Diamond Exploration and Regional Prospectivity of Greenland

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Abstract

Greenland is dominated by cratonic nuclei that provide conditions for diamond formation. Pre-1.6 Ga rocks are exposed over 43% of ice-free land and many basins in younger areas evidence underlying Archean basement. Studies of mantle xenoliths reveal thick mantle lithosphere up to 220 km. Kimberlites, ultramafic lamprophyres, lamproites and carbonatites are exposed abundantly in almost all regions, and span 1632 Ma of geological time. A total of 3029 discrete diamond-prospective bedrock occurrences are known, mostly occurring as sheets but with diatremes and evidence for volcaniclastic rocks in the south. Known diamondiferous bodies are well represented over 930 km of Greenland's west coast. Recovered multi-carat diamonds and favourable mineral chemical data demonstrate the potential for diamondiferous bodies with large, good quality diamonds in potentially economic concentrations. Areas where pipes and diatremes are rare evidence extensive glacial erosion but retain the potential for better-preserved bodies to be discovered at high elevation and diamonds to be present offshore. Records of 120 334 good quality mineral chemical analyses, allow a regional diamond prospectivity analysis of Greenland to be conducted. Garnet, ilmenite, spinel, Cr-diopside and orthopyroxene all reveal mineral chemistries consistent with diamond-stable mantle sources. All geographic subdivisions overlap chemistries of indicators from diamond-producing areas of Canada. Quantitative prospectivity modelling incorporating geophysical data shows that further opportunities exist for diamond exploration in Greenland particularly in the North Atlantic and Rae Cratons of western Greenland, the Ketilidian Orogen of southern Greenland, as well as within less-explored areas such as the east and north, and off-shore.

Keywords Diamond • Greenland • kimberlite • mineral exploration • indicator minerals • North Atlantic Craton • Rae Craton

Introduction

Greenland is dominated by cratonic nuclei to the Laurentia Super-craton (Pearson et al., 2021; Figure 1), accreted episodically (Gardiner et al., 2020), and which provide conditions for the formation of diamonds. Pre-1.6 Ga rocks are exposed over 43% of ice-free land and many basins in younger areas evidence underlying Archean basement. Re-Os dating studies of the mantle of west Greenland (Wittig et al., 2010) in particular, show consistent Archean and Proterozoic ages. Therefore, younger rocks at the surface may in some cases act as cover over diamondiferous rocks, rather than informing on the age and diamond prospectivity of the underlying mantle. Studies of mantle xenoliths reveal thick mantle lithosphere to 220 km in the North Atlantic Craton of western Greenland (Sand et al., 2009). Kimberlites, ultramafic lamprophyres (UML) and lamproites are known to be exposed in almost all regions, and span 1632 Ma of geological time (Larsen and Rex, 1992; Secher et al., 2009; Hutchison et al., 2024). Including also carbonatites, 3029 discrete bedrock diamond-prospective occurrences have been identified (Figure 1), mostly occurring as dykes and sills. Known diamondiferous bodies are well represented over 930 km of Greenland’s west coast, most notably the Garnet Lake four metre-thick composite aillikite / kimberlite sheet at Sarfartoq (Hutchison and Frei, 2009), and metamorphosed ultramafic lamprophyre sheets at Qeqertaa, Disko Bay (Bernstein et al., 2013). Data from these, and other localities, demonstrate that Greenland is a host for diamondiferous bodies with large, good quality diamonds in potentially economic concentrations, with potential for future discovery.

Fifty years of diamond research and exploration have generated abundant data, particularly from western and southern Greenland (Jensen et al., 2004; Hutchison, 2020a). While climate and remoteness provide challenges to exploration and mineral development, it is clear from the abundance of diamondiferous bodies and extent of prior exploration, that considerable scope exists for future diamond exploration in Greenland. This study aims to provide a framework for such exploration by reviewing the methods and efficacy of past work, applying modern methods of data interpretation to the internally consistent and large database of mineral chemical data of Hutchison (2020a), and applying established regional prospectivity modelling methods to Greenland data.

Methodology

Records of 24 996 Greenland exploration samples allow an assessment of the methodologies of past exploration and, combined with 120 334 good quality mineral chemical analyses (Hutchison, 2020a), allow regional diamond prospectivity modelling of Greenland to be conducted. In this study, critique of exploration methodologies predominantly relies upon industry reports submitted to government (with references compiled in Hutchison, 2020a and

2022), and prospectivity modelling follows a two-part approach. A quantitative modelling approach is framed by mantle lithosphere thickness, the age of surface rocks in the context of being cover over potential diamond deposits, and the density of sampling combined with recovery of visually-determined indicators. A mineral approach inspects diamond concentrations and physical features, and compares and contrasts indicator mineral chemistry among Greenlandic geological regions and with the diamond fields of neighbouring Canada. The approach to prospectivity analysis broadly follows the strategies and techniques developed for the Northern Territory of Australia and Western Australia (Hutchison, 2013 and Hutchison, 2018a), with modifications described herein.

Regional subdivisions

In order to rank different parts of Greenland in terms of diamond prospectivity, a geographical subdivision must be employed. The subdivision needs to create a number of discrete geographical regions that are numerous enough to constrain the explorer to reasonably small areas, but not so large a list as to assign few data to individual subdivisions and thus becoming statistically questionable. The geographical areas should be based also on distinct geological settings and identified age ranges which are as small as practical.

The solid geology of Greenland has been divided into onshore geological regions at 1:2 500 000 scale by Escher and Pulvertaft (1995). Because these regions are defined on the basis of surface and near-surface solid geology, they do not necessarily identify regions affected by the mantle conditions that control the likelihood of diamond formation. However, they do divide Greenland into areas of different geological ages that are relevant to the likelihood of near surface diamond occurrence, should underlying mantle conditions be favourable. Taking into account the area of ice-free land, the Escher and Pulvertaft (1995) subdivisions compare well in number to the subdivisions used in prior prospectivity analyses in Australia

(Hutchison, 2012 and 2018b). Therefore, the Escher and Pulvertaft (1995) subdivisions have been employed with modifications where the North Atlantic Craton (NAC) and Rae Craton have been subdivided, with the NAC split between east and western Greenland and the Rae Craton split between North, eastern and western Greenland. Furthermore, the Nagssugtoqidian Orogen has been integrated into the Rae Craton. Thus, 25 non-overlapping geological regions, with 19 having seen sampling for diamond exploration, form the geographic basis for the prospectivity methodology (Figure 1).

Regional diamond prospectivity modelling

Prospectivity based on sampling history

Sampling history can been treated quantitatively and is a useful metric in determining the completeness and results of diamond exploration. The number of onshore samples taken for the purpose of diamond indicator testing (including diamond-only samples) was counted for each prospectivity region and the numbers of samples which contained diamond indicator minerals (DIM) were compiled. The criteria used to score each region based on sampling history are described in Table 1. The method is based on the principle that regions where a high proportion of samples return positive visually-identified indicator minerals are favoured over those with low recovery success. Furthermore, under-sampled areas provide more opportunity for new discoveries and are therefore favoured over heavily sampled regions. The cut-offs for sampling density follow the scale definitions of McMartin and McClenaghan (2001) and are described in Table 1 in addition to definitions of relative indicator recovery success. Combining sample density with sample success generates a score (Table 1) which can be applied to each region. Some regions have seen no diamond exploration, and so in order to score sampling history in as consistent a geological context as possible, unsampled regions have been scored as follows. Regions, such as the Cenozoic, which have seen no diamond indicator sampling for geological reasons are assigned a score of 6 (consistent with Hutchison, 2012 and 2018b). Whereas regions which have sound geological reasons to be prospective, and yet have not been sampled due to inaccessibility, are assigned a score of 5.

Prospectivity based on geological age

In order to be exploited economically, diamondiferous bodies must be close to or at surface. Transported material such as glacial sediments, which are common in parts of Greenland, provide impediments to the discovery of primary bodies. However, it is the overlying solid geology that can provide the biggest impediment to economic extraction. Hence, in order to assess the likelihood that diamondiferous rocks will be present at or near the surface, it is important to understand both the likely age of intrusion, based on the known ages of diamondiferous rocks elsewhere, and the ages of the country rocks in the area of interest. If, for example, the age range of rocks in a region is younger than any known diamondiferous rock, then it would be expected that any diamondiferous bodies present would be covered, possibly with kilometres of rock.

Ranges of ages of Greenland’s 25 unique geological regions are shown graphically in Figure 2, with data sources referenced in Hutchison (2022). The wide range of ages (2.86 Gyr) of intrusive events giving rise to diamond-prospective rocks are provided in Figure 2 for context. It is evident that the four main phases of intrusion of diamond-prospective rocks, Jurassic, Ediacaran (Neoproterozoic), Ectasian (Mesoproterozoic) and Orosirian–Stratherian (Paleoproterozoic), postdate many of the rocks at surface in Greenland, certainly all of the cratonic blocks. Furthermore, only four of Greenland’s regions (the Cenozoic Basins, Kangerlussuaq Basin, Nuussuaq Basin and the North Atlantic Igneous Province) entirely post-date Greenland’s Jurassic diamondiferous kimberlitic rocks.

With age ranges of geological regions established, and a knowledge of the ranges of ages of diamond-prospective rocks, a scoring mechanism can be established which allows approximately similar numbers of regions to be assigned to each score. The established method with six classifications is described in Table 1.

Prospectivity based on lithosphere characteristics

Mantle lithosphere thickness imposes the strongest control on the formation of diamonds (Haggerty, 1994), and overlying crustal weaknesses, often driven by sharp changes in lithosphere thickness, impose the strongest controls on diamond emplacement to the Earth's surface (Helmstaedt and Gurney, 1995; Haggerty, 1999). Cratonic regions of the Earth are typically characterized by thick, cold and old mantle lithosphere that provides the conditions required for diamond formation (Haggerty, 1994; Pearson et al., 2021). Therefore, diamond explorers favour cratonic regions. While cratonic nuclei are the foci of diamond exploration (Pearson et al., 2021) the edges of cratonic regions or craton–craton terrane boundaries are often prospective because they allow diamond-hosting rocks to reach the surface more readily (Helmstaedt and Gurney, 1995).

Geothermobarometry of mantle xenoliths variously provide maximum source depths of 215 km (Maniitsoq / Sarfartoq; Sand et al. 2009) and 195 km (Sarfartoq; Hutchison and Frei. 2009), and Larsen and Rønsbo (1993) determined source depths for garnet lherzolites at 145–165 km for Sarfartoq and Sisimiut, and 220 km for the Maniitsoq area. Wittig et al. (2010) provide a review of mantle thickness for the whole of West and South-West Greenland with the deepest (> 220 km) mantle centred on Sarfartoq and Kangerlussuaq. Mineral chemical estimates of mantle lithosphere thickness compare favourably to geophysical measurements of the current lithosphere. They are most consistent with Model 2 of depth to the lithosphere / asthenosphere boundary using a method of thermal isostacy of Artemieva

(2019). Hence this model is used as the reference framework for prospectivity in this work. The seismic stations upon which the Artemieva (2019) model relies are reasonably evenly distributed throughout Greenland with between four and six seismic stations per five degrees of latitude for the majority of Greenland, and with the southern tip (south of 65°N) having three stations and the northern coastline (north of 80°N) having two stations. Thus while knowledge of the lithosphere thickness in the north of Greenland is anticipated to have more uncertainty, it is only marginally so compared to the rest of the country. Most likely a more impactful influence on uncertainty derives from the distance to earthquake-generating subduction zones, which is similar country-wide.

It is notable that known intrusive events of diamond-prospective rocks in Greenland span 2.86 Gyr (Figure 2), which would suggest that different ages and locations of Greenland intrusives may have witnessed different mantle lithosphere conditions over time. Changes may have occurred as a consequence of delamination leading to modified cratons (Pearson et al., 2021), such as seen in Wyoming. However, comparison of the current mantle lithosphere (Artemieva, 2019) and contemporary mantle lithosphere through studies of mantle xenoliths (e.g. Sand et al., 2009 and Wittig et al., 2010) do not provide evidence for delamination at least in western Greenland. Whereas, the Caledonian orogeny may have caused delamination of what is now thin mantle lithosphere (Figure 3; Artemieva, 2019) in east Greenland.

For this study, the vertical extents of the mantle lithosphere under Greenland have been subdivided into polygons reflecting the depth ranges of 25–75, 75–125, 125–175, 175–225 and 225–275 km using contours from Artemieva (2019; Figure 3). The two deepest subdivisions lie within the diamond stability field in the mantle lithosphere and the two shallowest subdivisions are outside the diamond stability field. The central subdivision, 125–175 km covers the range over which diamond may or may not be stable under mantle conditions depending on the geotherm. The intersection between each lithosphere polygon and each geological region has been calculated, providing an area in square kilometres for each depth range and each region. This allows the relative proportion of each depth range for each region to be calculated and subsequently an average depth to the lithosphere–asthenosphere also to be calculated. Each region is subsequently assigned a numerical score from 1 to 5, where 1 represents the thickest lithosphere (most diamond-prospective) and 5 the thinnest (Table 1). Scores are attributed to depth ranges to generate an approximate Gaussian distribution (only slightly skewed towards thick lithosphere) among Greenlandic regions.

Combined prospectivity

For each geological region, the scores for each of the three criteria of age, sampling history, and underlying lithosphere thickness are summed. The regions are ordered or ranked 1st, 2nd equal, 4th equal, and so on, resulting in twelve ranked groups. Each group is subsequently incrementally assigned a category number with 1 being the most prospective and 12 being the least prospective.

Mantle mineral modelling

Aside from diamonds themselves, mineral chemical characteristics are the single most important criteria, where available, for identifying diamond prospectivity of the deep Earth below any given near-surface location. However, only 44 % of Greenlandic samples reported to have visually-identified indicator minerals have corresponding mineral chemistry data. Consequently, insufficient data exist to allow mineral chemistry to be a statistically robust criteria at the resolution of 25-regions for the quantitative prospectivity described previously. Notwithstanding this shortcoming, abundant mineral chemical data do exist for locations within Greenland and inspection of these data provides useful insights into where mineral chemical techniques yielded exploration dividends and where shortcomings in approaches useful elsewhere may exist. The mineral chemical approach has the advantage that it leads to far fewer false positives and can be queried in a more sophisticated and varied manner than visual indicator mineral identification. Furthermore, the window provided into the lithosphere by mineral chemistry relates to the time of emplacement rather than the present-day picture provided by geophysics. Therefore, the two approaches to understanding diamond prospectivity applied herein – quantitative regional modelling and mineral chemistry, including diamond study – complement each other.

Results

Historical sampling

The large majority (92%) of Greenlandic diamond exploration samples have been taken from unconsolidated sediments with a relatively even split between alluvial sediments from current drainages and glacial material (typically tills). Most diamond exploration in Greenland has focussed on recovery of diamond indicator minerals. Sample sizes appear to have decreased with time with earlier explorers noting 30 to 35 kg alluvial samples being typical. Whereas historical data as a whole reveal of mode of 10 kg for alluvial and glaciogenic samples (Hutchison, 2020a; Hutchison, 2022). In a global diamond exploration context these are small samples, and the most common size range for mineral picking of 0.25 to 0.5 mm has a smaller upper limit than is routinely applied in neighbouring Canada (Hutchison, 2022). However, Greenland appears to present a weathering environment particularly beneficial to the preservation of Cr-spinels as well as less durable minerals including garnets and Cr-diopsides. While all indicator grains disaggregate, particularly Cr-diopside, data demonstrate that the effect on heavy mineral concentrates is that grains appear in smaller size fractions rather than disappearing altogether (Hutchison, 2022). Therefore, it is concluded that sampling strategies in Greenland have usually been adequate, and present a balance between generous sampling and the costs and logistical challenges of exploration.

Visually identified indicators overwhelmingly are olivines although these are expected to be largely false positives due to the inability to visually discriminate diamond-associated olivines from others. After olivine, ilmenite is the next most abundant indicator mineral, which itself presents challenges when identifying genuine indicators visually. Cr-diopside, garnet, orthopyroxene and spinel indicator proportions in samples mirror those found in Canada, but it is striking how numbers of garnets, Cr-diopside and orthopyroxenes are very considerably more abundant away from source than in chemically weathered environments such as Australia. In Greenland, the range of ubiquitous mantle minerals found in diamond-prospective rocks genuinely can be used as pathfinders considerably far from source, provided that carefully chosen sample sites are identified.

Regional prospectivity modelling

The results of prospectivity analysis in terms of the quantitative ranking of geological regions based on sampling density and success, ages of surface rocks and underlying lithosphere characteristics, and, separately, in terms of diamond recovery and the re-assessment of mineral chemical data using standardised datasets, are discussed in the following.

Results for individual criteria and total rankings contributing to quantitative prospectivity analysis are shown in Table 2.

Results of sample success scoring

Results of sampling history are provided in Figure 4, tabulated in the supplementary data appendix (Supplementary Table 1). Regionally, sampling density has been low, with no Greenlandic region experiencing what would be considered local sampling density (more than one sample per 4 km^2). The NAC of western Greenland has the highest average sample density of 2292 samples per 100 x 100 km area.

The Inglefield Orogenic Belt distinguishes itself by having a 100% sampling success rate. However, this is due to only one sample being collected, and being indicator-positive. This statistical bias is handled in the context that sample scoring is only one of three metrics, and, as shall be discussed later, empirical modifications can be applied to final scoring where considered justifiable. The other top score from sample success is assigned to the Franklinian Basin, where 82% of samples are indicator-positive. This result is contributed to most significantly by the visual identification of orange and red garnets in surface sediment samples (Hutchison, 2020a, 2022) in the vicinity of the inlier designated as part of the Rae Craton (Nutman et al., 2019). The most statistically robust high scores (value of 2) were found for the Gardar Province, Ketilidian Orogen, NAC in western and eastern Greenland and the Rae Craton in western Greenland.

Results of age dependent scoring

As may be expected, the top score exclusively falls to all Greenland's exposed cratonic nuclei, namely the NAC in western and eastern Greenland and the Rae Craton in western, eastern and North Greenland. While not discriminated between, in terms of scoring, the NAC of eastern Greenland and Rae Craton of North Greenland distinguish themselves as having no reported rocks younger than the oldest of any known diamond-prospective rock in Greenland. However, given that this oldest occurrence is the 2664 Ma Sîngertat Carbonatite which has no known diamondiferous rocks associated with it to date, the distinction is perhaps academic.

Other regions which score well due to age are the Caledonian basement, Inglefield Orogenic Belt, Karrat Basin, Ketilidian Orogen and the small Prøven Igneous Complex of North-West Greenland.

It is noteworthy, however, that since the age-dependent scoring is focused on primary diamond deposits, the low score for the Nuussuaq Basin contrasts with the prospectivity of its sedimentary successions as sources of re-worked diamonds as palaeoplacers (Hutchison, 2022).

Results of lithosphere thickness scoring

Due to the prominent, thick mantle lithospheric keel under West Greenland, the NAC and Rae Craton of western Greenland score best for lithospheric prospectivity. This high ranking is consistent with the abundant deep-sourced mantle xenolith data from western Greenland (e.g. Sand et al., 2009; Wittig et al., 2010), and the known occurrences of diamond, from Pyramidefjeld to Svartenhuk Halvø (both extents being consistent with a depth of 200 km to the lithosphere / asthenosphere boundary following the model of Artemieva, 2019). High rankings are also achieved by the basins surrounding these cratons, such as in the Disko Bay area, the Inglefield Orogenic Belt, and the Ketilidian Orogen and Gardar Province (scoring 2). However, perhaps surprisingly, northern Greenland also scores well with the Independence Fjord and Franklinian Basins both scoring 3. This is a consequence of a relative thickening of the mantle lithosphere moving increasingly north from the Humboldt Glacier (80°N) with its maximum corresponding with the small inlier of rocks attributed to the Rae Craton in North Greenland (Nutman et al., 2019).

Overall ranking

All 25 regions ranked from 1st to equal 22nd place give the 12 discrete ranking categories previously described and these are used to colour-code the prospectivity map of Greenland (Figure 5). The Rae Craton and NAC of western Greenland distinguish themselves by having the highest modelled diamond prospectivity rankings. This derives from the good success in visually identified indicator mineral recovery, including diamonds (albeit with many samples deriving from already identified bodies), the age of the rocks and also the thick mantle lithosphere keel lying well within the diamond stability field. The next best score, however, is assigned to the Inglefield Orogenic Belt. The high scoring derives from good indicator recovery from very low density sampling, but also the old age of the rocks and the thick lithospheric keel under this small, northern region of Greenland. Notable, with a final score of 3 are the Ketilidian Orogen and NAC of eastern Greenland. The Ketilidian is known for strongly-prospective indicator minerals and known ultramafic lamprophyres and its ranking is boosted by sitting on the edge of the thick mantle keel of western Greenland and being comprised of relatively old rocks. The ranking of the NAC of eastern Greenland falls below the NAC of the west due to thinner lithosphere (although still within the diamond stability field). The Rae Craton of eastern Greenland (scoring 5) falls quite far below its counterpart in western Greenland due to considerable portions falling within the thin, likely strongly delaminated lithosphere (Figure 3) affected by the Caledonian Orogeny. The Rae Craton of North Greenland scores poorer still (scoring 6) but this region is pulled dramatically downwards by the absence of any sampling having been conducted in this small region.

Indicator mineral chemistry

Acquisition of mineral chemical data is costly and time consuming. However, the process of fieldwork, sampling, transporting, processing and picking indicator minerals is extremely costly. Hence, acquiring mineral chemical data is proportionally not a large part of an exploration budget. Nevertheless, mineral chemical determination has often been neglected among Greenland diamond exploration with less than half of visually identified indicator-positive samples being subjected to mineral chemical testing (Hutchison, 2022). Where mineral chemical data are available, they provide valuable insights into diamond prospectivity as demonstrated for the Sarfartoq area by Grütter and Tuer (2009), and as discussed in the following.

Pyroxene chemistry

Mineral chemical data have been derived from diopside-hedenbergite grains from the NAC and Rae Cratons in western Greenland, the Ketilidian Orogen, and the Karrat Basin (which lies north of the Nuussuaq Peninsula; Figure 1). Figure 6 shows their compositions in terms of Al_2O_3 and Cr_2O_3 content. Two Rae Craton outliers contain over 13 wt% Al_2O_3 and one has over 15 wt%, and a further two outliers have Cr_2O_3 over 5 wt% and are not plotted in Figure 6.

Clinopyroxenes from the NAC of western Greenland express compositions well constrained to within the garnet peridotite field and rarely with Cr_2O_3 above 3 wt%. The core of NAC compositions is constrained between approximately 1 and 2.5 wt% Al_2O_3 with variable Cr-content within the garnet peridotite field. However, there is also a small discernible trend of increasing Al-content into the spinel lherzolite field. In contrast, grains from the Rae Craton show a wider range of composition extending above 5 wt% Cr_2O_3 in rare cases, and similar to the diversity of compositions seen in Canada (Northwest Territories Geological Survey, KIDD/KIMC, 2017). Wide compositional variability reflects both a range of depths of origin and also bulk mantle chemistry. The trend through the spinel lherzolite field and beyond with increasing Al content is more marked in Rae Craton samples, than the NAC, and similar to Baffin Island samples from the moderately to poorly diamondiferous

Brodeur Peninsula (Northwest Territories Geological Survey KIDD/KIMC, 2017) and Chidliak (Pell and Nielson, 2008). Ketilidian Orogen clinopyroxenes describe two distinct groups within the garnet peridotite field, being a high Cr group (with Cr_2O_3 between c. 2-3 wt%) with Al_2O_3 constrained between 0.7 and 1.5 wt%, and a low Cr group (with Cr_2O_3 below 2 wt%). The low Cr group, as also evident in Rae Craton samples, extends across all Al_2O_3 concentrations between c. 0.3 wt%, into the spinel lherzolite field and beyond to over 10 wt% Al_2O_3. While the Brodeur Peninsula kimberlites in Canada show the same shallowing depth trend as apparent particularly in Rae Craton samples, encouragingly from a diamond prospectivity perspective, the Chidliak diamondiferous kimberlites show the same strong variability in Cr-content within the garnet peridotite field as Greenlandic NAC, Rae Craton and Ketilidian Orogen samples.

Further to general chemical trends in unclassified pyroxenes as described previously, single clinopyroxene grains can also provide opportunities for determination of temperature and pressure (and, hence depth) of equilibration within the mantle. The methodology of Sudholz et al. (2021a) applies their revised Cr-in-clinopyroxene barometer and relies on the enstatite-in-clinopyroxene thermometer of Nimis and Taylor (2000). Since clinopyroxene grains recovered from surface sediment samples have no demonstrable genetic association with accompanying mineral grains, and can have a range of sources throughout the crust and mantle, Sudholz et al.'s (2021a) methodology provides very rigorous filters (following methods of Grütter, 2009 and Ziberna et al., 2016) to ensure derivation from garnet lherzolites.

The database of Hutchison (2020a) provides 16 563 analyses of Greenlandic clinopyroxenes which pass criteria described by Hutchison (2020b) as acceptable analyses. The method of Sudholz et al. (2021a) has been applied to all data, both from known kimberlites and aillikites, and surface sediments, and rigorous filters result in 956 mineral grains providing defensible pressures and temperatures of origin. All accepted grains derive from the North Atlantic and Rae Cratons of western Greenland, and the Ketilidian Orogen. Geothermobarometry data are presented in Figure 7 plotted as temperature against depth, and with mantle geotherms of Hasterok and Chapman (2011) and the diamond / graphite phase transition of Day (2012) for reference.

North Atlantic Craton garnet lherzolite clinopyroxenes derive from locations covering the whole extent of the Craton on the west coast. Sub-100 km origin clinopyroxenes (outside the diamond stability field) are sourced from the same geographic extent (reflecting being accumulated on ascent from melts sourced at a wide range of depths). However, with three exceptions from a Tikiusaaq sample (up to 199 km, 65.2 kbar, 1352 °C, Hutchison 2020a sample ID 459144) all clinopyroxenes from over 160 km in depth come from the northern extent of the Craton on either side of the Maniitsoq (Sukkertoppen) Icecap. From latitude 61°N to 67°N, the thickness of mantle lithosphere sampled increases (from 57 km to 176 km), with the maximum depth increasing, and the minimum depth decreasing as clinopyroxenes derive from more northern latitudes. At the large scale, there is no clear trend in geographic source among clinopyroxenes derived from over 200 km deep, aside from the fact that the super-deep samples (over 220 km in origin) all come from Garnet Lake. The deepest clinopyroxene discovered in Greenland by this method is calculated to derive from 228 km (74.5 kbar, 1272 °C, from kimberlite sample MHG9_6, Hutchison, 2020a).

Rae Craton clinopyroxene data scatter around a slightly wider range of reference mantle geotherms, both cooler and warmer than North Atlantic Craton clinopyroxenes but the difference is minor. Aside from an unremarkable sample from the Disko Bay area within the graphite stability field at 116 km depth of origin, all Rae Craton samples derive from 35 km of the southern boundary with the North Atlantic Craton and sample 164 km of thickness of mantle. Many samples lie respectably within the diamond stability field with the deepest being sourced from 222 km (72.6 kbar, 1312 °C, Hutchison 2020a sample ID 111735).

The samples from the Ketilidian Orogen revealing single clinopyroxene geothermobarometry data cover the northwestern part of the Orogen, from Narsarsuaq (Johan Dahl Land) to almost as far west as Kobberminebugt (south of Grønnedal). There is no geographic distinction between the clinopyroxenes which express warm mantle geotherms (40 to 50 mWm^{-2}) compared to the deeper sourced (over 146 km depth of origin) mineral grains which derive from cooler (35 to 40 mWm^{-2}) geotherms more favourable to diamond formation. However, the large majority of deep sourced grains derive from Johan Dahl Land samples. Among these are the deepest sourced Ketilidian Orogen grain (Hutchison 2020a grain ID 3941 from 208 km, 68.0 kbar, 1225 °C) which derives from the same sample – Hutchison (2020a) sample 100071 – which also produced 108 km and 193 km-sourced clinopyroxenes. All these clinopyroxenes derive from comfortably within the diamond stability field and emphasise the significance of the Ketilidian Orogen on par with the deeper portions of the North Atlantic and Rae Cratons. Recent diamond exploration in a portion of Johan Dahl land and near to Narsaq (Bernstein et al., 2025) failed to reveal diamond indicator minerals. However, their findings, restricted to fairly small geographic areas (15 km radius), include previously unreported UML dykes which demonstrate the variability of diamond prospective bodies in comparison to known South Greenland breccias (e.g. Upton et al., 2006) and the impact that alteration can have on preservation of indicator minerals.

Orthopyroxene does not commonly survive in diamond exploration samples worldwide. However, a statistically significant number (1202) of good-quality mineral chemical analyses for orthopyroxene are available in Hutchison (2020a) with 817 being considered genuine indicators following Ramsay and Tompkins (1994). All orthopyroxene grains of interest for diamond exploration with reported mineral chemistry data derive from the NAC and Rae Cratons and the Ketilidian Orogen. Classification following Ramsay and Tompkins (1994) show distinct difference between orthopyroxenes from the Rae Craton, compared to western Greenland's NAC and grains from the Ketilidian Orogen (Hutchison, 2022). While Rae Craton grains generally are less Mg-rich, falling into megacryst and eclogitic fields, NAC and Ketilidian Orogen grains have compositions consistent with peridotites, particularly those from diamondiferous garnet lherzolites. While Mg-compositions reflect different dominant mantle compositions, increasing Al-content reflects shallowing depth. Hence the Rae Craton samples demonstrate a range in source depths, into non-diamond prospective, shallow depths, whereas NAC compositions are more consistently deep. The Ketilidian Orogen samples express two distinct compositional fields, both deep-sourced with the shallower consistent with diamondiferous lherzolites and the deeper, or at least more depleted, consistent with harzburgites. Canadian samples (Northwest Territories Geological Survey KIDD/KIMC, 2017) reveal both diamond-associated compositions, but also a range of higher Al-content orthopyroxenes into the shallower spinel lherzolite field not seen in Greenlandic samples. Away from the highly diamond-prospective Canadian Lac de Gras area, the compositional range to more Fe-rich orthopyroxenes is also mirrored in western Greenland's Rae Craton samples.

Garnet chemistry

Garnet is considered a particularly useful mineral for diamond exploration because its large compositional variability can often allow attribution to very specific geological environments associated with high pressures within the mantle lithosphere (Grütter et al., 2004). In contrast to warmer climates, arctic environments such as in Greenland or Canada allow garnets to survive as an indicator mineral distal from its source rock (Hutchison, 2022).

Mineral chemistries have been obtained from pyrope-almandine–grossular garnets from five regions (Hutchison 2020a), namely the NAC and Rae Cratons in western Greenland, the NAC in South-East Greenland, the Nuussuaq Basin (samples which derive from western Rae Craton basement rocks), and the Ketilidian Orogen. Garnet mineral chemistry is shown in terms of Ca and Cr content in Figure 8, compared with Canadian data from northern Baffin Island (Rae Craton at the Brodeur Peninsula) and elsewhere in the Northwest Territories and Nunavut (Northwest Territories Geological Survey, KIDD/KIMC, 2017). Data are plotted according to CaO and Cr_2O_3 content and subdivided following the methodology of Grütter et al. (2004). The spread of mineral chemistry, among both mantle-derived and other garnets is wider for the Rae Craton samples compared to the NAC samples. All of the Rae Craton, NAC, Ketilidian Orogen and Nuussuaq Peninsula garnet compositions show strong and convincingly G9 lherzolitic compositional trends. Rae Craton, NAC and Nuussuaq Peninsula garnets from western Greenland also yield many compositions residing in the diamond-prospective G10 field. Furthermore, chemical analyses of a suitably high quality (as determined by electron microprobe) and with measured Mn-contents, allow definitive classifications in the G10D (diamondiferous) field for Rae Craton and NAC samples. Very few Brodeur Peninsula (Rae Craton of Canada) garnets fall within the G10 (and G10D) fields (Figure 8). In this regard, Canadian samples of the Brodeur Peninsula most closely mirror the small number of Ketilidian Orogen garnets, which express compositional variability in the G9 lherzolitic field. The Greenlandic garnets from the NAC and Rae Cratons of western Greenland, with the presence of G10 compositions, therefore reflect a more diamond-prospective mantle source than on the Canadian side of the Rae Craton. Similar compositional ranges into the G10 field to Greenland's NAC, Nuussuaq Peninsula and Rae Craton in the west, can be found further south on Baffin Island in garnets from the diamondiferous aillikites at Chidliak (Pell and Neilson, 2012). Greenlandic garnets compare favourably with those presented in the Canadian database of Northwest Territories Geological Survey, KIDD/KIMC (2017) from the diamond-mining fields of Ekati and Diavik.

Particular importance is placed on the role of G10 composition garnets as an indicator of diamond prospectivity. Certainly, there is a strong association between G10 composition garnets and known diamondiferous bodies, including those which are mined. However, G9, lherzolitic garnets can very much also be associated with diamondiferous bodies, such as at

Diavik (Moss et al., 2018), Victor (Stachel et al., 2017) and Forte à la Corne (Banas et al, 2025). Therefore, aside from the significance of G10 garnets, the presence of G9 garnets among Greenland samples can be taken as a positive for diamond prospectivity, particularly due to the shared geological history with Canada.

Garnet compositions also lend themselves well to diamond-provenance assessment using the Ni-in-garnet thermometer of Griffin and Ryan (1995), refined most recently by Sudholz et al. (2021b). As for G-classifications following Grütter et al. (2004), inspection of Hutchison (2020a) data shows that Greenlandic garnets perform well in terms of diamond prospectivity by this method.

Ilmenite chemistry

Acceptable mineral chemical data have been obtained for 47 722 ilmenite grains from Greenlandic samples. A total of 44 845 have indicator mineral compositions following Wyatt et al. (2004) – i.e., only 2877 grains, 6%, fall in Wyatt et al.'s (2004) non-kimberlitic field – with 43 121 being in Wyatt et al.'s (2004) kimberlite field and the remainder being classed as with intermediary compositions..

Ilmenite chemical compositions shown in Figure 9 are plotted according to TiO_2 and MgO. This diagram aims to discriminate ilmenites with a potential kimberlitic association from so-called intermediary compositions and those not consistent with a kimberlite source. Samples from the NAC and Rae Cratons of western Greenland, and from the Nuussuaq Basin (samples presumably derived from re-worked Rae Craton rocks) all show high proportions of ilmenites falling clearly within the field associated with kimberlites from worldwide. The Ketilidian Orogen samples are few in number and less convincingly diamond-prospective by this method, with only one grain falling within the kimberlite field. Similar to the observation for garnet chemistry, the spread of mineral chemistry among both kimberlite-associated and other ilmenites is wider for the Rae Craton samples compared to the NAC samples. Bernstein et al. (2025) made similar findings amongst Ketilidian origin ilmenites, and it is hypothesised that ilmenite compositions may have been affected by metamorphism among these rather older (Proterozoic; Figures 1 and 2) southern Greenland diamond-prospective bodies.

It is evident when comparing Figure 9a and 9b that among Canadian ilmenites, the marginally diamondiferous-Brodeur Peninsula samples show a very slightly lower Mg and higher Ti compositional range than the more diamondiferous Canadian samples which include those from the Ekati and Diavik mining districts. This regional Canadian trend is mirrored very closely by the western Greenlandic NAC ilmenites to the full extent of their high-Mg range (Greenlandic samples are, in fact, more Mg-rich). With a wider ilmenite compositional variability, western Greenland's Rae Craton samples also comfortably completely encapsulate ilmenite compositions from Canada's diamond-mining districts, including the Lac de Gras area.

In addition to providing valuable insights into the likely derivation of ilmenites from kimberlites or related rocks, ilmenite compositions can also indicate the likely preservation of diamonds should they be present as xenocrysts in ilmenite-bearing rocks. Diamond can be chemically degraded in oxidising conditions and so by inspecting the relationship between ferric (Fe^{3+}) iron and Mg in ilmenites, ambient oxidation can be inferred. In some cases, it has been demonstrated that oxidations calculated in this way has a correlation with diamond grade and morphology (Gurney and Zweistra, 1995), although this is not universally the case (Robles-Cruz et al., 2008). Nevertheless, ilmenite composition at least remains useful as a qualitative indicator of the environment within which diamonds have been transported.

All 54 777 good-quality chemical analyses of ilmenite in Hutchison (2020a), and from Northwest Territories Geological Survey, KIDD/KIMC (2017) have had cation concentrations of ferrous and ferric iron calculated by charge balancing to achieve 2 cations per 3 anions. Each ilmenite chemical formula has then been re-cast to oxide percentage abundances by mass to achieve assessments of FeO and Fe_2O_3 concentrations. These data have been plotted against measured MgO contents as shown on Figure 10, showing ranges of inferred diamond preservation following Gurney and Zweistra (1995).

Compositions of ilmenites derived from the Nuussuaq Peninsula (with a likely Rae Craton source) match those from diamond-marginal kimberlites of the Canadian Rae Craton in northern Baffin Island (Northwest Territories Geological Survey, KIDD/KIMC, 2017). However, western Greenlandic Rae Craton samples, and particularly those from the NAC also reflect the highest degrees of preservation. This preservation index is seen also among Chidliak diamondiferous kimberlites (Pell and Nielson, 2008), and matching the NAC compositions, is strongly seen among ilmenites from the diamond-mining districts elsewhere in Canada (also from Northwest Territories Geological Survey, KIDD/KIMC, 2017). For indicator mineral-classed ilmenite compositions (as for other indicator minerals) Rae Craton samples show the widest range in ilmenite compositions recovered in Greenland. This range reflects kimberlite oxidation values which, if a useful metric in this context, would cause the whole range of diamond survival from full resorption to complete diamond preservation.

Spinel chemistry

Spinels compiled in Hutchison (2022a) have been classified according to major and minor element compositions adapted from Ramsay (1992) as described in Hutchison (2020b). Attribution as indicator minerals for diamond potential follows this classification where aluminospinel-(Mg) ± Ti, Cr and gahnite-(Fe), and all chromites apart from end-member aluminochromite are all classed as indicators – other compositions are excluded. Among the indicator spinels, the majority are chromites (13 860 grains). In terms of provenance, almost equal numbers of spinel indicator minerals were reported from the western extents of the NAC (6954 grains) as the Rae Craton (6808 grains). However, the abundance of different spinel compositions differs significantly. While 34% of NAC indicator spinels are Ti-bearing, this proportion is much higher in Rae Craton samples (62%). In contrast, the proportion of Al-bearing chromites is considerably lower amongst Rae Craton samples (constituting 3%) compared to making up 14% of NAC indicator spinels.

Indicator spinels have been further subdivided according to the methodology of Grütter and Apter (1998). A total of 111 chromites with compositions consistent with chromite inclusions in diamond (designated SP-CID or CID in the database) have been identified, all from the western parts of the NAC and Rae Craton. This makes them rare, but they are significantly more abundant from the NAC (1.2% of all indicator spinels) compared to the Rae Craton (0.4%).

Further chemical discrimination using only spinels that were determined to be indicator minerals has the potential to provide a more specific attribution to host rocks. Figure 11 shows Cr relative to Cr + Al cations plotted against Fe^{2+} relative to Fe^{2+} + Mg cations where Fe has been attributed to both ferric and ferrous oxidations states based on cation calculations and charge balance (i.e., projected onto the oxidized prism of Mitchell, 1986). This diagram allows comparison with spinels from worldwide locations associated with kimberlites, xenoliths in kimberlites and as inclusions in diamond (Mitchell, 1986). The numbers of chromites consistent with inclusions in diamond according to both this criteria (the labelled field in Figure 11) and Grütter and Apter's (1998) separate methodology is small. Whereas Grütter and Apter's (1998) methodology identifies three times the proportion of chromite inclusion in diamond compositions from the NAC compared to the Rae Craton, in contrast, Mitchell's (1986) method attributes almost all diamond-association chromites as being from the Rae Craton (Figure 11). For the Ketilidian Orogen, it is interesting to note that there appear to be two distinct groups of compositions, being a trend towards both chromium and magnesium-rich compositions, and a Cr-poor and ferrous Fe-poor group. NAC and Rae Craton spinel compositions also express a Cr-poor and ferrous Fe-rich group, outside kimberlite-associated compositions, which possibly reflects serpentinite and greenschist origins such as from the Tartoq Greenstone Belt in the southern NAC (van Hinsberg et al., 2018).

Comparison with Canadian spinels (Figure 11), both from the Brodeur Peninsula of northern Baffin Island (the closest part of the Rae Craton in Canada with known diamondiferous kimberlites) and elsewhere in Nunavut and the Northwest Territories (Northwest Territories Geological Survey, KIDD/KIMC, 2017) show good comparisons with Greenlandic indicators. Inspection of the distribution of 99% of Canadian samples, some of which derive from the vicinities of the world-class diamond mines of Diavik and Ekati, shows that a similar very low proportion of inclusion-in-diamond spinel compositions is evident in Canada as Greenland. Therefore, a rarity of CID spinels should not necessarily be taken as an indication of reduced diamond prospectivity.

It is unfortunate that while spinel is an abundant indicator mineral, and certainly a useful tool, major and minor element chemistry does not allow for a discrimination between a diamond-prospective and nondiamond-prospective source as robustly as for other some indicator minerals. Methods based on trace element compositions (such as Co, Cu, Ga, Mn, Nb, Ni, Sc, Ti, V and Zr; Griffin and Ryan, 1995) yield much more definitive diamond-prospective associations than for major and minor elements. Although this method has been used with success elsewhere on the NAC in Scotland (Hutchison et al., 2018), and is considered to be a fairly standard procedure for the larger companies overseas, trace element compositions of spinels have not been reported during diamond exploration in Greenland.

Diamonds

Diamond survives chemical and physical degradation better than any other mineral derived from diamond-hosting rocks. Consequently, with increasing distance from host rocks, diamond increasingly becomes the most likely diamond-associated mineral to be recovered from exploration samples. Only eight samples of transported sediment recovered during Greenland diamond exploration have proven to contain diamonds (with three of those being palaeochannel mini-bulk samples of several hundreds of kg). However, diamond recovery from transported or in situ rocks known or suspected to be kimberlitic is much more common (176 samples reported in Hutchison, 2022). The craton-sourced diamond samples in Greenland extend from 61.4°N at Pyramidefjeld, north of Ivittuut (Grønnedal) to 69.9°N at Anap Nunaa on the north side of Disko Bay. Diamonds occur in six discrete areas coincident with most of the clusters of kimberlites and ultramafic lamprophyres known in western Greenland.

The largest numbers of microdiamonds and macrodiamonds, and the largest stones, derive from the most intensely studied bodies, being the Garnet Lake kimberlite / aillikite sill complex (NAC of western Greenland; Hutchison and Frei, 2009) and the cluster of aillikite dykes at Qeqertaa (Rae Craton; Bernstein et al., 2013). Garnet Lake produced the sample with most macrodiamonds (1096; Hutchison, 2020a) and Qeqertaa the sample with most microdiamonds (1452; Hutchison, 2020a). Notable stones from Garnet Lake are a 2.39 metric carat diamond from a 47-tonne sample and 2.51 metric carat (8.9 x 8.2 x 7.5 mm) from a 160 tonne DMS sample taken the following year (Hutchison, 2022).

Detailed information on the features and characteristics of Garnet Lake diamonds are discussed in Hutchison and Heaman (2008) and Hutchison and Frei (2009) and are combined with descriptions of the full range of Greenlandic diamonds in Hutchison (2022). Diamonds from southern West Greenland, in the northern part of the NAC and southern Rae Craton have approximately two thirds of stones described as colourless. Most remaining southern West Greenlandic stones are described as grey which may reflect surface frosting hiding a clear interior. Of the 167 stones from central West Greenland in the vicinity of Disko Bay there is a yet higher proportion of colourless stones (83%). Garnet Lake stones are more likely to be octahedral (43%) than the local Sarfartoq average, both of which are lower than the 60% seen from south of the Maniitsoq (Sukkertoppen) Ice Cap, in the area east of the town of Maniitsoq. In contrast, Disko Bay stones are exceptional, in having 90% of stones described as octahedral (Hutchison, 2022). In terms of more marked resorption (rather than surface features) where changes have occurred in the morphologies of the whole diamond, once again, Disko Bay diamonds distinguish themselves. Approximately half of Disko Bay stones show 85 – 95% preservation.

The relative abundance of diamonds of varying size is a powerful predictive tool in assessing the economic interest of a diamond deposit (Chapman and Boxer, 2004). Hutchison and Heaman (2008) investigated the size distribution of Garnet Lake diamonds from 425.1 kg of kimberlite from the main Garnet Lake sheet recovered from drill holes and surface samples. The smooth distribution of different diamond sizes was cited as evidence for a single population of stones with little growth of diamond within the kimberlitic melt. The same methodology is applied to subsequently much larger samples of Garnet Lake diamond processing, in addition to data from the Qeqertaa ultramafic lamprophyre, Disko Bay (references in Hutchison, 2022). Size fraction distributions from these expanded data in the context of results from similarly advanced Canadian exploration projects are shown in Figure 12. Both Garnet Lake and Qeqertaa microdiamond abundance (diamonds are smaller in size, but more abundant on the left side of the abscissa) compares very well with similar-stage exploration projects from Canada, with Qeqertaa samples being particularly microdiamond-rich. A shallow slope towards larger stones compared to Canadian deposits is particularly pronounced among Garnet Lake microdiamonds. Qeqertaa samples, particularly, show a good consistency between chemically-recovered microdiamonds from mechanically-recovered larger stones, reflecting efficiency in DMS processing. Comparing Garnet Lake and Qeqertaa samples further shows the absence of large stones at Qeqertaa (identified with the largest Qeqertaa diamond being 0.02 metric carats compared to 2.51 metric carats from Garnet

Lake). This difference is explained by the larger size of Garnet Lake samples. However, what is also evident is that the Qeqertaa samples show a steeper reduction in the diamond size compared to Garnet Lake. If Garnet Lake recovery efficiency of large stones could be improved to match microdiamond recovery, size distributions would match the best of similar-stage Canadian exploration samples.

Discussion

Caveats and enhancements to modelling

The regional prospectivity modelling presented herein, as for similar studies in Australia (Hutchison, 2012 and 2018b) takes a quantitative approach. Focus is on visually identified indicator minerals, as these remain the primary method for diamond exploration and generate the largest amount of quantifiable data. However, visual determination is imprecise and can lead to false positives and negatives. For example, it is unclear what the chemically untested red and orange garnets (Hutchison, 2020a) reported from the largely under-explored Franklinian Basin of North Greenland, and its associated Rae Craton Inlier, reveal about diamond prospectivity. While mineral chemical data would, ideally, be available for all candidate indicator minerals, cost and time have prohibited this.

Numerous factors have an influence on the attractiveness of specific areas, both at a small and large scale and sometimes with considerable effect. Known diamondiferous bodies, favourable mineral chemistry, and anomalous diamond occurrences in surface samples are all positive variables not quantified in the core prospectivity model. Negative factors can be influential, for example, much of Greenland is remote and the cost and benefit considerations of exploration can be heavily influenced by locality. Deep glacial weathering can be detrimental to prospectivity for primary diamond deposits. However, glacial activity results in considerable offshore (quantified by Weidick and Bennike, 2006) and onshore sedimentary successions, having considerable potential for diamond presence. Of particular note in that regard is the Nuussuaq Basin (references in Hutchison, 2022) where, depending on concentration mechanisms, palaeoplacers derived from Rae Craton diamonds may occur. However, the prospectivity modelling is not designed to capture offshore placer diamond deposits because of the bias towards old, rather than young rocks. Reworked deposits are naturally downgraded in the quantitative analysis and must therefore be manually upgraded when considering exploration planning. Therefore, despite the rigour and utility of the prospectivity model, explorers are encouraged to consider less quantifiable variables, with more detailed examples discussed in Hutchison (2022).

Un- and under-explored localities

Specific observations of under-explored localities include the presence of a single diamond reported from a 28.6 kg sample taken from an in-situ occurrence of metamorphosed ultramafic lamprophyre in the Karrat Basin (71.9°N; Hutchison, 2022). This discovery is anomalous and significant. Unexplored land abounds, even in otherwise well-explored areas with good diamond recovery, such as inland areas close to the Inland Ice both north and south of the Maniitsoq (Sukkertoppen) Ice Cap. The Maniitsoq area has been significantly explored near sea level, particularly at Majuagaa and Søndre Isfjord (Nielsen and Jensen, 2005). However, as Bonow et al. (2006) demonstrate, sea level is not an optimum place to look in western Greenland for more economically prospective parts of a kimberlitic volcanic succession, namely diatreme and crater rocks in pipes.

The Ketilidian Orogen and Gardar Province of southern Greenland score well on prospectivity modelling. While indicator minerals are apparently not abundant, this may mirror a similar paucity of fresh indicator minerals seen at Qeqertaa (S. Bernstein, 2022, pers. comm.). Both the Rae Craton at Qeqertaa and the Ketilidian Orogen have seen low grade metamorphism, thus it is hypothesised that these areas may lend themselves less well to non-diamond indicator mineral prospecting than areas of fresher primary bodies such as the NAC of western Greenland. Among known indicator grains from the Ketilidian Orogen and Gardar Province, mineral chemical analyses are encouraging, and Upton et al (2006) reported prospective aillikite diatremes. In fact the southern Greenland ultramafic lamprophyres are considerably distinct in age (Proterozoic), despite perhaps having similar metasomatic origins (Beard et al., 2024), from the succession of Phanerozoic intrusives younging north to south as the Davis Strait expanded from the coast of western Greenland (Larsen et al., 2009). Thus, Ketilidian and Gardar hosted rocks with diamond potential should be considered completely separately from those further to the north. It is also noteworthy that while the basement is relatively young in South Greenland (1.30 to 1.12 Ga Gardar rocks, Upton et al, 2003, intrude into 1.87 to 1.72 Ga Ketilidian host rocks, Henriksen et al, 2009) compared to Greenland's cratonic nuclei, precedent exists among diamondiferous rocks elsewhere in relatively young cratons. For example, the diamondiferous kimberlites in the vicinity of the Wyoming Craton are intruded into 1.8 to 1.4 Ga basement (Carlson et al., 2004). Furthermore, South Greenland does not seem to have experienced the same mantle lithosphere delamination (Artemieva, 2019) that the Wyoming Craton has experienced.

It is noteworthy that while reports of indicator minerals (referenced in Hutchison, 2022) may be spurious due to confusion between submitted samples and laboratory standards (G. Della Valle, 2023, pers. comm.), at Skjoldungen (Figure 1) a pipe-like outcrop is reported and three rock samples (two being from in-situ bodies) have compositions evidencing low crustal contamination and a strong similarity with diamond-producing kimberlites from Gribb, Russian Federation and Diavik, Canada (Hutchison, 2022).

Volume potential

The presence of diamonds in Greenland is well-established. Of the 3029 diamond-prospective rocks known from Greenland (Hutchison, 2020a), 41 have been proven to be diamond bearing. However, the proportion of Greenlandic indicator mineral samples that were analysed for diamond specifically is low compared to other localities (11% compared to, for example, 84% in Western Australia, Hutchison 2018b). So, considering few known bodies or even discrete occurrences have been tested, the abundance of diamondiferous rocks is significant. Diamonds on occasion are demonstrably large, and occur in commercially-interesting concentrations (Hutchison and Frei, 2009) and mineral chemistry and the results of this study demonstrate significant potential for further discoveries. However, one of the most significant challenges to the commercial significance of Greenland's diamondiferous bodies is volume potential. The sizes of diamond-prospective rocks in Greenland vary considerably, with 5 km being the longest known (the Paternoster Dyke, potentially up to 0.1 km^2 exposed at surface, Hutchison, 2022) and Garnet Lake is of comparable size to Snap Lake in Canada (Hutchison and Frei, 2009). However, due to glacial weathering, and while this provides opportunities for re-worked deposits (both on and off-shore), most known diamondiferous bodies represent the hypabyssal components of the intrusive plumbing system. That said, bodies not yet known to be diamondiferous, but still diamond-prospective are known from a wider geographic area extending into eastern Greenland at Skjoldungen (Hutchison, 2022a) and include the ultramafic lamprophyre diatremes of southern Greenland (Upton et al., 2006).

Concluding remarks

The Garnet Lake aillikite / kimberlite multiply-intruded dyke system distinguishes itself as a diamondiferous body of commercially interesting volume, diamond size, quality and concentration. Diamonds of 2.39 and 2.51 carats have been recovered from small bulk samples. To the north, within Disko Bay, diamondiferous ultramafic lamprophyres host diamonds with high levels of preservation and colourless diamonds are abundant throughout Greenland. The common presence of dykes and sills, evidencing removal of volcanic components of diamond-hosting rocks infers high quantities of diamonds in sedimentary deposits. Nonetheless, the presence of diatremes of Gardar-age ultramafic lamprophyres also demonstrates the potential for discovery of further bodies with significant volume potential. The mantle lithosphere is demonstrably thick, under a high proportion of Greenland's ice-free coastline, as testified by the presence of diamonds and the chemistries of their companion mantle-derived minerals. Greenland is established as a diamond prospective country.

Historical data and regional prospectivity metrics identify further opportunities for diamond exploration in Greenland particularly in selected areas of the west and southern coasts, as well as within less-explored areas such as eastern and northern regions, and off-shore. The NAC of western Greenland, distinguishes itself by numerous known in-situ diamondiferous bodies including the most diamondiferous occurrence in Greenland at Garnet Lake. The northern part of the NAC in western Greenland sits above the thickest (>225 km) mantle lithospheric keel. The Rae Craton of western Greenland contains diamondiferous bodies (as observed in the Rae craton in Canada) and presents a varied range of sampled mantle lithosphere depths and compositions in its regional indicator minerals. It is notable for larger bodies, such as the Paternoster Dyke. The southern Greenland Ketilidian Orogen, and associated Gardar Province, while less geologically stable than the attractive cratonic nuclei hosts prospective mineral chemistries and in-situ ultramafic lamprophyres revealing significant volume potential for exploitation. Further prospective areas that are considerably under-explored for diamonds include the Inglefield Orogenic Belt, NAC and Rae Cratons of eastern Greenland, and the Rae Craton of North Greenland.

This work demonstrates that Greenland is considerably under-explored for diamonds and presents compelling geological arguments for further study.

Acknowledgements The author's thirty-one year span of engagement with the geology of Greenland, particularly in the field of diamonds, has been greatly assisted by the companionship and insights of Stefan Bernstein, Lotte Larsen and Troels Nielsen (GEUS), Urban Burger (De Beers Marine), Rory Changleng (Pennsylvania State University), Ole Christiansen (Kommune Kujalleq), Guy Della Valle (independent), John Ferguson (deceased), Chuck Fipke (CF Minerals), Karen Hanghøj (British Geological Survey), Julie Hollis (EuroGeoSurveys), Anette Juul-Nielsen (Government of Greenland), Matilde Rink Jørgensen (Gribskov Gymnasium), Ekaterina Kiseeva (American Museum of Natural History), Louise Nielsen, Graham Pearson (University of Alberta), Geoff Nowell (University of Durham), Jonas Petersen (Government of Greenland), Jennifer Porter, Karina Sand (University of Copenhagen), Agnete Steenfelt (deceased), Jamie Tuer (Fjordland Exploration), Chad Ulansky (Metalex Ventures) and Brian Upton (University of Edinburgh). They are all gratefully acknowledged. Tjerk Heijboer and Kristine Thrane (GEUS) are thanked for support on classifications and ages of Greenland's geological regions. Barrett Elliott (NTGS) is thanked for contributions regarding Canadian data. Wayne Taylor, Lynton Jaques and Zachary Sudholz are thanked for invaluable insights into mineral chemistry and assisting with geothermobarometric calculations. Thomas Stachel is thanked for provision of PTEXL software. This work was funded by the Government of Greenland. This manuscript benefitted from insightful and constructive reviews by Graham Pearson and Kristoffer Szilas, who are gratefully acknowledged.

Declarations

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Figures

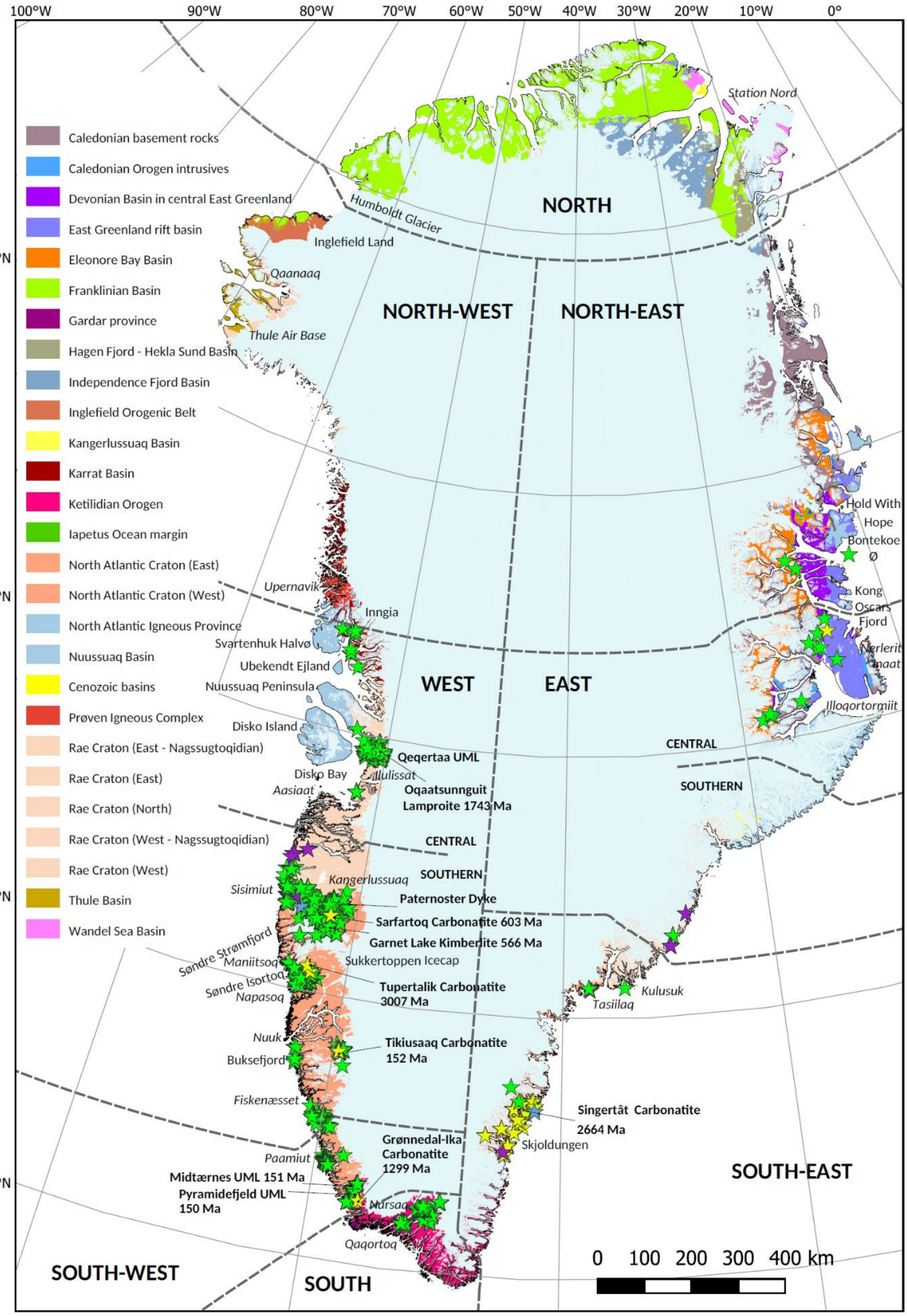

Fig. 1 Geographic and geological locations of note for diamond exploration in Greenland. Geographic subdivisions follow Ghisler (1990) and are applied throughout the text.

Geological regions are modified from Escher and Pulvertaft (1995) as described in the text and form the basis for diamond prospectivity modelling. Principal placenames referenced in the text are included. In-situ occurrences of known kimberlites and ultramafic lamprophyres, including aillikites (green stars), lamproites (purple stars), carbonatites (yellow stars), and their coarse-grained variety, sövites (blue stars), are indicated with principal sites named. Favoured emplacement ages, following Hutchison (2020a), are indicated for selected bodies. Figure modified from Hutchison (2022)

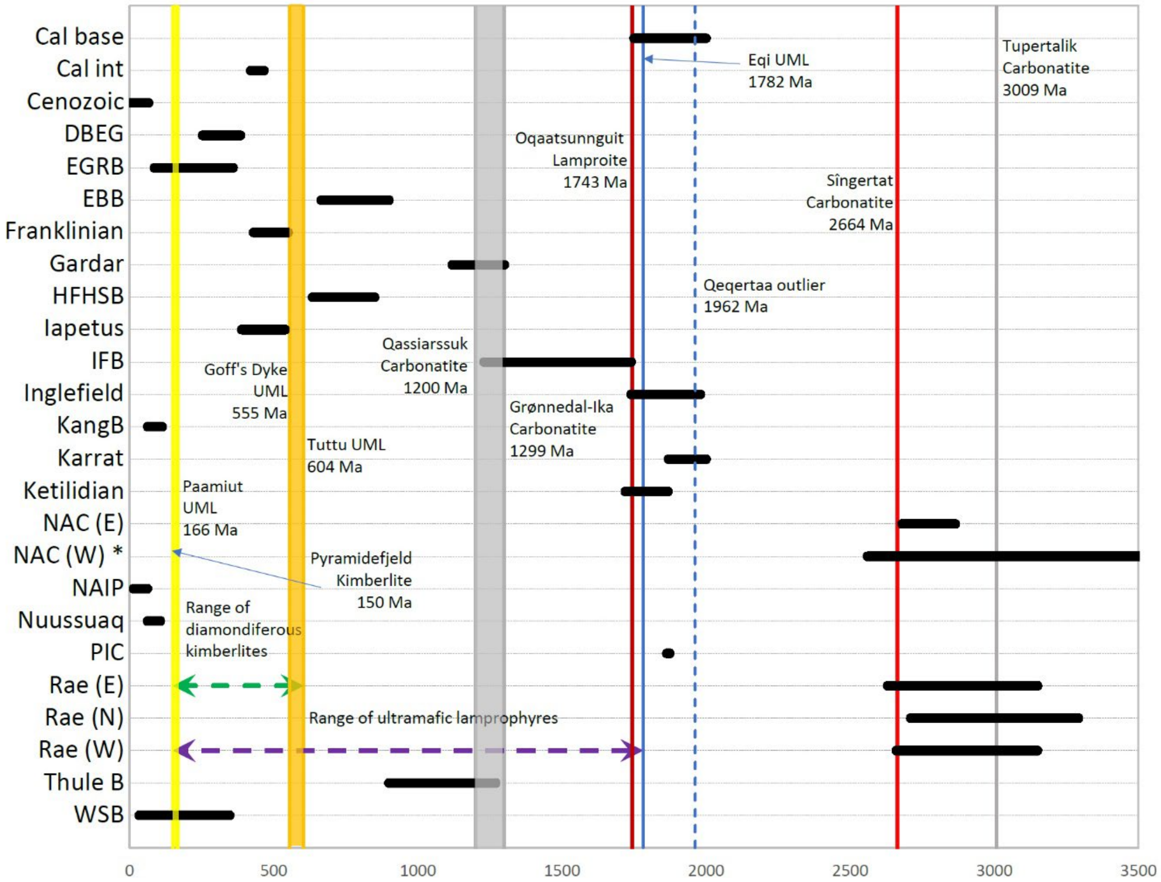

Fig. 2 Ranges of ages (Ma) of rocks present in geological regions of Greenland in the context of ages of selected diamond-prospective rocks. References to age ranges in Henriksen et al. (2009) and Hutchison (2022). Cal base = Caledonian Orogen basement, Cal int = Caledonian Orogen intrusives, Cenozoic = Cenozoic basins, DBEG = Devonian Basin of East Greenland, EGRB = East Greenland Rift Basin, EBB = Eleanore Bay Basin, Franklinian = Franklinian Basin, Gardar = Gardar Province, HFHSB = Hagen Fjord - Hekla Sund Basin, Iapetus = Iapetus Ocean Margin, IFB = Independence Fjord Basin, Inglefield = Inglefield Orogenic Belt, KangB = Kangerlussuaq Basin, Karrat = Karrat Basin, Ketilidian = Ketilidian Orogen, NAIP = North Atlantic Igneous Province, Nuussuaq = Nuussuaq Basin, PIC = Prøven Igneous Complex, Rae (E), (N) and (W) = Rae Craton of eastern, northern and western Greenland respectively, Thule B = Thule Basin, WSB = Wandel Sea Basin. * The NAC of west Greenland rocks extend in age to 3890 Ma. The youngest and oldest-dated intrusives for each age cluster are indicated. The single outlier of 1962±80 Ma from Th/Pb age determination of

a monazite grain from the diamondiferous Qeqertaa UML is shown, older than the peak metamorphic ages from two samples at 1788±16 Ma and 1819±23 Ma and possibly representing an emplacement age (Hutchison et al., 2024). For reference, the diamondiferous, multiply intruded aillikite / kimberlite at Garnet Lake, Sarfartoq (NAC of western Greenland) has been dated at 566 Ma (Hutchison and Heaman, 2008) and lies at the later end of the Neoproterozoic (Ediacaran) western Greenlandic kimberlitic cluster

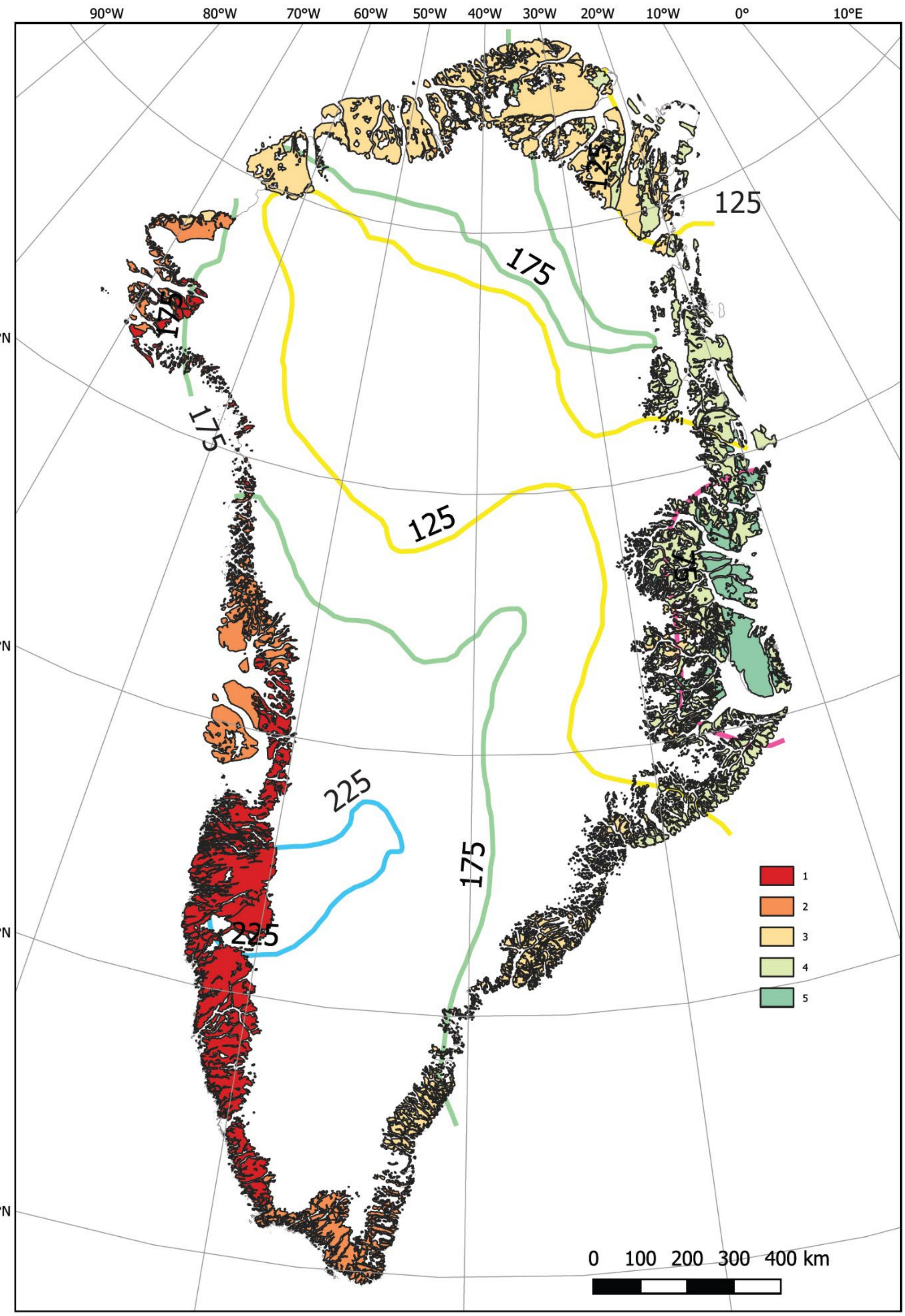

Fig. 3 Geological regions scored according to lithosphere thickness. The surface area above each range of depths to the asthenosphere / lithosphere boundary (shown by the coloured lines

and following Artemieva, 2019) was calculated for each geological region and a weighted depth calculated. These weighted depths were used to assign a score to each geological region with lower values representing thicker, and thus more diamond-prospective mantle lithosphere. While the prominent mantle keel in excess of 250 km in western Greenland results in a good score for the Rae Craton and NAC in this area, it is notable that Inglefield Land in northern North-West Greenland scores well. Significant mantle thinning as a consequence of the Caledonian Orogeny results in poor scores for eastern Greenlandic regions centred on 72°N (Kong Oscars Fjord)

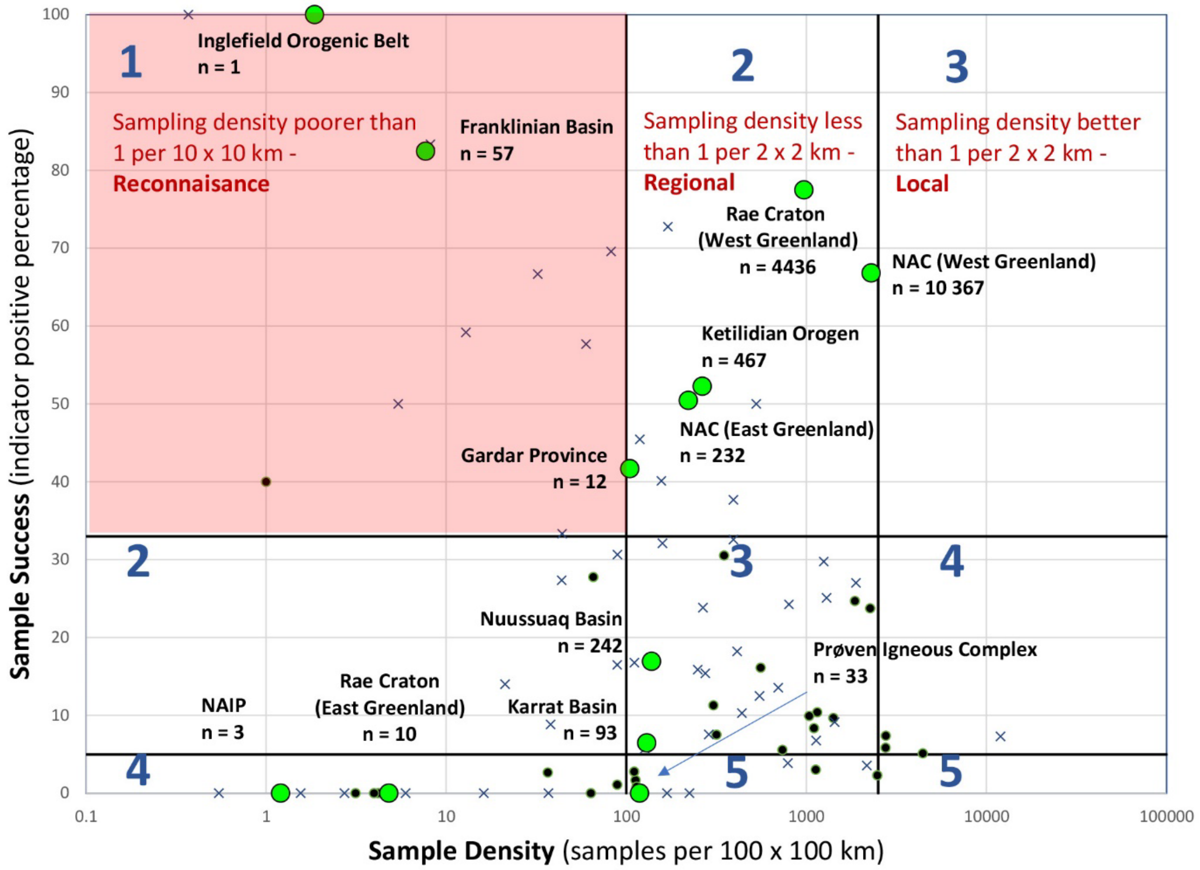

Fig. 4 Sampling success versus sampling density for samples taken for diamond indicator identification. Geological regions are labelled, with the numbers of indicator mineral samples shown (both positive and negative samples). Sampling success is measured as the percentage of samples collected for diamond indicator minerals that returned a positive recovery (i.e., at least one visually determined indicator mineral, including diamond). Sampling density is the number of samples (n) taken per 10 000 km^2 area within each region. Blue numbers represent prospectivity scores assigned to regions plotting within shaded areas of the chart. Regions with good indicator recovery (over 1/3 of samples being positive) but explored only at reconnaissance scale (< 1 sample per 100 km^2) are favoured. Regions with poor recovery (under 1/20 of samples being positive) that have been sampled with average sampling density better than 1 sample per 100 km^2 are less favoured (scoring 5). Completely unsampled areas, not represented in the figure, are scored 5 or 6, depending on whether lack of sampling is based on geological or logistical reasons. Data from the Northern Territory (Hutchison, 2012,

black dots) and Western Australia (Hutchison, 2018b, crosses) are provided for comparison, showing that relative to the diamond-producing nation of Australia, Greenland is significantly under-sampled, whereas the sampling which has occurred has been more directed, and thus more successful

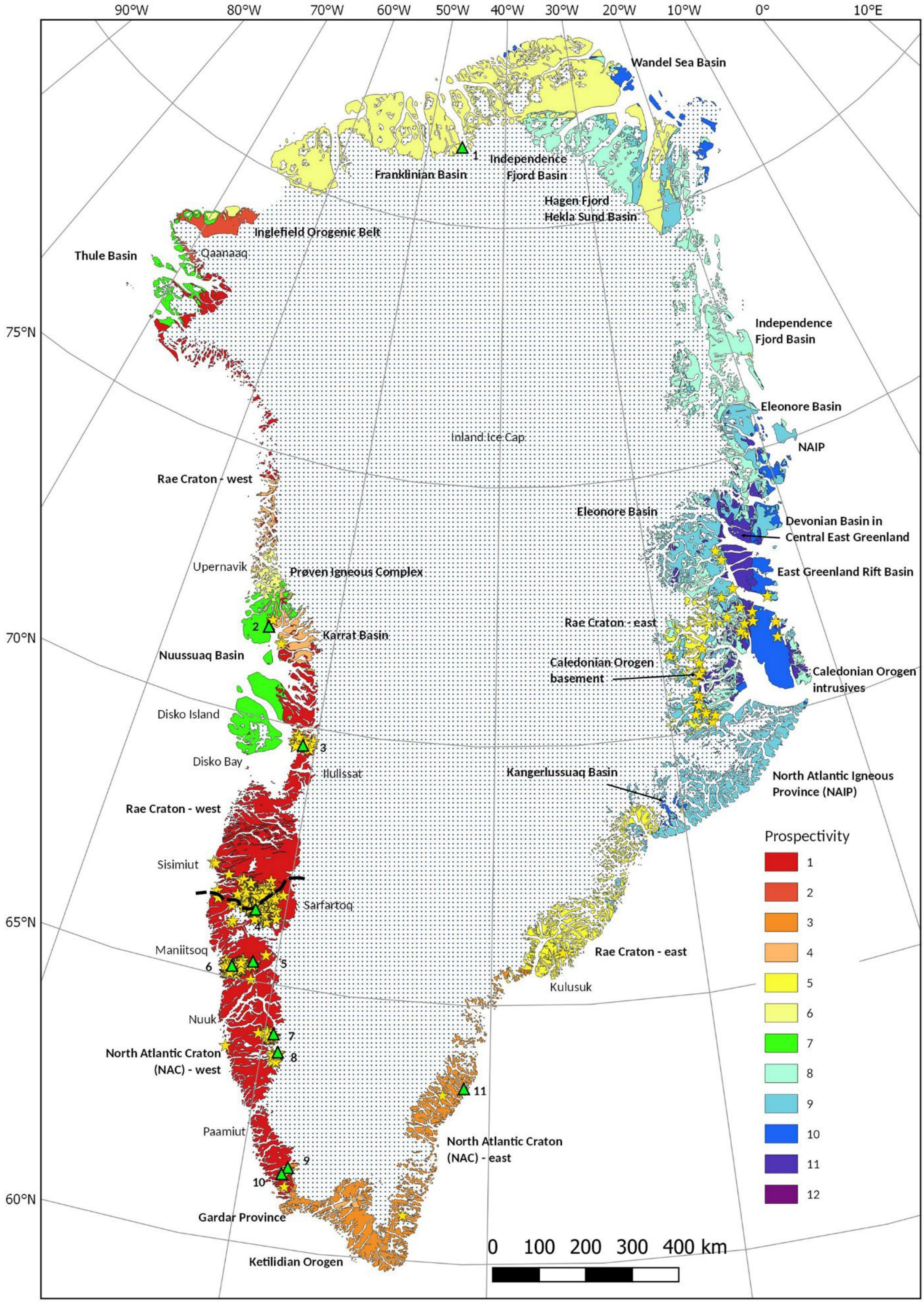

Fig. 5 Prospectivity map of Greenland. Geological sub-divisions are ranked for prospectivity, following the methodology described in the text, in the context of mantle structure, the age of

surface rocks, the extent of sample coverage and recovery of visually-determined indicators. Ranking follows the key, with 1 being the most prospective area and 12 the least. Areas of permanent ice are identified by stippling. In-situ diamond-prospective rocks are shown by yellow stars, with notable localities numbered and identified by green triangles: 1 – Rae Craton of north Greenland with associated visually identified garnets, 2 – Svartenhuk Halvø, 3 – Qeqertaa diamondiferous metamorphosed ultramafic lamprophyre dykes, 4 – Garnet Lake diamondiferous multiply intruded aillikite / kimberlite sheet, 5 – Qaamasoq diamondiferous kimberlitic float, 6 – Majuagaa diamondiferous kimberlite dyke, 7 – Tikiusaaq Carbonatite and associated diamondiferous aillikite dykes, 8 – Nunatak 1390 with abundant kimberlitic float, 9 – Midternæs diamondiferous aillikite sills, 10 – Pyramidefjeld diamondiferous aillikite sheets, 11 – Skjoldungen Carbonatite complex and neighbouring indicator garnet and possible kimberlite

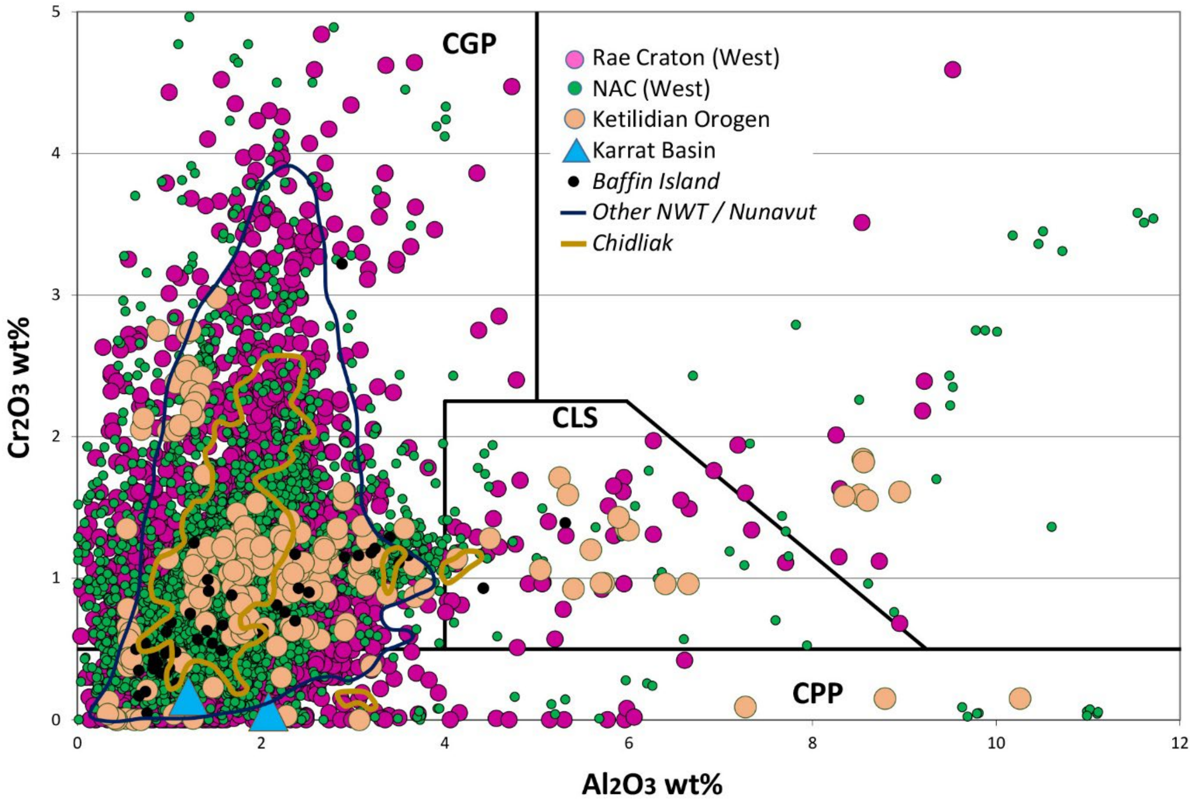

Fig. 6 Chemical composition of clinopyroxenes in terms of Cr_2O_3 and Al_2O_3. Compositional fields CGP (clinopyroxene from garnet peridotite), CLS (clinopyroxene from spinel lherzolite) and CPP (eclogitic, megacrystic and cognate clinopyroxene) are from Ramsay and Tompkins (1994). Greenland clinopyroxene compositions are presented following the key. For comparison, a hand-drawn field for regional samples from Nunavut and Northwest Territories reflects 99% of the compositional data range omitting outliers (Northwest Territories Geological Survey, KIDD/KIMC, 2017). Individual compositions from Brodeur Peninsula (Rae Craton in Canada) samples are also included, as is an approximated field of 90% of Chidliak samples reported by Pell and Neilson (2008)

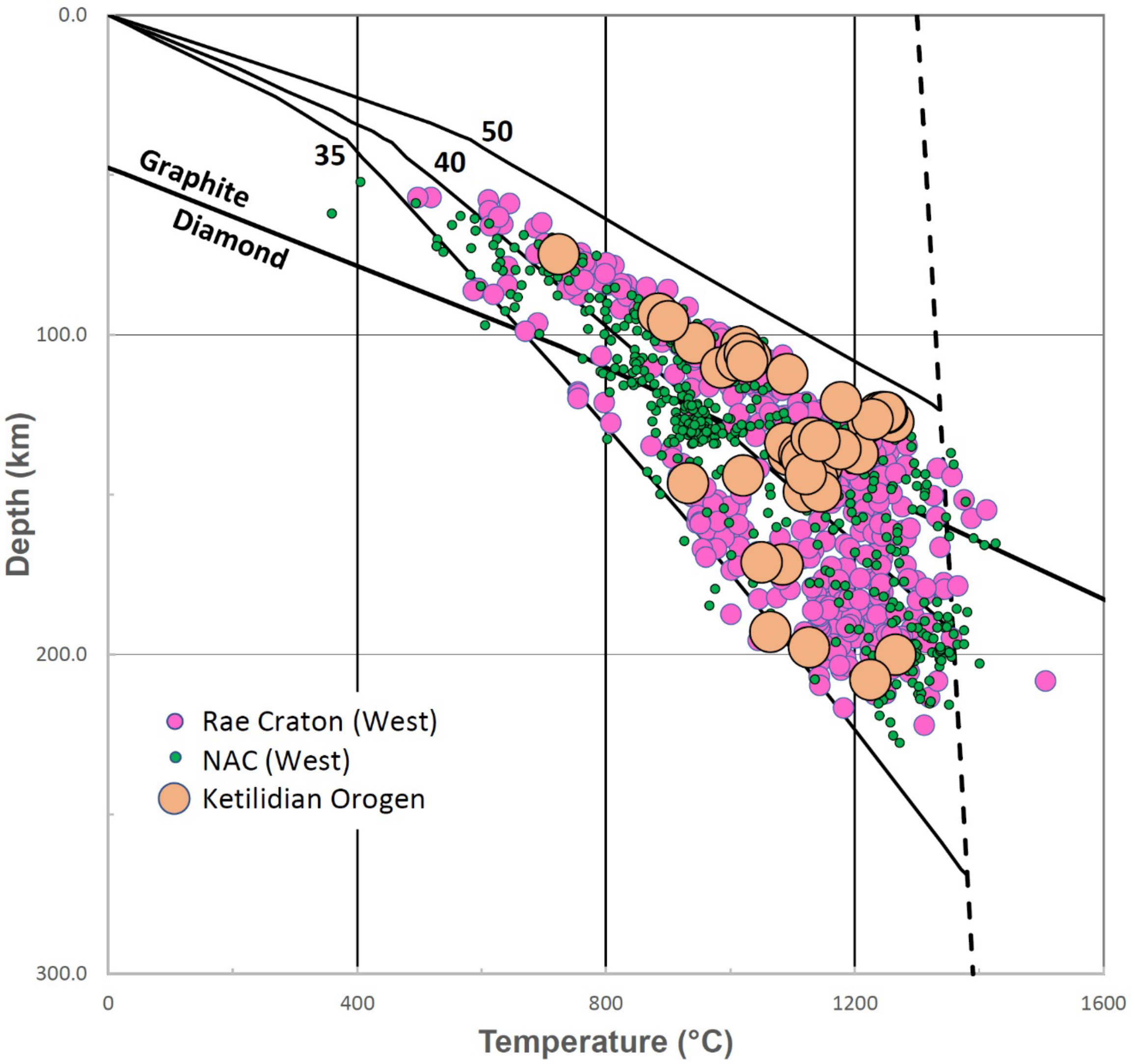

Fig. 7 Calculated temperature and depths of origin of garnet lherzolite-derived clinopyroxenes grains from surface sediment and solid rock samples, following the methodology of Sudholz et al. (2021a). The diamond-graphite phase transition of Day (2012) is annotated, and dashed mantle adiabat and 35, 40 and 50 mWm^{-2} geotherms of Hasterok and Chapman (2011) are shown. High proportions of clinopyroxenes derive from within the diamond stability field. North Atlantic Craton grains, among which is the deepest calculated clinopyroxene (Garnet Lake sample from 228 km, 74.5 kbar, 1272 °C), express a slightly tighter clustering of formation conditions than Rae Craton grains. While several Ketilidian Orogen grains express a relatively warm ~44 mWm^{-2} geotherm, deeper-sourced grains clearly demonstrate a

considerably cooler geotherm comparing favourably with deep-sourced clinopyroxenes from the Rae and North Atlantic Cratons, and particularly conducive to diamond formation

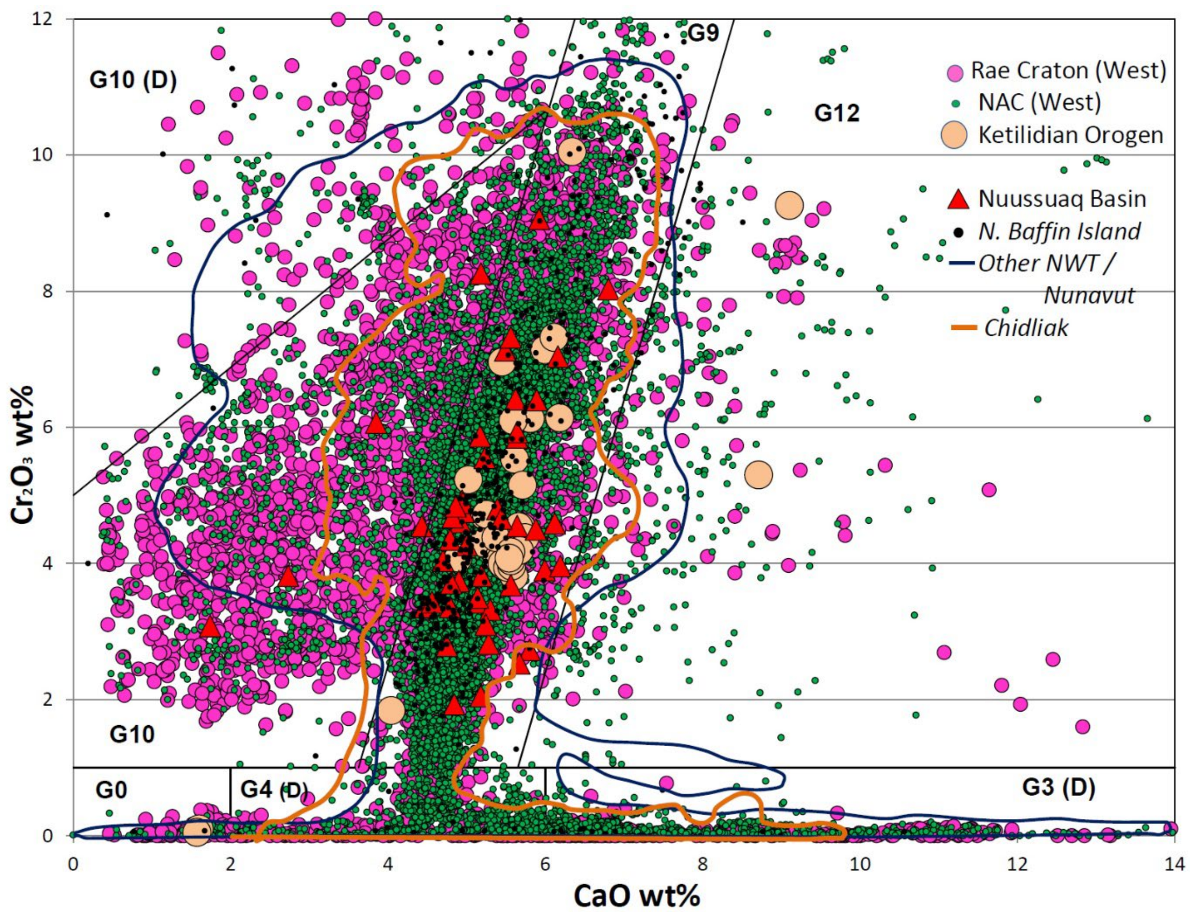

Fig. 8 Chemical composition of pyrope–almandine–grossular garnets in terms of CaO and Cr_2O_3. Classifications follow Grütter and Quadling (1999) and Grütter et al. (2004). Compositions of Greenlandic garnets are subdivided according to the key. For comparison, the extent of 99% of Nunavut and Northwest Territories compositions from Northwest Territories Geological Survey, KIDD/KIMC (2017) indicator garnets is shown, as are individual compositions from the Brodeur Peninsula (Rae Craton in Canada) from the same reference. The range of approximately 90% of garnet indicator compositions from till samples from Chidliak (Pell and Neilson, 2012) is also shown

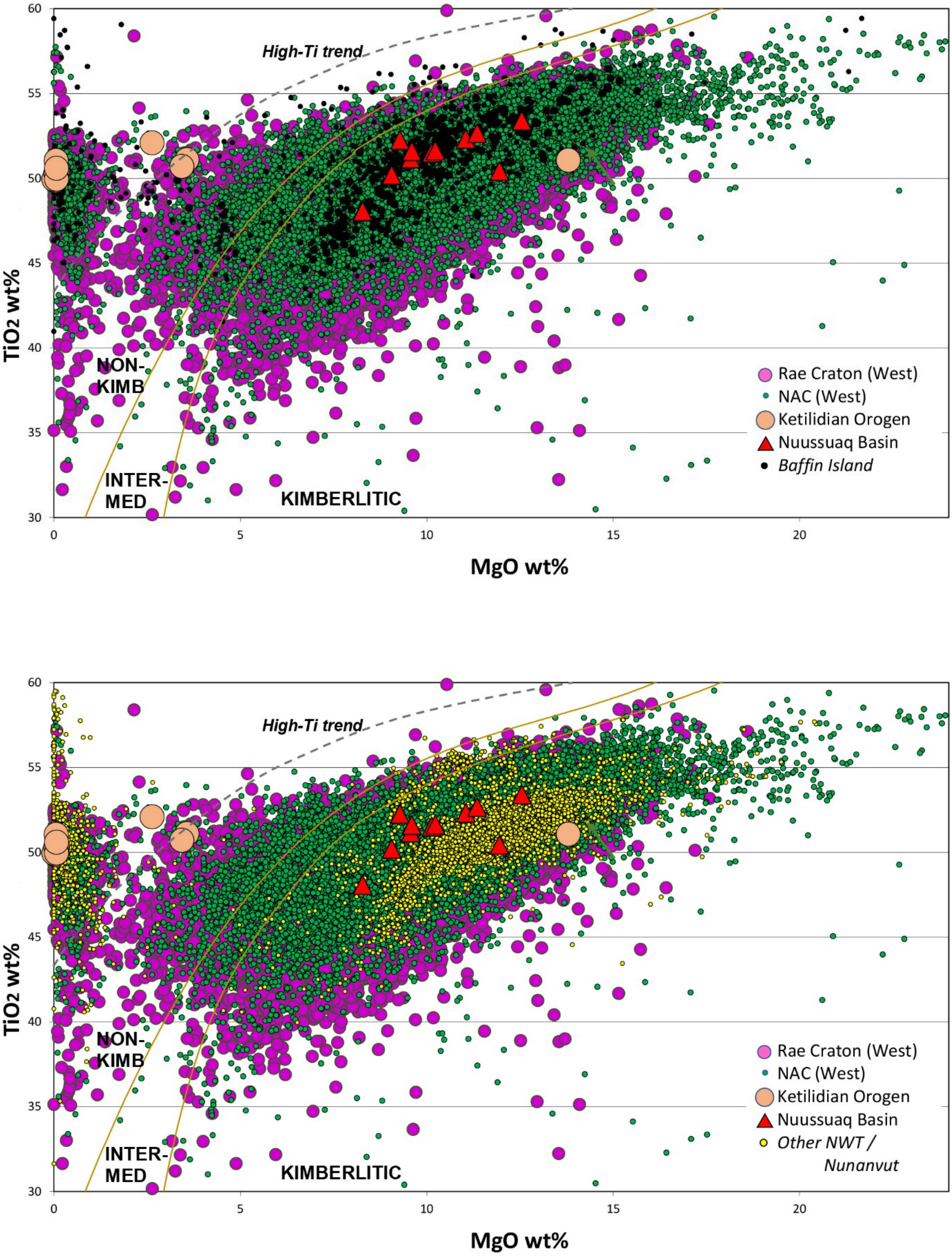

Fig. 9 Chemical composition of ilmenites in terms of TiO_2 and MgO. Mineral chemistry is subdivided according to likely association with kimberlite following Wyatt et al. (2004). Compositions of Greenlandic ilmenites from different localities are plotted according to the

key: a) Greenlandic ilmenite compositions in comparison with Canadian samples from northern Baffin Island Brodeur Peninsula diamondiferous kimberlite field (Northwest Territories Geological Survey, KIDD/KIMC, 2017). Both the NAC and Rae Cratons of western Greenland reveal very abundant numbers of ilmenites well within the field of compositions associated with kimberlite. All Nuussuaq Orogen ilmenites fall firmly within the kimberlitic field, and while the numbers of Ketilidian Orogen ilmenites with compositional data are very small (12 samples), one analysis plots within the kimberlite field. While NAC ilmenites from western Greenland extend to particularly high Mg-concentrations, Brodeur Peninsula ilmenite compositions sit comfortably within NAC and Rae Craton compositional fields and, in particular, are closely mirrored by Nuussuaq Basin samples; b) Greenlandic ilmenite compositions compared with the range of 99% of Canadian ilmenites from Northwest Territories Geological Survey, KIDD/KIMC (2017) excluding Brodeur Peninsula samples

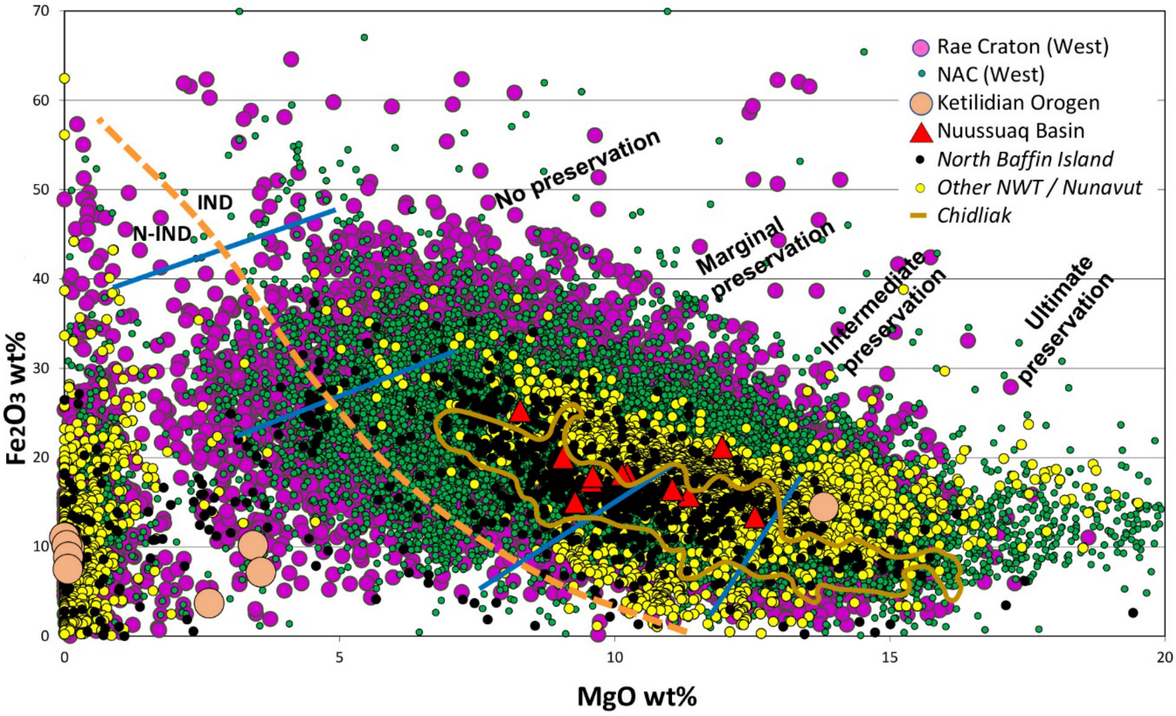

Fig. 10 Distribution of ilmenite compositions in terms of ferric iron oxide ($Fe(III)_2O_3$) and MgO wt% for Greenlandic and selected Canadian sources. All ilmenite analyses were treated by stoichiometric charge balance to calculate ferric relative to ferrous iron, thus generating the ferric iron data used in the figure. Ilmenite compositions are subdivided following Wyatt et al. (2004), with ilmenites considered to be indicators divided by the heavy, dashed orange line. Among indicators, the extent of likely diamond preservation, based on modelled kimberlite oxidation state (Gurney and Zweistra, 1995), is shown by the labelled fields separated by heavy black lines. Canadian data from northern Baffin island and elsewhere in the NWT and Nunavut derive from Northwest Territories Geological Survey, KIDD/KIMC (2017) and Chidliak data derive from Pell and Nielson (2008)

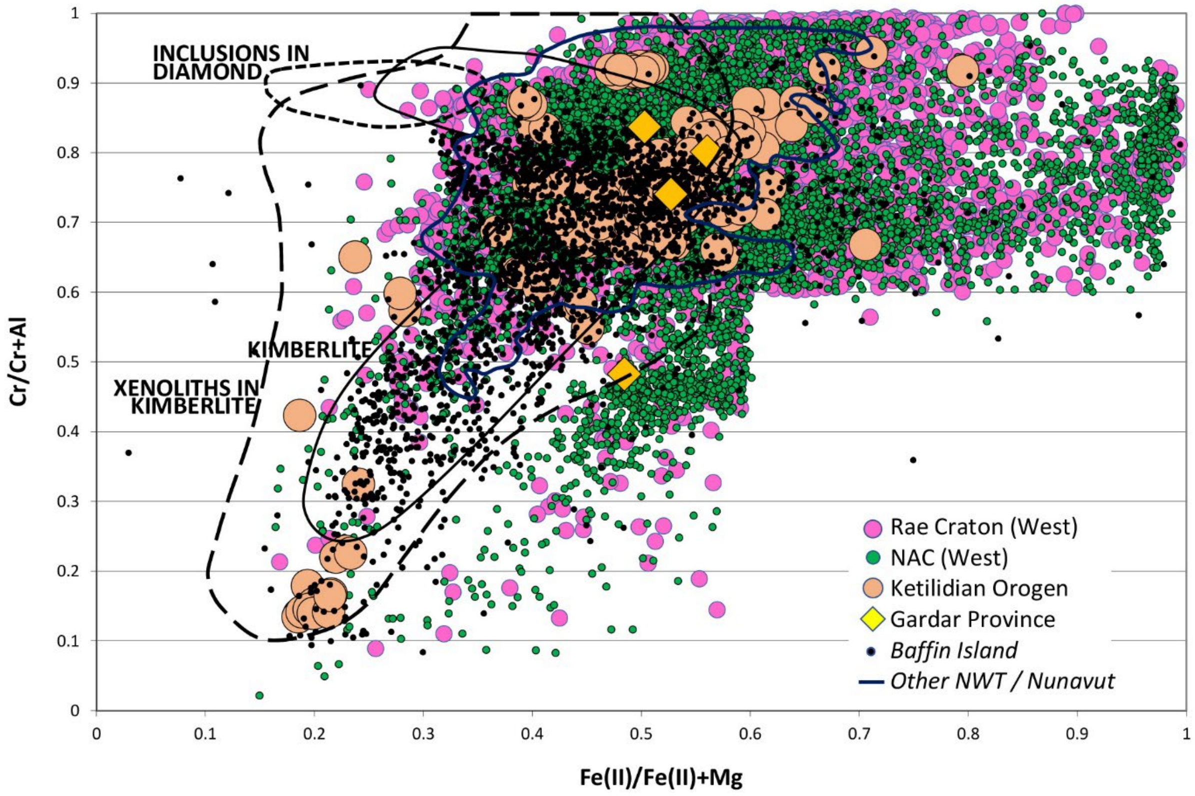

Fig. 11 Chemical composition of indicator spinels projected from the oxidized prism in terms of Cr to Al ratio and Fe^{2+} to Mg ratio. Compositional fields coincident with chromite inclusions in diamonds, kimberlite groundmass grains and xenocrysts in kimberlites have been derived from Mitchell (1986). Projection onto the oxidized prism requires iron to be calculated as ferrous and ferric. Greenland spinel compositions are presented following the key. For comparison, the extent of 99% of Nunavut and Northwest Territories compositions from Northwest Territories Geological Survey, KIDD/KIMC (2017) indicator spinels is shown, as are individual compositions from the Brodeur Peninsula (Rae Craton in Canada) from the same reference. Few chromites have compositions consistent with inclusions in diamond. All of the Gardar Province, Ketilidian Orogen, NAC and Rae Craton show compositions of spinel indicators consistent with both xenocrysts and phenocrysts in kimberlites. The Rae Craton shows the widest compositional range. All Greenlandic regions with spinel compositional data show strong similarity with data from diamond producing

regions of Canada, including the rare, yet significant proportion of spinels with compositions in the diamond inclusion field

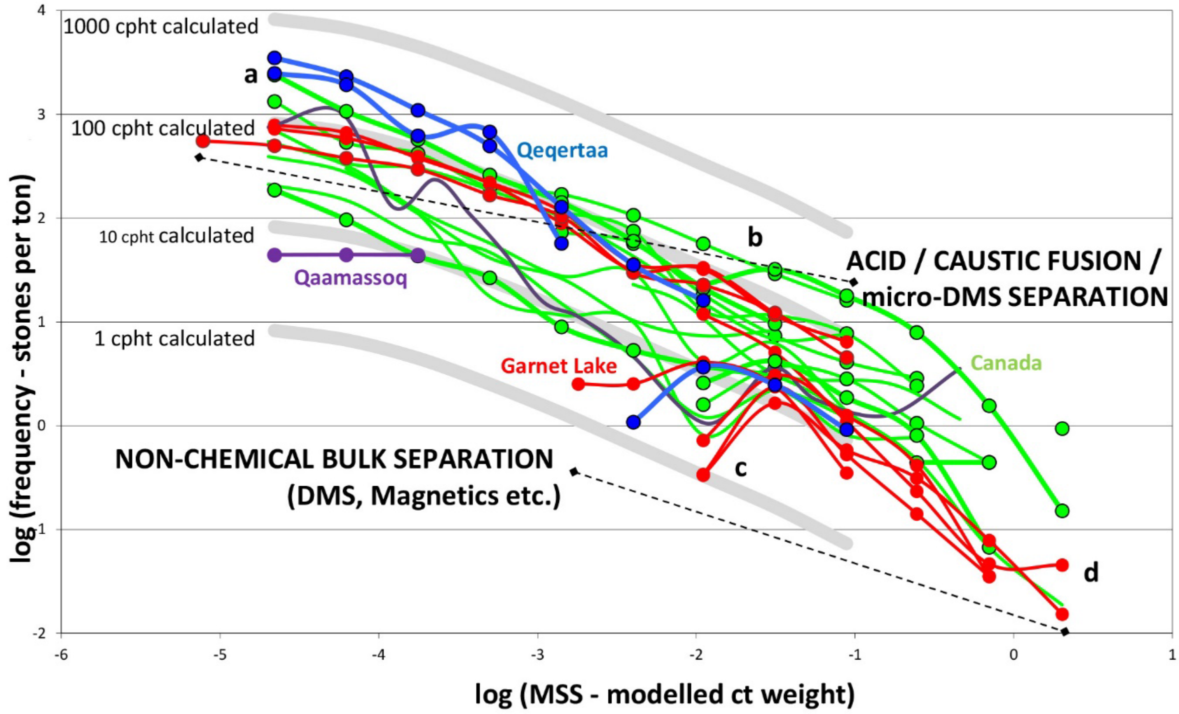

Fig. 12 Abundance of diamonds recovered according to size from Greenlandic and Canadian exploration projects. Calculations of modelled stone size (MSS) following methodology modified from Chapman and Boxer (2004). Garnet Lake data are shown in red, Qeqertaa data are shown in blue and Qaamasoq data are shown in purple. Canadian data are shown in green and derive from Stornoway Diamonds (Canada) Inc. (2010 and 2011), Peregrine Diamonds Limited (2010 to 2012), Twin Mining Corporation (2006), North Arrow Minerals Inc. (2015) and Diamondex Resources Limited (2008) press releases and public technical reports, with industry-sourced data references provided in Hutchison (2022). Data from the Chidliak kimberlites (later acquired by De Beers) are indicated with green markers. Also, for comparison, the data from a 1.5 tonne sample of the small, commercially mined kimberlite pipe at Merlin (Lee et al., 1997) are shown with a solid black line. Diamonds recovered by chemical means compared to non-chemical (DMS and magnetic) methods are indicated by dashed lines. Qaamasoq recovery is not sufficiently large to fully assess the diamond-potential of this locality

Tables

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

Ranking	Description	n	Ranking	Description	n
(a) Sampling history scoring criteria					
1	Reconaissance-scale sampling (< 1 sample per 100 km^2) with good recovery (> 1/3rd of samples are indicator positive)	2	4	Local-scale sampling with reasonable recovery or reconaissance-scale with poor recovery (< 1/20th of samples are indicator positive)	2
2	Regional-scale sampling (between 1 sample per 4 km^2 and 1 sample per 100 km^2) with good recovery, or reconaissance-scale with reasonable recovery (1/20th to 1/3rd of samples are indicator-positive)	5	5	Poor recovery from regional or local sampling density, or regions unsampled due to inaccessibility	7
3	Local-scale sampling (> 1 sample per 4 km^2) with good recovery or regional with reasonable recovery	2	6	No sampling conducted on geologically non-propsective regions	7
(b) Regional age range scoring criteria					
1	All rocks are Archean and may, or may not predate the two recorded Archean carbonatites (2664 Ma Singertât Carbonatite Complex, Bizzarro et al., 2002; the 3007 Ma Tupertalik carbonatite, Blichert-Toft et al., 1995)	5	4	All rocks pre-date the Neoproterozoic diamond-prospective rocks, the oldest being the 603.6 Ma Tuttu lamprophyre (Secher et al., 2009), but they are younger than the Mesoproterozoic diamond-prospective rocks extending to the 1200 Ma Qassiarssuk Carbonatite (Andersen, 1997)	2
2	All rocks are Proterozoic and also pre-date the earliest Mesoproterozoic ultramafic lamprophyres (1299 Ma Grønnedal-Ika Complex, Secher et al., 2009), which include the diamondiferous Qeqertaa lamprophyre (possibly as old as 1962±80 Ma, Hutchison et al., 2024)	5	5	Some, or all rocks are older than the youngest diamond-prospective rock (Pyramidefjeld kimberlite, 149.8 Ma, Larsen et al., 2009), but all rocks are younger than than Neoproterozoic diamondiferous kimberlite / aillikite suite, which includes Garnet Lake and has its youngest manifestaion with Goff's Dyke (555 Ma, Secher et al., 2009)	6
3	All rocks pre-date the Neoproterozoic diamond-prospective rocks (extending from the 603.6 Ma Tuttu lamprophyre, Secher et al., 2009), however, some overlap the Mesoproterozoic diamond-prospective rocks with the youngest age being 1200 Ma (Qassiarssuk Carbonatite, Andersen, 1997)	3	6	All rocks are younger than the youngest diamond-prospective rock (Pyramidefjeld kimberlite, 149.8 Ma, Larsen et al., 2009)	4
(c) Lithosphere thickness and density scoring criteria					
1	Mean depth > 200km	2	4	Mean depth > 75 km and ≤ 125 km	5
2	Mean depth > 190 and ≤ 200 km	8	5	Mean depth < 75 km	4
3	Mean depth > 125 and ≤ 190 km	6			

n, number of regions assigned to each ranking

Table 2 Prospectivity scores and rankings of Greenlandic geological regions

Region	Sampling score	Age score	Lithosphere score	Cumulative score	Prospectivity
Caledonian Orogen basement	5*	2	4	11	8
Caledonian Orogen intrusives	6	5	5	16	12
Cenozoic Basins	6	6	3	15	11
Devonian Basin of East Greenland	6	5	5	16	12
East Greenland Rift Basin	6	5	5	16	12
Eleanore Bay Basin	5*	4	4	13	9
Franklinian Basin	1	5	3	9	6
Gardar Province	2	3	2	7	4
Hagen Fjord - Hekla Sund Basin	5*	4	4	13	9
Iapetus Ocean Margin	6	5	5	16	12
Independence Fjord Basin	5*	3	3	11	8
Inglefield Orogenic Belt	1	2	2	5	2
Kangerlussuaq Basin	6	6	3	15	11
Karrat Basin	3	2	2	7	4
Ketilidian Orogen	2	2	2	6	3
NAC (eastern Greenland)	2	1	3	6	3
NAC (western Greenland)	2	1	1	4	1
NAIP	4	6	4	14	10
Nuussuaq Basin	3	6	2	11	8
Prøven Igneous Complex	5	2	2	9	6
Rae Craton (eastern Greenland)	4	1	3	8	5
Rae Craton (north Greenland)	5*	1	2	8	5
Rae Craton (western Greenland)	2	1	1	4	1
Thule Basin	5*	3	2	10	7

Region	Sampling score	Age score	Lithosphere score	Cumulative score	Prospectivity
Wandel Sea Basin	6	5	4	15	11

NAIP = North Atlantic Igneous Province

* Sampling score modified from 6 to 5 because region was not neglected due to low perceived prospectivity, rather due to logistical factors

1244 **Supplementary Table 1** Sampling metrics and scoring by geological region

Region	Area (km^2)	Total onshore samples	DIM and diamond processed samples	Samples per 100 x 100 km area	% of indicator-positive samples	Initial score	Adjusted score*
Caledonian Orogen basement	35 663	1024	0	0	na	6	5
Caledonian Orogen intrusives	4996	789	0	0	na	6	6
Cenozoic Basins	312	3	0	0	na	6	6
Devonian Basin of E Greenland	8805	218	0	0	na	6	6
E Greenland Rift Basin	16 150	2077	0	0	na	6	6
Eleanore Bay Basin	24 601	2271	0	0	na	6	5
Franklinian Basin	74 110	57	57	7.7	82	1	1
Gardar Province	1147	12	12	104.6	42	2	2
Hagen Fjord - Hekla Sund Basin	8183	0	0	0	na	6	5
Iapetus Ocean Margin	809	68	0	0	na	6	6
Independence Fjord Basin	19 168	0	0	0	na	6	5
Inglefield Orogenic Belt	5377	1	1	1.9	100	1	1
Kangerlussuaq Basin	809	0	0	0	na	6	6
Karrat Basin	7150	105	93	130.1	6	3	3
Ketilidian Orogen	17 646	471	467	264.6	52	2	2
NAC (eastern Greenland)	10 471	780	232	221.6	50	2	2
NAC (western Greenland)	45 231	11 288	10 367	2292.0	67	2	2
NAIP	24 931	213	3	1.2	0	4	4
Nuussuaq Basin	17 515	242	242	138.2	17	3	3
Prøven Igneous Complex	2780	33	33	118.7	0	5	5

Region	Area (km^2)	Total onshore samples	DIM and diamond processed samples	Samples per 100 x 100 km area	% of indicator-positive samples	Initial score	Adjusted score*
Rae Craton (eastern Greenland)	20 829	423	10	4.8	0	4	4
Rae Craton (north Greenland)	276	0	0	0	na	6	5
Rae Craton (western Greenland)	45 771	4921	4436	969.2	77	2	2
Thule Basin	5329	0	0	0	na	6	5
Wandel Sea Basin	3456	0	0	0	na	6	6

NAIP = North Atlantic Igneous Province, na = not applicable

* Regions with no sampling initially score 6, by definition. However, where sampling has been absent due to non-geological reasons (such as inaccessibility), such regions are assigned a score of 5, matching those with poor recovery despite sampling being conducted at local or regional-scale