trap site quality is determined largely by topography, with old flatter landscapes lending themselves to non-energetic river systems and hence poor sorting (Muggeridge, 1989). With both the Northern Territory and Western Australia generally being dominated by ancient cratonic regions, both regions have similarly developed drainage systems. Furthermore, if anything, focus on the importance of choosing the best available trap sites has initially developed in Western Australia rather than the Northern Territory (Muggeridge, 1989). Therefore, although different companies have been more active in different places (e.g. Elkedra Diamonds NL in the Northern Territory and Astro Mining in Western Australia) it is not expected that quality and competency of sampling trap sites has played a major role in favouring heavy minerals in the Northern Territory samples. The most striking difference between the Northern Territory and Western Australia is the difference in geographic latitude. Almost all Northern Territory samples come from north of 20ºS and the majority less than 200 km from the coast. Western Australian samples come from a much broader geographical range, with 68% of samples derived from south of 20ºS and a higher proportion of inland samples. Although current inland dry regions of Western Australia have experienced profound tropical weathering in the past (Maidment, 2015), this applies less in the southern reaches of the State. Hence, it is fair to say that Northern Territory samples are typically derived from a current tropical environment, whereas Western Australian samples are more likely to be derived from a drier climate with less-weathered rocks. Processes of tropical weathering favour the removal of felsic minerals through dissolution and subsequent concentration of heavy minerals (Butt et al., 2000). In extreme cases, silicates can be thoroughly broken down and favour concentrations of typically denser oxides including spinel. Such processes give rise to residual mineral deposits. Hence, it would be reasonable to expect the higher heavy mineral concentrations seen in the Northern Territory compared with Western Australia.

Irrespective of the reasons for the differences between heavy mineral abundances in the Northern Territory compared with Western Australia, the statistics demonstrate that explorers cannot necessarily rely on the favourable median of 30 g of heavy minerals for 25 kg of sample that has been determined for the Northern Territory (Hutchison, 2012). As shown previously in Table 2, explorers should expect a value closer to 8 g of heavy minerals for 25 kg of sample and may wish to adjust sample sizes accordingly.

Sieve sizes

In terms of size fractions from which indicator minerals have been picked, for Western Australian exploration few cases of minimum sieve sizes above 0.3 mm have been reported. Most maximum sizes have been 1.5 and 2 mm and the most commonly reported full size range is 0.3 – 1.5 mm. Spinel grains are normally <0.4 mm in size. Hence, Western Australian exploration has not suffered from the same problem as the Northern Territory where almost a fifth of exploration samples were too coarse (>0.425 mm) to capture the majority of indicator spinels. Furthermore, the path to discovery of the Argyle lamproite pipe where 27 chromites and 11 microdiamonds were found in three samples (Muggeridge, 1995), and more recent work in the size range 0.3 – 1 mm at Ullawarra (Muggeridge, 2009), are considered typical of Western Australian exploration methods.

Diamond characteristics

The high abundance of octahedral forms in regional Western Australian samples compared with the Northern Territory, where cubes dominate (Hutchison, 2013), suggests a relatively high formation temperature for Western Australian diamonds (Clausing, 1997). High temperatures would result from mature, deeper and more prospective diamond-growth settings than farther east-northeast in the Northern Territory. However, the high abundance in Western Australia of dodecahedral or tetrahexahedral stones, and surface etching and resorption of octahedral stones, shows that considerable proportions of diamonds have been distressed. This may have taken place at either formation depths (Zhang and Fedortchouk, 2012) or during emplacement, and is consistent with the chemical incompatibility between diamond and some Western Australian diamond-host rocks, particularly leucite lamproites (Kozai and Arima, 2005). In other words, while diamonds are more likely to have formed under Western Australia, in places they are also more likely to have been damaged later.

With respect to the colour of the stones, the presence of yellow and pink diamonds in regional samples, particularly the brownish-pink stone described near the Brockman Creek kimberlite (Barley and Blake, 1991), is significant. However, there are two pertinent and significant caveats regarding the percentage occurrences described in Table 3. Firstly, the numbers of described diamonds includes a total of 202 where colour is attributed. A sample set over 100 data points can be considered as statistically meaningful. However, the numbers involved are small. A large relative uncertainty applies particularly to the single digit percentages. Furthermore, there is a significant difference between a stone that displays a yellow or pink tint under the binocular microscope to stones that are considered to be fancy or vivid yellow or pink for the purposes of certification and valuation. Among some productions of South African diamonds, yellow is quite a common colour ('Cape Yellows;' Kitawaki, 2007) and these are much more subtle in colouration than the fancy yellows that command the high prices from Ellendale (Downes et al., 2006). The rigorous gemmological criteria applied to classify diamonds as fancy yellow or pink are not those applied to informally identify components of these colours in small exploration-derived diamonds. Therefore, exploration samples describing 'yellow' or 'pink' diamonds do not necessarily imply associations with gemmologically significant diamonds. However, particularly for pinks, there are few geological scenarios that gives rise to the colour. The presence of any pink diamonds should not be ignored and the possibility that they may be taken as a proxy for fancy pinks in their source rocks should be considered.

Mineral chemistry

A strong emphasis has been placed on the importance of mineral chemistry as an integral part of indicator grain identification. Considerable attention has been paid to occasional grains with notable mineralogies. It is important to note that the discovery of Western Australia's most productive diamond mine, Argyle, resulted from an initial discovery of a handful of indicator grains. This point has been made by Muggeridge (1995), who illustrated that the discovery of the Argyle lamproite rested on 27 lamproitic spinels and 11 microdiamonds. The intricacies of indicator mineral chemistry provide far-reaching insights into both regional and locality-specific exploration potential and this is discussed below.

Chromite and other spinels

As the most durable diamond indicator mineral aside from diamond itself, explorers have focused strongly on members of the spinel group. As discussed below, study of spinels contributes both advantages and shortcomings to the diamond exploration picture.

Al in spinels

Increasing Al content in chromites is interpreted as being a sign of a shallower source than for Al-depleted Mg-chromites. Hence, the relative abundance of Al-bearing spinel indicators in the WAC outside of the Pilbara and Yilgarn Cratons (Table 4; Fig. 17) is interpreted to be due to host rocks derived from shallower depths in the mantle. As current geophysical data shows, the Pilbara Craton has a relatively shallow lithospheric keel (Kennett et al., 2013) compared with the Yilgarn Craton (Fig. 24b). With chromite compositions reflecting depth of origin within the lithosphere, then the similarity in chromite Al-content between the Pilbara and Yilgarn Cratons may reflect a time when the lithospheric thickness under both was similar. Certainly the current lithosphere thickness under the Pilbara Craton is inconsistent with the presence of lithospheric diamonds. Given that diamonds are evident in the Pilbara Craton, there is a case to be made for lithospheric thinning or delamination, which seems to be supported by regional chromite compositions. A more extreme example of regional Al-rich chromites is apparent from the NAC and WA East samples. WA East chromites also contain the highest proportion (2%; Table 4) of indicator Al-spinel. Certainly, the mantle lithosphere under eastern (non-cratonic) Western Australia is relatively thin. However, the Al-rich spinel indicators from the NAC indicate either a thinner mantle lithosphere at the time of their emplacement at surface or, more likely, that the host rocks for Al-chromites in the NAC were sometimes derived from shallower depths within the lithosphere. A similar conclusion is reached from examining the compositions of orthopyroxenes, as discussed below.

Zincian overprints

With Zn overprints to chromite being interpreted as a consequence of low-grade metamorphism and metasomatism, it is notable that such grains are present in the Yilgarn Craton and elsewhere in the WAC outside of the Pilbara Craton, but not elsewhere in the State. Where they do occur regionally, some zincian chromites in Western Australia have nondiamond-prospective sources. However, there are enough known occurrences within or very close to diamond-prospective rocks to conclude that many regional samples may have diamond-relevant sources. Whatever mechanism is responsible for Zn overprints in Northern Territory kimberlites, it is not nearly as evident in Western Australia. In the Northern Territory, Zn overprints to chromites are striking among Merlin and Timber Creek kimberlites (Hutchison, 2013). Similar grains from regional samples, which are found in both the east and west Northern Territory do not come from the Kalkarindji Basalts (which have chromites without elevated Zn contents; Glass, 2002) and therefore may also have kimberlitic sources. While not extending to the immediate west into Western Australia's part of the NAC, similar geological processes are occurring in parts of the WAC. Hence, attention to zincian spinels should be area specific.

T1 and T2 composition spinels

The fact that all T1 composition spinels are aluminous brings into question whether they are genuinely derived from diamond-prospective rocks. Some samples have been found far from known diamond-prospective bodies. However, the intimate association with the Turkey Well TW10 kimberlite and the proximity of the Nabberu kimberlite field to some samples indicates that the T1 discriminatory tool is capable of identifying genuine kimberlitic spinels in regional samples.

The large majority of indicator spinels are consistent with the T2 compositional trend, which is consistent with kimberlites or lamproites. There are few richterite–T2 spinel associations from regional samples; a criterion necessary to definitively identify lamproite sources. However, richterite is not generally the subject of particular scrutiny in exploration. Given the large abundance of T2 spinels that may or may not have associations with diamond-prospective rocks, it is important to augment spinel chemistry by establishing mineral associations. Identification of richterite, particularly Ti–K richterite, provides a mechanism to do so. Hence, it is suggested that more focus should be applied to identifying this mineral in field samples, particularly where chromites are also known.

Clinopyroxene

Wide compositional variations and overlapping fields make regional distinctions between the sources for NAC and WAC clinopyroxenes hard to reach. However, the bimodal characteristic of the Yilgarn Craton samples (Fig. 19a) suggests that different depths of mantle lithosphere have been sampled. Kimberley Basin samples, being more consistently eclogitic than other parts of the NAC, suggest a dominance of this rock type in the mantle sampled below the Kimberley Basin. Furthermore, the abundance of Cr-depleted clinopyroxene from some regions emphasizes the exploration benefits from determination of mineral compositions. Grains with compositions that classify them as indicators, in both the spinel and garnet peridotite fields and the eclogitic field, would not be classified as Cr-diopsides based on the Cr_2O_3 threshold of 1 wt%. Such grains may not also pass the test of being sufficiently vivid green in colour to be considered for further classification. All clinopyroxenes from the Skerring kimberlite would fail the Cr_2O_3 threshold as would some from Argyle. Future equivalents to the Argyle pipe would be revealed by the most Al-depleted clinopyroxenes, including those that are not necessarily very Cr-rich. The area with the most compositionally similar grains to these criteria is the Pilbara Craton. Regional compositional trends demonstrate the importance of applying a wide latitude in the application of clinopyroxene compositions in exploration.

Within the NAC, clinopyroxene compositions show similarities between the eastern Northern Territory, where the diamondiferous Merlin pipes are to be found, and Western Australian samples. However, there is a gap to more Cr-depleted compositions that is coincident with the less diamond-prolific western Northern Territory. This compositional gap occurs at the same place where Kennett et al. (2013) showed the mantle lithosphere to be thinner. If the Merlin Ti-altered ilmenites are recalculated to Ti-free compositions, they lie within the kimberlite field and are consistent with their host rocks (Hutchison, 2013). By reversing the effects of Ti-alteration in this way, the same distinct compositional gap seen in clinopyroxenes also occurs between the eastern Northern Territory and Western Australia for ilmenite compositions.

Locality-specific observations provide the explorer with further insights. The incremental change among NAC Cr-diopside compositions in terms of diminishing Al-content from Ellendale 7, Ellendale 4, through Bow Hill to the Argyle lamproites (Fig. 19b) indicates both a narrower source depth range and a greater depth of origin. While changes in Al-content of clinopyroxene can arise due to equilibration on ascent (Spengler et al., 2012), the continuous trend rather than discrete compositions, particularly for Ellendale 7 samples, indicates a wide depth of origin. The trend out of the spinel-stability field into the deeper, garnet peridotite field matches the relative abundance of diamonds in the higher grade Ellendale 4 pipe compared with the Ellendale 7 lamproite, and the diamond-rich Argyle pipe in comparison to the Bow Hill dykes. The absence of a strong influence of host rock, whether lamproite or kimberlite, on Cr-diopside compositions demonstrates the importance of targeting the mantle component and the companion minerals to diamond during exploration. The data do not justify clinopyroxene compositions being used in isolation to predict diamond abundance. However, data indicate that within and between geographical areas, clinopyroxene compositions are useful for indicating likely relative diamond tenor. Hence, as a prospecting tool, it is not only the identity of Cr-diopside in exploration samples that is of significance, but also compositional determination is strongly justified.

Garnet

Garnet mineral chemistry has proven itself particularly useful in subdividing geographical areas of Western Australia in terms of mantle lithosphere characteristics, as discussed below.

Pyrope–almandine

While the WAC stands out as having the most striking G10 garnet abundance, and hence diamond-prospective tenor (Fig. 20), it is notable that the highly diamondiferous Argyle lamproite exhibits the most CaO-rich and reasonably Cr-poor garnet trend, and is the most G9 rather than G10 in character. This merely reflects lherzolitic rather than harzburgitic source rocks and is not necessarily a predictor of high pressures of formation or diamond abundance. Hence, the occasional tendency for diamond explorers to downgrade G9-rich provenances would be unwise in Western Australia, particularly in the NAC where the precedent of a G9-dominated diamond mine already exists.

In terms of regional trends, Kennett et al. (2013) estimated that the base of the mantle lithosphere is deep (220–230 km) under the Northern Territory's Merlin kimberlite field. Similarly, thick mantle lithosphere is also present under parts of the NAC in Western Australia, particularly the southern and eastern parts of the Kimberley Basin and in the WAC, particularly the central Eastern Goldfields and northern Youanmi Terrane of the Yilgarn Craton. However, the progression of garnet chemistry through G9 compositional space and into the G10 field from WA East, through the NAC, WAC and to the Northern Territory's Merlin field either suggests large-scale compositional variation in the mantle or an incrementally increasing source depth for each of these areas. If the latter interpretation is made, although the mantle lithosphere may be of a similar thickness among many of the Northern Territory and Western Australian cratonic regions, the depth sampled as reflected in garnet chemistry, and hence diamond prospectivity, differs from place to place. In a similar fashion to clinopyroxenes, garnet compositions show that despite diamond production being associated with the NAC, it is the WAC that particularly distinguishes itself for having indicators sourced from the deep mantle, particularly as a result of the abundance of grains extending far into the garnet G10 field. Notably, rather than corresponding to the thickest mantle lithosphere, the WAC G10 garnets come from the Edmund, Earaheedy and Hamersley Basins that overlie 170–210 km of lithosphere (Fig. 24b; Kennett et al., 2013). Furthermore, despite the 220–230 km mantle lithosphere thickness measured under Merlin, mineral barometry estimates the maximum equilibrium depth for the Merlin mantle component to be approximately 160 km (Hutchison, 2013), further emphasizing that diamond host rocks are not necessarily derived from the base of the lithosphere. In short, garnet chemistry shows the WAC to be more prospective than the NAC.

Ilmenite

The difference between Northern Territory and Western Australian ilmenites with respect to both exploration samples and known diamond-prospective rocks is striking. Western Australian ilmenite indicator compositions suggest the State to be regionally considerably more prospective for kimberlite than the Northern Territory (Fig. 21). This is ironic because the Northern Territory is known for its kimberlites (no diamondiferous lamproites are known), whereas the NAC of Western Australia is dominated at its peripheries by diamondiferous lamproites. Lamproite-hosted ilmenites can be decidedly Mg-depleted and are not considered to be indicators following Wyatt et al. (2004); however, special attention is required in Western Australia since ilmenites from the Argyle lamproite are dominantly non-indicators (Fig. 21). Despite the abundance of lamproites, kimberlites do still occur in the Kimberley Basin of the NAC, and this likely explains Western Australia's higher proportions of kimberlite-associated ilmenites.

Elevated Ti in ilmenites from the Merlin kimberlites (Reddicliffe, 1999; Hutchison, 2013) places their compositions above the typical indicator compositional field (Fig. 21). This effect is not seen in the western Northern Territory, which has genuine non-kimberlitic ilmenites. There is therefore a gap in prospectivity between the NAC in Western Australia and the NAC in the eastern Northern Territory, as evidenced by both clinopyroxene and ilmenite compositions. Zn overprints on spinel (with exceptions in parts of the WAC), Ti-enrichment of ilmenite and ubiquitous regional microdiamonds appear to be largely concerns restricted to the Northern Territory

In the WAC, ilmenites are consistent with the dominance of kimberlite over lamproite in this part of Western Australia. Statewide though, and as for other minerals such as garnet, application of indicator mineral chemistry in ilmenites should be applied based on location. While regional trends and known occurrences make the case for kimberlites dominating the WAC, care should be applied to not discount low-MgO ilmenites in NAC prospecting. Argyle ilmenite compositions are testament to this.

Orthopyroxene

The garnet peridotite compositions (Fig. 22) among WAC orthopyroxenes reflect deep lithospheric origins. The Hamersley Basin distinguishes itself by showing a marked coincidence with compositions known to be associated with diamond. Similar deep origins are not as well constrained among the NAC samples from this study, although rare garnet peridotite grains are known to occur. However, data from Ramsay (1992) places orthopyroxene from known diamondiferous rocks in deep-sourced compositional fields. The diamond-association orthopyroxene compositions from Argyle are particularly consistent with the high diamond grade in the Argyle diamond mine, whereas the overall large range in orthopyroxene compositions reflects a much wider variation in depth of origin at Argyle, from the deep diamond fields to the shallow spinel lherzolite field. The variations in diamond grade in lamproites throughout the Ellendale field are likely to be due to a range of depths of origin as evidenced in the Ellendale orthopyroxenes. Based on orthopyroxene analyses, the NAC which is dominated by lamproites and the WAC which is dominated by kimberlites are equally prospective. As an effective indicator mineral, it appears to be unimportant whether orthopyroxene is derived from lamproite or kimberlite.

Synthesis of mineral chemical results

Conclusions regarding diamond prospectivity based on each mineral phase are summarized in Table 12. It should be noted that characteristics that enhance the prospectivity of an off-craton area do not imply that, on the whole, it becomes as prospective as neighbouring cratonic areas. The Pilbara Craton and WAC stand out as demonstrating metrics that enhance their already high prospectivity due to them being cratonic areas. It is cautioned that the numbers of grains on which Pilbara Craton conclusions are drawn are reasonably small. Nevertheless, they largely relate to unidentified sources warranting further exploration attention. The Yilgarn Craton also stands out as having variable but locally-specific characteristics consistent with thick lithosphere and an emphasis towards kimberlite rather than lamproite. In the north, the NAC shows considerably more variability in terms of depths of origins of mantle-derived material compared with other Western Australian cratonic areas. In cases, such as Argyle and individual pipes at Ellendale, where variability occurs within individual bodies, occasional unprospective mineral chemistry does not have a strong negative bearing on prospectivity. However, locations where chemistries are exclusively unprospective would be justifiably downgraded.

Prospectivity rankings

The small number of samples recovered from some regions, particularly those with high indicator-positive proportions (Fig. 26; Aileron Province, Biranup Zone, Musgrave Province, Roebuck Basin, Rudall Province and Wolfe Basin) should be treated with caution. A very small number of indicator minerals can be extremely significant, as evidenced by the discovery of Argyle (Muggeridge, 1995). However, regions with small numbers of samples can be adversely influenced by errors in reporting, laboratory contamination or misinterpretation of the results. The latter factor is particularly relevant because the sampling component of the prospectivity methodology relies upon visual rather than chemical observations. Two other variables, the age of regional rocks and the underlying lithosphere thickness, serve to buffer any shortcomings of sampling data for regions with low sample numbers. Furthermore, the specifics of mineral chemical data as previously discussed serve also to add confidence to small numbers of grains recovered in some regions.

It is important to recognize that the present lithosphere does not necessarily reflect the lithosphere of the past, particularly at the time of diamond and host-rock formation and emplacement. In the prospectivity model's defense, understanding of the current lithosphere is a developing field where while we can interpret the surface expressions of the lithosphere (crustal blocks) moving over time, understanding of whole-lithosphere changes over time is limited. The current mantle snapshot is the most defensible information available. Furthermore, the lithosphere component is only a 33% contributor to the overall ranking of each region. The other two components rely on well-constrained geological variables that specifically take account of the age ranges of rocks in each region and the actual results of exploration as to whether diamonds and associated minerals are present or not. These factors therefore dilute the effect of rare cases where the lithosphere has dramatically changed from diamond emplacement to the present day. It is also fortunate that the lithosphere which is of most relevance to diamond exploration is the very lithosphere that is most stable and happens to survive relatively unchanged even over the span of geological time covering the diamondiferous rocks of interest. Where changes in the mantle lithosphere are expected to have taken place, the Pilbara Craton is the most notable. There is clear evidence for diamonds being formed under the Pilbara Craton (e.g. the diamondiferous Brockman Creek kimberlites; Booth, 2001), yet the current thin mantle lithosphere (Kennett et al., 2013) would suggest that diamond formation is at present unlikely. In this case, it is likely that delamination has taken place at some time after the emplacement of the Brockman Creek 01 kimberlite at 1868 Ma (White, 2000). The end result of the prospectivity analysis is that the Pilbara Craton still scores rather well, and the adjoining Hamersley Basin extremely well, despite the scoring of current lithosphere characteristics under-representing its importance. This observation provides confidence that the model is robust enough to handle local deviations.

Other factors affecting regional prospectivity

The prospectivity model presented for the Western Australian geological regions is based on a quantitative approach using variables that are considered to be most insightful to diamond exploration. However, numerous other factors have an influence on the attractiveness of specific areas, both at a small and large scale and

Table 12. Summary of prospectivity analysis based on mineral chemistry

Area	*Chromite – Zn overprint*	*Chromite – Al content*	*Chromite – CID / garnet peridotite*	*Clinopyroxene*	*Garnet – pyrope–almandine*
NT East*	Abundant	Abundant(a) - PROSP	Low ratio	Cr-rich, moderate Al + PROSP	G9/G10 trend + PROSP
NT West*	Abundant	Abundant(a) - PROSP	Low ratio	Cr-depleted Be Aware	insufficient data
NAC	Rare	Abundant - PROSP	High ratio + PROSP	Cr-depleted Be Aware	G4, G9
WA East	Rare	Abundant - PROSP	Moderate ratio, low abundance	Moderate comp. range	G3, G9, G10D + PROSP
WA West	Rare	Largely absent(b)	Moderate ratio, low abundance	no data	no data
Pilbara	Absent	Largely absent + PROSP	Moderate ratio	Strongly Al-poor ++ PROSP	no data
Yilgarn	Most WA examples Be Aware	Largely absent + PROSP	Low ratio but high abundance	Al-poor with exceptions Be Aware	G3, G4 little data
WAC	Present Be Aware	Present Be Aware(c)	Moderate ratio	Mod. Al-poor Be aware	G3, G4, G9, G10D ++ PROSP

Area	*Ilmenite*	*Orthopyroxene*	*Synthesis*
NT East*	Ti-enriched Be Aware	insufficient data	Zn and Ti enrichments complicate the process of exploration in this prospective area.
NT West*	Low-Mg - PROSP	insufficient data	Presents a prospectivity dip between eastern NT and eastern WA evidenced in clinopyroxene and ilmenite.
NAC	Kimberlitic(d) + PROSP	Ranges into spinel field Be Aware(f)	Mineral chemical criteria do little to change the picture of the NAC being prospective. Chemical variations reflect varying depths and compositions of source rocks and can occur within and between pipes with large local variation.
WA East	no data	no data	As for the NAC, chemical variation may reflect sampling depths within individual pipes where datasets should be considered as a whole. Occasional G10D occurrences reveal specific local prospective locations
WA West	Mg-enriched + PROSP	no data	Little chemical evidence for amendment to off-craton prospectivity being low. However, local ilmenite concentrations may merit further attention.
Pilbara	no data	no data	Al-depletion in both clinopyroxene and chromite reflect a consistently deep-mantle source at the time of explacement, emphasising strong prospectivity.
Yilgarn	Highly Mg-enriched(e) + PROSP	Al-depleted + PROSP(f)	Variability in mineral chemical metrics emphasise variations in local prospectivity. Particular Mg-rich ilmenites reveal locally prospective localities.
WAC	Mg-enriched + PROSP	Al-depleted(g) ++ PROSP	Already prospective as an on-craton location, WAC has most prospectivity-enhancing chemical observations, particularly for garnet, ilmenite and orthopyroxene.

NOTES: * – from Hutchison (2013); Be Aware – does not affect prospectivity but should be taken account of during exploration. Where a characteristic affects diamond prospectivity positively or negatively, compared to other areas, this is annotated by: – PROSP – diminished prospectivity; + PROSP – enhanced prospectivity. (a) – NT chromites are relatively Fe-enriched compared to WA samples (Hutchison, 2011), reducing their prospectivity. (b) - While the rarity of Al-spinel and Al-chromite is a positive, the numbers of indicator spinels in this area are low. (c) – Presence of Al-chromite and Al-spinel indicators is taken to reflect a range of depths of origin, sometimes within individual diamondiferous bodies. Sources exclusively with Al-rich compositions should be avoided, but if they constitute only a part of the compositional range they are not taken as a strong negative. (d) – Argyle lamproite-derived ilmenites, with very low Mg content, would not be classed as kimberlite indicators. (e) – While Eastern Goldfields samples are highly Mg-enriched, Marymia and South West Terrane ilmenites are more marginal in composition. Explorers should be aware of Mn-alteration in some Eastern Goldfields ilmenites. (f) – Some orthopyroxenes are low in Mg and not clearly associated with diamond-prospective sources, hence caution is advised. (g) – The Hamersley Basin has a tight cluster of diamond-association composition orthopyroxenes (Mg-rich), similar to Argyle.

sometimes with considerable effect. For example, much of Western Australia is remote and the cost and benefit considerations of exploration can be heavily influenced by locality. The nature of the country rock in terms of its influence on remote sensing, such as the prevalence of Fe-rich rocks in the Hamersley Basin, can have significant negative effects. Sociopolitical considerations are important, particularly where additional requirements for engagement with traditional landowners are necessary. These apply to much of northern and eastern Western Australia in particular, but can happen in any part of Western Australia (e.g. Towie, 2004). In contrast, the establishment of known diamondiferous bodies, favourable mineral chemistry, and anomalous diamond occurrences in surface samples are all positive variables not quantified in the core prospectivity model. Table 13 documents the principal non-quantified modifications to the prospectivity model. The prospectivity categories from Table 10 have been reproduced and documented contributing criteria have been applied to the proposed non-quantified modifications to enhance, diminish or unchange the prospectivity categories. It is emphasized that the decision to upgrade (identified in Table 13 by '+ ve') or downgrade a region's prospectivity is at times considerably subjective. For example, whether the presence of encouraging mineral chemistry is enough to offset parts of a region being very remote is open to considerable debate and ultimately will be decided by the individual prospector. In the same fashion that the core prospectivity model, while having a rigorous scientific basis, is intended to be used as a guideline for exploration, the subjective modifications are intended as suggestions aimed at highlighting some of the important additional variables.

Table 13 demonstrates that the specifics of mineral chemistry serve to upgrade the prospectivity of slightly more regions than are downgraded by other factors. The criteria considered in Table 13 are far from exhaustive and it is likely that as time passes different criteria will come to prominence.

Also at play in diamond prospectivity is the important role of lithosphere and crustal structure in assisting the emplacement of diamond-bearing rocks. The prospectivity analysis of this study serves to draw attention to particular regions of interest. However, the explorer would further benefit from the examination of structures at a larger scale by following methodologies such as those described by Jaques and Milligan (2004).

Due to its importance as the sole region occupying the top prospectivity category, the Hamersley Basin merits particular attention. This basin is known for its abundant Fe-rich rocks, including banded iron-formations. Consequently, it can be expected that country rocks provide additional challenges to the diamond explorer. These come in the form of highly magnetic country rocks that influence the geophysical landscape by both impacting on resistivity and magnetic surveys and also affecting heavy mineral concentration. Iron oxides tend to dominate trap sites in drainages, displacing other less-dense minerals such as DIMs. Finding suitable accumulations of indicator minerals free from a dominant background of Fe-rich minerals using normal methods is difficult. Furthermore, the proliferation of Fe has a strong influence on mineral grains during weathering as indicator minerals can become coated in Fe-oxide, thus resulting in them being both unreliably separated, as they will naturally be attracted to magnetized rather than non-magnetic fractions and also hard to identify. Fe-laterite leaching processes designed specifically for such an environment have been reported (Towie, 2004) to greatly assist in cleaning indicator minerals, thus allowing their concentration and identification to proceed more normally. Archer (1986) reported a similar reduction roasting technique to deal with high-laterite content in samples in the Northern Territory. One of the most diamond-prospective orthopyroxene sites in Western Australia that was present in the central part of the Hamersley Basin, and also associated with G9 and G10D garnet and kimberlitic spinel and ilmenite, was reported by Towie (2004) to have been abandoned due to a shortage of funds and challenges regarding Native Title. The signing of Native Title agreements took two years from the original acquisition of the tenements. However, the final heritage surveying and commencement of work took six years (Petts et al., 2011).

Extraction of samples from drilling is also challenging in the Hamersley Basin because country rocks are hard and tough; compounded by silicification. Drilling is often very slow and hence costly, and hardness is compounded by common brecciation that results in poor recovery. Although the age of the Hamersley Basin rocks is sufficiently old to pre-date the majority of the Western Australian diamond-prospective rocks known, the toughness of the Fe-rich shales and concentrated Fe-formations is such that some explorers question whether kimberlite magmas have the physical characteristics capable of surface emplacement through such country rocks (Ceplecha, 2007). It is expected that many of the diamondiferous rocks in the Hamersley Basin may be present at depths of 100 m (Towie, 2004), which considerably contributes to the challenges presented by this region. Due to the extreme difficulties in drilling, it has been recommended that targets with a likely surface expression of diamondiferous rocks should be focused on rather than blind targets with cover (Ceplecha, 2007). Surface exposed rocks are likely in any case to have larger volume potential because they are more likely to reflect pipes than dykes or sills.

Modelling regional diamond prospectivity is important to aid the process of focusing future diamond activities. The Hamersley Basin provides an important case study demonstrating that local considerations can be very variable and can have a strong bearing on the practicalities of diamond exploration. The Hamersley Basin remains highly prospective but logistically challenging. However, inspection of Table 13 also shows that category 2 prospective regions are either enhanced (Eastern Goldfields Superterrane) or unchanged (Yilgarn Craton and the Goodin Inlier) by external variables.

Underexplored features

Western Australia has experienced at least a 45-year history of considerable diamond exploration that has been successful in placing Australia both as a primary worldwide diamond producer as well as the top producer of fancy pink and yellow diamonds. Western Australia is chronically underexplored for diamonds, even in the most prospective regions (Fig. 25). These two statements may seem contradictory. However, it should be borne in mind that Western Australia is very large and is dominated by prospective old cratonic rocks that are extensively weathered and often hard to access. Diamond exploration in Australia is expensive, but the indicators for diamond prospectivity are well established and the potential for future discoveries, based on geological considerations, is high. Unexplored land abounds. However, there are also numerous indicators of specific diamond provenance in local areas that can serve to provide the explorer with entry into the field. These localities are identifiable by their anomalous diamond or indicator occurrences, particular mineral chemistry or geophysical characteristics. Many have been mentioned throughout the text and a few are highlighted in the following section.

The Fohn lamproites are undoubtedly very large, in a global context. The buried, offshore crater-facies lamproite pipes of Fohn-01 (1.5 × 1 km) and Fohn South (2.7 × 2.6 km) display clear seismic-reflection signatures indicating their size. Approximately 40 km southwest of this location lies another well-characterized seismic anomaly called feature P (P1-3), which has not been tested by drilling. It has a 2.3 km-diameter central core that has been identified by a distinctive seismic high-velocity zone and a 5 km-diameter ejecta horizon. Like Fohn-01, it is a body with a large potential volume.

The Cundeelee intrusive complex (also known as Ponton Creek) that intrudes the southern margin of the Yilgarn Craton is also a very large (4563 ha) body. It is an intrusive complex with carbonatitic affinities (Raetz and Johnstone, 1998). It has no outcrop and is identifiable in the spinifex plain it resides in by its prominent magnetic signature. It is relatively untested, with only a handful of drillholes. Even in the central zone, as determined by gravity surveying (Raetz and Johnstone, 1998), the petrology is not pervasively carbonatitic, and instead has been described as a magnetite pyroxenite with chlorite-carbonatite veins up to 20 mm thick. As such, the complex is extremely poorly understood given its large size. Various tenement holders have postulated the existence of associated kimberlite intrusives and although mafic pipes have been identified and discounted as prospective by some workers (Raetz and Johnstone 1998), the potential association has been largely untested. Carbonatites are known to be intrinsically associated both spatially and temporally with diamondiferous kimberlites (Hutchison and Frei, 2009), so there is real potential for a kimberlite occurrence at Cundeelee.

Historically in Western Australian diamond exploration, long-standing occurrences of diamonds have not been fully resolved. The provenance of minerals reported as diamond in the Nullagine region (Sofoulis, 1958; Carter, 1974) remains unexplained. It is cautioned that historical, rare and widely spaced diamonds are best treated with a degree of skepticism, as false positives are known (e.g. Faithfull, 2007).

Potential for future discovery in well-established fields also exists. Hissink (1997), referring to the Big Spring and Cajaput Creek area (Canning Basin and Lamboo Province, NAC), concluded that 'this tenement has more prospectivity for beef cattle raising than diamond mines.' The area has been well explored and the point that any large bodies should have already been found is well made. However, known bodies have not been fully explored. For example, Big Spring West, due to its significant magnetic response, is likely a considerably larger body than has been so far investigated. It has been described as occurring as a series of small (15 cm) stringers of leucite lamproite in an outcrop of approximately 30 × 30 m, and although it has been described as meriting further exploration (Lewis, 2008) this has not, to date, been carried out. Furthermore, unresolved indicator mineral anomalies are present at various locations in the Big Spring area (Allen, 1993b), particularly at Little Spring Creek (Diamond Exploration Consultants Pty Ltd, 2001), which suggest that there are undiscovered primary bodies underlying the abundant black soil in the area. Work is currently being conducted in the area by the Lucapa Diamond Company Ltd with new discoveries recently reported. Even the vicinity of the Argyle mine has not apparently been exhaustively explored. Lamproites under basalt cover in the vicinity of Argyle have been proposed by Vanderhor (2006).

Returning again to the highest ranking region for diamond prospectivity, Towie (2004) reported highly prospective indicator minerals such as olivine and phlogopite with likely very short transportation distances in the Hamersley Basin. The sources of these indicators are so far undiscovered (Petts et al., 2011). Orthopyroxene with diamond lherzolite and diamond harzburgite inclusion chemistry and associated with G9 and G10D garnets and abundant picroilmenites that plot in the kimberlite compositional field based on Ti and Mg content have been reported from an in situ rockchip (Towie, 2004) from the central Hamersley Basin. No diamond-prospective rock has been reported at this locality, although Towie (2004) described the sample and the area as 'indicative of a high diamond potential.' Rock fragments within the mineral separate are of ferruginous and siliceous sediment with a soft, possible highly weathered ultramafic component. The morphologies of the indicator minerals show very strong unabraded characteristics, including the diamonds themselves. This has led explorers to conclude that kimberlite stringers exist within the Brockman Iron Formation (Towie, 2004). Highly altered ultramafic 'amorphous ferruginous material' has been identified as a possible source of the indicators. As discussed previously, exploration is challenged in the area by extreme lateritization that to some extent has been mitigated against by using a specific iron digest before indicator mineral inspection. Observations indicate that a kimberlitic source may have already been intersected, but not fully recognized due to alteration. Similar unsubstantiated occurrences are present throughout the State and the DED has compiled a referenced list of these bodies (termed Inferences).

Table 13. Principal non-quantified modifications to regional prospectivity

Region	*Category*	*Adjustment*	*Contributing criteria*
Aileron Province	5	even	No modifying observations.
Amadeus Basin (Phase 1)	8	even	Single garnet peridotite-composition clinopyroxene recovered. Contains minor diamond occurrences with unknown sources.
Amadeus Basin (Phase 2)	13	even	No modifying observations.
Arid Basin	8	even	No modifying observations.
Ashburton Basin	3	even	No modifying observations.
Badgeradda Basin	7	even	No modifying observations.
Barren Basin	10	even	No modifying observations.
Bastion Basin	8	even	No modifying observations.
Biranup Zone	3	even	No modifying observations.
Birrindudu Basin	5	even	No modifying observations.
Bresnahan Basin	7	even	No modifying observations.
Bryah Basin	3	even	No modifying observations.
Canning Basin	8	even	Abundant diamondiferous bodies are known in the north (63 diamondiferous lamproites at Ellendale, Big Spring, Calwynyardah, Walgidee Hills). Prior mining occurred at Ellendale 4 and 9. CID chromites and garnet peridotite-composition clinopyroxene identified by mineral chemistry. It is cautioned that the Canning Basin is a very large region and all indications suggest maximum prospectivity occurs within about 150 km of the boundary with the Lamboo Province. *Parts of the region are very remote, over 200 km from a paved or principal road*.
Carr Boyd Basin	8	+ ve	Contains diamond occurrences with unknown sources.
Collier Basin	7	+ ve	Garnet megacryst-composition orthopyroxenes identified by mineral chemistry.
Earaheedy Basin	5	+ ve	Known diamondiferous body (Bulljah Pool 1 ultramafic lamprophyre) present. Garnet megacryst-composition orthopyroxenes, garnet peridotite-composition clinopyroxene. G10 composition garnets, kimberlitic ilmenite, CID chromites identified by mineral chemistry. Contains diamond occurrences with unknown sources.
Eastern Goldfields Superterrane	2	+ ve	Garnet megacryst-composition orthopyroxenes, kimberlitic ilmenites, CID chromites identified by mineral chemistry. Contains diamond occurrences with unknown sources. *Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Edmund Basin	4	+ ve	Known diamondiferous body (Eestelling 2 ultramafic lamprophyre) present. G10 composition garnets, CID chromites identified by mineral chemistry.
Eucla Basin	13	- ve	*Parts of the region are very remote, being over 200 km from the nearest paved or principle unpaved road.*
Fortescue Basin	3	even	Known diamondiferous bodies (Yanyare-02 lamproite and Blacktop 01 kimberlite) present. CID chromites identified by mineral chemistry. Contains diamond occurrences with unknown sources. *Parts of the region are remote, being over 100 km from the nearest paved or principal road.*
Fraser Zone	8	- ve	*Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Gascoyne Province	4	even	No modifying observations.
Granites–Tanami Orogen	5	even	No modifying observations.
Gunbarrel Basin	10	- ve	*Parts of the region are very remote, being over 200 km from the nearest paved or principal unpaved road.*
Hamersley Basin	1	- ve	Garnet megacryst-composition orthopyroxenes, garnet peridotite-composition clinopyroxene, G10 composition garnets, diamond harzburgite and lherzolite-association orthopyroxene, kimberlitic ilmenite identified by mineral chemistry. Contains diamond occurrences with unknown sources. *Small parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road. Abundant ferricrete makes processing of sediment samples complex and expensive. Proliferation of Fe-rich country rock significantly complicates geophysical targetting and drilling operations.*

Table 13. continued

Region	*Category*	*Adjustment*	*Contributing criteria*
Kimberley Basin	4	+ ve	Numerous known diamondiferous bodies (Sandy Gorge A1, five kimberlites at Aries and fifteen North Kimberliey kimberlites including Seppelt, Ashmore and Pteropus) present. Garnet megacryst-composition orthopyroxenes, G10 composition garnets, kimberlitic ilmenite, CID chromites identified by mineral chemistry. Contains diamond occurrences with unknown sources. *Parts of the region are very remote, being over 200 km from the nearest paved or principal unpaved road.*
Lamboo Province	3	+ ve	Known diamondiferous bodies are present (Lissadel Road lamproite dykes near Argyle and Big Spring 1 and 4 olivine lamproits in the southwest).
Louisa Basin	6	even	No modifying observations.
Moora Basin	10	even	No modifying observations.
Murraba Basin	8	- ve	*Parts of the region are very remote, being over 200 km from the nearest paved or principal unpaved road.*
Musgrave Province	5	- ve	*Parts of the region are very remote, being over 200 km from the nearest paved or principal unpaved road.*
Narryer Terrane	3	even	No modifying observations.
Nornalup Zone	10	even	No modifying observations.
Northern Bonaparte Basin	9	+ ve	Contains diamond occurrences with unknown sources. Contains very large and underexplored lamproite bodies offshore at Fohn.
Northern Carnarvon Basin	13	even	No modifying observations.
Northern Foreland, Albany–Fraser Orogen	9	- ve	*Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Officer Basin (Phase 1)	8	- ve	*Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Officer Basin (Phase 2)	11	- ve	*Parts of the region are extremely remote, being over 300 km from the nearest paved or principal unpaved road.*
Ord Basin	5	+ ve	G10 composition garnets and garnet peridotite-composition clinopyroxenes identified by mineral chemistry. Contains diamond occurrences with unknown sources.
Osmond Basin	8	even	No modifying observations.
Perth Basin	9	even	Contains minor diamond occurrence with unknown source.
Pilbara Craton	3	+ ve	Known diamondiferous bodies (Brockman Creek 01 and 02 kimberlites) present. CID chromites and garnet peridotite-composition clinopyroxene identified by mineral chemistry. Contains diamond occurrences with unknown sources. *Small parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Pinjarra Orogen	10	even	No modifying observations.
Ragged Basin	10	even	No modifying observations.
Recherche Supersuite	8	even	No modifying observations.
Red Rock Basin	4	even	No modifying observations.
Roebuck Basin	10	even	No modifying observations.
Rudall Province	4	- ve	*Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Salvation Basin	6	- ve	*Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Scorpion Basin	8	+ ve	Two garnet peridotite-composition clinopyroxenes identified by mineral chemistry. *Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
South West Terrane	4	+ ve	Kimberlitic ilmenites and garnet peridotite-composition clinopyroxene identified by mineral chemistry.
Southern Bonaparte Basin	7	+ ve	Known and mined diamondiferous body (Argyle AK1 olivine lamproite) present. Garnet peridotite-composition clinopyroxene identified by mineral chemistry. Contains diamond occurrences with unknown sources.
Southern Carnarvon Basin	11	+ ve	Kimberlitic ilmenites and CID chromites identified by mineral chemistry. Contains off-shore ultramafic lamprophyre at Edel.

Table 13. continued

Region	Category	Adjustment	Contributing criteria
Speewah Basin	4	+ ve	Known diamondiferous bodies (Maude Creek kimberlite and Devils Elbow No.1) present. Contains diamond occurrences with unknown sources.
Tanami Basin	5	even	No modifying observations.
Texas Downs Basin	7	even	No modifying observations.
Tropicana Zone	8	- ve	*Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Turee Creek Basin	5	even	No modifying observations.
Victoria Basin	4	even	No modifying observations.
Wolfe Basin	4	even	No modifying observations.
Woodline Sub-basin	8	even	No modifying observations.
Yandanooka Basin	11	even	No modifying observations.
Yeneena Basin	12	even	Contains diamond occurrences with unknown sources. *Parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*
Yerrida Basin	4	even	No modifying observations.
Yilgarn Craton, Goodin Inlier	2	even	No modifying observations.
Yilgarn Craton, Marymia Inlier	3	+ ve	Known diamondiferous bodies (Methwin 02, Nabberu 8 and 15 kimberlites and Nabberu 2 and 4 ultramafic lamprophyres) present. Garnet megacryst-composition orthopyroxenes, CID chromites and kimberlitic ilmenites identified by mineral chemistry.
Youanmi Terrane	3	+ ve	CID chromites and garnet peridotite-composition clinopyroxene identified by mineral chemistry. Contains diamond occurrences with unknown sources. *Small parts of the region are remote, being over 100 km from the nearest paved or principal unpaved road.*

NOTE: Categories are prospectivity scores from Table 10. Adjustments are caveats to a region's calculated prospectivity, either promoting (+ ve) or demoting (- ve) their attractiveness based on non-quantified geological or geographic criteria. Adjustment field entry 'even' denotes that the positive and negative observations may balance each other. Criteria contributing positively to a region's prospectivity are in normal font and negative criteria is shown in italics.

Summary and conclusions

Known diamond-prospective rocks of Western Australia

A total of 524 diamond-prospective rocks (kimberlites, lamproites, ultramafic lamprophyres and carbonatites) are now known for Western Australia (Hutchison, 2018), covering much of the State. Of these, 114 have been proven to be diamond bearing and age determinations have been made for 63 bodies.

Diamond-prospective bodies occur both as clusters and as isolated occurrences. Around the NAC are the North Kimberley and Aries kimberlite clusters, the Ellendale and associated lamproite fields to the southern margin of the Kimberley Craton and the small number of lamproites associated with the Argyle AK1 pipe to the east. Around the WAC, the Brockman Creek kimberlites occupy locations in the Pilbara Craton and the Blacktop kimberlites lie to the west. The Eerstelling and associated kimberlites and ultramafic lamprophyres lie farther south in the Edmund Basin. In the Yilgarn Craton, the Nabberu kimberlite cluster is particularly significant, but numerous other clusters are present further south within the craton, including the Akbar ultramafic lamprophyres, kimberlites at Mileura and Mount Weld, and also south around Norseman.

The sizes of diamond-prospective rocks in Western Australia vary considerably (Fig. 4), with Walgidee Hills being the largest known lamproite in the world (461 ha). Lamproites are usually considerably larger than the ultramafic lamprophyres, followed by the known kimberlites.

Australia produced approximately 11% of global rough-diamond production by weight in 2015, ranking it fourth in the world. These production figures were accounted for by two mines, both in Western Australia. Production has now closed at the Ellendale mines (known for fancy yellow-coloured diamonds; Downes et al., 2012), but production continues at Argyle (known for its vivid pink diamonds; King et al., 2014) and consequently Australia continues to contribute significantly to global diamond sales.

Exploration methods

Some 68% of the State's onshore areas lie over 20 km from a known diamond-exploration sample site (Fig. 3). There are notable unsampled areas in the north and west NAC. Probably due to its small size, the Pilbara Craton has reasonably high-density diamond exploration coverage, but the remaining parts of the WAC can be described in the same way as the NAC: localized dense pockets of exploration with prominent gaps.

The overwhelming majority (approximately 90%) of surface and drillhole exploration samples for diamond have been taken for separation of diamonds or other minerals indicating diamond potential. Sampled material has more or less been evenly split between the two dominant types of alluvial samples (43%) and loam samples (39%). Sample weight modes are 45 kg for both alluvial and loam samples and an average of 1.65 kg/l of loam sample measured volumetrically has been calculated (Hutchison, 2018). The most common size ranges inspected for minerals have been 0.3 – 1.5 mm (45%), 0.2 – 1.5 mm (15%) and 0.3 – 1 mm (7%). Unlike in the Northern Territory, Western Australian exploration has generally been suitable for capturing the majority of indicator spinels, which are three times more abundant in the <0.5 mm size range than above.

The proportion of heavy mineral recovery within samples, taking into account the bimodality of concentrate percentage for coarse samples and a small proportion of bulk samples, increases from fine- to medium- to coarse-grained samples and from loam, through alluvial to rock samples. For all sample types, concentrate recovery has been less than that seen in the Northern Territory.

A typical or median Western Australia 25-kg alluvial sample yields 18 g of heavy minerals. Smaller recoveries result from rock and loam samples where the median heavy mineral recovery is 0.03%, which is equivalent to 8 g from a 25 kg sample.

Exploration results

Diamond exploration in Western Australia has successfully resulted in economic diamond production placing Australia at one point in time fourth in the world for diamond production by weight. Analyses of DED data show that some exploration methodologies work well and others are less suited to the geological and environmental conditions present in Western Australia.

Nondiamond indicators

Indicator distributions and sampling methodologies show that programs recovering >0.3 or 0.4 mm grains from high-energy trap sites are most successful. Nondiamond indicators were identified by visual inspection in 28% of samples.

The large majority of nondiamond indicators are spinels, which are relatively durable in the harsh Western Australian weathering environment. In addition to chromite, diopside, garnet, ilmenite, monticellite, orthopyroxene, olivine, perovskite, phlogopite, pseudobrookite and tourmaline with indicator chemistries have all been recovered. False positives occur among grains that are identified only visually. However, 80% (over 25 000) of good-quality mineral compositional analyses are classified as genuine indicators.

Diamond recovery

Diamond was present in 3.5% of the indicator mineral samples and yellow and pink diamonds responsible for much of the revenue from Western Australia's diamond mines were also recovered from exploration samples. Diamond morphology is dominated by octahedral forms, but later etching and resorption is also common. These observations suggest a relatively high formation temperature and mature, deep diamond-growth settings combined with distress, either at formation depths or during emplacement. The diamonds that have been recovered suggest that diamonds are more likely to have formed under Western Australia compared to the Northern Territory. However, in some places they are also more likely to have been damaged later on before reaching the surface.

Diamonds in exploration samples are particularly common around the larger clusters of kimberlites in the northern Kimberley Basin, and the lamproites in the southwestern extent of the NAC. However, in the NAC, diamond locations (including macrodiamonds) with unknown sources occur in the central Kimberley Basin north of the Aries kimberlite cluster, and to the east. To the west, unexplained occurrences have been reported in the Pilbara Craton, Yilgarn Craton (Eastern Goldfields Superterrane and Youanmi Terrane) and elsewhere in the WAC (Earaheedy, Fortescue and Hamersley Basins; Fig. 15). Anomalies are particularly pronounced in the Hamersley Basin (Towie, 2004) and the Yerrida Basin (Hamilton, 1984).

For diamond-bearing samples, one would expect to recover between 1 to 1000 times more indicators than diamonds, particularly for loam and rock samples. Occasionally, alluvial samples may be expected to yield more diamonds than indicators, depending on their distance from the source. However, the confusing effect of a large regional background of microdiamonds that is present in the eastern Northern Territory does not generally apply to Western Australian samples.

Mineral chemistry of indicator minerals

The majority of indicator spinels are Al-free chromites and 91% of indicator spinels are derived from the mantle according to the mineral chemical criteria. Some samples, mostly from the Yilgarn Craton, have zincian overprints, which are concluded to be due to a mix of diamond-related and nondiamond-related host rocks and a localized feature.

The Yilgarn and Pilbara Cratons and WA West are particularly dominated by Al-free chromites, whereas Al-chromite indicators are abundant in the NAC and WA East. Increasing dominance of Al in chromites is interpreted as a sign of a shallower source than for Al-depleted Mg-chromites. Further mineral classification shows chromites to be largely of a garnet peridotite affinity and the more diamond-prospective CID compositions are largely confined to craton-sourced samples.

As for chromites, clinopyroxene indicators largely show a garnet peridotite affinity. Kimberley Basin samples are more consistently eclogitic than other parts of the NAC. Clinopyroxenes not classed as Cr-diopsides are associated with diamondiferous rocks in Western Australia, particularly at Argyle. In light of compositions not normally considered highly diamond-prospective, it is recommended to apply a wide latitude in the use of clinopyroxene compositions in exploration.

For garnets, the progression of garnet chemistry through G9 compositional space and into the G10 field from WA East, through the NAC, WAC and to the Northern Territory's Merlin field suggests an incrementally increasing source depth for each of these areas. Garnet compositions, in a similar fashion to clinopyroxenes, show that despite diamond production being associated with the NAC, it is the WAC that particularly distinguishes itself for having deep mantle-sourced indicators.

Among ilmenites, 93% with indicator chemistry fall within the kimberlite field of Wyatt et al. (2004). Samples from the Eastern Goldfields Superterrane are most kimberlitic. As with clinopyroxenes, Argyle-hosted ilmenites (Ramsay, 1992) would not be classed as indicators following Wyatt et al.'s (2004) scheme.

Synthesis of mineral chemistry data shows that the Pilbara Craton and WAC stand out as the most highly prospective. It is cautioned that the numbers of grains on which the Pilbara Craton conclusions are drawn are reasonably small. The Yilgarn Craton stands out as having variable but locally specific characteristics consistent with a thick lithosphere and an emphasis towards kimberlite rather than lamproite. In the north, the NAC shows considerably more variability in terms of depths of origins of mantle-derived material compared with other Western Australian cratonic areas, but clearly diamond-prospective localities are present.

Diamond prospectivity

An enhanced recent interest in diamond exploration, partnered with improved opportunities for financing projects, the recent closure and ageing of mines and the underexplored character of the State make compilation of diamond exploration data and its analysis timely.

Prospective locations

From this work there are several specific Western Australian occurrences that have been identified as warranting follow-up study. These are discussed from north to the south below.

A large seismic anomaly (Feature P) is present among 47 circular to subcircular seismic forms southwest of the Fohn-1 and Fohn South offshore lamproites in the Northern Bonaparte Basin (Gorter et al., 2004).

Headless diamond concentrations are particularly evident in the central Kimberley Basin, north of the Aries kimberlite cluster and an anomaly is present in the Speewah Basin (Paradigm North Pty Limited, 2004).

Anomalous diamonds are present in the Amadeus Basin (Phase 1), Northern and Southern Bonaparte, Carr Boyd, Ord and Yeneena Basins.

The Cundeelee intrusive complex (Ponton Creek), an extremely large body (7.7 × 7.7 km) that exceeds the size of the Fohn 1 and Walgidee Hills lamproites, is largely interpreted to be an alkali igneous complex. However, it contains carbonatitic sections (Raetz and Johnstone, 1998) and by extension has a possibility for kimberlite association (following Hutchison and Frei, 2009). The body is unexposed, under spinifex-rich cover and underexplored.

Magnetic surveying has indicated that the Big Spring West body, east of Ellendale, is considerably larger than its extent as tested by drilling. Unexplained indicator mineral anomalies have been found throughout the field in this area (Allen 1993b). Abundant black soil provides the most significant impediment to exploration by means of mineral-dispersion surveying.

The WAC has firmly proven its diamond prospectivity in terms of known diamondiferous bodies, prospective mineral chemistry and favourable mantle conditions. Unexplained diamond anomalies are present in the Nullagine region (Carter, 1974). Exploration efforts in the Hamersley Basin have yielded locations with diamond lherzolite- and diamond harzburgite-association orthopyroxene, associated with G9 and G10D garnets and abundant picroilmenites from in situ samples (Towie, 2004). There are clearly diamond-prospective rocks in the near vicinity, but these are of unknown size and distribution. Exploration in the immediate area is challenged by extreme lateritization that to some extent has been mitigated against by using a specific iron digest before indicator mineral inspection.

Prospective regions

In order to more formally quantify prospectivity, the State has been subdivided into 67 onshore tectonic units in four geographic areas. The Hamersley Basin scored the highest (Figs 25–27; Table 10) in prospectivity ranking based on sample density and visually identified indicator success, relative country-rock age to known Western Australian diamond-prospective rocks, and lithosphere characteristics. Equal second were the Eastern Goldfields Superterrane and Goodin Inlier, both located in the Yilgarn Craton. Category-three ranked regions are the WAC's Ashburton Basin, the Biranup Zone, the Bryah and Fortescue Basins and Narryer Terrane, the Lamboo Province of the NAC, the Pilbara Craton, the Marymia Inlier and the Youanmi Terrane of the Yilgarn Craton. Poorest scoring areas such as the Eucla Basin lie the farthest from craton margins and contain the youngest rocks.

Various factors act to enhance or downgrade the prospectivity score of Western Australian regions, whether geological, geophysical considerations or mineral chemical characteristics. Furthermore, there are socioeconomic and logistical factors to consider. Perhaps unsurprisingly, mineral chemistry and anomalous diamond concentrations, not individually accounted for in the prospectivity model, serve to enhance all of the Yilgarn regions (apart from the Goodin Inlier), the Pilbara Craton and most additional WAC regions. This also applies to most NAC regions. Off-craton, the Canning Basin has local areas of particular interest, mostly around the known bodies at Ellendale. However, the Amadeus Basin (Phase 1) and the Southern Carnarvon Basin also yield anomalously prospective locations. The principal negative factors identified include distance to principal roads, paved or otherwise although, with the exception of parts of the Eastern Goldfields Superterrane, Fortescue, Hamersley and Kimberley Basins and small parts of the Pilbara Craton and Youanmi Terrane, this drawback generally applies to off-craton settings of low prospectivity. In addition, the Hamersley Basin has been identified as a location where despite good exploration-sampling results, there are significant challenges presented by heavy ferricretization and Fe-rich country rocks that complicate both geophysical exploration and drill sampling.

Despite prolific diamond exploration, Western Australia is considerably underexplored and the ageing Argyle mine and recent closure of operations at Ellendale warrant a re-evaluation of the State's diamond potential. Indicator mineral chemistries reflect mantle sources with respectable diamond tenor, consistent with diamond and visually determined indicator recovery, known diamondiferous source rocks and mining in parts of the State. However, analysis of exploration data also draws attention to underexplored areas, particularly in the WAC. As kimberlite and lamproite emplacements span 2500 million years, there are significant opportunities for diamond-affinity rocks being present near the surface, even within the large, underexplored sedimentary basins that overlie the thick mantle lithosphere through much of the State. The results of prospectivity analysis make a compelling case for renewed diamond exploration.

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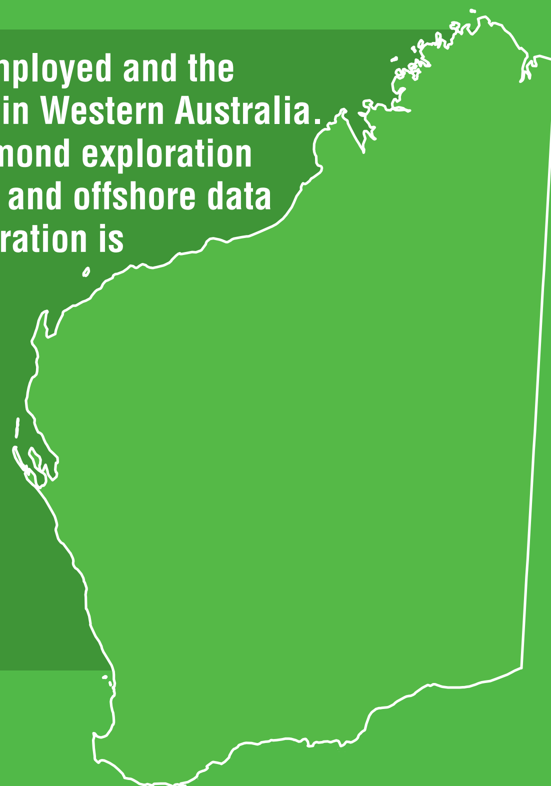
This Report summarizes the methodologies employed and the findings made during the search for diamonds in Western Australia. The study relies heavily on the concurrent diamond exploration database for the State, including both onshore and offshore data (available separately on USB). Diamond exploration is critiqued, drawing attention to successes and shortcomings in methods applied to different geographic areas. The statewide picture of indicator mineral recovery and mineral chemistry are independently evaluated to create a prospectivity model attributed to major geological subdivisions. The results of the study aim to encourage and direct future diamond exploration in Western Australia.



Further details of geological products and maps produced by the Geological Survey of Western Australia are available from:

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