30 YEARS OF DIAMONDS IN CANADA
8-12 July 2024 • Yellowknife
12th International Kimberlite Conference Extended Abstract No. 12IKC-60, 2024

Emplacement of the Argyle diamond deposit into an ancient rift zone triggered by supercontinent breakup

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Introduction

Argyle, the world's largest source of natural diamonds discovered to date, is one of only a few economic deposits hosted a Paleoproterozoic orogen. Argyle (formally AK1) is situated in the Carr Boyd Basin, a small Meso- to Neoproterozoic intracontinental basin in the Paleoproterozoic to Paleozoic Halls Creek Orogen at the southeastern edge of the Kimberley Craton in Western Australia (Fig. 1A). Argyle is hosted in olivine lamproite, rather than kimberlite, and has yielded >90% of all pink diamonds ever discovered (Bulanova, et al. 2018). The discovery of Argyle in 1979 resulted in a paradigm shift that led to diamond exploration in non-Archean terranes (Smith, et al. 2018). Despite its importance, the geodynamic drivers responsible for the emplacement of such an unusual diamondiferous pipe complex remain unclear mainly because of uncertainties on its age of emplacement.

Argyle is situated in an intracontinental rift that formed as a result of various, discrete far-field tectonic drivers between c. 1910 and 1805 Ma, the most important of which are the c. 1870–1850 Ma Hooper and c. 1835–1805 Ma Halls Creek Orogenies (Maidment, et al. 2022). The age of emplacement of the Argyle lamproite has been previously estimated from whole-rock and altered phlogopite K-Ar and Rb-Sr dates, ranging from 1240 to 1110 Ma (Pidgeon, et al. 1989; Skinner, et al. 1985; Sun, et al. 1986). However, K-Ar and Rb-Sr systematics are not ideal as they can easily be modified by alteration, with previous workers recognising that the K contents of dated phlogopite in the main diatreme complex were "anomalously low" and indicative of partial chloritization. Although there is relatively fresh phlogopite in some of the lamproite dykes, dating it with high precision $^{40}Ar/^{39}Ar$ has proved challenging due to the presence of excess radiogenic Ar. Moreover, whilst the excess radiogenic Ar issue may be obviated with in situ Rb-Sr dating, minor alteration of the phlogopite and uncertainty around whether the dykes are coeval with the diatreme still make dating these phlogopite grains problematic.

Here, we provide comprehensive geochronological data for fresh high-grade mineralised diatreme (AK1-Lh01) from diamond drill core (Fig 1B,C,D,E), including U-Pb geochronology of titanite, and U-Pb and (U-Th)/He dating of zircon and apatite to resolve the age of the Argyle deposit and provide an explanation for when and why Argyle formed.

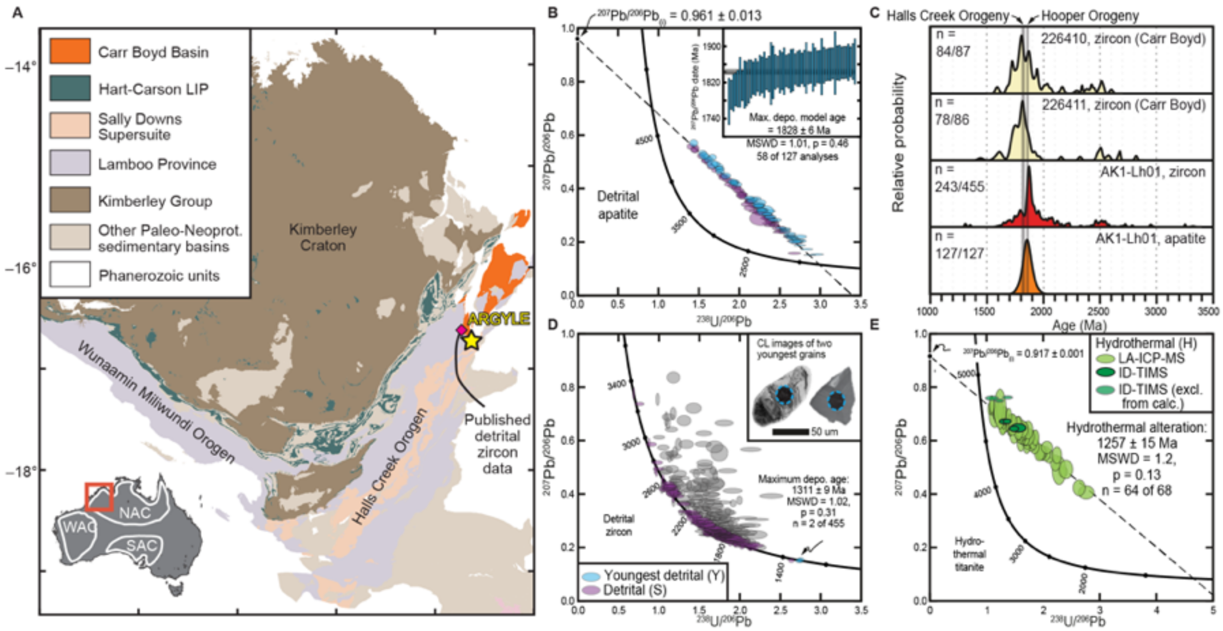

Figure 1: (A) 1:500,000 geological map of the Kimberley Craton and surrounding orogens with location of Argyle lamproite, with inset showing the location of the West (WAC), North (NAC) and South (SAC) Australian Cratons.(B) Detrital apatite concordia plot; inset shows the weighted mean of youngest grains. (C) Probability density plot of detrital zircon and apatite, including published zircon data from two proximal samples from elsewhere in the Carr Boyd Basin. (D) Detrital zircon, with inset showing cathodoluminescence images of the two youngest grains. (E) Hydrothermal titanite concordia plot.

Results

Three minerals—detrital zircon, detrital apatite, and hydrothermal titanite—were analyzed using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and isotope dilution thermal ionisation mass spectrometry (ID-TIMS) techniques. This analysis provided a maximum depositional age from detrital zircon and apatite and a minimum age of hydrothermal alteration from titanite, effectively bracketing the emplacement of the Argyle lamproite. Apatite's ^{207}Pb-corrected dates suggest erosion from rocks formed during the Hooper and Halls Creek orogenies, with a weighted mean of 1828 ± 6 Ma for the youngest grains, indicating a maximum emplacement age older than the host Carr Boyd Group. The U-Pb system in apatite was not thermally reset post-Halls Creek Orogeny, avoiding alteration that could skew dating. Detrital zircon age peaks correlate with the Hooper Orogeny and other significant geological periods, with some grains dating back to 1311 ± 9 Ma, providing a stringent maximum emplacement age for the Argyle lamproite. Titanite, indicative of hydrothermal activity, showed an imprecise but robust lower concordia intercept age of 1268 ± 40 Ma using LA-ICP-MS, refined to 1257 ± 15 Ma when combining LA-ICP-MS and ID-TIMS data, suggesting pervasive hydrothermal alteration around 1260 Ma. This age represents a conservative minimum emplacement age for the Argyle diatreme complex, not attributable to a discrete heating event since apatite was not reset.

Discussion and conclusion

Around 1300 Ma, the supercontinent Nuna was nearing fragmentation. Plate tectonic models suggest Argyle was on the edge of the McArthur-Yanliao Gulf, a Mesoproterozoic basin bordered by proto-Australia, North China, Siberia, Laurentia, and possibly India and South China (Li, Liu and Ernst 2023). Evidence points to Nuna's cohesion around 1320 Ma but its dispersal by 1220 Ma, though the precise breakup timing is elusive due to limited data. Between 1330–1295 Ma, dyke swarms and volcanism occurred around this Gulf, forming the Derim Derim-Galiwinku-Yanliao large igneous province, impacting

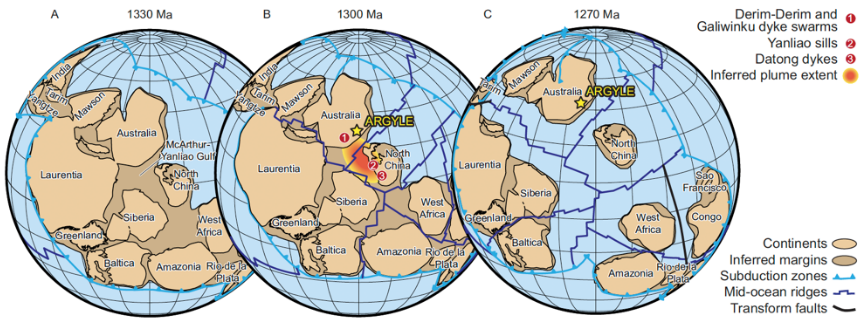

Figure 2: Plate tectonic reconstructions showing the position of Argyle within the McArthur-Yanliao Gulf at 1330 Ma (A), 1300Ma (B), and 1270Ma (C) using the full-plate model of Li, et al. (2023). The potential extent of plume head that caused the Derim Derim-Galiwinku-Yanliao LIP is also shown, with its dimension elongated along rift zones (Kirscher, et al. 2021; Nixon, et al. 2022).

regions including the North China and North Australian Cratons. This geological activity likely contributed zircon grains to Argyle, aligning with sediment transport models from the Gulf's center towards a peripheral ocean, passing the Kimberley Craton. Argyle is located in the Halls Creek Orogen, a zone with thinner lithosphere that is susceptible to reactivation. Heat from the large igneous province or tectonic extension due to Nuna's breakup could have enabled the rapid rise of volatile-rich melts, such as lamproites. This process is reflected in continental rift zones where emplacement of kimberlites and similar rocks is recognized during continental breakups, including during Nuna, Rodinia, and Gondwana/Pangea separations. Although precise breakup onset timing remains uncertain, paleomagnetic data suggest separation of major cratons occurred between 1320 and 1220 Ma, concurrent with Argyle's lamproite emplacement. Global patterns indicate continental extension significantly influences kimberlite and related rock formation, underscoring crustal processes over preservation biases.

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