Diamond Exploration and Regional Prospectivity of the Northern Territory of Australia

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Abstract

The North Australian Craton occupies a large part of Australia's Northern Territory. However, while much of the Territory is prospective for diamonds, its large size has meant that it is under-explored. Historical exploration methods have been reviewed and critically assessed. Combined with data on mantle lithosphere thickness and structure, and the ages of primary diamond deposits compared to regional rocks, results have been used to rank and model regional diamond prospectivity. The ranking scheme has been supplemented with qualitative modifications and it is concluded that the Territory's western and eastern flanks are the most prospective. The Territory's three known diamondiferous kimberlite fields were all discovered using indicator minerals as the principal exploration technique. However, due to intense Cenozoic weathering, traditional indicators are unusually small or absent. Surveys using coarse-spaced sampling or that ignored fine sand particles (<0.25 mm) may therefore have returned false negatives. Indicators are often outnumbered in exploration samples by microdiamonds, considered as unreliable as regional prospecting vectors due to wind transport and their ubiquity in the east. Alteration resulting in elevated Ti relative to Mg in ilmenite and Zn overprints on chromites, and relatively high G9-garnet abundances in diamondiferous pipes place many diamond indicator compositions outside preferred discriminatory fields. The effects of intense weathering on traditional indicator mineral compositions are expected to promote the use of more durable indicator minerals in future exploration, and place a heavier reliance on remote sensing. Given the large areas involved, future diamond exploration will most effectively be conducted as parallel programs to established exploration for other commodities.

Keywords

Northern Territory • Australia • Diamond • Exploration • Indicator minerals • Pyrope • Picro-ilmenite • Spinel • Chromite • Cr-diopside • Zircon • Nb-rutile • Corundum • Kimberlite • Orangeite • Lamproite • Lamprophyre • Merlin • Emu • E.Mu • Packsaddle • Blackjack • Timber Creek • Coanjula • Mount Bundey • Mantle lithosphere • Craton • North Australian Craton

Introduction

Australia contributed 6 % to global rough diamond production by weight in 2011 (https://kimberleyprocessstatistics.org). All currently producing Australian mines (at Argyle and Ellendale) are associated with Proterozoic mobile belts surrounding the Kimberley Craton in Western Australia (WA) and diamondiferous kimberlites are also known from locations within

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the craton itself and the overlying Kimberley Basin (Atkinson et al. 1990; Jaques and Milligan 2004; Fig. 1). The neighbouring Northern Territory (NT) hosts some 2,200 km^2 of exposed Archean rocks and over half a million km^2 of Paleoproterozoic rocks, comprising around 40 % of the area of the Territory. Similar to Western Australia, much of the Northern Territory's orogenic belts and sedimentary basins are underlain by thick, Archean mantle-lithosphere constituting the North Australian Craton (Graham et al. 1999; Luguet et al. 2009; Hollis et al. 2009), of which the Kimberley Craton is a part, and providing the conditions necessary for the formation of diamond (Haggerty 1986). In addition to a number of known kimberlites and secondary deposits, the NT hosted the only mined Australian primary diamond deposit outside of WA at Merlin until its closure in 2003 (Reddicliffe 1999; Jaques and Milligan 2004). Outside of the areas of exposed Archean and Paleoproterozoic rocks, most younger basins in the NT predate or overlap the age range of known diamond-bearing rocks, which are dated as being as young as 179 Ma in the NT (Timber Creek kimberlites, Belousova et al. 2001), and ~20 Ma in WA (Ellendale lamproites; Phillips et al. 2012). Hence, much of the NT is prospective for diamonds and there is significant scope for extrusive kimberlitic bodies to be exposed. Both theory and precedent therefore exist in support of future potentially economic diamond discoveries in the Northern Territory.

The Northern Territory benefits from having experienced continuous diamond exploration since the early 1970s. Reviews of the most active period of diamond exploration history in the NT are provided by Tyler (1987), Atkinson et al. (1990) and Smith et al. (1990) and the regional geophysical context is discussed in Jaques and Milligan (2004). Also of relevance are the descriptions of exploration in neighbouring WA (Atkinson et al. 1984; Jaques et al. 1986; Jaques and Milligan, 2004).

In the Northern Territory, three fields of diamond-bearing kimberlitic rocks are known (Fig. 1) namely: (i) two dykes constituting the Roper Field (Fried 1990) (ii) the Timber Creek Field (Berryman et al. 1999) and (iii) the Merlin Field (Lee et al. 1997; Reddicliffe 1999) incorporating the Merlin kimberlites, Emu pipes (otherwise referred to as "E.Mu"), Abner Range pipes and the Coanjula microdiamond occurrence. All deposits were discovered with traditional stream sediment sampling as the principal exploration technique (Fried 1990; Smith et al. 1990; Berryman et al. 1999; Reddicliffe 1999). Weathering has been intense throughout the Cenozoic in much of Australia (May et al. 2011) and hence even deep within pipes, pristine rock is rarely found. Thus, in the NT, the distinction between Group 1 and Group 2 kimberlites (Mitchell 1995, p. 11) and lamprophyres (e.g. Tappe et al. 2005), and perhaps even in some case lamproites, is rarely possible. In this study such petrological terms are accordingly used as precisely as available data permit. Hence, unless otherwise noted, the term 'kimberlite' is used as a general term to denote a kimberlite-affinity rock.

Northern Territory Kimberlites

The main part of the Merlin Field comprises 13 small pipes (up to ~1.2 ha) forming a NNE trend over ~10 km. They were emplaced subparallel and to the east of the Emu fault which forms the eastern extent of the regionally significant Batten Fault Zone (Fig. 1). The rocks are often highly silicified (Lee et al. 1997) though bulk chemical analyses of fresher samples conform to that of kimberlites (Reddicliffe 1999). Unlike most kimberlites, however, ilmenite is rarely observed at Merlin, even in the least altered samples (Reddicliffe 1999). The pipes are Devonian in age with most recently acquired age determinations being 382 ± 3 Ma (Hell et al. 2003) and 368 ± 4 Ma (2σ) (McInnes et al. 2009) for samples from the Sacramore pipe.

The Roper Field consists of the Blackjack and Packsaddle dykes, ~7 km apart and trending almost N–S (Fried 1990). Given their extensive weathering, they cannot be confidently classified beyond being of kimberlite affinity. They contain mantle-derived Cr-spinel, garnet and diamond. The Roper Field bodies are undated.

The Timber Creek field consists of five discrete bodies, the largest (TC-01) being ~0.07 ha. TC-01 has effectively been mined out during the course of exploration. All the Timber Creek bodies are dykes, with TC-01 being interpreted as a blow. They lie on an E-W trend over ~2.7 km (Berryman 1995). All samples are strongly weathered and whilst monticellite relicts and some possible relict perovskite has been reported (Barron 2005), available data do not allow a conclusive identification as kimberlite. The emplacement age is controversial with early age determinations based on zircon separates from an associated drainage (Berryman et al. 1999) being Proterozoic. The most recent age determination (Belousova et al. 2001), also on zircon, gives an emplacement age of 179 ± 2 (2σ) Ma. It is notable that this mid-Jurassic age is the same as some South Australian kimberlites (Cooper et al. 2008) and coincides with the commencement of rifting of the Indian continent from Western Australia and Antarctica. As rifting progressed, the 122 Ma carbonatite/aillikite magmatism of the Antarctic Prince Charles Mountains (Belyatsky et al. 2008) and the 105–121 Ma so-called 'Gondwana Lamprophyres' of eastern India (Sarkar et al. 1980) were emplaced. This is not the only apparent coincidence of emplacement ages of diamondiferous rocks from India and Australia, with

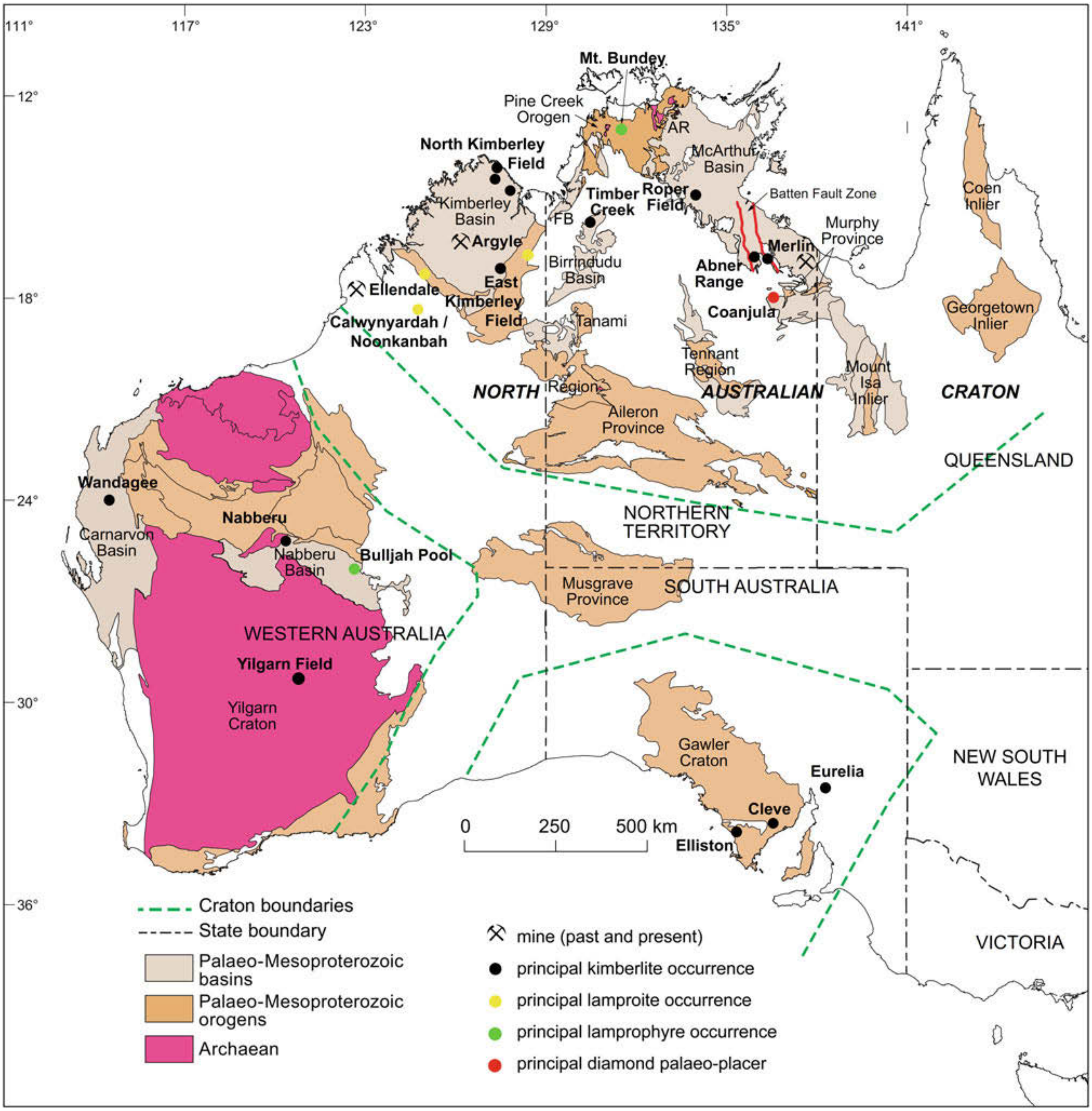

Fig. 1 Overview map of geological regions and principal kimberlite, lamproite and lamprophyre fields of interest. General geological and craton boundaries follow Atkinson et al. (1990), Kennett et al. (2011) and Ahmed and Munson (2013). The Ellendale lamproites reside within the King Leopold Mobile Zone and the Argyle pipe within the Halls Creek Mobile Zone. *FB* Fitzmaurice Basin; *AR* Archaean Region. Labels of mined bodies are appended (per key)

the 1,178 Ma age of the Argyle AK1 pipe (Pidgeon et al. 1989) lying in the middle of the 1,050–1,350 Ma age range of the East Dharwar kimberlites and lamproites (Fareeduddin and Mitchell 2012, p. 147). Whilst some reconstructions of Rodinia place the Indian continent along strike from Western Australia (Weil et al. 1998) in this age range, the components of Rodinia are highly controversial.

Diamond Exploration and a Prospectivity Model

The principal tool of Northern Territory diamond exploration has been surface sediment sampling aimed at recovering so-called 'traditional' indicator minerals, namely picro-ilmenite, Cr-diopside, pyrope garnet, chromite and diamond (Hutchison 2011). This exploration generated a small number of academic papers and over 700 publicly available company reports. Hutchison (2011) compiled data for 76,965 exploration-stage samples from these reports, mostly for indicator minerals, covering visual counts of diamond and non-diamond indicators, compositionally confirmed indicator counts, and diamond descriptions, plus available major, minor and trace element mineral chemical analyses. The purpose of this study is to examine the Hutchison (2011) database in order to evaluate the successes and shortcomings of exploration methods applied to the Northern Territory over the past 40 years, in the context of contemporary mineral classifications and exploration tools. In addition, the study uses results of exploration sampling in combination with regional mantle geology and relative ages of basement rocks, supracrustal cover and broadly alkaline intrusives within different regions to create a diamond prospectivity model of the Northern Territory. The model comprises a quantitative component with qualitative modifications based on local criteria. The ultimate aim is to provide a platform for future exploration in the NT and more generally for regions with similar, heavily weathered tropical and subtropical settings.

Methodology

Samples and Analyses

Sample treatment, mineral identification and description, and mineral chemical determinations have been conducted at both academic research facilities and commercial laboratories over the course of 40 years (Hutchison 2011), hence, a rigorous quality control was applied prior to the use of each analysis. Further to the filtering applied by Hutchison (2011), samples without recorded weights are not included in diamond distribution mapping, laboratory contamination was assessed regarding outlier occurrences of indicator minerals by personal communication where possible, and exploration samples containing only single indicator mineral grains were removed from the assessment of diamond/non-diamond indicator correlations. Mineral chemical data were assessed based on analyses totals and stoichiometry, and chemical discriminations were based on analyte uncertainty. For example, energy dispersive spectrometry (EDS) analyses (with the exception of high-precision electron microprobe EDS following Ware 1981) are regarded as suitable for Ca/Cr classification of garnet (Keulen et al. 2009) but due to poor precision of Na and Mn determinations, are unsuitable for Mn-derived 'D' sub-classification following Grütter et al. (2004) and eclogite diamond association following Grütter and Quadling (1999). Furthermore all determinations were too imprecise to apply Ni in garnet thermometry. Notwithstanding the quality controls applied, sampling and analytical methods have evolved throughout the duration of exploration and have varied by sampler. Data have been used without prejudice to these variables.

Regional Prospectivity

The solid geology map of the Northern Territory is subdivided into 31 geological regions on land, in addition to the Arafura Sea (Ahmad and Munson 2013). Being defined on the basis of surface and near-surface solid geology, the distinctions between geological regions are not necessarily related to changes in mantle structure, which may have a bearing on diamond formation. However, the regions conveniently subdivide the NT into areas of differing ages relevant to exposed potentially diamondiferous bodies. Hence they provide a convenient Territory-wide jigsaw of surficial geological domains, which provides a framework to assess diamond prospectivity. Region-specific prospectivity was calculated with the following three general principles in mind: (i) the extent and success of prior sampling in identifying indicator minerals (ii) the age of regional geology compared to emplacement ages of known primary diamond deposits and (iii) mantle lithosphere thickness and structure. An integer score was assigned to each region for each of these three principles and the sum of the scores used to determine the relative prospectivity of each region. Scores were assigned using the following criteria.

Sampling History. In order of decreasing prospectivity, sampling history scores were assigned as follows where the percentage of samples with visually determined, positive indicator recovery (including macro- and microdiamond) is represented by ρ, and δ represents sampling density:

1. under-explored yet with good indicator mineral recovery where $\delta < 1$ per 100 km^2 and $\rho > 5$ %;
2. regional-scale sampling and with good recovery where $\delta < 1$ per 4 km^2, $\rho > 5$ %; or under-explored and with poor recovery where $\delta < 1$ per 100 km^2, $\rho < 5$ %;
3. local-scale sampling and with good recovery where $\delta > 1$ per 4 km^2 and $\rho > 5$ %; or regional-scale sampling and with poor recovery where $\delta < 1$ per 4 km^2, $\rho < 5$ % positive recovery;
4. local-scale sampling/poor recovery: $\delta > 1$ per 4 km^2, $\rho < 5$ %; and,
5. no sampling undertaken or publically reported.

Sampling density discrimination follows the methodology of McMartin and McClenaghan (2001). Based on sampling history, under-explored areas score well, particularly those where, despite little work being conducted, results have been good (that is, these areas will retain significant exploration potential). Conversely, completely unsampled regions score poorest assuming there are significant geological reasons why a region has been completely ignored. These are discussed on a case by case basis in the Results and Discussion sections.

The reliance on visual identification of non-diamond indicators presents some drawbacks. Definitive recognition of indicator minerals requires precise mineral chemical analyses. However, such data are available for only a limited number of the visually positive samples to the extent that under-sampled areas in particular, would either have no corresponding mineral chemical data or too few analyses to be statistically reliable. Furthermore, chemically confirmed indicator-positive samples in themselves are not necessarily a reliable data resource as there may still be potential laboratory contamination and low-precision issues.

Geological age. An primary diamond source which is younger than any of the other rocks within the region into which it is emplaced, has the greatest chance of being exposed. Following this premise, Northern Territory regions were scored based on their age ranges (Ahmad and Munson 2013) as follows:

1. All rocks within the region are older than the oldest known diamond-bearing rocks in Australia (i.e. Argyle, 1178 Ma). In this case, an eruptive diamond-bearing body of any likely age will be exposed or be near-surface, assuming that it has not been removed by erosion;
2. The age range of rocks within the region is older than the oldest, robustly dated Northern Territory kimberlites (i.e. Merlin, 368 Ma), although some rocks do not pre-date Argyle;
3. The median age of rocks within the region is older than the Merlin emplacement age of 368 Ma;
4. The median age of rocks lies between that of Timber Creek (179 Ma) and Merlin (368 Ma); and,
5. The median age of regional rocks is younger than 179 Ma. In such regions, it is most likely that any primary diamond-bearing body will be masked by younger consolidated rocks.

It is noted that diamondiferous lamproites at Ellendale are quite young ($\sim$20 Ma, Phillips et al. 2012), so an age score of 5 implies prospectivity remains for mid-Jurassic or younger intrusives.

Mantle structure. Old, thick, continental, mantle-lithosphere typical of Archean cratons and extensive Paleoproterozoic terranes are expected to provide the necessary conditions for formation of diamonds (e.g., Haggerty 1986). Furthermore, transportation of diamonds by kimberlites, lamproites and related rocks to the Earth's surface is facilitated by deep (Moho tapping), large-scale structures such as terrane sutures and craton edges (Jaques and Milligan 2004). An integer score from one to four has been assigned based on the relative variation of teleseismic S-wave velocities at 200 km depth below the North Australian Craton (Fig. 2, after Fishwick et al. 2006). Lower scores reflect faster S-waves, interpreted as delineating thick cold dry and refractory mantle lithosphere with high potential for diamond formation and retention and/or the interpreted presence of edges or boundaries between thick mantle lithosphere blocks where the potential to transport diamonds to surface along permissive lithosphere-scale structures may be the greatest.

Modifying factors. Other factors affect the prospectivity of a region such as terrain, the amount and type of unconsolidated cover, and sample and analytical quality. Logistics also affect a region's attractiveness. None of these effects can be justifiably quantified, however, they impact the calculated prospectivity score where they have affected the success of prior sampling. Furthermore, regions with unique modifying factors are treated individually in the Discussion section.

Results

Sampling Methods: Successes and Failures

Of the 76,965 publicly described samples taken during the course of diamond exploration in the NT (Hutchison 2011) most exploration sampling has been conducted in the northern half of the NT and in particular around its borders. The WA-border area sampling (Atkinson et al. 1990; Smith et al. 1990) has largely been driven by the proximity to the producing mine at Argyle and buoyed by finds on the NT side at Timber Creek. The Queensland border sampling, and north into Arnhem Land, has been triggered by the discovery of the anomalous and ubiquitous occurrence of microdiamonds (Tyler 1987) including those at Coanjula. Table 1 provides a comprehensive listing of the aerial extent of each ranked region, the number of samples taken, indicator-specific samples taken and counts of samples positive for diamond indicator minerals.

Sampling density. In areas of the world where indicator preservation is good (such as the Arctic) a sampling density poorer than 1 sample per 100 km^2 is regarded as a reconnaissance-style density (McMartin and McClenaghan 2001) and is suitable for identifying geochemical provinces rather than focussing on specific kimberlite fields. However, for the deep weathering profiles in both tropical and arid northern Australia (May et al. 2011), one sample per 50 km^2 has been preferred for reconnaissance surveys (Atkinson 1989). The same logic can be applied to regional surveys where a sampling density of one sample per 4 km^2 is probably only marginally effective in an area such as the NT where indicator minerals do not survive long transport distances (Atkinson 1989; Cornelius et al. 2005). Detailed surface sampling in the Merlin Field (up to 1 sample per

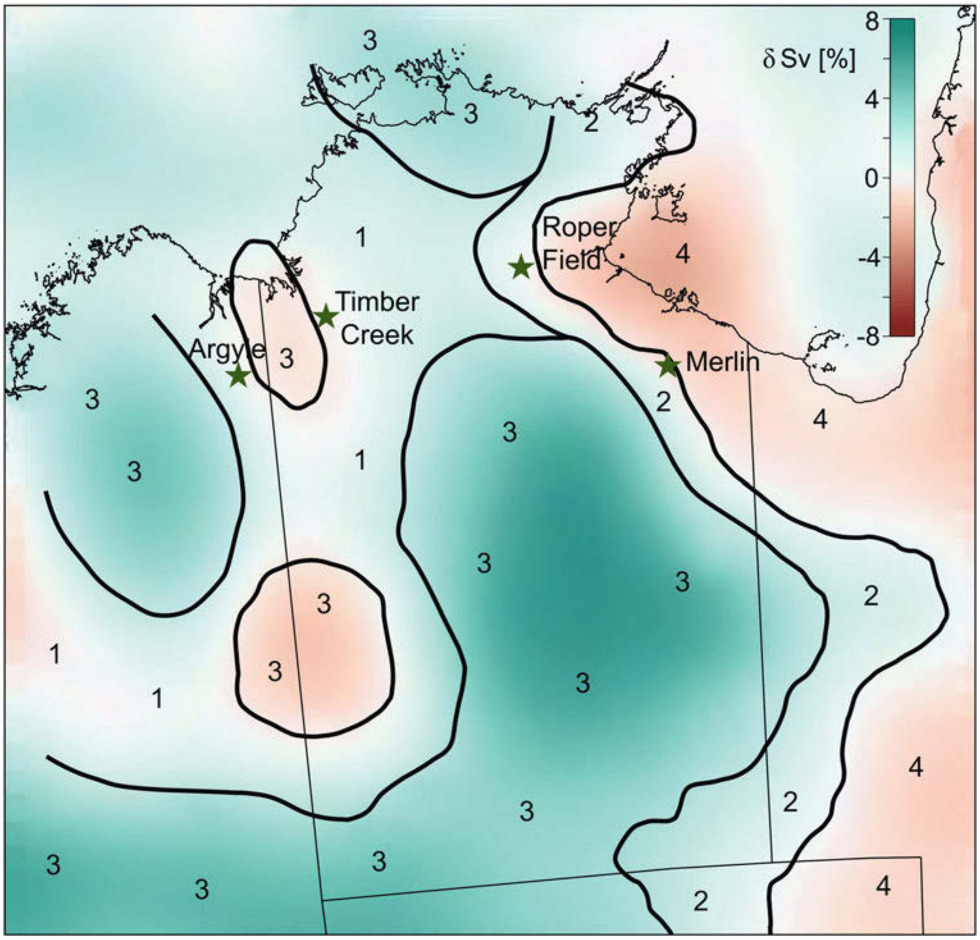

Fig. 2 Seismic S-wave velocity profile modelled at 200 km depth below the NT and neighbouring states. The map is based on GRS80, follows a simple conic projection centred on longitude 134°E and is adapted from Fishwick et al. (2006). *δSv* percentage shear-wave velocity perturbation relative to global reference model AK135. Primary diamond deposits are indicated by stars. Numbered regions represent areas of differing diamond prospectivity where lower numbers are more prospective

50 m; Reddicliffe 1999), for example, recovered only two samples with pyrope garnet from outside of a kimberlite pipe (Colliver 1987).

Only three regions have been sampled at a greater average density than 1 sample per 4 km^2 (Table 1), the Halls Creek Orogen and the Birrindudu and Wolfe Basins. This fact alone emphasises the extent to which the NT is generally under-explored for diamonds. Even the Halls Creek Orogen, host to the Argyle mine in WA, and the most intensely sampled NT region, was noted by Smith et al. (1990) to have been under-explored. It has arguably remained so, in some parts, due to land access issues.

In contrast, and despite the significant sample coverage, particularly in the north of the NT, there are only 20 samples recorded from the Archean Region (areas where Archean rocks are exposed). This is partly due to coincidence with Kakadu National Park. Other considerations include native title claims and the Archean in Arnhem Land being a high priority uranium target, which has dominated exploration in this area.

Sampling methods. Most sampling conducted has been alluvial (65 %) followed by loam sampling (contributing a further 24 %). Common practice has seen alluvial samples of ~40 kg taken and sieved to −2 mm in the field (Smith et al. 1990). The most common size ranges from which indicator minerals have been exclusively picked (constituting 52 % of 6096 samples reported in Hutchison 2011), in decreasing numbers of samples, were >0.3 to <0.5 mm, >0.425 to <1 mm and >0.25 to <1.2 mm.

Heavy mineral recovery. In order to assess the relative abundance of indicators in samples, sample weight and concentrate weight are key variables. Values are known for both for 1982 samples (Hutchison 2011). The median recovery of heavy minerals (concentrate weight) from all samples is ~0.15 %, which varies little between size fractions processed. Hence, a 25 kg sample would produce ~37 g of concentrate. Muggeridge (1989, 1995) emphasised the considerable benefit of collecting from high quality trap sites. Rock samples (mostly kimberlites) followed by alluvial samples and finally loam samples showed decreasing average heavy mineral recoveries.

Indicator recovery. The highest concentration of **indicators** in rock samples from Hutchison (2011) is 576 indicators per kg (all size fractions combined) and the

Table 1 Sampling history data contributing to the diamond prospectivity model

Region	Area (km^2)	Total samples	Indicator samples[a]	Positive samples[b]
Amadeus basin	125,300	796	796	0
Arafura basin	15,889	193	179	3
Archaean	2,746	20	18	5
Arnhem province	2,383	187	1	0
Arunta region	184,437	1,851	1,643	18
Birrindudu basin	35,104	10,250	9,700	717
Bonaparte basin	10,228	357	357	109
Canning basin	5,035	2	2	0
Carpentaria basin	128,871	4,837	4,082	307
Daly basin	16,114	1,817	1,817	55
Eromanga basin	78,645	5	5	2
Fitzmaurice basin	6,168	694	681	57
Georgina basin	198,435	15,653	11,069	1,784
Halls Creek Orogen	176	78	78	4
Kalkarindji province	45,512	7,064	6,424	621
Lawn Hill platform	1,711	126	126	7
McArthur basin	145,687	18,721	16,740	1,738
Money Shoal basin	19,401	0	0	0
Murraba basin	1,982	0	0	0
Musgrave province	33,750	0	0	0
Murphy inlier	1,718	321	320	79
Ngalia basin	12,742	4	4	0
Ord basin	1,675	592	379	90
Pedirka basin	1,693	0	0	0
Pine Creek Orogen	46,803	1,602	1,426	161
South Nicholson basin	11,857	1,231	1,231	122
Tanami region	30,921	373	353	3
Tennant region	35,932	437	397	11
Victoria basin	33,188	8,274	8,223	189
Wiso basin	112,700	413	413	11
Wolfe basin	3,666	1,011	1,010	59

[a] Number of samples processed for diamond recovery, non-diamond indicator recovery or both. This number is sometimes less than entries in the Samples column which includes samples taken for other types of processing such as bulk chemical analyses. Based on aerial extent, this number contributes to the prospectivity ranking

[b] Number of samples from which at least one indicator mineral, including diamond, was recovered. Entries in this column, calculated as a percentage of Indicator Samples, contribute to the prospectivity ranking

equivalent maxima for alluvial and loam samples are 250 and 69 grains per kg, respectively. Such maximum numbers of visually identified indicator grains per kg of sample compare well with samples from pristine environments such as the Arctic (e.g. McClenaghan and Kjarsgaard 2007). However, considering the 2326 indicator-positive samples from the NT where sample weight is known, the **median** recovery is only 0.046 indicators per kg. Hence for a 25 kg sample, only one indicator should be expected and based on Hutchison (2011), this grain is likely to be a chromite.

In order to minimise the cost of sample collection and processing, the central tenet to traditional indicator mineral sampling is that non-diamond phases should be more abundant than the diamonds themselves. Using NT data (Hutchison 2011), for diamond-positive samples no correlation could be identified between the number of indicators recovered and the number of diamonds. However, improving the statistical robustness of the dataset by including samples yielding more than one diamond and more than one non-diamond indicator, and considering

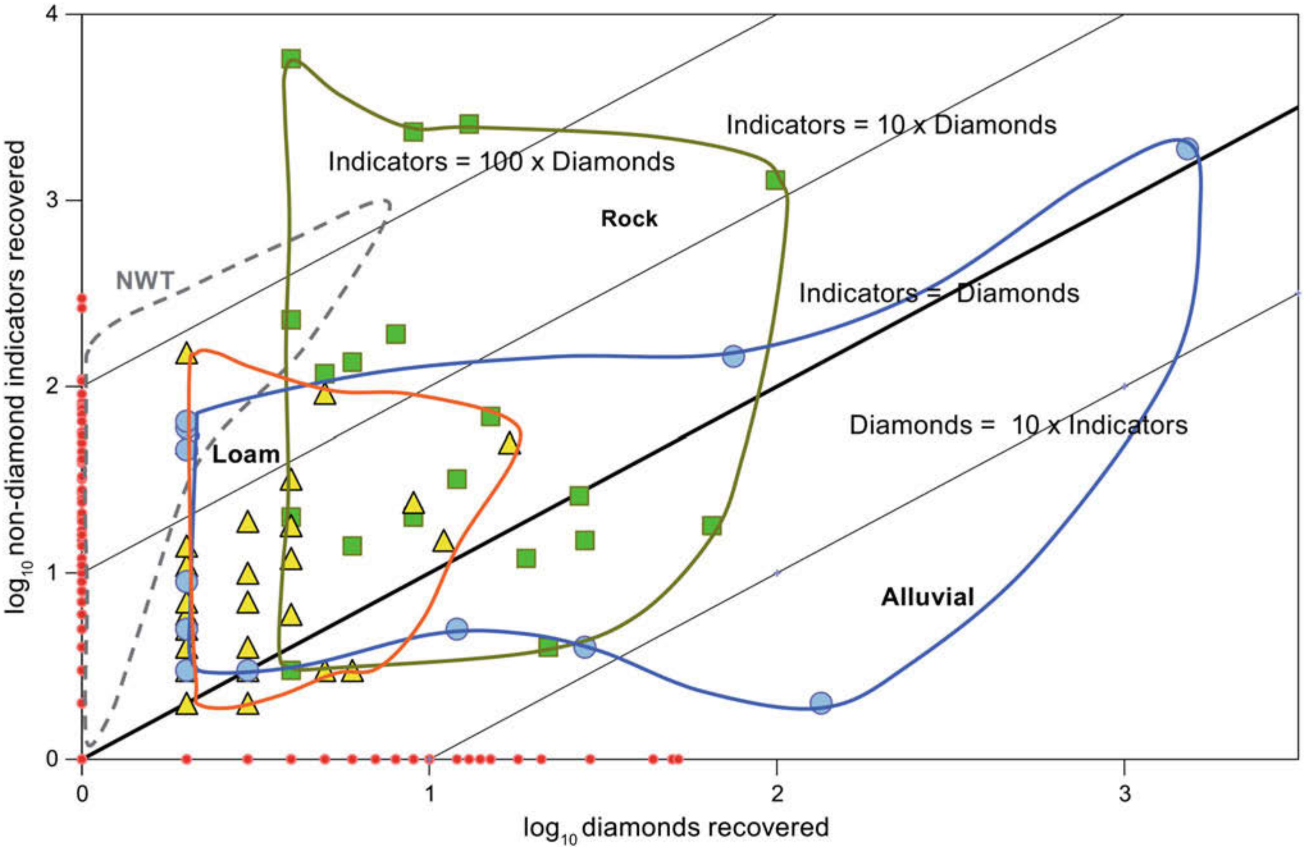

Fig. 3 The relative abundance of non-diamond indicators to diamonds from Northern Territory rock samples (*green symbols*), alluvial samples (*blue symbols*) and loam samples (*yellow symbols*). Red dots denote sample results excluded from calculations of average non-diamond/diamond recovery. Dashed grey field delineates indicator/diamond recovery data for Northwest Territories (NWT, Canada) samples, from Armstrong and Chatman (2001)

different sample types, some relationships can be discerned (Fig. 3). For NT samples as a whole, rock samples yield the highest ratios of non-diamond indicators to diamonds, presumably because they are the best preserved samples. Strikingly, alluvial samples typically contain more diamonds than traditional non-diamond indicators (Fig. 3). This observation is interpreted as both a reflection of the poor survival of indicators in the alluvial environment in the NT and the pervasive occurrence of microdiamonds in some regions, and is consistent with empirical observations of relative microdiamond abundance (Atkinson 1989; Redicliffe 1999).

Diamonds Characteristics

One of the main driving forces for diamond exploration within the NT since the early 1980 s has been the so-called North Australian microdiamond anomaly (Tyler 1987). This anomaly was mapped based on the number of diamonds recovered rather than diamond concentration because sample weights were not historically reported in public documents (Hutchison 2011). A total of 43,111 diamond sampling locations where sample weights are known are now available (Hutchison 2011), and hence the microdiamond distribution can be plotted based on diamond recovery per kg of sample. Results are shown in Fig. 4 where a 20 km buffer around sample sites delineates zones where no diamond concentration data is available. Also shown are the locations of samples described as yielding macrodiamonds, and the locations of diamond recovery where sample weights are **not** known and hence data does not contribute to the contoured map. High microdiamond concentrations occur in a wide zone west and south of Coanjula and unlike previous studies (Smith et al. 1990; Lee et al. 1994) it is not clear whether Coanjula is in fact the source of regional microdiamonds only that it lies close to the edge of the zone of highest diamond concentration. The map shows sporadic and widespread diamond occurrences distributed over at least 500 km and extending throughout much of the McArthur Basin to the Roper River. In the eastern portion of the Northern Territory it is apparent that there is generally little correlation between microdiamond concentration and known kimberlite locations. Microdiamonds are so

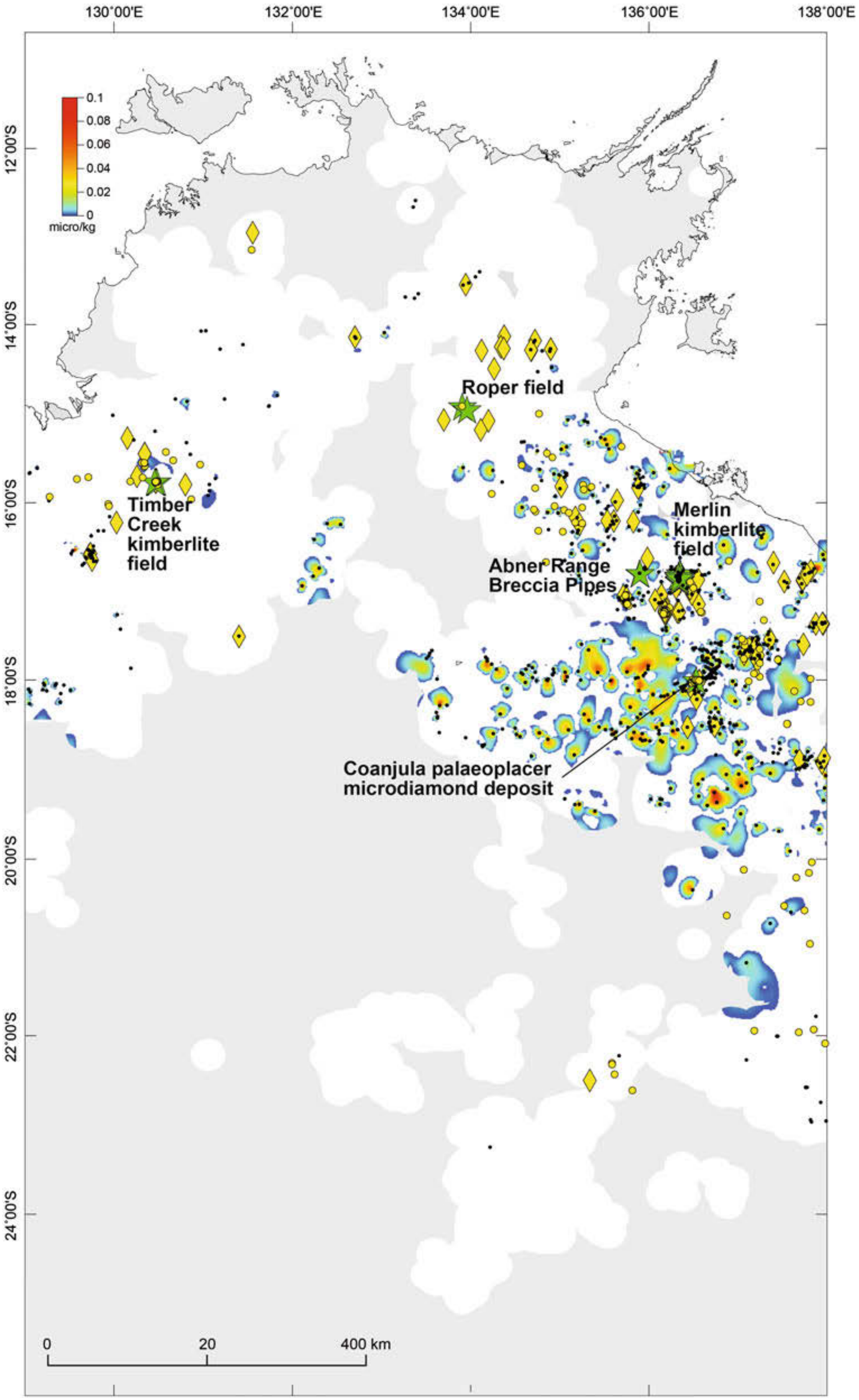

Fig. 4 Map of microdiamond concentration results in NT diamond exploration samples, based in large part on data compilation of Hutchison (2011). *Black dots* represent 1,098 microdiamond-positive results in 43,111 sites sampled where sample weights are known and microdiamonds/kg sampled can be calculated. These results contribute to the colour-ramped grid shown. Small *yellow circles* denote 292 microdiamond-positive sample sites with unknown sample weights, while filled *yellow diamonds* denote 177 sites with macro diamond recoveries. *Grey* hatched background denotes a large area with no available diamond data, demarcated as falling outside an arbitrary 20 km buffer zone (*white colour*) from the nearest sample site. *Green stars* locate labelled primary or significant secondary diamond deposits. See text for further discussion and variable historic size thresholds for reported macro diamonds. No single definition of a microdiamond exists and in the NT diamonds <0.8 mm (Lee et al. 1997), capable of passing through a 500 µm sieve (Gregory and White 1989) and <0.4 mm (Smith et al. 1990) have all been classed as microdiamonds. Data used in the figure are as reported in Hutchison (2011) without prejudice to definition

ubiquitous in the east that separating genuine indicator trains from the general background abundance based simply on diamond numbers becomes statistically very challenging. In the west, however, while there is also no clear correlation between microdiamonds and known primary sources regionally, there is also no pervasive

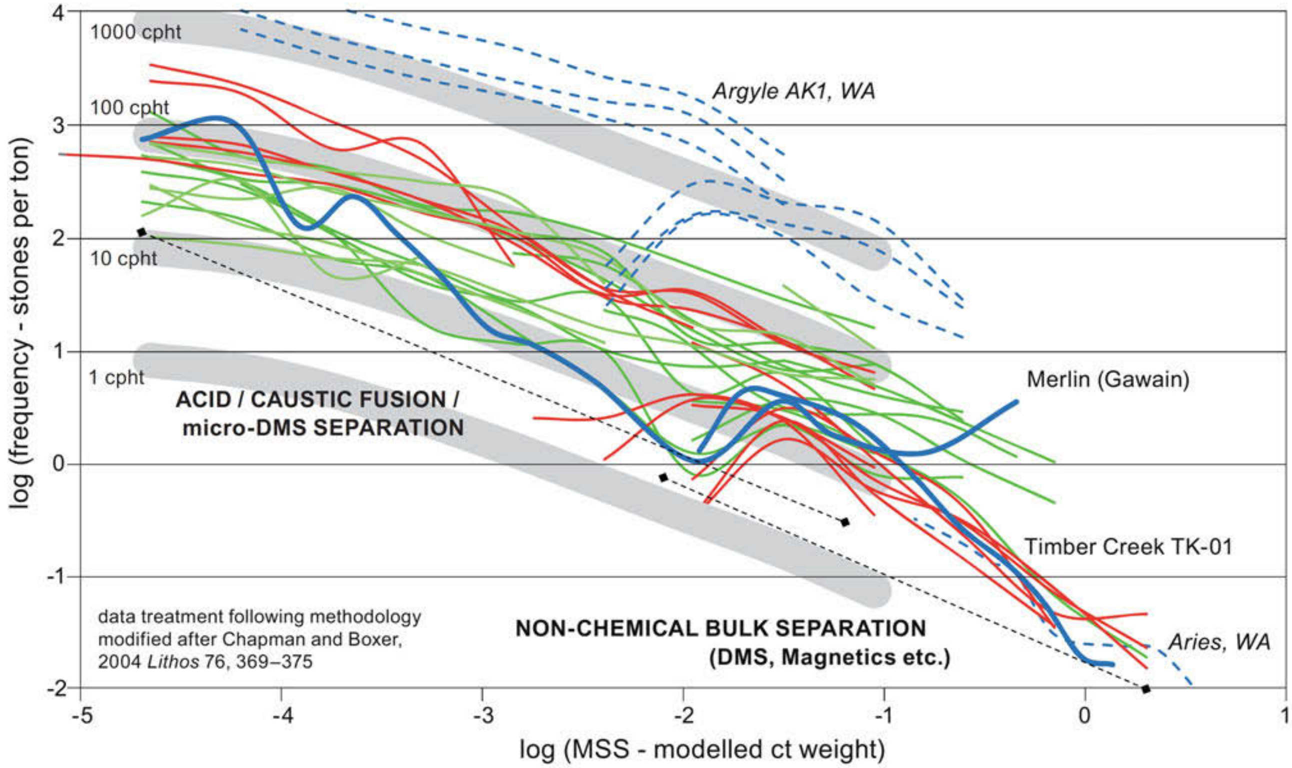

Fig. 5 Diamond size-frequency distribution for Northern Territory kimberlites, plotted in log (abundance) versus log (mean stone size) space (modified after Chapman and Boxer 2004). NT data (*blue lines*) are presented in context of exploration-stage projects in Canada (*green lines*) and Greenland (*red lines*). Non-NT data from Aries (Towie et al. 1994) and Argyle (Deakin and Boxer 1989) are shown as *dotted blue lines*. Fine-stippled straight black line segments denote diamond size ranges typical of chemical versus physical diamond processing and recovery techniques, which overlap at around −2.2 to −1.0 log (MSS). See text for discussion

occurrence of microdiamonds to complicate the exploration picture. In all areas with sufficient samples, reported macrodiamonds are demonstrated to be a better indicator of proximity to primary and major secondary sources of diamonds than microdiamonds.

A more detailed analysis of diamond features may provide the key to identifying specific sources. For example, size-frequency distributions can be characteristic of particular pipes or clusters (Chapman and Boxer 2004). Using data combined from Lee et al. (1997) and Reddicliffe (1999), size distributions from the Gawain pipe in the Merlin Field have been compiled, and similarly Timber Creek TC-01 distributions are derived from data in Cooper and Marx (2004) and Kolff (2010). These data are presented in Fig. 5 (after Chapman and Boxer 2004), alongside Western Australian Argyle AK1 (Deakin and Boxer 1989) and Aries size-frequency distributions (Towie et al. 1994). While grade often varies by up to 2 orders of magnitude within individual pipes (e.g. Kjarsgaard 2007), the slopes of diamond size distributions, and particularly the forms of bi-modal populations, can discriminate the different sources. Timber Creek samples show a reasonably smooth size-frequency distribution (Fig. 5) with relatively high microdiamond concentrations, though with few large stones (Kolff 2010), suggesting a steep drop in the diamond concentration in larger size fractions. The size characteristics of Merlin are unusual. Sizes drop off rapidly up to about 1 mm in size, however, abundances recover into larger size fractions. While sample treatment may contribute to this bi-modality, infra-red studies (Lee et al. 1997) suggest that Merlin diamonds derive from multiple populations. Furthermore, Merlin is known to produce large stones (up to 104.73 ct, Overton, 2003). The physical characteristics of diamonds also serve to discriminate multiple sources. Physical characteristics of primary-sourced NT diamonds are summarised in Table 2. The Merlin macrodiamond population (Lee et al. 1997) has abundant colourless, dodecahedral or more strongly resorbed stones and plastically deformed stones are rare. Amongst microdiamonds, macles are abundant (Lee et al. 1997) as are clear, sharp-edged octahedral forms (Reddicliffe 1999). In contrast, among micros from Timber Creek, octahedral stones are rare (Berryman et al. 1999) and stones are most commonly brown with yellow the next most abundant colour. Timber Creek diamonds are also characterised by green and brown radiation-damage surface spots, which is also evident in

Table 2 Abundances of different physical characteristics of diamonds described from NT samples

	Octahedral	Dodecahedral	Cube	Irreg./Frag.[b]	Macle	P.D.[a]
Merlin (macro) Lee et al. (1997)	Rare	~40 %	Rare	~40 %	–	Rare
Merlin (micro) Reddicliffe (1999)	42 %	32 %	1 %	9 %	50 %[d] 16 %	
Timber Creek (macro) Kolff (2010)	–	Majority	–	–	–	–
Timber Creek (micro) Berryman et al. (1999)	4.5 %	87 %[e]	–	8.5 %	60 %	21 %
Regional (macro) Hutchison (2011)	19 %	12 %	41 %[f]	28 %	15 %[g]	–
	Colourless	Brown	Yellow	White[c]	Green	Radiation spots
Merlin (mostly micro) Lee et al. (1997); Stiefenhofer and McClenaghan (1994)	63 %	8 %[h]	15 %	8 %	6 %	–
Timber Creek (macro) Kolff (2010)	Abundant	Abundant	–	–	–	Dominant
Timber Creek (micro) Berryman et al. (1999)	~14 %	66 %	20 %	–	–	40 %
Regional (macro) Hutchison (2011)	22 %	33 %[i]	12 %	19 %	14 %	17 %

[a] Plastic deformation evidenced by surface lamellae

[b] Crysts described as irregular or broken fragments. Irregular stones may occur as a result either of extreme resorption or breakage and the terms, where not defined in original sources, are not necessarily interchangeable

[c] Includes both white (*opaque*) and *grey coloured stones*

[d] Lee et al. (1997) reported 50 % of 40 microdiamonds from Merlin as being macles

[e] Berryman et al. (1999) noted that dodecahedral stones are very heavily resorbed being dominantly tetrahexahedral. Hence many of those stones may have been assigned to an irregular designation. All Berryman et al. (1999) Irreg./Frag. stones were described as fragments

[f] cube and cubo-octahedral forms

[g] comprises macles and aggregates

[h] comprises 6 % brown and 2 % pink

[i] This figure comprises brown stones (25 %) and stones whose dominant colour is pink or mauve (8 %)

WA at Aries (Towie et al. 1994). As at Merlin, macro dodecahedra are common at Timber Creek, however, the brown colourations and green spots distinguishing the microdiamonds are also prevalent amongst the larger stones (Kolff 2010). Of diamonds acquired during reconnaissance exploration, 84 % of diamonds were recovered from outside the Timber Creek and Merlin Fields (Hutchison 2011). Contrasting strongly with known primary sources, cubes are the most abundant forms amongst surface sediment-hosted diamonds. Whilst many are yellow, the whole colour range seen in non-cube forms is represented. In short, the regional distribution of exploration microdiamonds cannot be accounted for by the known kimberlites in northern Australia.

Indicator Mineral Chemistry

Spinel. Spinels, and in particular chromite, are by far the most abundant mineral phase identified during the course of diamond exploration in the NT. A total of 7773 analyses with good stoichiometry have been classified based on major element compositions (compiled in Hutchison 2011). Potential mantle-derived phases were further classified following Grütter and Apter (1998). Grains with compositions consistent with chromite inclusions in diamond (‘chromite-in-diamond’) are rare in the NT, with 30 of 90 such grains being recovered from Merlin pipes, a further 11 from Merlin exploration samples (Reddicliffe 1999) and 7 from the Timber Creek TC-01 and TC-05 bodies. Of the remaining grains, the large majority (32) derive from exploration around the Mount Bundey lamprophyre (Fig. 1) described by Manning (1992). Garnet-peridotite association spinels are common, much more so also than spinel-peridotite association spinels, reflecting a generally deep origin of mantle-derived grains throughout the NT. Amongst regional samples, identifying kimberlite-derived spinels is challenging given that other non-kimberlite sources of spinels are common. Using the reduced spinel prism method of Mitchell (1995, p.189), spinels from the Kalkarindji flood

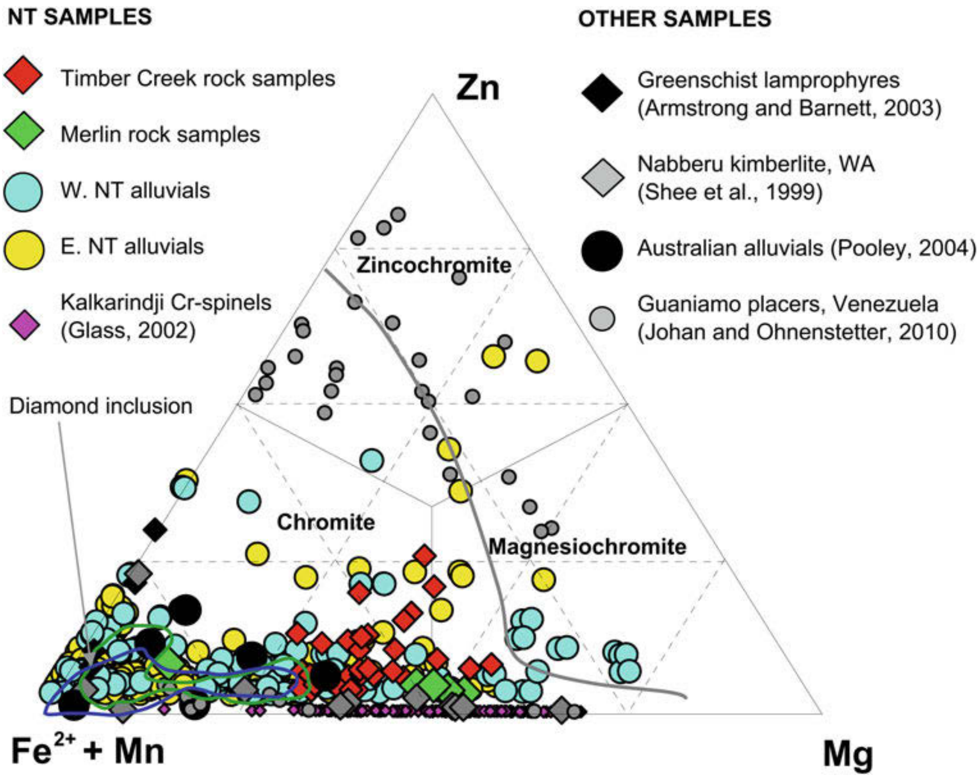

Fig. 6 Composition of selected Cr-spinels. *Coloured symbols* represent NT samples and fields and grey symbols represent non-NT samples. *Diamond symbols* represent chromites from rock samples and *circles* represent chromites from alluvial samples. *Green field* metamorphosed komatiitic chromite from Norseman, WA (Barnes 2000). *Blue field* metamorphosed ophiolitic serpentinite chromites from the Himalaya (Krishnakanata Singh and Bikramaditya Singh 2011). *Black field* all terrestrial chromites with ZnO $>$ 1 wt % from rocks which have no association with kimberlitic rocks from the database of Barnes and Roeder (2001). The 'Diamond inclusion' annotated represents the composition of the chromite inclusion in the Sierra Leonean diamond of Meyer and Boyd (1972)

basalts plot with a magmatic evolutionary trend typical of mantle-derived chromites (Barnes and Roeder 2001). However, Ti contents of spinels from the Timber Creek and Merlin fields are typically lower than those from kimberlites elsewhere in the world (e.g. Schultze and Roeder 2008). Hence assigning compositions to one or other of the Group A or Group B compositional fields of Mitchell (1995, p. 190) is challenging. If any tendency towards a particular field can be discerned, it would be that the Timber Creek samples appear more compatible with the Group A (Type I kimberlite) field, whereas Merlin samples tend towards the Group B (orangeite) field.

Mn alteration is seen in NT spinels, with 13 % of all chromites having more than 1 wt % MnO. However, this is a regional characteristic not shared with chromites derived from NT kimberlites or their immediate vicinity. Only two of 1,688 chromite analyses from Merlin samples have MnO greater than 1 wt % and the maximum Mn-content seen at Timber Creek is 0.39 wt % MnO. Zn alteration of chromites is also common in NT samples and Zn-enrichment is seen in chromites derived from kimberlite pipes (Fig. 6). Whilst some authors (e.g. Johan and Ohnenstetter 2010) cite Zn-enriched chromite as a diamond indicator mineral, Fig. 6 demonstrates that whilst Zn-chromites are found in kimberlites, they can also be attributed to other sources. Chromites sourced from metamorphosed komatiite and ophiolites overlap in composition with the exceedingly rare and likely epigenetic zincochromite inclusions in diamond, and can account for Mg-poor zincian chromites in regional NT samples. Cr contents can assist in discrimination but elevated Mg combined with Zn does not. Kalkarindji basalt chromites have not been metamorphosed and hence are Zn-poor. However, for tetrahedral-site cations (Fig. 6), the compositions of all NT Mg, Zn-rich chromites from surface sediment samples can be accounted for by Zn infiltration into basaltic chromite following the zonation trends of extreme Zn-enrichment demonstrated by Venezuelan samples (Johan and Ohnenstetter 2010). So whilst Timber Creek and Merlin zincian chromites form clear compositional fields, minerals sharing the same compositional space in regional samples cannot, per se, be taken as indicators of diamond potential.

Due to prolific Zn alteration, the Zn-in-chromite geothermometer of Griffin et al. (1994) cannot be applied to NT samples. Furthermore, Pooley (2004) concluded that difficulties in identifying altered from unaltered zones in chromites imposes limits on the usefulness of rapid screening methods to exploration samples. Additional minor and trace elements can, however, provide useful discriminatory criteria following the methods of Yaxley (2008). Trace element data (Hutchison 2011) for Timber Creek chromites plotted as $\log_{10}$(Ga/Nb) to $\log_{10}$(Co/V) fall neatly within the mantle array even for most of Zn-enriched grains (up to 9.7 wt % ZnO), whereas samples taken from outside the Merlin and Timber Creek Fields contain a component of crustal-derived compositions likely reflecting the interplay of

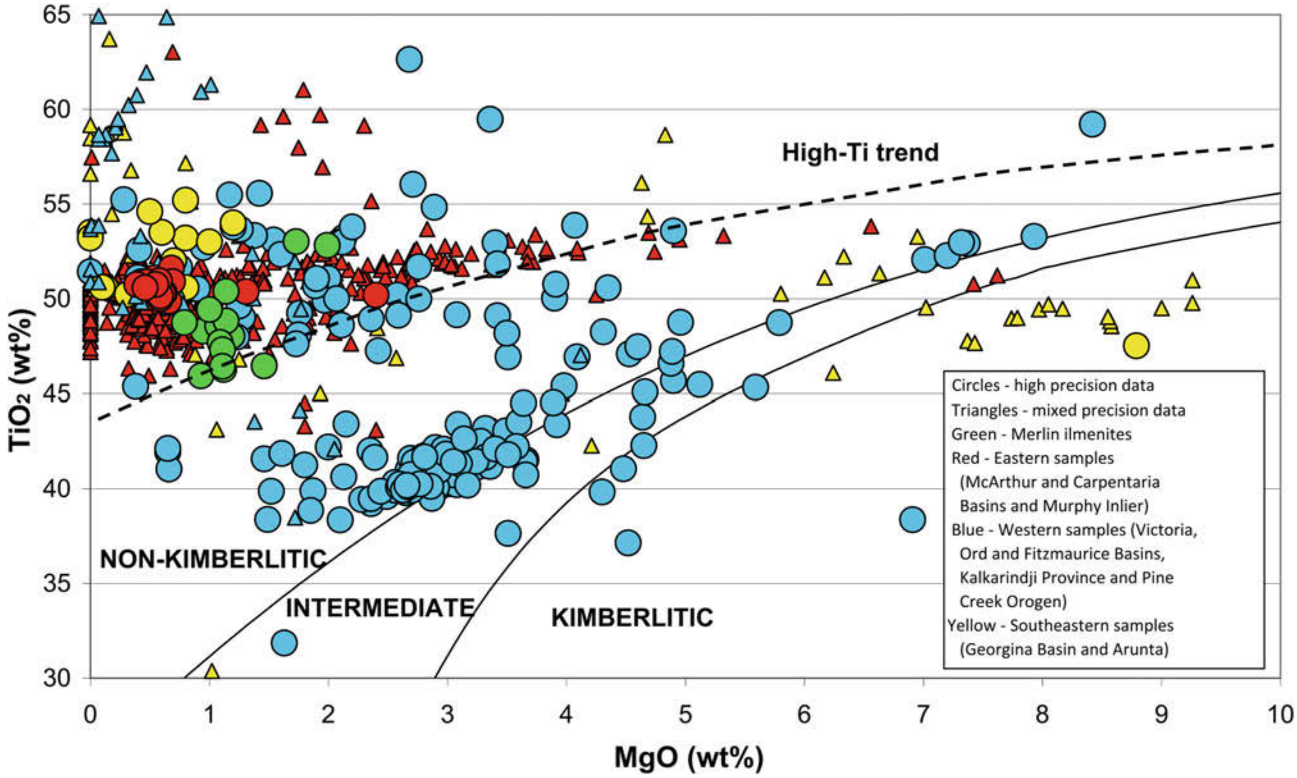

Fig. 7 Composition of ilmenite from Northern Territory samples, with labelled discriminatory fields after Wyatt et al. (2004). Consult key for localities and text for further discussion

different sources in regional samples. Hence despite Zn-alteration, trace element methods allow for discrimination between mantle and kimberlitic spinel from those of crustal origin.

Ilmenite. While ilmenite is common in surface sediment samples throughout the NT (Hutchison 2011), its abundance in known kimberlites is low. Figure 7 shows 1021 ilmenite Ti and Mg contents, subdivided according to analysis quality and geographic area. Among all of the high quality analytical data, dominantly from outside the Merlin and Timber Creek Fields, few ilmenites plot in the kimberlitic field of Wyatt et al. (2004). Furthermore, ilmenite sampled directly from the Merlin kimberlites also do not plot in the Wyatt et al. (2004) kimberlitic field, but rather considerably into the 'non-kimberlitic' field at elevated Ti relative to Mg. Eastern NT ilmenites, particularly from the McArthur Basin, follow a trend parallel to Wyatt et al.'s (2004) discriminatory boundaries but also at considerably higher Ti contents. In contrast, western NT samples follow a more typical magmatic trend close to Wyatt et al.'s (2004) intermediary field. This contrast between eastern and western NT ilmenites combined with observations of spinel compositions emphasises a pervasive eastern NT enrichment in Ti. Weathering can introduce Mn-substitution for Mg but in the case of high precision ilmenites from Merlin, the highest MnO content is 0.76 wt % and most grains have less than 0.4 wt % MnO. Outside known kimberlite fields, some, more Mn-rich ilmenites occur, but only 5 % of grains have MnO over 1 wt %, and then only marginally. Recalculating all Mn as Mg has little effect on where ilmenite compositions lie with respect to the fields of Wyatt et al. (2004), particularly for Merlin. Cr was only reported in three Merlin grains (Reddicliffe 1999), up to 0.22 wt % Cr_2O_3. However, ferropseudobrookite (an ilmenite weathering product commonly observed in mineral separates) may account for elevated Ti relative to Mg when occurring as micro-inclusions in analysed ilmenites.

Despite the paucity of ilmenite in known kimberlite pipes a number of samples taken from outside of known areas of in situ kimberlite have kimberlitic ilmenite chemistry. For example, six kimberlitic picro-ilmenites from the southeast Georgina Basin were reported by Leadbeatter (2006), the primary source of which is unknown.

Garnet Mantle-derived garnets, which are important in diamond exploration, are almost entirely absent in the NT outside kimberlite pipes (Hutchison 2011). The large majority of garnet analyses compiled in Hutchison (2011) are of very poor analytical quality, leaving 1796 stoichiometric analyses of largely unknown precision for further consideration. However, analytical precision has little impact on the classification of Cr-rich pyropes (Keulen et al.

2009), except for the Mn- or Na-based D-subdivisions based on known associations with diamond (Grütter et al. 2004).

Garnets from the Merlin Field (Reddicliffe 1999) closely follow the lherzolitic trend in Cr_2O_3/CaO space (Fig. 8). Many analyses fall into the G9 (lherzolite) compositional field of Grütter et al. (2004) however there are also many harzburgitic G10 garnets, some of which are sufficiently high in Cr_2O_3 to classify as G10D without recourse to Mn content. Compositions compare favourably with garnets from most Australian diamond-bearing bodies from outside of the NT (Ramsay 1992). Lucas et al. (1989) reported numerous striking examples of highly diamondiferous bodies from WA, mostly lamproites, where G9 garnets outnumber G10 s, sometimes to their exclusion. In such cases, G9 garnets likely represent a fertile mantle composition rather than shallow depths.

Other Indicator Minerals. Few other 'traditional' indicator minerals are reported from NT samples and fewer still with accompanying compositional analyses. Ten high precision analyses of Cr-diopsides were reported from the Gareth pipe of the Merlin Field (Reddicliffe 1999). A further 15 EDS-analysed grains are from the Emu 2 pipe (Stiefenhofer and McClenaghan 1994). All Merlin Cr-diopsides have compositions consistent with the garnet peridotite field of Ramsay and Tompkins (1994), in contrast to regionally derived samples whose distribution straddle the lower Cr fields, including those of crustal-derived samples. A single orthopyroxene grain from the Palomides pipe of the Merlin Field was reported by Reddicliffe (1999). This grain has 0.94 wt % Al_2O_3 and plots within the garnet megacryst field of Ramsay and Tompkins (1994). A single Launfal pipe-derived grain, also from Merlin, plots in the

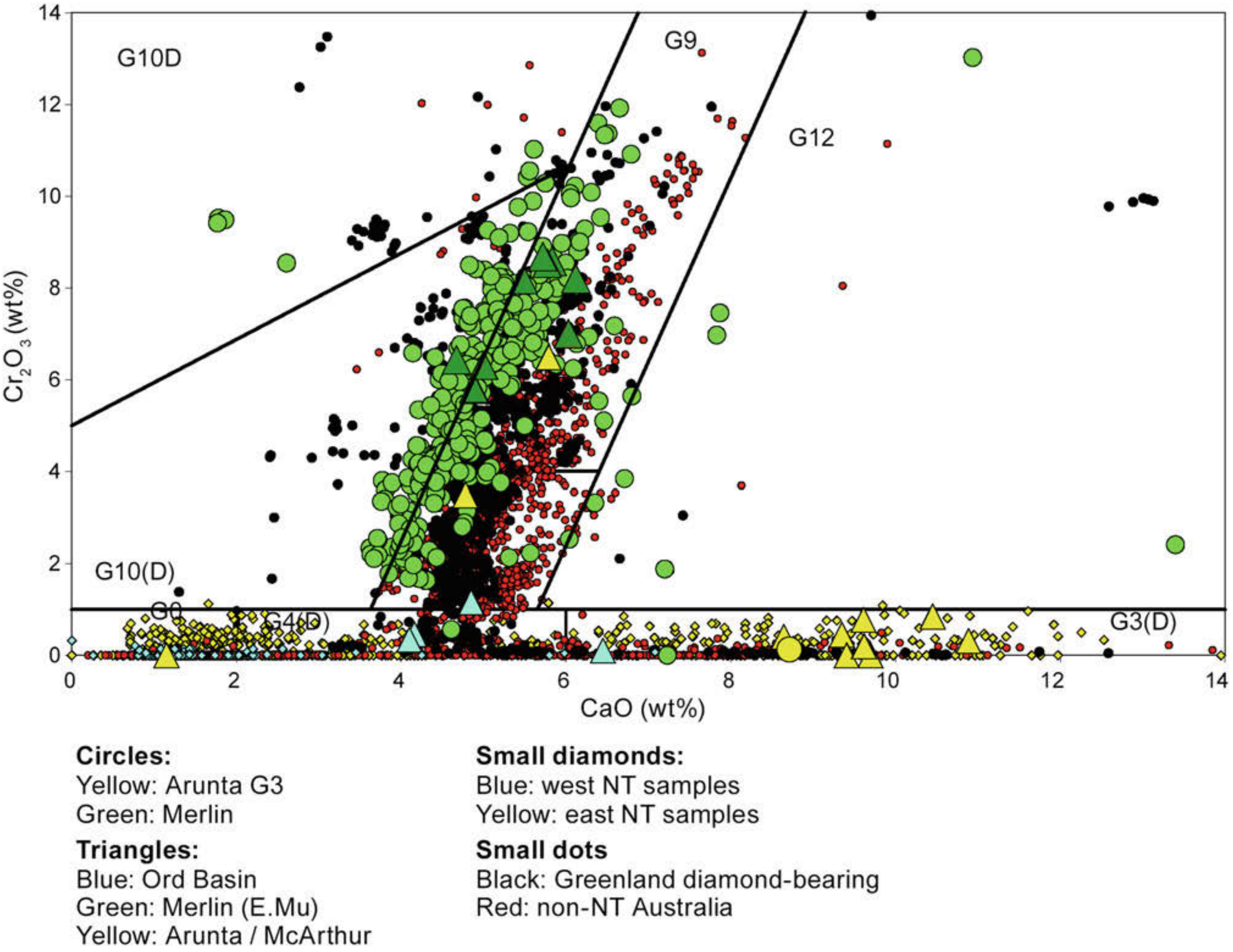

Fig. 8 Composition of garnet from Northern Territory samples (per key), with labelled discriminatory boundaries after Grütter et al. (2004). *Circles* are used for inferred and reported high-precision analyses, triangles for unknown precision or semi-quantitative analyses and small diamonds for garnets with crustal compositions. Background data are from un-weathered Greenlandic diamond-bearing kimberlites and aillikites (*small black circles*, Hutchison and Frei 2009) and non-NT diamondiferous kimberlites and lamproites (*small red circles*, Ramsay 1992)

garnet peridotite field. While no mantle xenoliths are reported from the NT some indicator minerals are fresh enough to be useful for geothermobarometric modelling. Applying the Al in orthopyroxene barometer of McGregor (1974) and the Ca in orthopyroxene thermometer of Brey and Köhler (1990) the Palomides orthopyroxene composition (Hutchison 2011) allows a pressure/temperature estimate of 3.89 GPa at 950 °C, corresponding to a depth of 116 km assuming a 41 mWm^{-2} geotherm (Chapman and Pollack 1977). A temperature of 950 °C corresponds well with the low temperature group of Merlin diamonds established by Lee et al. (1997) based on nitrogen aggregation. Also, the presence of higher temperature diamonds (Lee et al. 1997) implies that the Palomides orthopyroxene does not reflect maximum lithosphere thickness below Merlin, but rather the depth of final equilibration (and diamond formation) prior to kimberlite emplacement. Based on the high temperature diamond group at 1200 °C (Lee et al. 1997) and a 42 mWm^{-2} geotherm, an estimated diamond formation depth of 158 km is returned, which would be deeper assuming a cooler geotherm. A value of 158 km for the current lithosphere thickness below Merlin is consistent with regression of seismic tomography models of Fishwick et al. (2006). Merlin diamonds and mineral separates therefore reflect a multi-stage history of diamond formation and ponding before final emplacement in the crust.

Diamond Prospectivity Mapping

Data contributing to the ranking of regions based on sampling history are provided in Table 1. Contributing scores based on the criteria of relative age and lithosphere character and the final prospectivity scores are shown in Table 3. Final scores are also shown in Fig. 9 where NT geological regions are coloured based on their diamond prospectivity. The Fitzmaurice Basin, located in the northwestern quadrant of the NT (Fig. 1), close to the Timber Creek Field, scores best in terms of regional diamond prospectivity. This score is due to good sample recovery, and particularly because exposed bedrock is relatively old (1500–1800 Ma, Ahmad and Munson 2013) and lies over thick mantle lithosphere on a boundary with thinner lithosphere abutting the Kimberley Craton. The regions which host known primary diamond sources, namely the Birrindudu Basin (Timber Creek), the Georgina Basin (Merlin) and the McArthur Basin (Roper Field) all score reasonably well (2, 5 and 3, respectively). The old age and mantle lithosphere character particularly favour the Birrindudu Basin (1550–1780 Ma, Ahmad and Munson 2013) and the old age (1430–1800 Ma, Ahmad and Munson 2013) and positive sample recovery favour the McArthur Basin. The Georgina Basin (360–850 Ma, Ahmad and Munson 2013) returns a lower score because it contains younger cover rocks. Conversely, blocks of exposed Archean rocks score well (2). Although little sampling has been conducted in areas of exposed Archean rocks in the Northern Territory,

Table 3 Final and contributing diamond prospectivity scores for Northern Territory geological regions

Region	Final score[a]	Sampling	Age	Lithosphere
Amadeus basin	5	2	3	3
Arafura basin	5	3	3	2
Archaean	2	1	1	3
Arnhem province	2	2	1	2
Arunta region	4	2	2	3
Birrindudu basin	2	3	1	1
Bonaparte basin	4	2	4	1
Canning basin	6	2	4	3
Carpentaria basin	6	2	5	2
Daly basin	3	3	2	1
Eromanga basin	5	1	5	2
Fitzmaurice basin	1	2	1	1
Georgina basin	5	2	3	3
Halls Creek Orogen	4	3	1	3
Kalkarindji province	2	2	2	1
Lawn Hill platform	4	2	1	4
McArthur basin	3	2	1	3
Money Shoal basin[b]	10	5	5	3
Murraba basin	7	5	2	3
Musgrave province	7	5	2	3
Murphy inlier	4	2	1	4
Ngalia basin	4	2	3	2
Ord basin	3	2	3	1
Pedirka basin[b]	9	5	4	3
Pine Creek Orogen	2	2	1	2
South Nicholson basin	4	2	1	4
Tanami region	3	3	1	2
Tennant region	4	3	1	3
Victoria basin	3	3	2	1
Wiso basin	5	2	3	3
Wolfe basin	5	3	2	3

[a] Final Score is the sum of the three component scores normalised as an integer from 1 to 10. The three components have equal weight

[b] Scores poorly in part due to absence of sampling. This is largely due to the young age of the rocks, as reflected in age scores

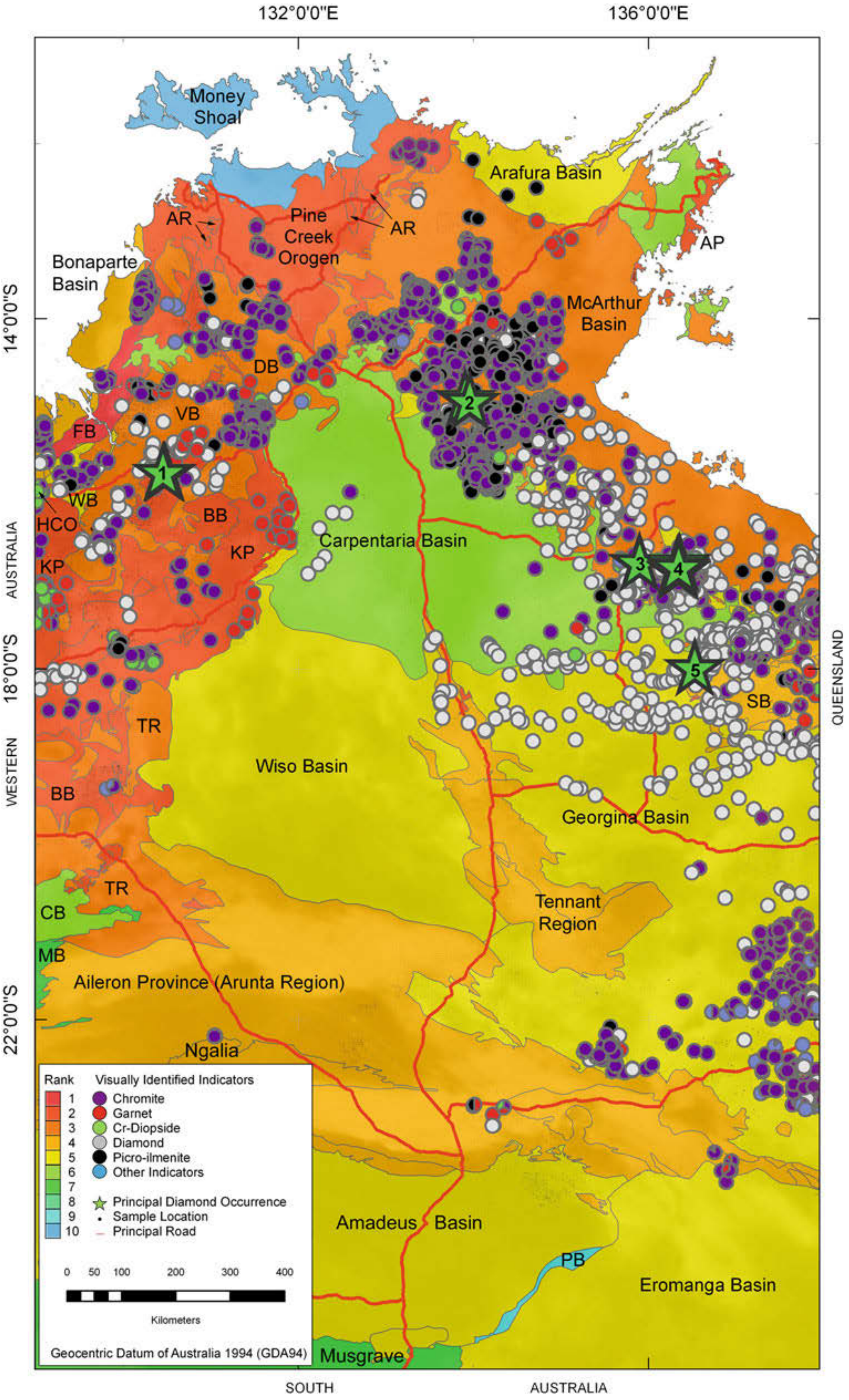

Fig. 9 Diamond prospectivity map of the Northern Territory of Australia. Geological regions are colour-coded based on their overall aggregate prospectivity as shown in the key, where a rank of 1 is most prospective. Principal geological regions are labelled and a full description of rankings for each region is provided in Table 3. Principal diamond fields are numbered (1) Timber Creek; (2) Roper; (3) Abner Range Breccia Pipes; (4) Merlin; (5) Coanjula microdiamond paleoplacer. Other abbreviations are *AP* Arnhem Province; *AR* Archaean Region; *BB* Birrindudu Basin; *CB* Canning Basin; *DB* Daly Basin; *FB* Fitzmaurice Basin; *HCO* Halls Creek Orogen; *KP* Kalkarindji Province; *MB* Murraba Basin; *PB* Pedirka Basin; *SB* South Nicholson Basin; *TR* Tanami Region; *VB* Victoria Basin; *WB* Wolfe Basin. The most prospective regions for diamonds lie to the outskirts of the NT primarily in the northern and eastern portion and in particular in the west sharing the border with Western Australia

the few results are good (28 % of samples returning positive indicator mineral recovery).

The prospectivity model presents a rigorous and measurable approach to diamond exploration, however, region-specific characteristics can have an important bearing on whether a region, or a specific part of a region can be considered to be a good target area. Such subtleties are discussed below.

Discussion

Mineral Sampling

In general terms, the sampling density in the Northern Territory is sparse even for a pristine weathering environment. Only three of 31 regions have been sampled on a better than regional-scale. Local-scale sampling has largely been restricted to areas where primary deposits are known or where earlier reconnaissance sampling has been positive. As indicator mineral sampling has been the principal method of regional exploration in the NT (other methods, including geophysics, largely being applied locally, Smith et al. 1990), the Northern Territory can be considered to be largely under-explored for diamonds.

There have also been some shortcomings in sampling methodology. In pristine environments, indicator minerals consistently are at least five times more abundant in the finer >0.25 to <0.5 mm fraction than the coarser >0.5 to <1 mm fraction (e.g. Kerr et al. 2000). The mineral that is most abundant in the finer fraction is chromite (~8:1). The dominance of indicators in fine fractions is therefore expected to be even more apparent in a weathered environment such as the NT. Chromite is also the only traditional non-diamond indicator which survives more than ~1 km from source in the NT (Atkinson 1989). However, the coarse >0.425 to <1 mm fraction has been the second most common size range utilized for indicator extraction in NT samples, and is expected to exclude over 75 % of chromite grains. False negative results should consequently be expected amongst historical exploration data, including for samples from the Georgina Basin (host to the Merlin Field), McArthur Basin (host to the Roper Field) and Victoria Basin (downstream from the Timber Creek Field). With the median indicator recovery being 0.046 indicators per kg, and diamond often being more abundant than non-diamond indicators in alluvial samples, collecting large samples (>50 kg) and picking from <0.425 mm fine size fractions is crucial.

Diamond as an indicator mineral. In contrast to the paucity of traditional indicator minerals even in local-scale sampling, the abundance of microdiamonds in the eastern parts of the NT (Fig. 4) presents its own challenges. Taken at face value, microdiamonds may be misleading in an attempt to identify primary sources. They travel long distances by wind, so tracing back to source is difficult and microdiamonds from primary sources are likely to be masked by those derived from weathering of the palaeodeposit at Coanjula (Lee et al. 1994). However, the variation in the diamond characteristics from and amongst different fields in the NT suggests that more information on recovered diamonds, such as morphology, colour and spectral characteristics, should be integrated into an exploration strategy. A similar approach has been taken by Neilson et al. (2012) in unravelling overlapping indicator mineral trains amongst mantle-derived garnets. Merlin and Timber Creek Field diamonds can be distinguished from each other based on morphology, colour and size distribution. Outside these areas, cubes which cannot be attributed to primary sources, are common in surface sediment samples. Many of these diamonds may share the same derivation as those comprising the Coanjula microdiamond occurrence (Lee et al. 1994). It is thus important to determine the characteristics of any diamonds recovered from exploration samples.

The observation that microdiamonds are not pervasive in surface sediment samples in western parts of the NT may be attributed in part to the common occurrence of black soil plains where drainage is very poorly developed thus inhibiting efficient diamond distribution and sampling (May et al. 2011). However, microdiamond clusters do occur in western NT so that they are evidently transported in some regional drainages. This supports their use in regional exploration in the west, with the caveat that, as for non-diamond indicators, large samples are required. Deakin et al. (1989) conclude that in WA, average weight per stone decreases by 50 % over ~17 km from source. A 50 % reduction in weight is equivalent to a reduction in diameter of only ~20 %. Hence it can be expected that no significant change in size fraction sampled from local to reconnaissance (10 km +) scales are necessary. However, as macrodiamonds show much better correlations with distance to source than microdiamonds, larger size samples are necessary to increase the chances of recovering rarer, larger diamonds.

Increasing sample sizes is costly, with regard to both collection and processing, and in the unfavourable weathering environment of the NT, the returns are questionable. The reliance on traditional indicators as the dominant diamond exploration tool in the NT has been very significant and alternative exploration approaches may be necessary.

Traditional and alternative indicators other than diamond. In the NT, abrasive weathering (which affects ilmenite and spinel more than garnet) combines with chemical weathering (facilitated by wet conditions, which strongly affects garnet). When ilmenites are weathered, the elevation of Ti content of kimberlite-derived ilmenites from the NT necessitates raising the Ti cut-off for candidate ilmenites. By doing so, one naturally would expect to introduce considerably more crust-derived ilmenite perhaps leading to false positives, particularly as kimberlite-derived ilmenites do not survive far from source. Spinels are also demonstrably altered (Zn-rich) in surface sediment samples (Fig. 6), again necessitating a wider compositional range than would be ideal to exclude crustal spinels. When garnets are found, they show considerably less alteration, however, they almost never survive outside of their primary sources.

Other, non-traditional indicator minerals could be used for diamond exploration in the NT. The most common alternative minerals are zircon (Meyer and Svizero 1973; Mitchell 1986, p. 264; Fipke et al. 1995; McInnes et al. 2009), corundum (Hutchison et al. 2004), rutile (Mitchell 1986, p. 266), kyanite (Prinz et al. 1975), tourmaline (Fipke et al. 1995) and andradite (Smith 1984). All have the advantage of being more resistant to weathering but kimberlitic-derived grains may be swamped by grains from non-kimberlitic sources. Advances in rapid, automated identification and quantification techniques such as discussed by Keulen et al. (2009) have the potential to circumvent or at least reduce the impact of high relative abundance of background minerals. Of the non-traditional minerals, perhaps one of the more promising is zircon, where crust or mantle-derived igneous rocks such as granites or basalts are absent. Kimberlite-derived zircons can be identified based on low U-content, short fission tracks and their radiometric ages, as determined by low cost laser ICPMS (U-Th)/He geochronology (McInnes et al. 2009). Dating relies on a good understanding of the regional geology, however, and also requires expensive ion microprobe characterisation of regional zircons.

As an alternative, Nb-rich rutiles show promise, having been occasionally reported as discrete crystals and megacrysts intergrown with ilmenite in kimberlites and Australian lamproites (Mitchell 1986, p. 267; Fipke et al. 1995). Such rutiles have distinctive visual characteristics (e.g. being jet-black in colour) that can be applied as a precursor to chemical determination and they can be discriminated from crustal Nb-rutile when they have elevated Cr_2O_3 (>1 wt %, Mitchell 1986, p. 287; Cooper et al. 2008). Nb-rutile has been identified in NT surface sediment samples in surveys that have specifically targeted this non-traditional indicator mineral (e.g. Leadbeatter 2006). Otherwise, while routinely reported (as compiled in Hutchison 2011), the non-traditional indicators exist in collected samples but have not been fully scrutinised by NT diamond explorers to date.

Bulk Chemical Exploration Methods

Recognising that diamond-bearing rocks are highly weathered, and indicator minerals (with the exception of diamond) are generally extremely compromised, Singh and Cornelius (2006) used regolith geochemistry for exploration at the Aries pipe, WA. They concluded that Cr, Co, Nb, La, Sm and P can readily distinguish kimberlites from other ultramafic rocks and certainly most country rocks. While necessitating sampling above or close to a near-surface kimberlite, the technique is low cost (about two orders of magnitude lower than indicator picking) so the distance between samples can be 1/10th of what is required for indicator sampling.

The differences in bulk chemistry, particularly the alkali component, between kimberlitic pipes and surrounding country rocks, can promote contrasting and sometimes luxuriant vegetation above pipes. For example, Alexander and Shrivastava (1984) demonstrated that in Central India trees of certain species are taller and considerably denser above the Hinota kimberlite, to the extent that the pipe can readily be identified in aerial photographs. Geobotanical techniques have been applied in the NT. Reddicliffe (1999) described a similar survey at Merlin, using geochemical analyses of new growth tips of spinifex grasses. Samples from the immediate vicinity of the pipes were clearly anomalous in Ba, Ni, Pb, Ce, La, Pr and Nb. Reddicliffe (1999) reported that amongst tests of bacterial leach, enzyme leach, gas vapour phase geochemistry and vegetation geochemistry analyses conducted at Merlin, the spinifex survey gave the most definitive results. As for soil geochemistry sampling, spinifex samples must be taken immediately above the primary body. Hence, sampling density must be suitably high to account for the expected size of the target body. The cost of a high sample density is mitigated, however, by simple sample collection, very low sample weights, and low analytical costs.

Another biological approach, which has yielded good results in southern Africa is termite mound sampling (Lock 1985), either by mineral separation or bulk chemistry. Minimal sampling of this nature was carried out in the NT (compiled in Hutchison 2011). Only 123 samples are reported and of these, 111 were processed for bulk chemical analysis of the <0.177 mm fraction. Despite the abundance and high density of termite mounds in the NT, the technique is very much under-utilised.

Geophysical Exploration Methods

Geophysical techniques are commonly used world-wide for diamond exploration and have seen sporadic application in Australia. Drew and Cowan (1994) report poor pipe resolution using airborne, ground and downhole magnetic and electromagnetic methods at Argyle, WA. However, at the Ellendale Field in WA, the quiet background geology resulted in the diamond-bearing lamproite pipes standing out very clearly in magnetic surveys (Jenke and Cowan 1994). A few regional studies have been conducted in the NT (e.g. Jaques and Milligan 2004). However, geophysical techniques have mostly been applied as a follow-up to surface sediment sampling (Fried 1990; Smith et al. 1990; Berryman et al. 1999; Reddicliffe 1999). While Timber Creek bodies do not show up on satellite imagery, aerial photography, ground and airborne magnetics, nor on input EM (Berryman et al. 1999), geophysical exploration at Merlin has been more successful (Reddicliffe 1999). The distinct advantages of geophysical techniques are the coverage of large areas at relatively low cost and that they can be integrated with exploration for other commodities. In light of the considerable complexities of indicator mineral exploration, significant potential lies in the use remote-sensing techniques.

Regional Prospectivity

The prospectivity of regions of the NT has been ranked using measurable variables, although other qualitative factors can also contribute to a region's attractiveness. These include geological considerations and infrastructure and socio-political issues. Relevant issues in the NT relate to Commonwealth National Parks, Aboriginal sacred sites and areas subject to the Aboriginal Land Rights Act (NT) 1976 (ALRA).

Table 4 summarises the principal issues that may modify the quantitative ranking of regions or parts thereof documented in Table 3. Each region has a positive, negative or no adjustment, based on the balance of factors considered to be important and separated according to geological or logistical considerations. Due to the numbers of variables involved and their qualitative characteristics, a numerical change to prospectivity ranking shown in Table 3 is not implied.

Particularly noteworthy geologically is that the Fitzmaurice Basin yielded two microdiamonds recovered from catchment areas with no known primary diamond source. A nearby sample contained 76 garnet-peridotite chromites. Floodplain sediments with large catchment areas are abundant in the Fitzmaurice Basin, complicating exploration. A similar microdiamond anomaly (evident in Fig. 4), with no known source, appears in the southern part of the Victoria Basin. These indicator mineral observations emphasise the significance of the NT's western border with WA as a diamond exploration target area. In central northern NT, the area surrounding the Mount Bundey lamprophyres, which are not diamondiferous themselves (Sheppard and Taylor 1992), holds promise. Highly prospective chromite chemistries and diamonds occur in numerous surface sediment samples with no known source.

Remoteness has a particular bearing on the parts of the Amadeus, the Eromanga, Murraba and Wiso Basins, the Lawn Hill Platform and the Musgrave Province, whereas the Pine Creek Orogen is particularly well served with mining-related infrastructure.

Summary and Conclusions

Diamond exploration in the Northern Territory has been dominated by sampling for indicator minerals from surface sediments. Other geochemical techniques and geophysical methods have usually contributed to local follow-up programs. In almost all cases, traditional indicator minerals chrome-spinel, picro-ilmenite, pyrope garnet, Cr-diopside and diamond have been utilised. However, due to considerable weathering only chromite and diamond survive outside their primary sources and even then, chromite degrades within a maximum of ~10 km of source.

Regionally, sample density has been low, even in the more highly prospective areas such as the Archean inliers, although around known bodies or particular indicator concentrations, some local exploration has been intense. On the whole, the Northern Territory is considerably under-explored for diamonds.

Whilst surface sediment sampling, based on current stream sediments, has often been rigorous, the poor survival of indicators means that often sample sizes of ~40 kg are insufficient. The median recovery of non-diamond indicators in indicator-positive samples is low at 0.046 per kg, i.e. approximately one indicator per 25 kg. This problem is exacerbated by the fact that while the size range >0.3 to <0.5 mm is the most commonly reported picking range, some 17 % were examined only in the >0.425 to <1 mm fraction. Even for pristine environments, omitting grains under 0.5 mm excludes ~90 % of chromites. Hence small exploration samples are made more marginal in cases where size fractions are too coarse. This methodology has doubtless led to a number of false negatives. Future sampling programs based on traditional indicator minerals will require considerably larger samples and size fractions ideally down to ~0.2 mm. Once a nearby source has been inferred, local surveying can utilise smaller samples size (around 25 kg) but with the same, small ~0.2 mm lower picking cut-off.

Table 4 Principal non-quantifiable geological factors influencing regional prospectivity, and practical considerations

Region	Score[a]	G[c]	P[d]	Contributing criteria[b]
Amadeus basin	5	nmc	−ve	Parts are remote with some locations being ∼280 km from the nearest main road
Arafura basin	5	nmc	−ve	Large areas subject to ALRA
Archaean	2	+ve	−ve	Whilst not from exposed Archaean rocks, samples from the neighbouring Pine Creek orogen have highly favourable chromite in diamond chemistry spinels. Large areas subject to ALRA
Arnhem province	2	nmc	−ve	Large areas subject to ALRA
Arunta region	4	nmc	nmc	Favourable mineral chemical data available for spinel, clinopyroxene and garnet with garnet being mantle G3 composition. Aeolian cover is abundant
Birrindudu basin[e]	2	even	nmc	Presence of known diamondiferous kimberlite bodies and also large-scale faults provide a potential pathway for mantle-derived rocks. Garnets described as indicators have not been chemically analysed and may be sourced from country rocks
Bonaparte basin	4	+ve	nmc	Abundant Cr-spinel in coastal samples with garnet peridotite field chemistry
Canning basin	6	nmc	+ve	Despite being under-sampled and on the western border of the NT, the basin has reasonable road access being no more than 140 km away from a main road at any point
Carpentaria basin	6	+ve	+ve	Occurrence of chromite in diamond composition spinel-bearing samples. Some Cretaceous cover may be thin enough to allow identification of shallow-buried kimberlites by remote techniques. Despite being a large region, main road coverage is reasonably good
Daly basin	3	−ve	nmc	No mineral chemical data has been derived from any visually determined indicator minerals
Eromanga basin	5	−ve	−ve	Thin in places, implying that any sub-basin primary diamond sources may be accessible. The underlying Pedirka basin is also young mitigating most of the advantages of thin Pedirka sediments. Aeolian cover is abundant. The basin is remote with some locations being ∼380 km from the nearest main road
Fitzmaurice basin[f]	1	−ve	nmc	Abundance of floodplain sediments sourced from a large catchment area
Georgina basin	5	+ve	nmc	Presence of known diamondiferous kimberlite bodies associated with large-scale and pervasive crustal weaknesses. Macro-diamonds and ilmenites, clinopyroxenes and Cr-spinels determined to have favourable chemistry are known
Halls Creek orogen	4	+ve	nmc	Host to the highly diamondiferous Argyle AK1 pipe currently mined across the border within Western Australia
Kalkarindji province	2	−ve	nmc	A single recovered macro diamond and a cluster of garnet peridotite field Cr-spinels and orthopyroxene and intermediate-composition ilmenites are reported. Heavily explored geophysically anomalous locations in the northern extent of the principal outcrop of the Kalkarindji have all proven negative for diamonds. Spinel indicators determined only visually are quite likely to be a component of the Kalkarindji basalts
Lawn Hill platform	4	nmc	−ve	Remote, some locations being ∼220 km from the nearest main road
McArthur basin	3	even	nmc	Presence of known diamondiferous kimberlite bodies. Macro diamonds occur at numerous locations with no apparent primary source. Recovery of G9 and G11 garnets in reconnaissance samples is encouraging. Visually identified garnets reported by Stockdale from early 1970s sampling may be laboratory contaminant. Limmen National Park comprises a small part of the basin
Money Shoal basin[g]	10	nmc	+ve	Relatively good road infrastructure and an extensive coastline
Murraba basin	7	+ve	−ve	Scores poorly in part because it is unsampled. However rocks are reasonably old making a case for some exploration. The Murraba Basin is remote with some locations being ∼210 km from the nearest main road. Large areas are subject to the ALRA
Musgrave province	7	+ve	−ve	Scores poorly in part because it is unsampled. However rocks are reasonably old making a case for some exploration. The province is remote with some locations being ∼210 km from the nearest main road. Large areas are subject to the ALRA
Murphy inlier	4	nmc	nmc	No modifying comments
Ngalia basin	4	nmc	nmc	No modifying comments

(continued)

Table 4 (continued)

Region	Score[a]	G[c]	P[d]	Contributing criteria[b]
Ord basin	3	+ve	nmc	Abundant clinopyroxene grains with prospective garnet peridotite field chemistry
Pedirka basin	9	nmc	nmc	No modifying comments
Pine Creek orogen[h]	2	nmc	even	Well developed exploration and mining infrastructure. Presence of highly prospective chromite in diamond chemistry spinels associated with lamprophyre dykes. Large tracts are assigned National Park status as Kakadu National Park
South Nicholson basin	4	−ve	nmc	Whilst some macrodiamonds are known, these are likely associated with the known Coanjula diamond source
Tanami region	3	nmc	+ve	Two samples returned Cr-spinels with chromite inclusion in diamond chemistry. Despite being close to the border with Western Australia and distant from population centres, the Tanami region is crossed by a main road. Aeolian cover is abundant
Tennant region	4	even	+ve	Benefits from being intersected by the main NT-SA arterial road and rail routes and lamprophyres are abundant (Duggan and Jaques 1996). Aeolian cover is abundant. Positive microdiamond recovery is likely influenced by the regional eastern NT microdiamond background and is not expected to have a local source. No macro diamond nor any non-diamond indicators are known from the Region
Victoria basin	3	even	nmc	Numerous diamond-positive samples, some being macro diamonds and not associated with known primary diamond deposits. Micro-diamonds and possibly some macrodiamonds recovered may have been sourced upstream from the Birrindudu Basin at Timber Creek. Garnets described as indicators have not been chemically analysed and may be sourced from country rocks
Wiso basin	5	−ve	−ve	Aeolian cover is abundant. Remote, with some locations being ~220 km from the nearest main road
Wolfe basin	5	−ve	+ve	Bisected by a main road and also has river access. None of the visually identified indicator minerals have been verified chemically

[a] Final score from Table 3

[b] Black text represents factors enhancing a region's attractiveness for exploration, text in red represents factors diminishing a region's attractiveness for exploration

[c] Modifications based on geological considerations

[d] Modifications based on practical considerations (access, infrastructure and socio-political factors). *nmc* No modifying comments

[e] Part of Birrindudu Basin is designated as the Gregory National Park however as a Territory Park, exploration is permitted

[f] Part of the Fitzmaurice Basin is proposed as an extension to the Keep River National Park however as this is designated as a Territory Park, exploration is permitted

[g] Much of the area is designated National Park (Garig Gunak Barlu) however as a Territory Park, exploration is permitted

[h] Litchfield and the proposed Mary River National Parks are Territory Parks which allow exploration activities. *ALRA* Aboriginal Land Rights Act (NT) 1976

The abundance of microdiamonds, on average being greater than the number of non-diamond indicators in alluvial samples, further complicates the exploration picture. This is particularly the case in eastern NT where the ubiquity of microdiamonds introduces background noise. It has been demonstrated that microdiamond recoveries from much of the eastern NT can be misleading as a regional exploration tool, specifically without careful examination of physical and chemical attributes of the microdiamonds. Their efficacy is greater in the west, where their presence is not ubiquitous, however as a rule, macrodiamond recoveries provide much stronger clues to nearby sources.

Spinels often have a Zn alteration and are typically lower in Ti than would be preferable in exploration programs. Kimberlite-derived ilmenites are elevated in Ti relative to Mg, placing them outside of the commonly used kimberlite field of Wyatt et al. (2004). Finally garnet populations, whilst almost non-existent outside pipes, show respectable numbers of G10 garnets (after Grütter et al. 2004). G9 types may also derive from diamondiferous sources as is the case for the Merlin Field.

The diamond prospectivity of the geological regions of the NT has been assessed quantitatively based on sampling density and indicator recovery, relative age of country rocks and mantle lithosphere thickness and structure. Quantitative assessments have been further qualified based on knowledge of sampling quality and the specific nuances of indicator survival and chemistry discussed above. The western border of the NT with WA and its eastern border with Queensland and north into Arnhem Land are geologically most prospective. The Fitzmaurice Basin, in the catchment of the Timber Creek kimberlite Field, ranks highest and a number of microdiamond anomalies with unknown sources exist in this and neighbouring areas.

The dependence on traditional indicators for diamond exploration in the NT contrasts with their paucity in surface sediment samples under the conditions of NT weathering. Hence advances will likely be achieved more through non-traditional phases such as zircon and Nb-rutile than established pathfinder minerals. Realistically, it is expected that future diamond exploration in the NT would benefit by cost-sharing on projects funded predominantly for other commodities. Such an approach has the advantage that useful regional geophysical methods and some geochemical techniques, which have direct application to other commodities, require little modification to achieve concurrent goals in diamond exploration.

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