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DIAMOND EXPLORATION AND PROSPECTIVITY OF THE NORTHERN TERRITORY OF AUSTRALIA

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INTRODUCTION

Australia contributed 7% of global rough diamond production by weight in 2010 (https://kimberleyprocessstatistics.org). All currently producing Australian mines are associated with Proterozoic mobile belts surrounding the Kimberley Basin in Western Australia (WA) and diamondiferous kimberlites are also known from locations within the basin itself (Jaques and Milligan, 2004). The neighbouring Northern Territory (NT) hosts some 2,200 km^2 of exposed Archaean rocks and over half a million km^2 of Palaeoproterozoic rocks, comprising around 40% of the area of the Territory. Similarly to Western Australia, much of the Northern Territory's orogenic belts and sedimentary basins are understood to be underlain by thick Archaean lithospheric mantle (Graham et al., 1999; Hollis et al., 2011) providing the conditions necessary for the formation of diamond. Indeed 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. Outside of the areas of exposed Archaean and Palaeoproterozoic rocks, most younger basins in the Northern Territory predate or overlap the age range of known kimberlitic-rocks which are dated as being as young as 179 Ma (Belousova et al., 2001). Hence only vegetation and float are expected to cover the majority of extrusive kimberlitic bodies existing throughout the NT. Both theory and precedent therefore exist in support of future economic diamond discoveries in the Northern Territory.

The Northern Territory benefits from having experienced continuous diamond exploration since the early 1970s, generating over 700 publicly available company reports comprising sampling data (references available via http://apps.minerals.nt.gov.au/strike). This study examines 76,965 individual diamond exploration samples recovered within the Northern Territory, incorporating both available company reports and academic sources of data, particularly Reddicliffe (1999) and compiled in Hutchison (2011). Data include accounts of visually determined non-diamond mineral grains characterised as indicators (54,056 grains), chemically-defined indicators (5,246 grains), diamond crysts (17,752 classified as macros and 6,932 micros), diamond descriptions and major, minor and trace element mineral chemical analyses both of indicators and background grains. Data have been interpreted with an eye to contemporary mineral classifications and Australia-specific models. The data, subject to quality assessment, represents a valuable resource for examining approaches taken to exploration, assessing the merits of different procedures and developing an understanding of the mantle origins, mineralogical context, surface distribution and survival of NT diamonds and their mineral indicators. The ultimate aim of the study has been to recommend exploration strategies specific to the NT and more generally in the context of similar, heavily-weathered tropical settings.

METHODOLOGIES

SAMPLING METHODOLOGIES

Regolith distribution in the NT is reflected in the sampling distribution where alluvial samples contributed to 65% of the total followed by loams (24%) then soils and rock samples contributing 4% each. Where data for maximum grain size were recorded (35,784 samples) 91% were collected either at -2, -4 or -1 mm in decreasing order of prevalence. Where minimum grain size was also reported, the most popular size range subsets used for indicator mineral picking (constituting 52% of 6,096 samples), in decreasing order of importance were -0.5+0.3 mm, -1+0.425 mm and -1.2+0.25 mm.

ANALYTICAL TECHNIQUES

Sample treatment, mineral identification and description and mineral chemical determinations were conducted by commercial laboratories and academic research facilities using a variety of techniques. Major and minor element chemical data were acquired using low and high precision EDS and high precision WDS micro-analyses. Assessment of mineral chemical data has erred on the side of caution and a total of 15,315 mineral major / minor chemical analyses were determined to be useable for rigorous mineral classification.

Determining Regional Prospectivity

Regional prospectivity has been determined with the following principles in mind: extent and success of prior sampling in identifying indicator minerals, age of regional geology compared to emplacement of known primary diamond deposits and mantle lithosphere thickness and structure.

Sampling Ranking

In order of decreasing prospectivity, sampling history was scored as follows where ρ represents the percentage of samples with positive indicator recovery (including diamond), determined visually and δ represents sample density:

1 - underexplored / good recovery: $\delta < 1$ per100 km^2, $\rho > 5\%$
2 - regional sampling / good recovery: $\delta < 1$ per 4 km^2, $\rho >$ 5%; or underexplored / poor recovery: $\delta < 1$ per 100 km^2, $\rho < 5\%$
3 - detailed sampling / good recovery: $\delta > 1$ per 4 km^2 and $\rho >$ 5 %; or regional sampling / poor recovery: $\delta < 1$ per 4 km^2, $\rho < 5\%$ positive recovery
4 - detailed sampling / poor recovery: $\delta > 1$ per 4 km^2, $\rho < 5\%$
5 - no sampling undertaken.

Age Ranking

Cover can present a significant impediment to the discovery and economic potential of a primary diamond deposit. An emplacement age of a primary diamond source younger than any of the rocks within the Region / Province within which it is emplaced maximises the chance of a surface expression. Only unconsolidated cover and vegetation will mask a surface expression and a surface indicator halo may be expected as a result of weathering and transportation. Age ranges for NT Regions and Provinces (Fig. 1a) were ranked as follows:

1 - Age range > all regional diamond-bearing rocks known
2 - Age range > all Northern Territory kimberlites
3 - Average age > Merlin emplacement age of 363.5 Ma
4 - Average age between Timber Creek (179 Ma) and Merlin
5 - Average age < Timber Creek kimberlites.

Lithosphere Ranking

Old, thick, continental, mantle lithosphere typical of Archaean cratons and extensive Palaeoproterozoic terranes often provide the necessary conditions for formation of diamonds. Transportation of diamonds by means of kimberlites, lamproites and related rocks to the Earth's surface is facilitated by deep, large-scale structures such as terrane sutures and craton edges (Jaques and Milligan, 2004). Australia benefits from an extensive seismic array providing data suitable for modeling mantle lithosphere thickness and structure to a fine scale (Fishwick et al. 2006). Such models, of which the 200 km depth section shown in Fig. 1b is an example, have been used to rank areas within the NT favouring thick mantle lithosphere and particularly edges and boundaries between thick mantle lithosphere blocks. A ranking score has been assigned to each Region / Province based on the average score represented in Fig. 1b present within each.

The three scores for each Region / Province were added and the final rankings normalised to a score out of ten where one is most prospective. Resultant scorings are shown in Fig. 1c.

RESULTS

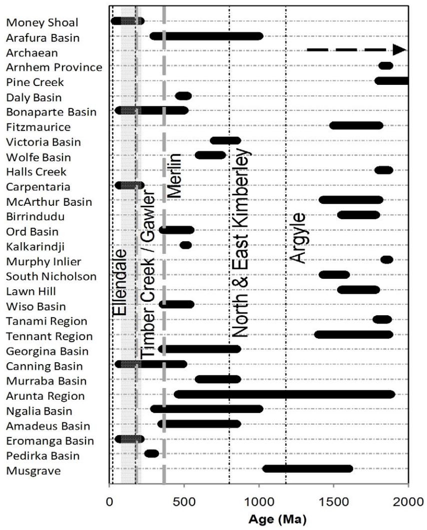
Indicator Mineral Recovery

Where heavy mineral concentrate weight was reported (n = 1,982) coarse-grained samples and in order of decreasing recovery, rock (4%), alluvial (0.3%) and loam (0.05%) samples yielded the best indicator mineral recovery. Figures in parenthesis are modes of heavy mineral concentrate weight.

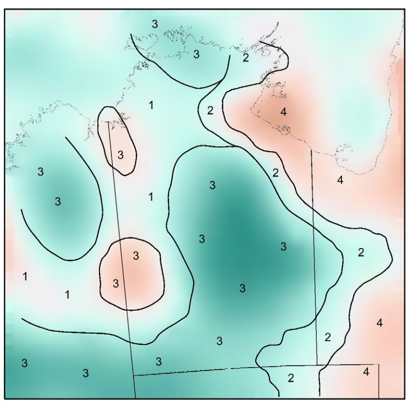
Few samples have been treated for both indicators and diamonds. However where this is the case and sample weight data is also reported (n = 150) non-diamond indicator concentrations fall typically at four times diamond concentration with the relationship being clearest for alluvial, then loam and finally rock samples reflecting the degree of sorting. Much more data is available for samples where weights have not been recorded and hence concentration cannot be calculated. For such samples which are diamond-positive (n = 1,470) and where both non-diamond indicator and diamond recovery > 1, only three samples of 64 have a ratio of non-diamond indicators to diamond over 100 (Fig. 2). In fact twelve samples in this category yielded more diamonds than indicators. Whilst there is quite a spread in the data, on the whole, loam and rock samples have similar, higher ratios of non-diamond indicators to diamond than alluvial samples. This latter observation is interpreted as reflecting the poor survival of indicators any significant distance from source, particularly where water is involved in transportation and also the background of micro-diamonds prevalent in the eastern NT where most samples were acquired. These findings support those made particularly during exploration at Merlin (Reddicliffe, 1999). On the whole the relative abundance of non-diamond indicators to diamond is much lower than for samples from for example an Arctic weathering environment where till sampling data from Armstrong and Chatman (2001) show an average of non-diamond indicators / diamond of 107.

The large majority of indicator minerals which survive are spinels which satisfy the criteria of being durable in the deep weathering environment imposed throughout the Caenozoic. Few other indicator phases survive in surface sediment samples however garnet, diopside, ilmenite, olivine, Cr-pseudobrookite, orthopyroxene and monticellite with indicator chemistries have all been recovered from mineral separates.

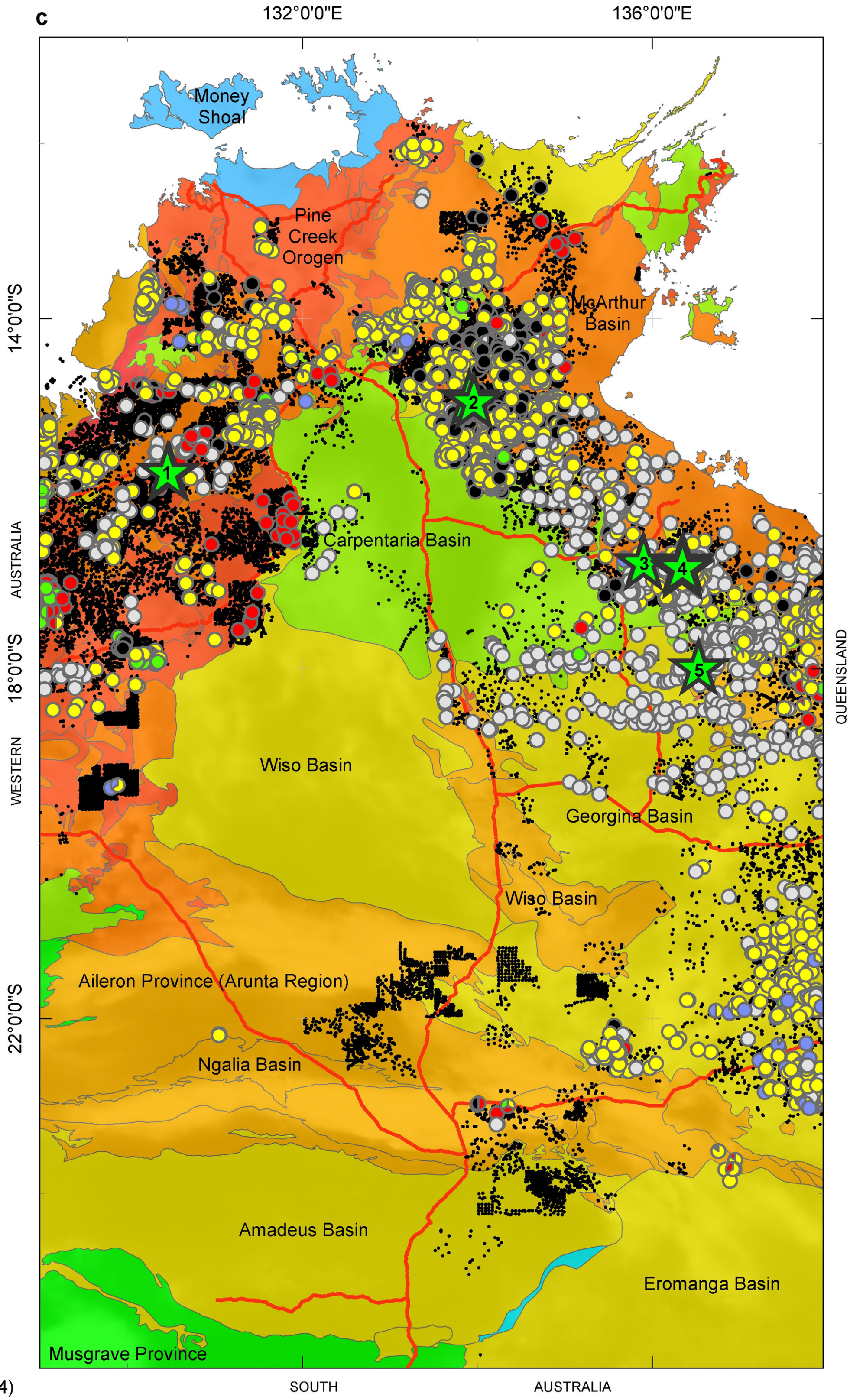
a



b



c



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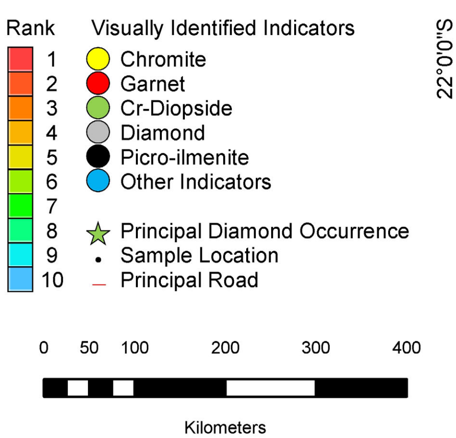

Geocentric Datum of Australia 1994 (GDA94)

Fig. 1 Diamond Prospectivity of the Northern Territory. **a:** Age ranges of Regions / Provinces in the NT in the context of emplacement ages of primary diamond occurrences. Heavy, dashed lines:- NT kimberlite emplacement ages; Light, dashed lines:- WA and South Australia diamond-hosting kimberlites and lamproites; Grey rectangle - Age ranges of NT Roper field kimberlites from 65-250 Ma; Dashed, heavy, black arrow:- the age range of Archaean rocks lies off the chart scale and extends from 2510-2674 Ma. Province and Region ages from Ahmed and Munson (in prep.), emplacement ages from Jaques and Milligan (2004). **b:** S-wave velocity modeled at 200 km modified after Fishwick et al. (2006). Projection is simple conic on 134°E with the NT boundary shown for scale. Dark green represents fast s-waves hence relatively cold, refractory and thick lithosphere, grading to brown being the converse. Numbers indicate the order of priority given to various areas with preference given to thickest mantle lithosphere and specifically thicker, transitional regions lying between such areas. **c:** Summary of prospective Regions and Provinces in the context of sampling and visually-determined indicator occurrence. Areas are ranked according to the key with 1 being most prospective. Numbered diamond occurrences (green stars): 1- Timber Creek; 2- Packsaddle & Blackjack kimberlites (Roper Field); 3- Abner Range kimberlites; 4- Merlin kimberlites; 5- Coanjulla micro-diamonds (secondary).

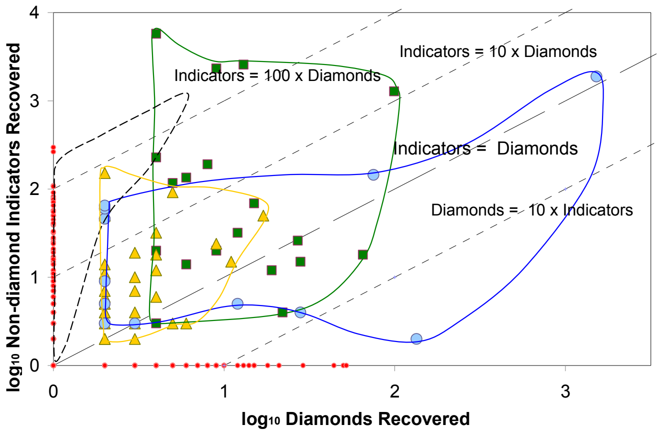

Fig. 2 Relationship between non-diamond indicators and diamonds recovered from individual samples. Fields for NT samples are based on yields of > 1 non-diamond and > 1 diamond recovered, considered to be more reliable data; Blue symbols / field:- alluvial samples; Yellow symbols / field:- loam samples; Green symbols / field :- kimberlite rock samples; Dashed field:- Canadian till samples (Armstrong and Chatman, 2001); Dashed lines:- constant non-diamond indicator / diamond ratios; Red dots:- samples with only one diamond or non-diamond indicator

Phlogopite / tetraferriphlogopite occur almost exclusively in kimberlite rock samples. Almost all indicator spinels are chromites, 93% falling within the garnet peridotite field and 20% of remaining grains falling in the chromite inclusion in diamond field of Grütter and Apter (1998). Of peridotitic indicator garnets, 44% are classified as G10 following Grütter et al. (2004) and whilst the quality of EDS analyses (7% of grains) are not suitable for discriminating the 'D' subdivision, all remaining G10s can be classified as G10D. The prevalence of eclogitic garnets is small, some 3% of all mantle garnets, and the large majority of these are G3. Of ilmenites with indicator chemistry known, 42% fall within the kimberlite rather than the intermediary field of Wyatt et al. (2004). Clinopyroxenes fall within the garnet peridotite and eclogite, megacryst and cognate fields of Ramsay and Tompkins (1994), and some examples occur as composites with garnet. Orthopyroxenes, usually occur as polyphase mineral separates with chromite. Applying Brey and Köhler's (1990) methods and assuming equilibrium, mineral separate chemistries support a depth of origin for Merlin mantle material of 120 km, well within the diamond stability field.

DIAMOND RECOVERY

Microdiamonds are ubiquitous to the central eastern areas of the NT (Fig. 1c) and show little relationship with proximity to known sources. In contrast in the west, and whilst uncommon, microdiamonds are found downstream from known primary sources and are hence more useful as indicators. Generally, macro-diamond has greater usefulness as an exploration tool.

Four hundred and seventy eight diamonds (90% being macros) mostly recovered from surface sediment samples were assessed for their physical characteristics. Whilst 16% were from the Merlin and Timber Creek kimberlites, the spread of geographical locations for described stones makes them representative of NT diamonds as a whole. A quarter of diamonds are brown, 22% are colourless, 14% are green and 8% have a pinkish or reddish colouration. The proportions of colourless and pink stones are regarded as favourable from an economic perspective. Of original growth forms, cubes dominate (51%) over octahedral / modified octahedral forms suggesting a typically low temperature of formation. Of octahedral stones, 62% show little resorption however of the total number of stones described, 26% are irregular suggesting a complex history of growth and deformation.

Specifically at Timber Creek, the largest body (TC-01) of the five kimberlites known is small (0.07 Ha) and has been 30% exhausted during exploration. Whilst with diamonds averaging $13/ct (2003 valuation, +1.5 mm) and a grade of 22 cpht (Kolff, L., Tawana Res. pers. comm. 2010), TC-01 shows no economic potential, its mineralogy provides the best available template for western NT diamond exploration. Diamonds from two bulk samples yielding 12,790 diamond crysts from the TC-01 kimberlite are described as mostly dodecahedrons with colourless and brown body colours predominating. Pink diamonds are also reported. The majority of diamonds have a transparent green coat, confirming the findings of Berryman et al. (1999) and black inclusions are common. The Timber Creek diamonds distinguish themselves from the NT population as a whole by their dodecahedral forms and green surface colour. Such colour is more common with alluvial diamonds, arising from damage from solar radiation (Lind and Bardwell, 1923), and supports the contention that the TC-01 kimberlite has lacked significant cover since emplacement.

PROSPECTIVITY RANKING

As described in the Introduction, much of the NT is prospective for diamonds. Within this context the process of ranking subdivides Regions and Provinces in terms of *relative* prospectivity. Caveats and specific nuances of particular Regions and Provinces not included in the ranking methodology will affect companies' preferences for various locations and will be the subject of a more extensive discussion. Examples are that the Fitzmaurice Basin which scores 1, has produced spinels and diamonds from its limited sampling which can be interpreted as being sourced from the Timber Creek kimberlites upstream within the Birrindudu Basin. Such a consideration would serve to downgrade the Fitzmaurice Region. Conversely, the Pedirka Basin is generally very thin (up to ~1,500 m; Ahmed and Munson, in prep.) and hence its unfavourable age ranking at 10, largely due to its young age may be mitigated by this thinness over much older rocks. Broadly speaking however the most prospective zones identified and based on the criteria presented (Fig. 2c) run in a swathe down the western portion of the Territory incorporating some 50% of the shared border with Western Australia. Next most prospective is a zone from Arnhem Land down to the eastern coastline incorporating the heavily explored Georgina and McArthur Basins, host of the Merlin and Roper kimberlite fields respectively. This region presents the considerable complexity of experiencing an almost ubiquitous cover of micro-diamonds. The third most prospective collection of areas can be regarded as much of southern and central NT coincident with the thickest lithosphere in the Territory.

CONCLUSIONS

- Much of the Northern Territory is prospective for diamonds based on mantle lithosphere thickness and structure, relative age of known primary diamond deposits to country rocks, mineral chemistry and the results of prior sampling.
- Most prospective areas lie on the western and to a lesser extent eastern flanks of the Territory.
- Traditional indicator minerals have very poor survival rates due to tropical weathering and are poorly reflected relative to diamond, particularly in the east of the Territory.
- In the east of the Territory, micro-diamonds cannot be used reliably as a prospecting tool on a regional scale whereas in the east, their occurrence in the west is likely more directly traceable to source.
- Future successful Territory diamond exploration will necessarily rely on innovative techniques using more durable indicator minerals such as zircon and corundum and remote sensing techniques, likely as parallel programs to established exploration for other commodities.

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