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ORIGINAL PAPER

Diamond exploration and regional prospectivity of Western Australia

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Abstract

Pre-1.6 Ga rocks comprise around 45% of the onshore area of Western Australia (WA), constituting the West Australian Craton (WAC) (including the Archean Yilgarn and Pilbara Cratons) and the western part of the North Australian Craton (NAC). These areas provide the conditions suitable for diamond formation at depth, and numerous diamondiferous lamproite and kimberlite fields are known. As emplacement ages span close to 2500 Ma, there are significant opportunities for diamond-affinity rocks being present near-surface in much of the State, including amongst Phanerozoic rocks. WA'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, a comprehensive database of results of diamond exploration sampling (Geological Survey of Western Australia 2018) has been assessed. The Yilgarn and Pilbara Cratons have spinel indicators almost exclusively dominated by chromite (>90% of grains), whereas (Mg,Fe,Ti)-bearing Al-chromites account for more of the indicator spinels in the NAC, up to 50% of grains at the Northern Territory (NT) border. Increasing dominance of Al in chromites is interpreted as a sign of weathering or a shallower source than Al-depleted Mg-chromites. Garnet compositions across the State also correlate with geological subdivisions, with lherzolitic garnets showing more prospective compositions (Ca-depleted) in WAC samples compared to the NAC. WAC samples also show a much broader scatter into strongly diamond-prospective G10 and G10D compositions. Ilmenites from the NAC show Mg-enriched compositions (consistent with kimberlites), over and above those present in NT data. However, ilmenites from the WAC again show the most diamond-prospective trends. Numerous indicator mineral concentrations throughout the State have unknown sources. Due in part to the presence of diamondiferous lamproites, it is cautioned that some accepted indicator mineral criteria do not apply in parts of WA. For example Ca-depleted garnets, Mg-depleted ilmenites and Cr-depleted and Al-absent clinopyroxenes are all sometimes associated with strongly diamondiferous localities. Quantitative prospectivity analysis has also been carried out based on the extent and results of sampling, age of surface rocks relative to ages of diamond-prospective rocks, and the underlying mantle structure. Results show that locations within the NAC and with proximity to WA's diamond mines score well. However, results point to parts of the WAC being more prospective, consistent with mineral chemical data. Most notable are the Hamersley Basin, Eastern Goldfields Superterrane and the Goodin Inlier of the Yilgarn Craton. Despite prolific diamond exploration, WA is considerably underexplored and the ageing Argyle mine and recent closure of operations at Ellendale warrant a re-evaluation of diamond potential. Results of mineral chemistry and prospectivity analysis make a compelling case for renewed exploration.

Keywords Western Australia · Diamond exploration · Kimberlite · Lamproite · Indicator minerals

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Introduction

Pre-1.6 Ga rocks comprise around 45% of the onshore area of Western Australia (WA) – 696,000 km^2 of exposed, onshore, exclusively Archean rocks and 439,000 km^2 of Paleoproterozoic rocks (Fig. 1). Seismic tomography demonstrates that considerable remaining portions of the State are also underlain by thick mantle lithosphere (Kennett et al. 2013). For example, the Aries kimberlite pipe is demonstrated to have been underlain by Archaean lithospheric mantle at the time of its ca 820 Ma emplacement (Downes

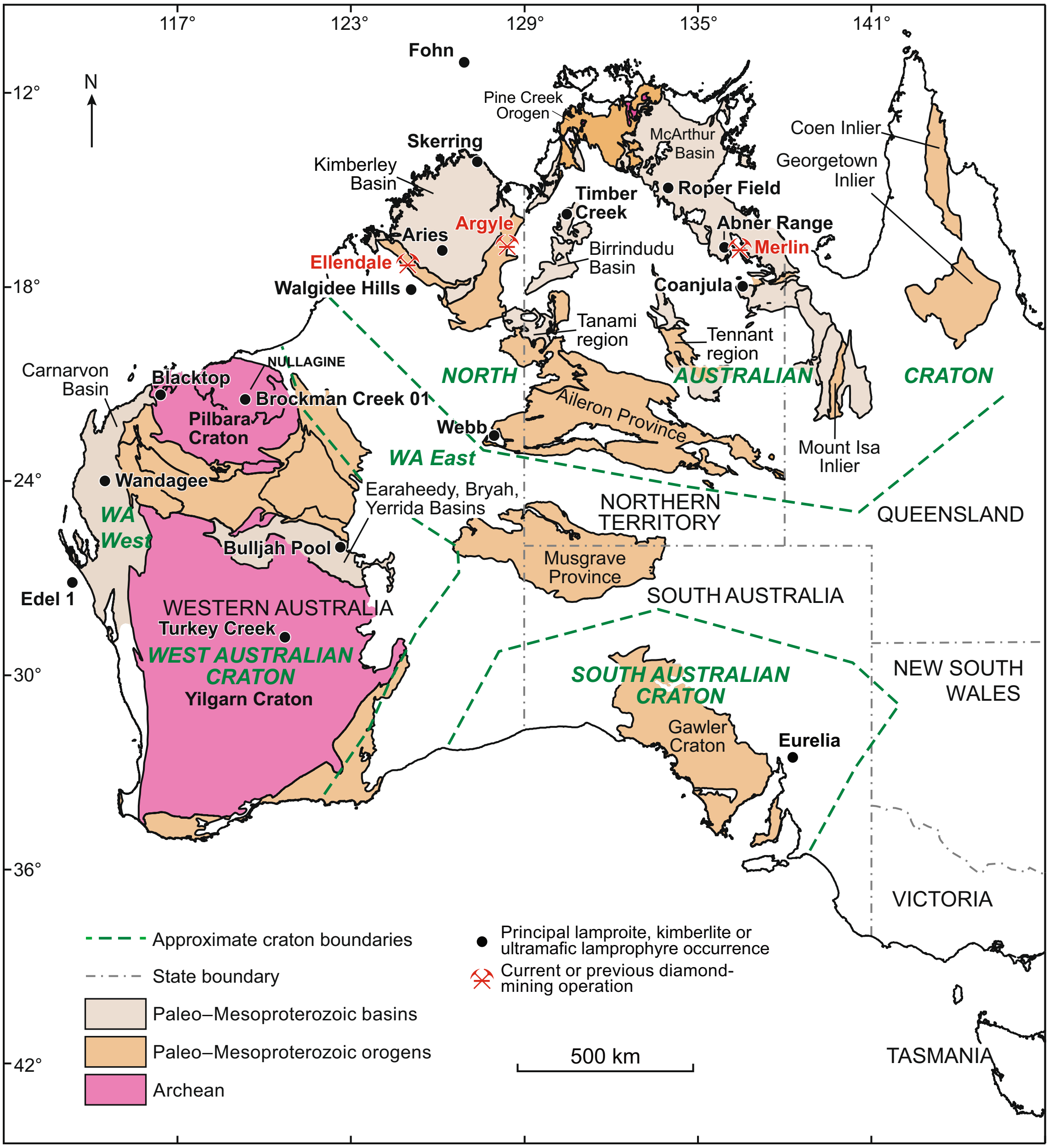


Fig. 1 Generalised map of cratonic Australia showing approximate craton boundaries and principal regions of Archean and Paleo–Mesoproterozoic rocks. Modified from Hutchison (2013). The boundaries of the North Australian Craton are adapted from Atkinson et al. (1990) and Kennett et al. (2011). Geological region boundaries follow current GeoScience Australia downloadable data, Kennett et al. (2011) and, for the NT, 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. Some of the lamproites in the vicinity of Fohn lie within the Joint Petroleum Development Area with Papua New Guinea. All occurrences are in-situ bodies with the exception of Coanjula which is a microdiamond paleoplacer

et al. 2007). The same conclusions are drawn for the Seppelt kimberlite, approximately concurrent with Aries, and the Proterozoic (1177 Ma; Pidgeon et al. 1989) Argyle lamproite, based on Re–Os systematics (Graham et al. 1999a). Combined, these old and deep-rooted regions make up the western part of the North Australian Craton (NAC) and the West Australian Craton (WAC; Yilgarn and the Pilbara Cratons). Cratons host the conditions under which diamonds form (Haggerty 1994) and numerous diamondiferous lamproite and kimberlite fields are known in WA. At its peak in 2015, Australia is estimated to have produced approximately 11% of global rough diamond production by weight, ranking it fourth in the world. These production figures are accounted for by two mines, both in WA. However, due to the closure of the Ellendale mine in 2015, 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).

The 1976 discovery, in WA, that lamproites can host diamonds, and in commercial quantities, was one of two WA discoveries which resulted in a very considerable widening of the range of rocks known to host diamonds world-wide. The second important WA contribution was the discovery that ultramafic lamprophyres can also carry diamonds (Bulljah Pool; Hamilton and Rock 1990) extending the field of potentially diamondiferous rocks beyond kimberlites and lamproites.

Emplacement of diamond-bearing rocks spans much of geological time, from the ca 1868 Ma Brockman Creek kimberlite in the Pilbara Craton (White 2000) to the ca 17 Ma Walgidee Hills lamproite, Noonkanbah field, West Kimberley (Phillips et al. 2012). Hence, even within Phanerozoic Basins overlying cratonic roots there is scope for undiscovered diamond-bearing rocks to be young enough to be found at or near-surface.

Despite successful finds, given WA's size, terrain, infrastructure and climate, many areas remain underexplored. For example, diamonds were first discovered in Western Australia in the Nullagine (Fig. 1) where they were identified during processing of the Proterozoic Beatons Creek Conglomerates for gold (Groom 1896). Diamonds continue to be discovered in this area but the sources are as yet unidentified. Numerous gaps in exploration coverage, and documentations of unexplained indicator minerals can be found. However, there exists a considerable legacy of public documents, including abundant company reports lodged with the government authorities dating back to the 1970s recording the methods and results of WA diamond exploration. These data have been recently compiled in a large dataset (Geological Survey of Western Australia 2018) drawing from ~ 4200 company reports and resulting in over 88,000 sample descriptions and over 30,000 good-quality mineral chemical analyses. Included are records of 523 in-situ occurrences of rocks with diamond potential, of which 63 have associated age determinations. The structure and methods for populating the database are described in Hutchison (2018a) and a detailed interpretation is provided by Hutchison (2018b).

In order to assess the effectiveness of prior exploration and draw attention to under-explored prospective areas, data from Geological Survey of Western Australia (2018) have been combined with literature data to model diamond prospectivity. This has been carried out using two approaches; a detailed critique of mantle mineral chemistry based on six small-scale subdivisions of the State, and a modelling based on 67 regional geological subdivisions based on quantifiable criteria and following modifications to the methodology applied to Australia's Northern Territory (NT) (Hutchison 2011 and 2013).

Methodology

State subdivisions

For the purpose of mantle mineral chemical subdivisions, the State has been divided into six geographic areas (Fig. 1). These comprise the Kimberley Basin and Paleo-Mesoproterozoic orogens constituting the exposed parts of the North Australian Craton (NAC), the Pilbara Craton (WAC Pilbara), the Yilgarn Craton (WAC Yilgarn), the remaining portions of the West Australian Craton (WAC), the rocks to the west and south of the West Australian Craton (WA West), and the remaining rocks south and east of the exposed parts of the NAC (WA East). The State has been further subdivided into 67 non-overlapping geological regions covering the whole of on-shore WA modified from Martin et al. (2016). Exclusively off-shore regions have been ignored, as have orogenic subdivisions in cases where they have been superimposed on more tightly constrained lithological regions. Each region constitutes a reasonably tight span of geological time, with a consistent geology, and the average size is suitable to incorporate statistically meaningful instances of diamond exploration data.

Regional diamond prospectivity modelling

Three quantifiable criteria have been identified as critical to diamond prospectivity. These are the extent and success of prior diamond exploration, the age range of surface rocks relative to the age of known diamondiferous and diamond-potential volcanic rocks, and the thickness and other physical characteristics of the mantle lithosphere. Each of the 67 WA regions has been assessed on the basis of these three criteria with scores assigned following the procedures described in Table 1.

Prospectivity based on sampling history

The number of onshore samples taken for the purpose of diamond indicator testing (including diamond-only) was counted for each prospectivity region with results lodged in the supplementary data appendix (Supplementary Table 1). Samples that contained diamond-indicator minerals were also counted. The scoring method (Table 1a; illustrated in Fig. 2) is based on the principle that under-sampled areas provide more opportunity for new discoveries and are therefore favoured over heavily sampled regions. However, regions which 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

Table 1 Prospectivity scoring criteria based on sampling history (a), age of exposed rocks (b) and mantle lithosphere characteristics (c)

Ranking	Description	n
(a) Sampling history scoring criteria		
1	Reconaissance-scale sampling (< 1 sample per 100 km^2) with good recovery (> 1/3rd of samples are indicator positive)	8
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 (1/20th to 1/3rd of samples are indicator-positive)	10
3	Local-scale sampling (> 1 sample per 4 km^2) with good recovery or regional with reasonable recovery	18
4	Local-scale sampling with reasonable recovery or reconaissance-scale with poor recovery (< 1/20th of samples are indicator positive)	7
5	Poor recovery from regional or local sampling density	4
6	No sampling conducted	20
(b) Regional age range scoring criteria		
1	All rocks pre-date oldest kimberlite (Turkey Creek; 2128 Ma)	10
2	All rocks pre-date oldest lamproite (Yanyare-02; 1724 Ma)	7
3	All rocks pre-date mined diamondiferous bodies (Argyle, 1177 Ma and Ellendale 9, 24 Ma)	19
4	At least some rocks are older than the youngest kimberlite (Skerring; 800 Ma) but are not all older than Argyle (1177 Ma)	19
5	All rocks are younger than the youngest kimberlite (Skerring, 800 Ma) but are also older than S.W. Kimberley lamproites (Ellendale 11; 25.2 Ma)	4
6	Some rocks are younger than the youngest of the S.W. Kimberley lamproites (Mt Gytha; 17 Ma)	8
(c) Lithosphere thickness and density scoring criteria		
1	On or near craton, edge of thickest lithosphere	16
2	On-craton, thickest lithosphere	24
3	Off-craton, thickest lithosphere	10
4	On or near craton, thinnest lithosphere	11
5	Far off-craton, medium lithosphere thickness	4
6	Off-craton, thinnest lithosphere	2

n number of regions assigned to each ranking

with low recovery success. The definitions of sample density – reconnaissance, regional and local-scale – follow McMartin and McClenaghan (2001).

Prospectivity based on geological age

In order to be exploited economically, diamondiferous bodies must be close to surface. Hence to assess the likelihood that this is the case, it is important to understand both the likely age of intrusion (derived from known ages of diamondiferous rocks elsewhere) and the ages of country rocks in the area of interest. Both criteria are known, from Geological Survey of Western Australia (2018) and Martin et al. (2016) respectively. Hence attribution of WA regions with relative prospectivity scores based on age can be achieved. The criteria used are described in Table 1b and illustrated in Fig. 3. The method compares the ages of all-diamond prospective rocks in WA to ages of rocks in particular regions. However, the full range of emplacement ages are not represented in all six large geographic areas. For example, the youngest lamproites (ca 20 Ma) are largely restricted to the Ellendale field (Fig. 1) whereas Cenozoic ages are unknown among diamond-prospective rocks in the WAC. As the number of known emplacement ages increases, future iterations of the current methodology may benefit from restricting comparison of regional rock age ranges with known emplacement ages from within a ~ 500 km buffer zone.

Prospectivity based on lithosphere characteristics

Understanding mantle structure is a critical component in regional-scale diamond exploration. The thickness of mantle lithosphere provides the strongest control on the formation of diamonds (Haggerty 1994). However, its morphology and overlying crustal features imposes the greatest influence on diamond emplacement at surface (Helmstaedt and Gurney 1995; White et al. 1995; Haggerty 1999). Australia's known diamond deposits often occur at step-changes in lithosphere thickness, due to the concurrence of conditions appropriate to diamond stability and volcanism (O'Neill et al. 2005). Once mantle weaknesses or strong contrasts in mantle architecture arise, they can give rise to melt generation and volcanism over extended periods of time. Examples include the considerable range of ages – and compositions – of volcanism associated

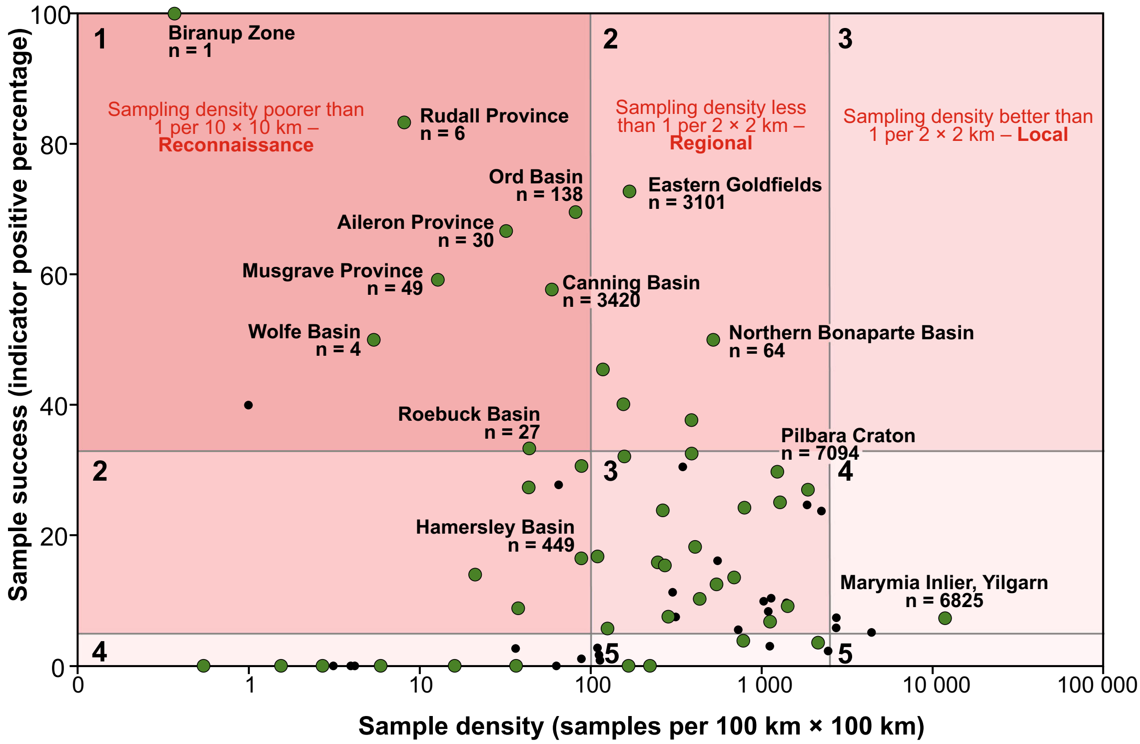


Fig. 2 Sampling success versus sampling density for diamond exploration samples from WA geological regions. Calculations are based on data derived from Geological Survey of Western Australia (2018). Selected regions are labelled. Sampling success is measured as the percentage of samples collected for 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 km^2 area within each region. Bold black numbers represent prospectivity scores assigned to regions plotting within shaded areas of the chart and following the methodology in Table 1. A score of 1 is assigned to the most prospective regions. Completely unsampled areas, not represented in the figure, score lowest (6) based on the assumption that they have been neglected for sound geological reasons. NT data (black dots) are provided for comparison (Hutchison 2013) showing that NT diamond exploration has covered a similar sampling density range but with fewer high success regions

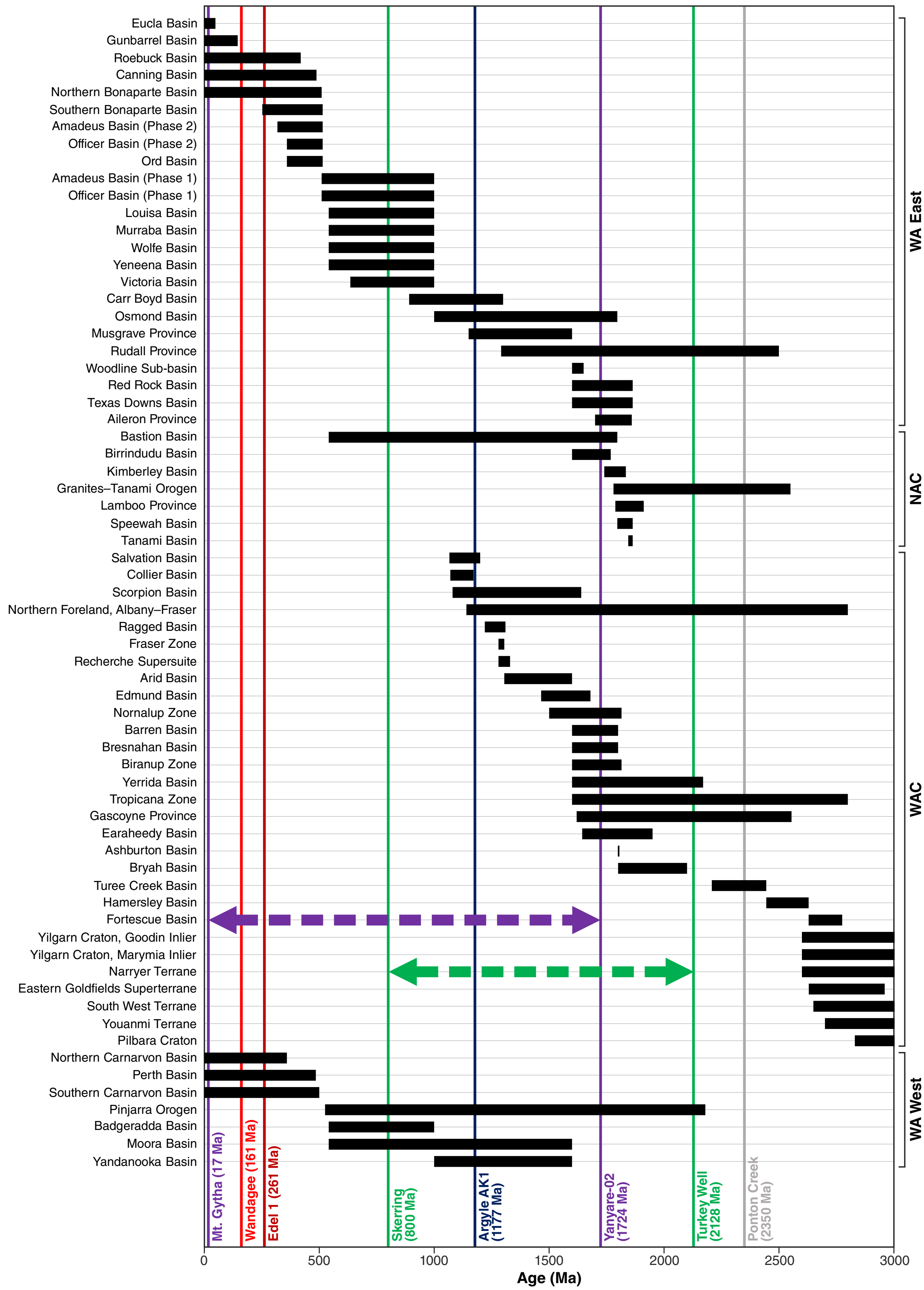
with the peripheries of the Yilgarn Craton (Fig. 4) illustrated by ca 1324 Ma kimberlites at Jewill (Phillips et al. 1997), ca 849 Ma melilitite volcanics at Norseman (Robey et al. 1989) and ca 305 Ma melnoites at Bulljah Pool (Hamilton and Rock 1990). Yet longer-lived diamond-hosting magmatism is apparent around the NAC, with intrusions spanning from ca 1177 Ma at Argyle (Pidgeon et al. 1989) to ca 17 Ma at Mt. Gytha, Ellendale (Jaques et al. 1984a).

Australia benefits from an extensive array of seismological recording stations from which shear wave velocity profiles are measured (Fishwick et al. 2006) and current mantle thickness (Fig. 5) is derived (lithosphere/asthenosphere boundary; Kennett et al. 2013). The shear wave velocity profile at 200 km depth (Fishwick et al. 2006) and the topography of the base of the mantle lithosphere have been used to subdivide the State following a methodology (Table 1c) favouring thick lithospheric mantle and in particular, the edges of thick blocks of lithospheric mantle (Fig. 5). In cases where a region lies within more than one lithosphere polygon, the average score by area has been used.

For each geological region the scores (from 1 to 6) for each of the three criteria; sampling history, age and underlying mantle lithosphere architecture, were added (Table 2). The regions were ordered (ranked; 1st, 2nd equal, 4th equal etc.) resulting in thirteen groups of equally-ranked regions which were assigned a category (from one – most prospective, to thirteen – least prospective).

Mantle mineral modelling

Mineral chemical characteristics are the single most important criteria, where available, for identifying diamond prospectivity of the deep Earth below any given near-surface location. However, in the WA diamond exploration database (Geological Survey of Western Australia 2018) only 25% of samples reported to have visually-identified indicator minerals (Fig. 4) have corresponding mineral chemistry (3411 of 13,659 sub-samples). Consequently, insufficient data exist to allow mineral chemistry to be a statistically robust criteria at the resolution of 67-regions for the study described previously. Notwithstanding this shortcoming, abundant mineral chemical data do exist for locations within WA and inspection of this data provides useful insights into where mineral chemical techniques yielded exploration dividends and where



shortcomings in approaches useful elsewhere may exist. The mineral chemical approach has the advantage that it can be queried in a more sophisticated and varied manner than visual indicator mineral identification and the window provided into the lithosphere relates to the time of emplacement rather than the present-day picture provided by geophysics. Therefore, the two approaches to understanding diamond prospectivity applied herein complement each other.

◀ **Fig. 3** Ranges of ages of rocks present in geological regions of WA in the context of diamond-prospective rocks. Regions are arranged according to craton or off-craton association and youngest, followed by oldest rocks present. Known kimberlite ages (Turkey Well, Jourdan et al. 2012 to Skerring, Pidgeon et al. 1989) lie between the green bars, and lamproites (Yanyare-02, Matchan et al. 2009 to Mt. Gytha, Jaques et al. 1984a) lie between the purple bars. The oldest potentially diamond-associated volcanic rock, at Ponton Creek (Graham et al. 2004) is shown in grey. The most diamondiferous body known, the Argyle AK1 lamproite (Pidgeon et al. 1989) is represented by a dark blue line. Age data for the ultramafic lamprophyre at Edel 1, brown, and Wandagee M142, red, derive from Killar (1972) and Pidgeon et al. (1989) respectively. The following WAC regions contain rocks extending to ages greater than the 3000 Ma displayed on the figure: Goodin and Marymia Inliers of the Yilgarn Craton (3131 Ma), Narryer Terrane (4000 Ma), South West Terrane (3100 Ma), Youanmi Terrane (3131 Ma) and the Pilbara Craton (3800 Ma)

Results

Regional prospectivity modelling

The results for sampling success (Table 2) are illustrated in Fig. 2. The Biranup Zone distinguishes itself by having a 100% sampling success rate. This result derives from the fact that the region only reports one sample from which 100 picroilmenites were recovered. The small number of samples recovered from some regions, particularly those with high indicator-positive proportions (Aileron Province, Biranup Zone, Musgrave Province, Roebuck Basin, Rudall Province and Wolfe Basin) should be treated with caution. However, a very small number of indicator minerals can be extremely significant (as evidenced by the discovery of Argyle based on very few indicators; Muggeridge 1995) and the two other modelling variables serve to buffer any shortcomings of sampling data for regions with low sample numbers. The most statistically significant top sampling score (value of one) derives from the Canning Basin (Fig. 4) from which 3420 samples were taken and with a success rate of 58%.

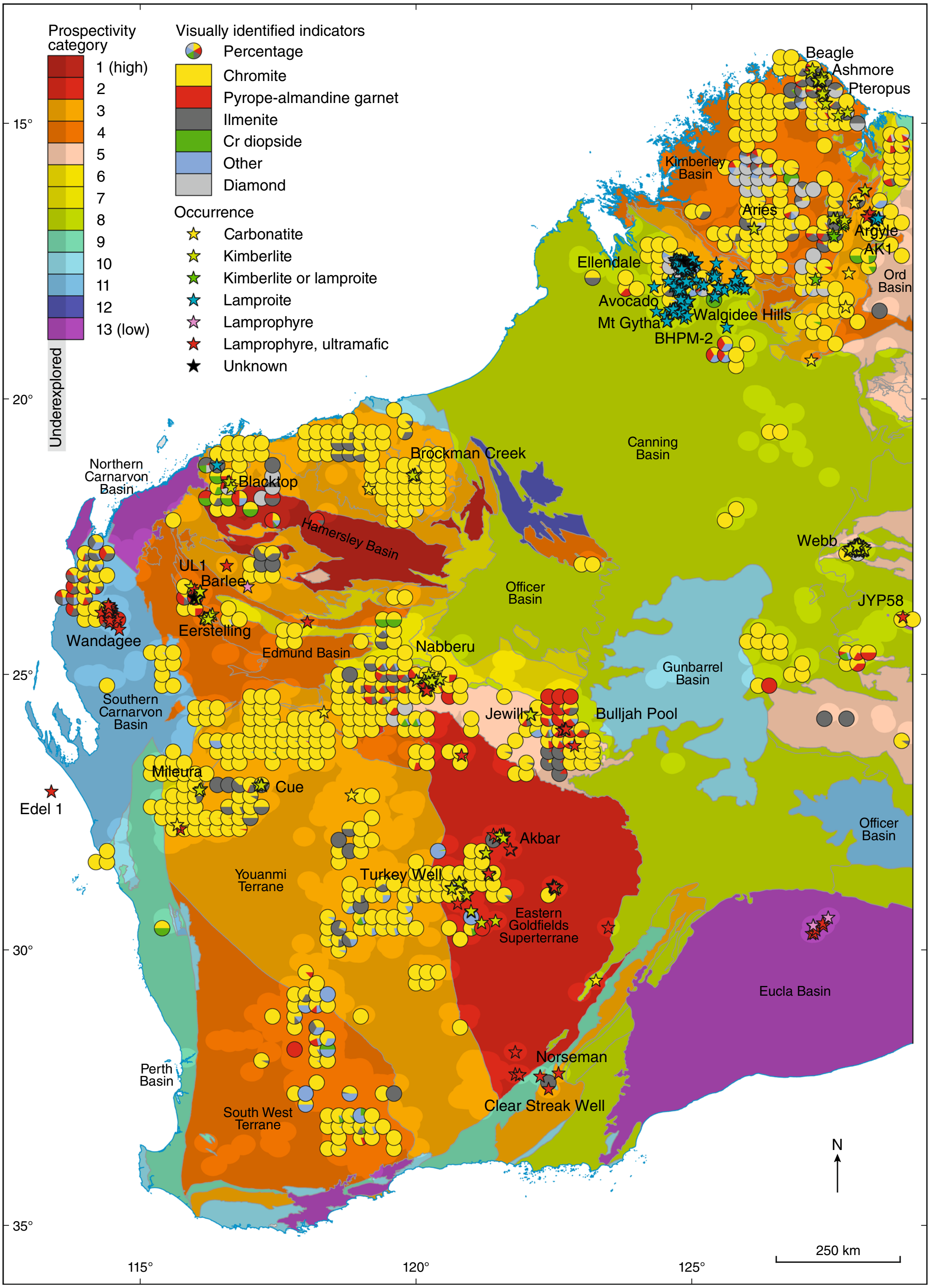
For age-related prospectivity (Table 2), the Yilgarn Craton scored particularly well with all six Yilgarn Craton regions receiving a top score. The Pilbara Craton also received a score of one in addition to the Fortescue, Hamersley and Turee Creek Basins elsewhere in the WAC. No NAC regions received top scores for prospectivity based on age.

Based on lithosphere thickness (Table 2), regions in eastern WA received numerous top scores (Osmond, Red Rock, Texas Downs and Victoria Basins) as a consequence of the NAC and its margins extending into the NT (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).

Combined, no region achieved a perfect score of three (Table 2). However, the single most prospective region, the Hamersley Basin of the WAC scored four. Equal second were 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 and Fortescue Basins and the Narryer Terrane, the Lamboo Province of the NAC, the Pilbara Craton, and Marymia Inlier and the Youanmi Terrane of the Yilgarn Craton. Poorest scoring areas lie the farthest from craton margins and with the youngest rocks, such as the Eucla Basin. The 13 discrete prospectivity categories (Table 2) have been used to colour-code the prospectivity map of the State (Fig. 4). Inspection of the map shows that as might be expected, most prospective areas are associated with the cratons. However, perhaps surprisingly, the established diamond producing areas of the NAC lose out to the WAC and its sub-cratons. Parts of these areas are under-explored, and yet with extremely attractive indicator mineral recoveries and mantle architecture. Furthermore, as will be discussed below, mineral chemical results lend further credence to the concept that future WA diamond exploration would benefit from particular focus being applied towards the WAC.

Indicator minerals

The overwhelming majority (~ 90%) of surface and drill-hole exploration samples for diamond in WA (Geological Survey of Western Australia 2018) have been taken for separation of diamonds or other minerals indicating diamond potential. Sampled material has more or less been evenly split between alluvial and loam samples with a sample weight mode of 45 kg. The most common range of sizes inspected for minerals has been 0.3 to 1.5 mm. Median heavy mineral recovery is 0.03% by weight (equivalent to 8 g from a 25 kg sample) although alluvial samples typically yield higher proportions. Non-diamond indicators were identified by visual inspection in 28% of samples and 80% of good-quality mineral compositional analyses are classified as genuine indicators. Diamonds occurred in 3.5% of indicator mineral samples. The large majority of non-diamond indicators are spinels, and typically double the number of spinels are found with sizes under 0.4 mm. Spinels are relatively durable in the harsh Western Australian weathering environment compared to other typically sought indicator minerals (aside from diamond). Garnet xenolith samples from Argyle studied by Jaques et al. (1990) showed that garnet had in all cases been replaced by kelyphite-like symplectite growth of Al-rich pyroxenes, Al-spinel and secondary silicates. In this case, garnet was already significantly compromised before release into the surface sediment environment. In the alluvial diamond deposits associated with Argyle, picroilmenite and Cr-diopside are found to be



absent (Deakin et al. 1989). However, indicator minerals other than spinel and diamond do occasionally survive (Fig. 4), and diopside, garnet, ilmenite, monticellite, orthopyroxene, olivine, perovskite, phlogopite, pseudobrookite and tourmaline with indicator chemistries have all been recovered from exploration samples. Mineral chemical data for clinopyroxenes, garnets, ilmenites and spinels have been scrutinised and results are discussed below.

◀ **Fig. 4** Prospectivity map of Western Australia. Geological regions are ranked for prospectivity following the 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. In-situ bodies with diamond potential (tested or otherwise) are shown by stars colour-coded according to the key with representative locations labelled. Sample site areas are indicated by shading where unshaded areas lie within 20 km from an exploration sample location. Pie chart symbols indicate sites of recovery of visually-determined indicator minerals with colours following the key. 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. Diamond and chromite distinguish themselves as the most robust and hence commonly-recovered indicator minerals. Much of WA is under-explored with prospective areas evident in the NAC and particularly the WAC

Clinopyroxene chemistry

WA clinopyroxene chemistries vary considerably. However, significant overlap amongst different geographic areas is apparent (Fig. 6).

The majority of WAC clinopyroxenes fall within the relatively Al-poor garnet peridotite field (after Ramsay and Tompkins 1994). Al-depletion is particularly evident amongst 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. The Yilgarn Craton clinopyroxenes also show a separate Al-enriched field consistent with derivation from spinel peridotite which forms at shallower depths than the diamond stability field.

WA East samples show an overlap into lower Cr compositions (under 1.5 wt% Cr_2O_3) similar to samples immediately across the border in the NT (Fig. 6). They also coincide with Cr-diopside compositions to the eastern extent of the NAC (also in the NT). An incremental decrease in Al-content, reflecting an association with garnet instead of spinel, is evident from samples from Ellendale 7 to Ellendale 4 and Bow Hill – Argyle has extremely Al-depleted clinopyroxenes (Jaques et al. 1990). Elsewhere in the NAC, samples from the Skerring kimberlite are relatively Cr-poor, overlapping with regional samples of eclogitic composition. Skerring is unusual within NAC kimberlites because it contains a discrete nodule (megacryst) suite, and samples are sub-calcic. These observations indicate high equilibrium temperatures (over 1400 °C) and depths relating to magmatic precursors to the ultimate kimberlite host (Nixon et al. 1987). None of the clinopyroxenes from Skerring reported by Ramsay (1992) which are classed as indicators following Ramsay and Tompkins (1994) would be classified as Cr-diopsides based on the Cr_2O_3 composition (they have <1 wt%). Some Argyle clinopyroxenes would also fail the Cr_2O_3 threshold. Such grains may also fail the test of being sufficiently vivid green in colour to be considered for chemical classification in the first place. Hence false-negatives among clinopyroxenes in prior WA exploration samples may be expected.

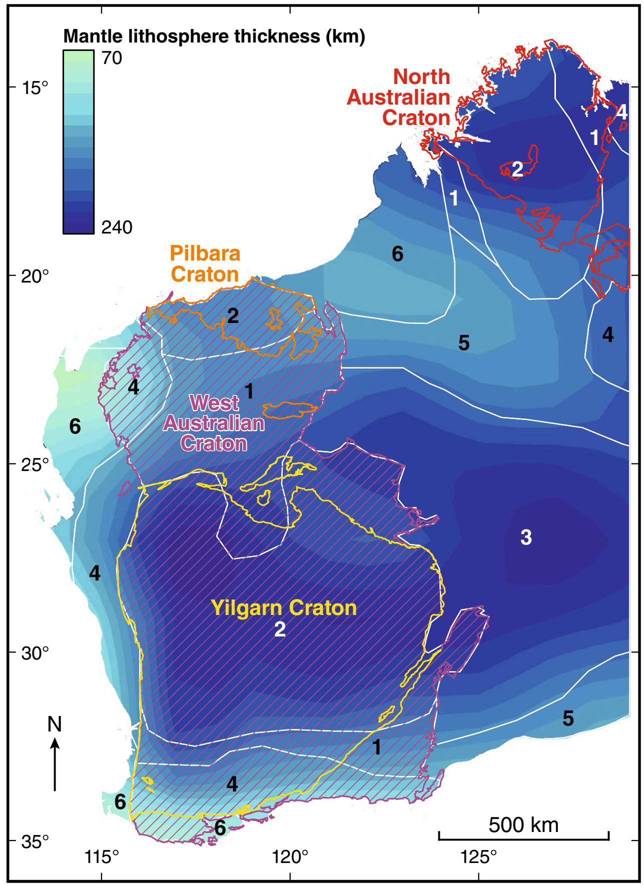


Fig. 5 Map of lithosphere thickness. Boundaries of WA cratonic regions at surface, following Martin et al. (2016), are indicated as described in the key. White-bordered polygons describe areas of differing diamond prospectivity based on lithosphere characteristics with 1 being most favourable and 6 being the least. Blue colouration denotes mantle lithosphere thickness – depth to the lithosphere/asthenosphere boundary –adapted from Kennett et al. (2013)

Garnet chemistry

Pyrope–almandine garnets have been classified following the methodology of Grütter et al. (2004). The broad geographical subdivisions of Western Australia reveal different distributions of garnet chemistry. The lherzolite trends are increasingly Ca-depleted from the NAC in WA (including Ellendale, Argyle and Bow River), through the WAC, to the Merlin field (NT) samples (Fig. 7). However, WAC samples also show a much higher proportion of G10 garnets with an intermediate-Ca lherzolite trend. Following the world-wide trend favouring harzburgitic garnet-bearing host rocks as more indicative of diamonds than those dominated by lherzolite, the WAC would be more prospective than the NAC. However, throughout the Kimberley region and the surrounds of the NAC, no clear

Table 2 Prospectivity scores and rankings of WA geological regions

Region	Sampling Score	Age Score	Lith [a] Score	Total Score	Ranking	Category
Aileron Province [b]	1	3	4	8	23	5
Amadeus Basin (Phase 1) [b]	3	4	4	11	38	8
Amadeus Basin (Phase 2) [b]	6	5	5	16	65	13
Arid Basin [c]	6	3	2	11	38	8
Ashburton Basin [c]	2	2	2	6	4	3
Badgeradda Basin [d]	3	4	3	10	33	7
Barren Basin [c]	6	3	4	13	53	10
Bastion Basin [e]	6	4	1	11	38	8
Biranup Zone [c]	1	3	2	6	4	3
Birrindudu Basin [e]	4	3	1	8	23	5
Bresnahan Basin [c]	6	3	1	10	33	7
Bryah Basin c	3	2	1	6	4	3
Canning Basin [b]	1	6	4	11	38	8
Carr Boyd Basin [b]	3	4	4	11	38	8
Collier Basin [c]	5	4	1	10	33	7
Earaheedy Basin [c]	3	3	2	8	23	5
Eastern Goldfields Superterrane [f]	2	1	2	5	2	2
Edmund Basin [c]	2	3	2	7	13	4
Eucla Basin [b]	6	6	4	16	65	13
Fortescue Basin [c]	3	1	2	6	4	3
Fraser Zone [c]	6	3	2	11	38	8
Gascoyne Province [c]	2	3	2	7	13	4
Granites–Tanami Orogen [e]	5	2	1	8	23	5
Gunbarrel Basin [b]	4	6	3	13	53	10
Hamersley Basin [c]	2	1	1	4	1	1
Kimberley Basin [e]	3	2	2	7	13	4
Lamboo Province [e]	2	2	2	6	4	3
Louisa Basin [b]	3	4	2	9	31	6
Moora Basin [d]	6	4	3	13	53	10
Murraba Basin [b]	4	4	3	11	38	8
Musgrave Province [b]	1	4	3	8	23	5
Narryer Terrane [f]	3	1	2	6	4	3
Nornalup Zone [c]	6	3	4	13	53	10
Northern Bonaparte Basin [b]	2	6	4	12	51	9
Northern Carnarvon Basin [d]	4	6	6	16	65	13
Northern Foreland, Albany–Fraser Orogen [c]	6	4	2	12	51	9
Officer Basin (Phase 1) [b]	4	4	3	11	38	8
Officer Basin (Phase 2) [b]	6	5	3	14	61	11
Ord Basin [b]	1	5	2	8	23	5
Osmond Basin [b]	6	4	1	11	38	8
Perth Basin d	2	6	4	12	51	9
Pilbara Craton [g]	3	1	2	6	4	3
Pinjarra Orogen [d]	4	4	5	13	53	10
Ragged Basin [c]	6	3	4	13	53	10
Recherche Supersuite [c]	6	3	2	11	38	8
Red Rock Basin [b]	3	3	1	7	13	4
Roebuck Basin [b]	1	6	6	13	53	10
Rudall Province [b]	1	3	3	7	13	4
Salvation Basin [c]	3	4	2	9	31	6

Table 2 (continued)

Region	Sampling Score	Age Score	Lith [a] Score	Total Score	Ranking	Category
Scorpion Basin [c]	5	4	2	11	38	8
South West Terrane [f]	3	1	3	7	13	4
Southern Bonaparte Basin [b]	2	5	3	10	33	7
Southern Carnarvon Basin [d]	3	6	5	14	61	11
Speewah Basin [e]	3	2	2	7	13	4
Tanami Basin [e]	5	2	1	8	23	5
Texas Downs Basin [b]	6	3	1	10	33	7
Tropicana Zone [c]	6	3	2	11	38	8
Turee Creek Basin [c]	6	1	1	8	23	5
Victoria Basin [b]	2	4	1	7	13	4
Wolfe Basin [b]	1	4	2	7	13	4
Woodline Sub-basin [b]	6	3	2	11	38	8
Yandanooka Basin [d]	6	4	4	14	61	11
Yeneena Basin [b]	6	4	5	15	64	12
Yerrida Basin [c]	3	3	1	7	13	4
Yilgarn Craton, Goodin Inlier [f]	3	1	1	5	2	2
Yilgarn Craton, Marymia Inlier [f]	4	1	1	6	4	3
Youanmi Terrane [f]	3	1	2	6	4	3

Total Score is the sum of Sampling, Age and Lithosphere Scores. Regions are then ranked in order of Total Score. Groups of regions with equal rank are subsequently assigned a Category with Category 1 being the most prospective region and Category 13 being the least prospective

[a] Lithosphere Score

[b] WA East

[c] West Australian Craton (WAC)

[d] WA West

[e] North Australian Craton (NAC)

[f] Yilgarn Craton (WAC Yilgarn)

[g] Pilbara Craton (WAC Pilbara)

association between garnet composition and diamond content of host rocks can be discerned (Lucas et al. 1989). Despite being dominantly lherzolitic, the NAC produces commercial quantities of diamonds. Elsewhere, Victor (Superior Craton, Canada) for example, is known as a lherzolitic diamond mine (Januszczak et al. 2013). It is important to note that lherzolitic indicators should not be ignored by diamond explorers, a conclusion also drawn by Jaques et al. (1990).

Ilmenite chemistry

Ilmenite mineral chemistry has been classified according to the criteria of Wyatt et al. (2004). As for garnets, ilmenites from different geographical locations reveal different mineral chemical trends (Fig. 8).

The NAC regional samples extend the compositional trend of samples from across the border to the east within NT (Hutchison 2013; identified by the open dashed field) to considerably more Mg- and Ti-rich compositions and well into the kimberlite field. A much higher proportion of WA ilmenites overlap with kimberlitic ilmenite chemistry than ilmenites from the NT (i.e. ~50% of grains compared to ~5%). The same trends are mirrored in site-specific samples. Kimberlite-derived samples (Skerring; Ramsay 1992) fall more clearly within the kimberlite compositional field than lamproite samples (Ellendale 4 and Argyle; Ramsay 1992). Mn is known to replace Mg in ilmenites, either during melt evolution or due to later metasomatism (Mitchell 1986). Mn contents of WA ilmenites can be quite high, with 38% of regional grains having over 1 wt% MnO. However, of the grains which fall outside indicator fields (Fig. 8), very few (4% of grains) would be re-classified as kimberlitic when Mn contents are re-assigned to Mg. There is one locality which is an exception and that is the Argyle lamproite. Following the Wyatt et al. (2004) methodology, Argyle ilmenites would not be classed as having indicator mineral compositions at all (being very Mg-poor), nor would they be classed as picroilmenites. However, with up to 9.8 wt% MnO (Ramsay 1992) reversing Mn content to Mg places most Argyle ilmenites in Wyatt et al.'s (2004) indicator fields. Hence consideration of MnO content is important in assessing the indicator potential of NAC ilmenites.

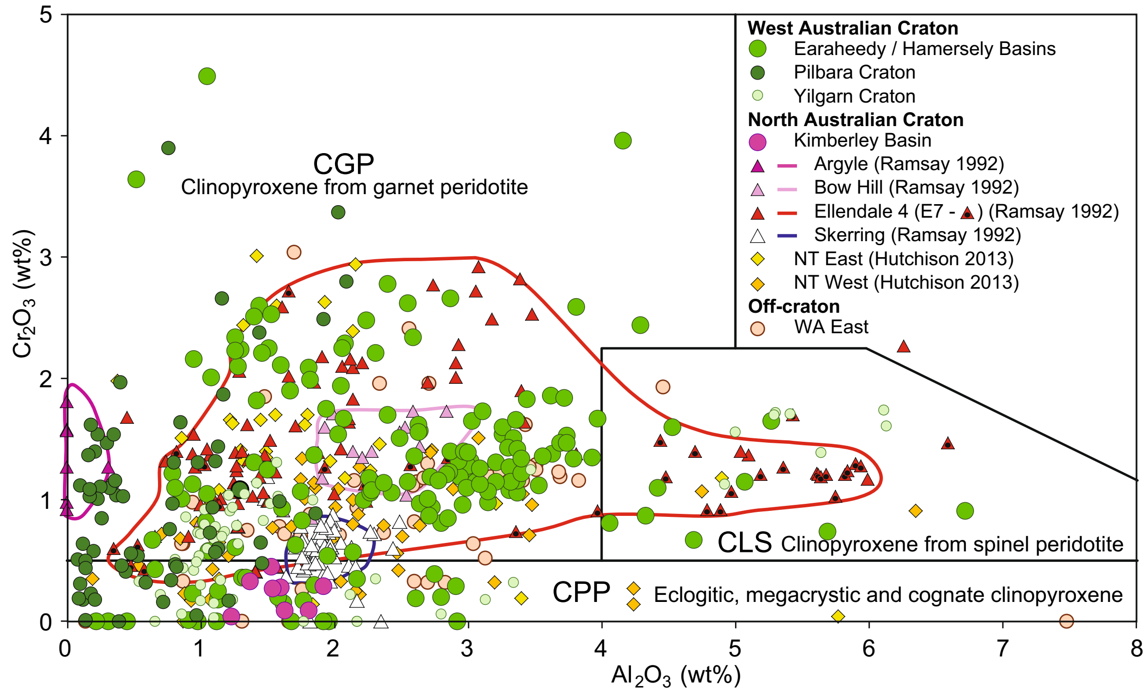


Fig. 6 Chemical compositions of clinopyroxenes in terms of Cr_2O_3 and Al_2O_3. Individual WA data points are from Geological Survey of Western Australia (2018) and are augmented by locality-specific data from Ramsay (1992) which are emphasised by unfilled polygons. Ellendale 7 (E7) samples are discriminated from Ellendale 4 samples by the addition of a black dot within the red triangle symbol. The extension of the NAC east of WA is represented by NT data (Hutchison 2013)

Ilmenites from the WAC show similar compositional variations for indicator composition grains as WA samples from the NAC (Fig. 8). 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 WA samples. Incrementally, Hamersley Basin, Marymia Inlier and South West Terrane ilmenites, followed by off-craton examples to

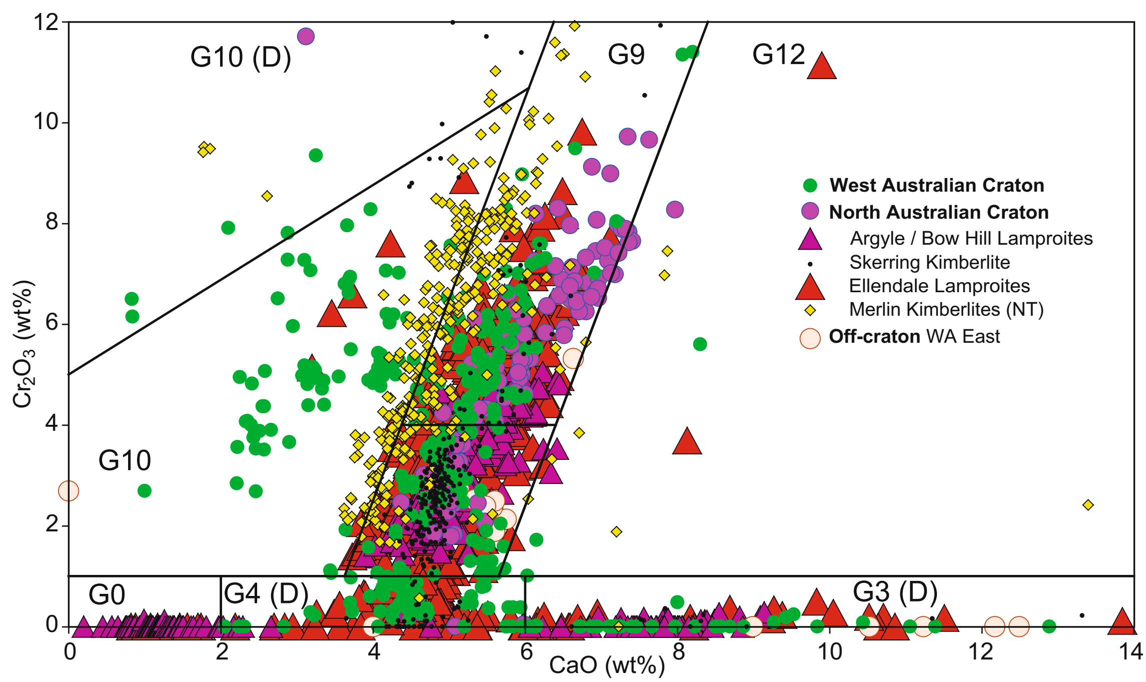


Fig. 7 Chemical compositions of pyrope–almandine–grossular garnets in terms of CaO and Cr_2O_3. Point data from all WA and NT samples with Argyle, Bow Hill and Skerring data from Ramsay (1992) and Merlin (NT) data from Reddicliffe (1999)

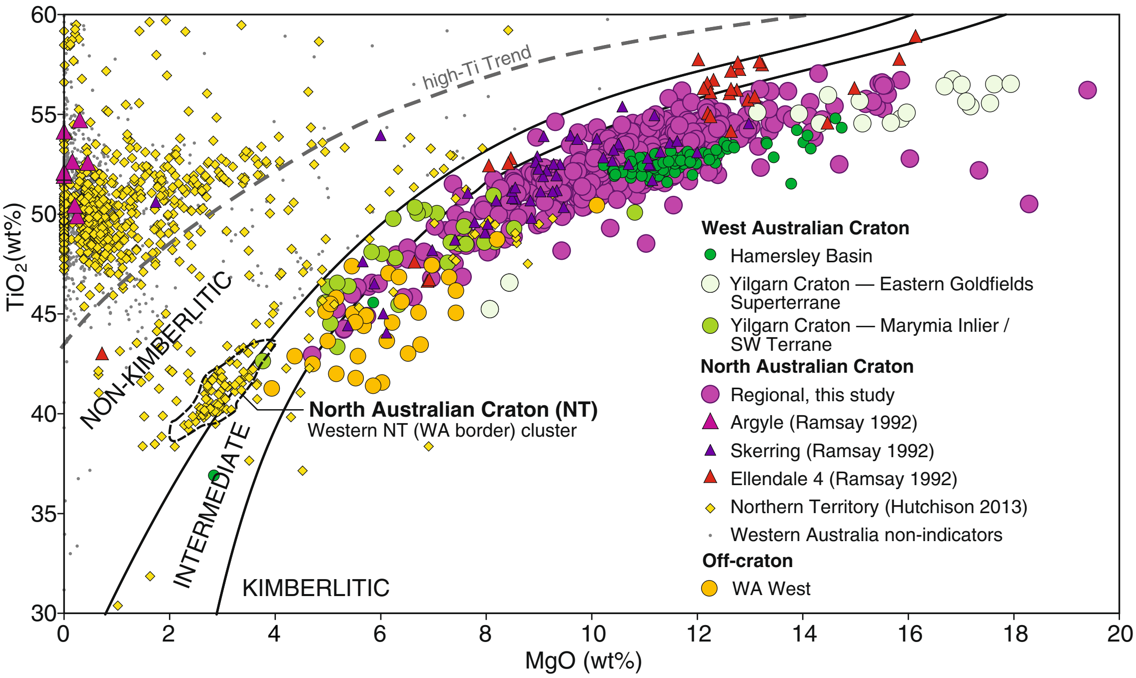


Fig. 8 Chemical compositions of ilmenites in terms of TiO_2 and MgO. Data points for WA derive from Geological Survey of Western Australia (2018) and locality-specific compositions from the NAC (Ramsay 1992). NT compositions (Hutchison 2013) are shown for comparison with a cluster of NT–WA border compositions circled

the west are increasingly Mg-depleted. Furthermore, even past the western flanks of the WAC in the Southern Carnarvon Basin, ilmenites are more Mg-rich and hence kimberlite-prospective compared to on-craton samples from the NAC in the NT (Hutchison 2013).

Spinel chemistry

Spinel compositions have been classified following a method adapted by Taylor WR (written comm. Wayne Taylor, Perth) from Ramsay (1992) and described in Hutchison (2018a). Mg, Al-spinel ± Ti, Cr and Fe, gahnite, and all chromites aside from end-member Al-chromite (Al-chromite with <1 wt% TiO_2 or Mg/(Mg + Fe) cations <0.4) are classed as indicators and other compositions are excluded. The large majority of visually identified indicators subsequently measured for mineral chemistry (Geological Survey of Western Australia 2018) are chromites. As for other minerals, chemical variations between regions are evident.

Three areas have spinel indicators almost exclusively dominated by chromite (over 90% of grains). These are the Yilgarn and Pilbara Cratons and west WA (where some chromites derive from near the Wandagee ultramafic lamprophyres and others do not). In the WAC outside the Yilgarn and Pilbara Craton, there is still a high dominance of chromite (88%), the shortfall being made up mostly by (Mg,Fe,Ti)-bearing Al-chromite indicators. Al-chromites with indicator chemistry are most prevalent in the NAC and, in particular in WA East (bordering the NT), where similar Al-chromite indicators constitute almost 50% of the indicator spinels.

Further sub-division of indicator spinels following Grütter and Apter (1998) shows that the numbers of chromite grains with diamond inclusion chemistry are fairly evenly distributed across the cratonic regions (110 from the NAC, 77 from the Pilbara Craton, 59 from the Yilgarn Craton and 62 from elsewhere in the WAC), the remainder (37) being mostly from the Walgidee Hills lamproite (Fig. 1). Chromites with inclusion in diamond chemistry are particularly represented compared to more common garnet peridotite association chromites amongst samples from the NAC, followed by the Pilbara Craton and other WAC locations.

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 diamond-and non-diamond prospective sources as well as for other indicator minerals. Examples for WA spinels are provided in Hutchison (2018b). 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 NT (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 WA.

Discussion

Quantitative prospectivity modelling based on subdivision of the State into 67 regions, and mineral chemical scrutiny at a smaller scale, both draw attention to parts of the NAC and WAC and their extensions under cover as diamond prospective. Subtle differences between neighbouring regions and variations in mineral chemistry both regionally, and between and within known diamondiferous bodies, reflect complex geological histories and ranges of sampled depth, both to the detriment and benefit of diamond prospectivity. These provide markers which diamond explorers would benefit from being aware of in interpreting future exploration results.

The North Australian Craton

The diamondiferous character of the lamproites of WA, which are all associated with the NAC, separate them from many non diamond-bearing lamproite provinces elsewhere (Nixon et al. 1984). This characteristic is evidenced by bulk rock chemistry which show more similarities with kimberlites than non-diamondiferous lamproites from other locations (Nixon et al. 1984). On this basis, WA lamproites are postulated to have derived from unusually deep and it is a consequence of this that they have had the opportunity to incorporate diamonds amongst their mantle xenocrysts.

Variations in depth of origin

The increasing Al-content of clinopyroxenes from Argyle, to Bow Hill, Ellendale 4, and Ellendale 7, and in regional samples between the NAC and WA East (Fig. 6), is interpreted to be due to a general decrease in sampling depth moving west and south through the NAC of WA. A detailed study from individual pipes supports this trend and also indicates changes in mantle geotherms. Garnet–clinopyroxene geothermometry of Argyle samples supports equilibrium conditions at 1050–1300 °C and 4.9–5.9 GPa, equivalent to 160–190 km in depth on a 41.5 mWm^{-2} geotherm (Luguet et al. 2009). Furthermore, some diamonds from Argyle are calculated to have formed as deep as 280 km (9.3 GPa, 1500 °C; Liu et al. 1990) – Taylor et al. (1990) favour a relatively hot equilibration temperature (~1255 °C) for Argyle diamond formation. For Argyle, Griffin et al. (1988) also measured a temperature range of 400 °C over which Argyle diamonds grew, attributing this to either spatial or temporal variations. A slightly cooler geotherm (40 mWm^{-2}) is calculated from the considerably younger Neoproterozoic kimberlites at Seppelt and Pteropus using Ni and Cr in garnet (Wyatt et al. 1999). Relatively cool temperatures (~ 1066 °C for Ellendale 4) are also indicated at the ca 20 Ma Ellendale field from nitrogen aggregation measurements of diamonds (Taylor et al. 1990). Geothermobarometry based on Cr and Ni in pyropes from the Aries kimberlite pipe in the Kimberley Basin place the equilibrium conditions of mantle material at 885–1025 °C, ~4–5 GPa along a cooler still 35–40 mWm^{-2} geotherm (Downes et al. 2007). In these cases, mantle temperature may be a function of diamond formation processes and/or age of volcanism. In any case, mineral chemistry data indicate cooler temperatures in southern and central NAC and greater depth in eastern NAC – both desirable characteristics for diamond formation and both borne out by diamond recovery in commercial or near-commercial quantities from each location. In other words, diamonds are evident in the Ellendale field, North Kimberley and Aries fields, compared to Argyle, for different reasons.

Mantle lithosphere thickness is important but it should also be borne in mind that even in close proximity, different pipes can have considerably different diamond concentrations because their melts derive from different depth, irrespective of local lithosphere thickness. For example, a large range in sampling depth between Seppelt 01 and Pteropus 02 only 20 km apart in the North Kimberley is reflected in geothermobarometry from mantle mineral chemistry and variations in diamond grades between the two bodies (Wyatt et al. 1999). Given enough samples, inspection of mineral chemistry on a local-scale should be able to discriminate such bodies using diamond prospecting methods akin to those of Grütter and Tuer (2009).

Variations in mantle bulk chemistry

Considerable variation in mineral chemistry regionally (such as evidenced by parallel lherzolitic trends in garnets; Fig. 7), and between and within NAC pipes also reflects complexity in mantle lithosphere compositions. A complex mantle history, including an enrichment event prior to magmatism is proposed for the Ellendale field based on Sr isotopic measurements (Jaques et al. 1984b). Initial Sr ratios are unusually high and variability within pipes (Allsop et al. 1985) suggests that different magma pulses derived from a mantle source which was heterogeneous on a local scale. Jaques et al. (1984a) interpret the Ellendale field to have derived from partial melting of phlogopite-rich, metasomatised, garnet and diopside-poor, lherzolite and harzburgite, under CO_2-poor conditions. The paucity of ilmenite and garnet indicator minerals is interpreted to evidence the depleted (garnet and clinopyroxene-poor) mantle chemistry, which at the same time had experienced a long-term large-ion lithophile element (LILE)-enriched component. Ellendale samples demonstrate a large range in spinel chemistry with early Ti–Al–Mg chromite, through Ti–Mg chromite to Ti–chromite, also interpreted to be metasomatic in origin (Jaques 2016).

Edwards et al. (1992) note that Aries also possesses a complicated range of textural, compositional and morphological variations in spinels. They interpret these to be due to a combination of factors relating to weathering, and re-equilibration during ascent and emplacement. However, they also attribute some variation to a complex interplay of magmatic reservoirs consistent with the observation that the Aries pipes are multiply intruded. Similarly, Reddicliffe et al. (2003) propose that Ti-enrichment on Skerring chromites is a consequence of mantle metasomatism. Skerring also distinguishes itself by revealing an eclogitic component in low-Cr clinopyroxenes.

Jaques et al. (1990) report extremely Cr-rich chromite from altered spinel peridotite from Argyle. On the other hand, Al-rich spinel has also been observed to derive from weathering of garnet at Argyle (Jaques et al. 1990) contributing to the range of spinel compositions in surface-derived exploration samples. Based on significant potassium in Argyle peridotitic diopsides, a metasomatic enrichment of the subcontinental lithospheric mantle is evidenced (Jaques et al. 1990). The complexity of the mantle lithosphere below Argyle is compounded by the fact that the abundant diamonds are interpreted to be derived from eclogitic material accreted to the craton root in the Proterozoic (Luguet et al. 2009).

The West Australian Craton

Similar variations to the NAC in both depth of origin and mantle composition are concluded from WAC in-situ bodies. By inference, these explain variations in mineral chemistry of regional exploration samples, for example the variations in the chemistry of garnets, and clinopyroxenes (evidencing eclogite, spinel and garnet lherzolite). Using whole-rock Sm–Nd and Re–Os systematics, Graham et al. (1999b) concluded that the kimberlites and melnoites north of the Yilgarn Craton within the West Australian Craton's Earaheedy Basin derive from a single mantle event. Although with different ages, isotope systematics indicate episodes of LREE enrichment associated with orogenesis, back-arc basin development and rift related magmatism to the west. This enrichment created the mantle lithosphere conditions appropriate for the generation and emplacement of the Nabberu and Jewill kimberlites and the Bulljah Pool ultramafic lamprophyres, triggered by suitable heating or de-pressuring events. Furthermore, rare low MgO and high ZnO and MnO chromites occur in the Nabberu kimberlites evidencing low temperature metamorphic re-equilibration (Shee et al. 1999). Spinel lherzolite xenoliths were identified in Bulljah Pool ultramafic lamprophyres, consistent with the array of mantle-derived minerals present in surrounding loams (Hamilton and Rock 1990). The presence of these bodies, and at Nabberu and Jewill raised the possibility that the Yilgarn Craton, like other cratonic regions, has the potential for sporadic arrays of diamondiferous rocks including around its margins. These postulated bodies are incrementally being identified (Fig. 4). However, given the expanse of under-explored areas in the Yilgarn and other parts of the WAC, potential exists for future discoveries.

Concluding remarks

The prospectivity model presented is based on an approach using variables which are both regionally quantifiable and considered most insightful to diamond exploration, while not constrained by traditional mineral chemical discriminatory criteria. The WAC, and particularly the Hamersley Basin stand out as being of highest diamond prospectivity using this approach. Numerous other factors have an influence on the attractiveness of specific areas. Much of WA is remote and the cost/benefit considerations of exploration can be heavily influenced by locality. The nature of country rock in terms of its influence on remote sensing (such as the prevalence of Fe-rich rocks in the Hamersley Basin; Towie 2004) can have significant negative effects. In contrast, the identification of diamondiferous bodies, favourable mineral chemistry and unconstrained indicator occurrences in surface samples are all positive unquantified variables which should be considered in exploration.

The WAC shows all mineral chemical criteria consistent with a highly diamond-prospective area following traditional exploration models targeting kimberlite – Al-depleted, Cr-rich diopsides, abundant harzburgitic (G10) garnets, high-Mg picroilmenites, and chromites with compositions similar to inclusions in diamonds. However, strongly diamondiferous bodies from the NAC (the Argyle mine returns grades of ~ 680 carats per hundred tonnes; Boxer and Jaques 1990) reveal mineral chemistry which would not be considered prospective following accepted criteria – low-Cr clinopyroxene, lherzolitic (G9) garnets, low-Mg ilmenite (due at Argyle to replacement of Mg by Mn) and some Al-chromite compositions. These features are not confined to lamproites, as the low-Cr clinopyroxene, diamondiferous Skerring kimberlite demonstrates and emphasises the importance of applying observations from mineralogies of known diamondiferous bodies to regional exploration strategies.

Despite prolific diamond exploration, Western Australia is considerably under-explored and the ageing Argyle mine and recent closure of operations at Ellendale warrant a re-evaluation of diamond potential. Indicator mineral chemistries reflect mantle sources respectably within the diamond stability field, 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 under-explored areas. As kimberlite and lamproite emplacements span 2500 Ma, there are significant opportunities for diamond-affinity rocks being present near surface even within the large, under-explored sedimentary basins overlying thick mantle lithosphere evident through much of the State. Results of prospectivity analysis make a compelling case for renewed diamond exploration in WA.

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