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The provenance of Borneo's enigmatic alluvial diamonds: A case study from Cempaka, SE Kalimantan

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Abstract

Gem-quality diamonds have been found in several alluvial deposits across central and southern Borneo. Borneo has been a known source of diamonds for centuries, but the location of their primary igneous source remains enigmatic. Many geological models have been proposed to explain their distribution, including: the diamonds were derived from a local diatreme; they were brought to the surface through ophiolite obduction or exhumation of UHP metamorphic rocks; they were transported long distances southward via major Asian river systems; or, they were transported from the Australian continent before Borneo was rifted from its northwestern margin in the Late Jurassic. To assess these models, we conducted a study of the provenance of heavy minerals from Kalimantan's Cempaka alluvial diamond deposit. This involved collecting U–Pb isotopic data, fission track and trace element geochemistry of zircon as well as major element geochemical data of spinels and morphological descriptions of zircon and diamond. The results indicate that the Cempaka diamonds were likely derived from at least two sources, one which was relatively local and/or involved little reworking, and the other more distal which records several periods of reworking. The distal diamond source is interpreted to be diamond-bearing pipes that intruded the basement of a block that: (1) rifted from northwest Australia (East Java or SW Borneo) and the diamonds were recycled into its sedimentary cover, or: (2) were emplaced elsewhere (e.g. NW Australia) and transported to a block (e.g. East Java or SW Borneo). Both of these scenarios require the diamonds to be transported with the block when it rifted from NW Australia in the Late Jurassic. The local source could be diamondiferous diatremes associated with eroded Miocene high-K alkaline intrusions north of the Barito Basin, which would indicate that the lithosphere beneath SW Borneo is thick (~ 150 km or greater). The 'local' diamonds could also be associated with ophiolitic rocks that are exposed in the nearby Meratus Mountains.

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The provenance of Borneo's enigmatic alluvial diamonds: a case study from Cempaka, SE Kalimantan

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ABSTRACT

Gem-quality diamonds have been found in several alluvial deposits across central and southern Borneo. Borneo has been a known source of diamonds for centuries, but the location of their primary igneous source remains enigmatic. Many geological models have been proposed to explain their distribution, including: the diamonds were derived from a local diatreme; they were brought to the surface through ophiolite obduction or exhumation of UHP metamorphic rocks; they were transported long distances southward via major Asian river systems; or, they were transported from the Australian continent before Borneo was rifted from its northwestern margin in the Late Jurassic. To assess these models, we conducted a study of the provenance of heavy minerals from Kalimantan's Cempaka alluvial diamond deposit. This involved collecting U-Pb isotopic data, fission track and trace element geochemistry of zircon as well as major element geochemical data of spinels and morphological descriptions of zircon and diamond. The results indicate that the Cempaka diamonds were likely derived from at least two sources, one which was relatively local and/or involved little reworking, and the other more distal which records several periods of reworking. The distal diamond source is interpreted to be diamond-bearing pipes that intruded the basement of a block that: (1) rifted from northwest Australia (East Java or SW Borneo) and the diamonds were recycled into its sedimentary cover, or: (2) were emplaced elsewhere (e.g. NW Australia) and transported to a block (e.g. East Java or SW Borneo). Both of these scenarios require the diamonds to be transported with the block when it rifted from NW Australia in the Late Jurassic. The local source could be diamondiferous diatremes associated with eroded Miocene high-K alkaline intrusions north of the Barito Basin, which would indicate that the lithosphere beneath

SW Borneo is thick (~150 km or greater). The 'local' diamonds could also be associated with ophiolitic rocks that are exposed in the nearby Meratus Mountains.

1. Introduction

The island of Borneo hosts numerous diamond-bearing alluvial deposits that are found in four separate districts in Kalimantan (Krol, 1922; Koolhoven, 1935; van Bemmelen, 1949; Sigit et al., 1969; Bergman et al., 1987; Smith et al., 2009) (Figure 1a). They occur in Upper Cretaceous to Recent rocks and sediments. These include clastic sedimentary rocks of the Upper Cretaceous to Lower Paleogene Manunggul Formation, which is found in the Meratus Mountains, as well as in Pleistocene fanglomerates, Holocene alluvials and Recent alluvial conglomerates and river terraces (Figure 1b) (Koolhoven, 1935; van Bemmelen, 1949; Spencer et al., 1988; Lennie, 1997; Parkinson et al., 1998).

The earliest studies of Kalimantan's diamonds concluded that they were sourced from kimberlite pipes associated with the ultrabasic rocks of the Bobaris Ophiolite (Figure 1a) (Krol, 1919, 1922; van Bemmelen, 1949; Seavoy, 1975). However, later investigations showed that the rocks that were originally thought to be diamondiferous peridotite (referred to as the "Pamili Breccia" or "Pamali Breccia") were actually sedimentary in nature and composed of brecciated material derived from the underlying Bobaris Ophiolite (Figure 1a) (Bergman et al., 1987; Burgath and Mohr, 1991). This realization and subsequent mineralogical, petrological and isotopic studies of Kalimantan's diamonds suggested an alternative origin: that they were sourced from the sub-continental lithospheric mantle and transported to the surface via kimberlite or lamproite pipes (e.g. Figure 2) (Smith et al., 2009) or derived from distant sources, possibly involving multiple sedimentary recycling episodes. Whereas ultrapotassic alkaline intrusives such as kajanite and minette intrusions occur in several locations in West, Central and East Kalimantan (Wagner, 1986; Bergman et al., 1987, 1988; van Leeuwen, 2014) (Figure 1a), no indications of true lamproite or kimberlites have been found to date, let alone a diamond-bearing pipe or dyke. This does not mean that a primary igneous source does not exist on Borneo as it could simply reflect: (1) the difficulty of finding a relatively small intrusion in a large, intensely forested tropical island, and/or (2) the difficulty of preserving diamond-bearing primary source rocks in a region that experiences significant rainfall and weathers rapidly. The widespread distribution of chromite-bearing ultramafic rocks as well as abundant chromite and chromian-spinel bearing sediments in the drainage system mean that commonly used exploration techniques that focus on characterizing accessory phases of kimberlites and lamproites have been unsuccessful in this region.

The inability to find a local primary diamondiferous source has led to a number of other geological models to explain Kalimantan's diamonds. These include: (1) the diamonds were associated with ultramafic rocks that were obducted as an ophiolite (Nixon and Bergman, 1987); (2) the diamonds formed in a subduction zone setting and were brought to the surface in a process that did not involve a kimberlite/lamproite intrusion (Barron et al., 2008a); (3) the diamonds were transported a great distance, via large river systems that drained the Sibumasu Terrane before SW Borneo rifted from Indochina (Griffin et al., 2001) or (4) the diamonds were transported via large river systems from northwestern Australia before the SW Borneo block rifted from Gondwana in the late Jurassic (Hall, 2012; Hall and Sevastjanova, 2012; Metcalfe, 1996, 2011, 2013). In order to test such models, and models that envisage a direct link between Borneo and the primary source(s) of its diamonds (e.g. van Leeuwen, 2014), we conducted a study of the provenance of heavy minerals from Kalimantan's Cempaka alluvial diamond deposit. Note, that the heavy minerals found in this deposit probably represent a mixture of heavy mineral species derived from multiple sources, and these sources likely differ from the primary source of the diamonds.

After 1987, work on the diamonds of the Cempaka region includes Spencer et al. (1988), Sun et al. (2005) and Smith et al. (2009). Spencer et al. (1988) report the discovery, testing and initial development of the Cempaka alluvial deposit, whereas Sun et al. (2005) and Smith et al. (2009) describe the morphology and genesis of present-day alluvial diamonds from Kalimantan. Sun et al. (2005) purchased 14 locally sourced gem-quality diamonds (ranging in size from 0.03 to 1.82 carats) for their study, while Smith et al. (2009) obtained 654 diamonds from South Kalimantan (with no precise locality details) from Rio Tinto Exploration. Thus, the research we present on diamonds in this paper represent the only suite obtained in situ from their alluvial host sediments.

Insert Figures 1 and 2

2. Tectonic history of Borneo during the Mesozoic

Before discussing the details of the possible provenance of the Cempaka alluvial deposit, it is useful to provide some background information on the tectonic evolution of Borneo in the Mesozoic. This is because the majority of geological models that have been proposed to explain the primary source of Borneo's diamonds are large-scale tectonic models and we refer to various terranes and their tectonic history throughout the paper. The Mesozoic tectonic history is particularly important as the oldest bearing diamondiferous sediments are the Upper Cretaceous Manunggal Formation, meaning that at least some of the diamonds were brought to the surface, eroded and re-deposited before the Late Cretaceous. In the Early Cretaceous, SW Borneo had rifted from northwestern Australia, but had not yet accreted to Sundaland (Hall, 2012) (Figure 3).

The continental crust of SE Asia has largely grown due to the amalgamation of various crustal fragments that were rifted from Gondwana and were later juxtaposed with rocks from Asia/Cathaysia as well as volcanic arc and ophiolitic rocks between the Paleozoic and Early Cenozoic (e.g. Metcalfe, 1996, 2011, 2013; Hall, 2012). This region of amalgamated continental crust marks the southernmost part of the Eurasian plate and is commonly called "Sundaland" (Figure 4). Westernmost Sundaland is composed of the Indochina-East Malaya, Sibumasu, West Burma and West Sumatra blocks (Figure 4). These amalgamated with the North and South China blocks during the Paleozoic to Triassic (Metcalfe, 1996, 2011, 2013; Hall, 2012).

Sundaland continued to grow during the Early to early Late Cretaceous with the addition of the SW Borneo, East-Java West Sulawesi and Sabah-NW Sulawesi blocks (Figure 4). These blocks were originally connected to Gondwana (western Australia), but were torn from the supercontinent in the Late Jurassic (Metcalfe, 1996, 2011, 2013; Hall, 2012; Hall and Sevastjanova, 2012). The Cenozoic Cempaka alluvial deposit, which is the focus of this paper, is found at the northeastern boundary of the

SW Borneo Block and the edge of the Meratus Suture Zone, which represents the Cretaceous tectonic boundary between the SW Borneo Block and the East-Java-West Sulawesi Block as defined by Hall (2012) (Figure 4).

Insert Figures 3 and 4

Much of Borneo and Sundaland is considered to have been emergent during the Jurassic and Cretaceous. Northern/northwestern Borneo however, was an active continental margin until early in the Late Cretaceous and was dominated by deep-water sedimentation (Hall, 2012, 2014). After about 80 Ma most of Sundaland was emergent (Hall, 2014). Volcanism and deformation phases associated with plate convergence and collision also mean that parts of Borneo (e.g. the Schwaner Mountains region) were likely to have been mountainous after 80 Ma (Clements et al., 2011; Hall, 2013; Davies et al., 2014). A terrestrial setting is supported by the development of a regional unconformity between the Cretaceous and Eocene (Clements et al., 2011), the presence of Laurasian conifer pollen in Late Cretaceous to Middle Eocene Sarawak sandstones (Muller, 1968), Cretaceous granitoids (Davies et al., 2014), and a predominance of Upper Cretaceous to Middle Eocene terrestrial sandstones in Sarawak and NW Kalimantan (Hall, 2013). A mountain chain also likely existed along the suture zone between Borneo and East Java from about 80 Ma, with this connection being marked by the now submerged Karimunjawa Arch (e.g. Hamilton, 1979; Smyth et al., 2007; Granath et al., 2011). The deep water sedimentation north of Borneo during this time combined with the high topographic relief of central Borneo means that that there were significant barriers to the transport of (diamond-bearing) sediments to, and within, Borneo.

3. The Cempaka Deposit

The Cempaka diamond deposit is located in SE Kalimantan (3°30'S, 114°45'E) (Figure 1). Following decades of placer mining by local residents, it is the only diamond deposit in Kalimantan that has been mined on a commercial scale, namely by BDI Mining and other companies from 2002 to 2009 (van Leeuwen, 2014). The earliest facies in the Cempaka area are Upper Cenozoic fanglomerates. These are extensively laterized in areas of elevated topography and podsolised in areas below the water table. The fanglomerates have been incised and eroded and subsequently deposited into palaeochannels that are concealed beneath present-day swamps. The palaeochannel sediments represent the last phase of alluvial reworking. These contain the highest in-situ diamond grades and were subject to mining operations. The diamondiferous fanglomerates and palaeochannel sediments were deposited at the base of the Meratus Mountains (Figure 1). These fanglomerates overlie Cenozoic sedimentary units within the Barito Basin, which in turn overlie Upper Jurassic to Cretaceous metasediments, metavolcanics and granitic rocks (e.g. the Upper Cretaceous to Paleogene Manunggal Formation from the Meratus Mountains, the Schwaner Granitoids and the Pinoh Metamorphics) (Katili, 1978; Spencer et al., 1988; Guntoro, 1999; Witts et al., 2011, 2012; Graham et al., 2014). The conglomerates of the Manunggal Formation are also diamondiferous, so it is likely that the younger alluvial deposits, such as Cempaka, were derived (at least in part) from reworking of these older sedimentary rocks (Spencer et al., 1988).

The Cempaka placer also hosts PGE minerals and gold (Graham et al., 2014), which not only constitute valuable by-products, but are also useful provenance indicators of the source of the sediment. For instance, the gold in the Cempaka deposit is characteristic of gold generated in an epithermal deposit and was transported more than 10 km and/or reworked several times (Graham et al., 2014). It is likely that the gold was sourced from one of the epithermal gold deposits from central Kalimantan (e.g. van Leeuwen et al., 1990; van Leeuwen, 1994; Davies et al., 2008). It is unlikely that the gold is related to the PGE minerals, which, based on their chemical composition, were found to be from two distinct sources, an ophiolite and an Ural-Alaskan complex (i.e. sub-arc cumulate) (Graham et al., 2014). Some of the PGE minerals may therefore have been sourced from the nearby Meratus and Bobaris ophiolites (Hattori et al., 1992, 2004; Graham et al., 2014).

Heavy mineral concentrates from the Cempaka alluvium are dominated by chromite with minor ilmenite. Other accessory minerals that are present include zircon, corundum, magnetite, rutile, diaspore and very rare garnet. The rutile and diaspore only occur as large heavy particles (centimeters in size), and are not found in the sand-sized fractions of heavy mineral separates. They are however, used by local explorers as indicators to the proximity of diamonds.

Garnet and chromite chemistry can be useful indicators of kimberlites and lamproites (Fipke et al., 1989; Barnes and Roeder, 2001), however, no typical 'kimberlitic' indicator minerals have ever been reported from Cempaka (Spencer et al., 1988). Such data may be restricted to propriety datasets or may not have been collected because the Cempaka deposit is located down-stream of the Meratus and Bobaris ophiolites, leading to the assumption that most, if not all, of the chromite was sourced from these ophiolites. However, as there are no reports of such data, we collected major element analyses of spinels, morphological descriptions of diamonds and zircons; as well as U-Pb isotopic, fission-track and trace element data from detrital zircons of the Cempaka deposit to assess their provenance.

4. Methodology

4.1 Sample Processing

A heavy mineral separate containing diamond, zircon and chromite was obtained by L. Spencer from the processing plant operated by BDI Mining. This sample consisted of material derived from the <2mm sieve fraction from run of mine ore. The screened material was passed through spiral separators to produce a low-grade heavy mineral concentrate. The low-grade spiral concentrate was then passed onto a Wilfley Table to remove silicates and the heavy concentrates from this were dried and passed over an Eriez rare earth magnet to remove chromite and ilmenite. The non-magnetic fraction was passed over a Gemini Table to produce a gold concentrate. Fine diamonds and zircons were obtained by manual sorting of the Gemini Table tailings. A parcel of 100 diamonds, ranging in size from 0.1 to 0.3 carats was selected for detailed morphological investigations. In addition, we also present data on the particle size distribution of 8863 diamonds that were included in an early feasibility study of the Cempaka mine (Spencer and Watson, 2002).

Spinel and zircon grains were hand-picked and mounted in circular resin blocks that were hand polished to expose the mid-section of individual grains for geochronological and geochemical analyses. Additional zircons were hand-picked for fission-track analyses. The possibility of contamination was extremely unlikely as the processing plant was new and only processed gravels from the Cempaka paleoalluvium at the time of sample collection preparation.

4.2 Geochemistry

4.2.1 Spinel Chemistry

Spinel grains were mounted in polished resin blocks and major element analyses of spinels were measured using WDS on a Jeol8100 Superprobe at University College London (UCL). Analyses were collected at an accelerating voltage of 15 kV, a beam diameter of 1μm and a beam current of 2.5 nA. The counting times for all elements were 20 seconds on the peak and 10 seconds each on the high and low backgrounds. The analyses were calibrated against standards of natural silicates, oxides and Specpure® metals, with the data corrected using a ZAF program. The standard BCR-2G (Rocholl, 1998) was independently measured at the beginning and end of the session, as well as between every twelve unknown analyses to assess beam stability. The ferric iron content of the spinels was calculated by stoichiometry.

4.2.2 Zircon Chemistry

Zircons were analysed by LA-ICP-MS using an Excimer UV laser (193 nm), a Helex sample introduction system (Eggins et al., 1998a) and an Agilent 7500 quadrupole mass spectrometer, at the Research School of Earth Sciences, Australian National University (ANU). The spot size selected was 40 or 70 μm. The laser pulsed at 5 Hz, delivering 80mJ per pulse.

Ablation under a mixed He+H_2 atmosphere provided material carried to the plasma in an Ar/He gas stream. The mass spectrometer was tuned to optimum sensitivity and to minimise production of interfering oxides species, with $^{232}Th^{16}O/^{232}Th$ routinely ≤ 0.5%. The analyses were performed in peak hopping mode with a dwell time of 0.05 sec/mass. For each analysis the gas blank was acquired for 30 seconds, the laser triggered, and the signal acquired for a further 50 seconds.

The analytical protocol followed that of Eggins et al. (1998b). The primary calibration standard was NIST-612 glass and secondary standards basaltic glass BCR-2G (Govindaraju et al., 1994) and zircon 91500 (Wiedenbeck et al., 1995) were routinely analysed as unknowns to check data quality. Batches of analyses of 8 "unknowns" (unknown zircons and secondary standards 91500 and BCR-2G) were bracketed by analyses of NIST-612 allowing monitoring of, and correction for instrumental drift.
Data reduction used background corrected count rates as established by Longerich et al. (1996). ^{91}Zr was measured enabling use of ZrO_2 abundances calculated on $ZrSiO_4$ stoichiometry (67.22 wt% ZrO_2) as the internal reference element. Calibration values for NIST-612 used in the data reduction are those of Eggins (2003). A linear drift correction based on the analysis sequence and on the bracketing analyses of NIST-612, was applied to the count rate for each sample. Data for the unknown zircons, based on multiple analyses of BCR-2G indicate that analytical reproducibility was better than 2% and accuracy was better than 5% for most reported elements. Data for the secondary standard zircon 91500 provided further control. La contents in six of the analysed zircons and in all 91500 standard zircon analyses were below the lower limit of detection (LLD) of 0.002 ppm, but in remaining zircons La values slightly

exceeded the LLD. Reported values for all other elements in the analysed and 91500 standard zircons were well above LLDs.

4.3 Zircon Geochronology

U-Pb isotopic measurements were collected from the detrital zircons using a Sensitive High Resolution Ion Microprobe (SHRIMP-RG) at the Research School of Earth Sciences, ANU. The zircon grains were imaged with a cathodoluminescent (CL) detector fitted to a scanning electron microscope at the Research School of Earth Sciences prior to collecting any isotopic data. The CL imagery as well as reflected and transmitted light microscopy were used to identify zircon cores and growth rims that were suitable for dating. Standard zircon SL13 (U = 238 ppm; Th = 21 ppm; Claoué-Long et al., 1995) was used to calibrate the U and Th concentrations and Pb/U ratios were corrected for instrumental interelement fractionation using the ratios measured on the standard zircon Temora 2 (416.8 ± 1.3 Ma; Black et al., 2004). One analysis of a Temora zircon was analysed for every four analyses of unknowns. The data have been reduced in a manner similar to that described by Williams (1998, and references therein), using the SQUID 2 Excel macro of Ludwig (2009). The decay constants recommended by the IUGS Subcomission on Geochronology (as given in Steiger and Jäger, 1977) were used in age calculations. Uncertainties given for individual U-Pb analyses (ratios and ages) are at the 1 sigma level. All age results that are less than 800 Ma are reported using ^{207}Pb corrected ^{206}Pb/^{238}U ages, whereas ages that are >800 Ma are reported using ^{204}Pb corrected ^{207}Pb/^{206}Pb ages.

4.4 Zircon Thermochronology

Fission-track thermochronological analyses were conducted on twenty zircon grains. Prior to analysis, the grains were subdivided into a >1 mm group of colourless rounded zircons and a <1 mm group of colourless euhedral zircons. Zircons greater than 1mm in size were first crushed into sub-mm fragments in order to make them suitable for analysis. We did not take multiple fragments from single grains for separate evaluation. The zircons were embedded in FEP Teflon sections, polished and etched in a molten KOH: NaOH eutectic mixture at ~ 220ºC (Gleadow et al., 1976) for over 39 hours (sub-mm grains) and 46 hours (+ mm grains) to reveal the fission tracks. The samples, along with low-U muscovite mica detector plates were irradiated at the Australian Atomic Energy Commission HIFAR research reactor, Lucas Heights, Sydney. The track counting was made using a Zeiss Axioplan microscope. The fission track ages were calculated using the zeta calibration method (Green, 1985) and a zeta factor of 87.7 ± 0.8 for dosimeter glass U3. The grain ages and errors incorporated Poissonian statistics and radial plot diagrams (Green, 1981; Galbraith, 1988, 1990).

5. Results

5.1 Spinel Morphology and Geochemistry

The spinel grains that were selected as part of this study are angular to sub-rounded grains that are ~0.5 – 1.0 mm in diameter. Eighty-nine major element analyses were collected from forty-four spinel grains (Supplementary Data Table 1). The grains showed no evidence of zonation on backscattered SEM images. Analyses were therefore collected from the center of each grain. The chemical data were used to verify the provenance of spinels and to test if a potential lamproitic or kimberlitic source was possible. We therefore compared our results with those in a global spinel database (Barnes and Roeder, 2001). The majority of Cempaka spinels are chromium spinels and plot within the 30th and 50th percentiles of the global 'ophiolite' field (Figure 5) (Barnes and Roeder, 2001). This finding reflects the local sedimentary input from (non-diamondiferous) ophiolites. This is not surprising as erosion and re-deposition of material from the nearby Bobaris and Meratus ophiolites (Figure 1a) were expected to dilute any spinels associated with a kimberlite or lamproite.

Insert Figure 5

The analyses that fall outside of the 30th and 50th percentiles (Figure 5) are not anomalous and are within the range of the global spinel database (Barnes and Roeder, 2001). Although some of the chemical analyses of Cempaka spinels plot outside the 30th and 50th percentiles of the global ophiolite field and might be interpreted to be derived from a kimberlitic or lamproitic source (Figure 5), such results also fall within the total range of spinel chemistries from ophiolites. From these results, we concluded that the spinel geochemical data do not provide definitive information as to the possibility of a diamondiferous diatreme.

5.2 Zircon Morphology, Geochronology, Thermochronology and Geochemistry

5.2.1 U-Pb dating and zircon morphology

U-Pb isotopes from fifty-eight zircons from the Cempaka deposit were analyzed using SHRIMP-RG (Supplementary Table 2). The majority of grains that were analyzed were concordant (Figure 6) and two thirds of the concordant zircon grains crystallized between 75 Ma and 110 Ma. The age results broadly correspond with the morphology of the zircons, as Cretaceous ages were obtained only from euhedral grains, outer growth rims or angular zircon grain fragments (Figure 7). The remaining analyses were Triassic or older (223 Ma, 314-319 Ma, 353-367 Ma, 402-414 Ma, 474 Ma, 521 Ma, 1135-1176 Ma, 1535 Ma and 2716 Ma). The Triassic and older analyses broadly correspond to the rounded, semi-rounded and angular zircon grains and cores (Figure 7), indicating that the older grains were derived from a more distal source and/or zircons that have undergone several phases of recycling.

Insert Figure 6

Insert Figure 7

The range of morphologies and textures from the Cempaka detrital zircons are best shown in secondary electron SEM images of non-polished grains (Figure 8). These include rounded and sub-rounded grains (Figure 8a-c) that are indicative of transport in a high-energy environment for some time. These also include euhedral angular grains (d-i), many of which preserve primary growth textures (Figure 8e-f), preserved mineral inclusions (Figure 8d) or zones where mineral inclusions have been chemically or mechanically removed (Figure 8g-i), all of which would not be preserved with prolonged transport in a high-energy environment.

Insert Figure 8

The U-Pb detrital zircon data that were collected as part of this study were compared with recently published detrital U-Pb age data from the Schwaner Granitoids, Pinoh Metamorphics and Barito Basin (Witts et al., 2011, 2012; Davies et al., 2014) as well as data from the Khorat Plateau Basin of eastern Thailand (Carter and Moss, 1999; Carter and Bristow, 2003) (Figure 9). All of the age results from samples that were collected within Borneo show a dominant age population between ~75 and 110 Ma and are broadly similar (Figure 9a-h). This Cretaceous age population does not exist in the zircons dated from the Khorat Plateau Basin (Figure 9i-j), and there are few similarities between these zircons and those obtained from the Borneo samples (Figure 9). This indicates that it is extremely unlikely that the Borneo sediments were derived from the same sources as those for the Khorat Basin.

We propose that Cretaceous zircons in the Cempaka alluvium are most likely to be sourced from the Schwaner Granitoids and Pinoh Metamorphics. This hypothesis is supported by: (1) ages reported from these granites and metamorphics (Davies et al., 2014); and (2) the angular morphology of zircon grains and rims that are younger than ~110 Ma indicates that these zircons have not been extensively reworked and/or transported from a distal source. It is also possible that these zircons could be sourced from much greater distances if they were derived from ash fall associated with explosive eruptions. However, since the Schwaner Mountain granitoids are the closest and largest area of zircon-rich material to the Cempaka deposit, and have very similar age populations, we consider them to be the most likely source of zircons. Cretaceous K-Ar ages are reported for igneous and metamorphic rocks in the Meratus Mountains and other nearby regions such as Java and SW Sulawesi (e.g. Bergman et al., 1996;

Hartano et al., 1999) but zircon-bearing rocks, such as granites, in these areas are absent or uncommon.

Detailed characterization of the regional stratigraphy using a combination of sedimentary logging, biostratigraphy and detrital U-Pb geochronology indicate that the erosion of the Schwaner Granitoids and Pinoh Metamorphics occurred during the Eocene to Miocene (Witts et al., 2011). The erosional products were redeposited in the sedimentary units of the Barito Basin along with material from another southerly source (Figure 1) (Witts et al., 2011). The southerly source of zircon was most likely the Karimunjawa Arch (or equivalent area). This provided material that was originally the sedimentary cover to the SW Borneo or East Java blocks and accounts for the Phanerozoic and Precambrian zircons within the Barito Basin (Witts et al. 2011). Reworking and re-deposition of the Barito Basin sediments can therefore explain the Phanerozoic and Precambrian zircons in the Cempaka alluvium. The majority of these grains are rounded to sub-angular (Figures 7-8), indicating transport from distal sources and/or multiple sedimentary cycles. We therefore interpret the pre-Cretaceous zircons to represent reworked detrital zircons from the Barito Basin. The Cempaka alluvium may also include zircons reworked from the Upper Cretaceous to Paleogene Manunngal Formation and potentially the Pinoh Metamorphics. However, this is more speculative since no detrital zircon age data are available for the former, and only one sample of quartzite from the Pinoh Metamorphics yielded pre-Cretaceous zircons (Davies et al., 2014).

Insert Figure 9

5.2.2 Zircon fission-track ages

Fission track ages were obtained from twenty zircon grains. The counting statistics, U contents and age analyses of the zircons are presented in Supplementary File 3. The zircons dated by fission track (FT) were subdivided into two groups according to their size prior to analysis. The ten grains that were >1 mm in diameter yielded a well-defined fission-track age of 129.6 ± 7.3 Ma (MSWD = 1.6), however, the sub-mm zircons yielded a mixture of Cretaceous to Pliocene ages. The results are best displayed on a relative probability-frequency plot that shows the relative proportion of ages obtained from the two size fractions (Figure 10). This plot shows that there are three dominant age populations where the oldest population corresponds to the >1mm zircons, whereas the two younger populations correspond to the <1mm zircons. A quantitative value for each of these populations was calculated using the 'unmix age' algorithm (Sambridge and Compston, 1994) within Isoplot 2.0 (Ludwig, 2003). The youngest population is 3.5 ± 1.8 Ma (2σ) and represents 10% of the population. The Late Cretaceous age peak is 80.2 ± 6.7 Ma (2σ) and represents 37% of the population. The oldest peak was calculated to be 122.4 ± 17 Ma (2σ) and represents 53% of the population. Several older FT ages were obtained (171, 175, 178 and 190 Ma), all of which have very large one-sigma uncertainties (20-50 Ma). The large uncertainties associated with these older ages mean that they are within error of the ~122 Ma age population.

The Late Cretaceous FT ages however, likely reflect the cooling history of the zircons after a period of Cretaceous magmatism and/or metamorphism led to the annealing of fission-tracks in pre-Cretaceous zircons across the region. Considering that the <1mm zircons are primarily angular euhedral grains, they were likely derived from a nearby source. We suspect the Schwaner Granites and Pinoh Metamorphics could represent possible sources for the Late Cretaceous zircon FT ages, especially considering that the 80.2 ± 6.7 Ma age population is within error of 76 ± 8.7 Ma apatite and zircon fission track ages obtained from an in-situ sample of the Batuan Pluton of the Schwaner Mountains (Sumartadipura, 1976). However, as mentioned earlier, it is also possible that the Cretaceous zircons were sourced from ash that was ejected from proximal or more distal explosive volcanic eruptions, with zircons being distributed (and later recycled) into surface deposits after they fell back to the Earth's surface.

If these zircons are from the mid-late Cretaceous Schwaner Granites or Pinoh Metamorphics, the FT results indicate that the source of Cretaceous zircons was uplifted relatively soon after zircon crystallization (i.e. to ensure the zircon passed its 240°C ± 30° closure temperature for fission-track development; Bernet and Garver, 2005). We suspect that the Pliocene zircon FT ages could reflect the uplift and cooling of Miocene or older intrusives or volcanics, or alternatively, represent zircons associated with the eruption or erosion of Pliocene volcanics in central Kalimantan (e.g. Soeria-Atmadja et al., 1999).

Insert Figure 10

5.2.3 Zircon geochemistry

Trace element geochemical data were obtained from forty-five zircons from the Cempaka alluvium (Supplementary Data 4). These zircons generally have <100 ppm Ce, Sm, Eu, Gd, Sr, Ho, Lu, and Nb, <400 ppm Dy, Er, Th and U as well as concentrations of Y between 100 ppm and 2300 ppm (Supplementary Data 4).

The trace element geochemistry of zircons has been used to infer information about their provenance, particularly in the search of kimberlites (e.g. Belousova et al., 2002). We therefore compared the range of trace element compositions of the Cempaka detrital zircons with those of zircons from igneous rocks (Belousova et al., 2002) (Figure 11a-e). This shows that there is a striking similarity between the Cempaka zircons and those of lamproites and basalts, particularly the Y content. These data also show that the Cempaka zircons have much higher concentrations of REE, Th and Y as well as higher Nb/Ta and Zr/Hf ratios than the average compositions of zircons from kimberlites (Belousova et al., 2002). The trace element compositions of the Cempaka zircons are also generally depleted relative to the range of composition of zircons from granitoids, however zircons from granitoids do span a large range of compositions (Belousova et al., 2002) (Figure 11a-e and Supplementary Data Table 4). Therefore, we do not consider these comparisons of zircon trace element data to be particularly useful provenance indicators.

Insert Figure 11

Such comparisons of zircon trace element geochemistry are also dependent on whether the data presented by Belousova et al. (2002) are representative of the proposed lithologies. Belousova et al. (2002) state that the lamproitic zircons that were analysed in their study represent xenocrysts, sourced from granitic and syenitic host rocks. This means that the striking similarity between the detrital Cempaka zircons with 'lamproitic zircons' is fortuitous, and that the trace element data reflects a granitic or syenitic source, rather than a lamproite. In addition, zircon is very rare in lamproite, with exception of the Smoky Butte lamproite. This is thought to be due to the higher degree of polymerization of lamproite melts (Mitchell and Bergman, 1991). Considering these points alongside the U-Pb data obtained in this study and our knowledge of the regional geology, we propose that trace element data obtained from the Cempaka zircons represents a mixture of igneous and metamorphic zircons that were probably sourced from the erosion of the Schwaner Granites and Pinoh Metamorphics as well as basaltic and ultramafic rocks in the Meratus Mountains and igneous rocks from the Kelian region. There is some indication of this mixture of sources in the trace element data (e.g. Ce vs. Hf) (Figure 11f). This is particularly apparent when we consider the trace element data alongside other factors such as grain size and the results obtained from the FT study (e.g. Figure 11f), which clearly indicates that the zircons that yielded Mio-Pliocene FT ages have a different composition to the majority of the other zircons that were analysed.

5.3 Diamond Morphology

Cempaka diamonds range in size from micro-diamonds (<0.1 mm) through to a maximum of 66.2 carats. Of the 100 macro-sized diamonds that were examined in this study, forty-three percent are colourless, indicating they have low nitrogen concentrations, whereas another forty percent of the diamonds are yellow/brown, indicating they have relatively high nitrogen concentrations. Both Spencer et al. (1988) and Sun et al. (2005) also found that the diamonds were yellow, brown or colourless, whereas Smith et al. (2009) found that yellow diamonds were less common. Of particular note is that Spencer et al. (1988) also recorded green diamonds and a 3.5-carat cobalt blue diamond was recovered during diamond mining operations at Cempaka in 2006. Importantly, also examined was a range of semi-opaque black diamonds and ballas. Spencer et al. (1988) noted that ballas was rare in their trial bulk sample, but neither ballas, nor opaque black diamonds were noted in other studies of SE Kalimantan diamonds (Sun et al., 2005; Smith et al., 2009). Also of note was the discovery of a large carbonado at Cempaka (e.g. van Leeuwen 2014).

In terms of morphology, the diamond population that we studied is dominated by variously modified dodecahedron, tetrahexahedron, octahedron and macles (Figure 12) while cubes are rare. This is in good agreement with the previous findings of Spencer et al. (1988), Sun et al. (2005) and Smith et al. (2009). In contrast, the semi-opaque to ballas diamonds comprise various forms of octahedron, cubo-octahedron or rough-textured ovoid-shaped grains (Figure 13). In this population, the black platy inclusions within the semi-opaque diamonds are graphite (Figure 13).

Other clearly distinguishable morphological features include:

- Seventy-five percent of the diamonds show evidence of plastic deformation during growth such as fine plastic deformation lamellae (Figure 12a), cross striae and volume strain birefringence. These were also found by Smith et al., (2009).
- Fifty percent of the diamonds are composite grains that show evidence of growth zoning, with outer ‘rims’ with abundant mineral inclusions and inner ‘cores’ with very few to no mineral inclusions (Figure 14).
- Twenty-six percent of the diamonds show resorption features (Figure 15a)
- Fifty percent of the diamonds have radiation damage (Figures 12c and 15b).
- Twenty percent of the diamonds have percussion marks while twenty eight percent have rhombic cracking.

- Some seventy-five per cent of the studied diamonds show at least some strain birefringence.
- Diamonds with well-developed sharp hexagonal-shaped negative crystal indentations are uncommon (Figure 15a)
- Micro-discs are relatively common on the surface of many of the gem-quality diamonds and are up to 0.2 mm in diameter (Figure 15c)
- As found by Smith et al. (2009), octahedral zonation is seen in polarized light for some of the diamonds (Figure 15d).
- As noted previously by Smith et al. (2009), a high proportion of the diamonds have smooth shiny polished surfaces (Figures 12b and 15a).

Insert Figures 12-15

The morphology, surface features and occurrence of ballas indicates that there are at least two different sources of diamonds in the Cempaka alluvial deposit. Some 26% of the observed diamonds have sharp resorption features and planar deformation features while 74% lack these characteristics. Such features include micro-discs (Figure 15a), fine planar deformation lamellae (Figures 12a and 12c) and euhedral negative crystal indents (Figure 15a). Similar surface features including trigons and cross-hatched lamination lines were reported by Sun et al. (2005). Additionally, only 20% of the diamonds studied have percussion marks, while Sun et al. (2005) reported percussion marks to be abundant in the diamonds that they studied. Alluvial transport surface features described by Smith et al. (2009) included rhombic cracks, abraded points and fretted edges. The combination of diamonds with sharp angular well-defined surface features with diamonds lacking such features suggests that at least two populations are present within the alluvial deposit, one from a distal and/or reworked alluvial source and one from a more proximal source.

In terms of the rhombic cracking, in this study it was found to penetrate some 200 microns into the diamond surface and thus represents activation of the [111] cleavage at or near the diamond's surface. In terms of distribution, rhombic cracking occurs on most diamond morphologies and only one of the diamonds with rhombic cracking was also found to show evidence of mechanical damage by alluvial transport. Although Smith et al. (2009) suggested that this texture was due to surficial transport, we instead suggest that this texture is due to elastic deformation up to the point of failure. Evidence for this explanation is that the texture occurs throughout the whole diamond, though sometimes it occurs in distinctive bands. The exact mechanism could be either: (1) regional stress during metamorphism of the surrounding country rock, or (2) local differential stress during rapid heating/cooling of the surrounding country rock. Although 50% of these diamonds also have brown radiation spots, only 10% of diamonds with radiation spots also have rhombic cracking. Thus, the diamonds with rhombic cracking may represent another distinctive source group.

Additional evidence for at least two sources of diamonds is provided by the occurrence of semi-opaque to opaque black diamonds with abundant graphite inclusions and subhedral to anhedral angular to well-rounded ballas (Figure 13). The semi-opaque varieties additionally contain brown outer radiation spots (Figure 13a). Barron et al. (2008) found that many of these ballas diamonds are composite diamonds (see below).

Four of the diamonds studied have a preserved green colour (Figure 14a), interpreted to be due to radiation damage of the surface. Similar partial to complete green outer surfaces on diamond have been previously described from the Timber Creek diatreme in the Northern Territory, Australia (Kolff, 2010). Brown radiation damage is far more common (Figures 12d and 14d) and occurs in 46% of the diamonds examined in this study. These radiation ‘spots’ are relatively sharp and well-defined with equant to rectangular shapes. The high abundance of diamonds with these radiation ‘spots’ suggests that they have been buried within an alluvial package containing a relatively high abundance of radioactive minerals such as zircon and/or monazite, or they were exposed to uranium-bearing fluids within the sedimentary basin. Four of the diamonds studied have both green and brown spots, indicating that they have been involved in multiple alluvial cycles. Some diamonds contain up to 100 radiation spots. Sun et al. (2005), Barron et al. (2008a) and Smith et al. (2009) also described the common occurrence of brown and green spots within Kalimantan diamonds. The green spots are ascribed to the diamonds having been in close proximity to radioactive minerals for extended periods of time (Vance et al., 1973) while the brown spots indicate exposure to alpha particle damage and temperatures of at least 550-600°C (Vance et al., 1973; Bosshart, 1993). This implies that the diamonds with brown spots were buried deep within a sedimentary package that was subsequently metamorphosed under amphibolite facies conditions (Miyashiro, 1994). The fact that almost half of the diamonds in this study contain obvious radiation damage while the other half do not is again strongly suggestive of two sources for the Cempaka diamonds. One population was deeply buried within a sedimentary package and subsequently metamorphosed, and the other population, most likely younger, was not subjected to such deep burial and radiation damage.

The composite diamonds (50% of the measured population) are also particularly characteristic of the Cempaka deposit, though these were not mentioned by either Sun et al. (2005) or Smith et al. (2009). These comprise a ‘core’ and ‘rim’ that consist of a semi-opaque to opaque overcoat on resorbed octahedrons. We speculate that these ‘cores’ and ‘rims’ indicate that the diamonds entered the diamond stability field twice, possibly due to upward and downward movement of the lithospheric root prior to the diamonds being brought to the surface in a diatreme (e.g. Figure 2). When viewed through normal light these diamonds appear to be opaque, when a “window” is cut through the surface, the bulk of the diamond is transparent (Figures 14b-14d). The outer overcoat comprises poorly defined 6-sided plates (Figure 14d). At the rim/core interface are abundant trapped inclusions of quartz, chamosite, Cr-magnetite, Y-xenotime, Y-churchite, and a KFeAlSi oxide glass. While the cores of these diamonds are extremely hard (amongst the hardest known), the outer diamond rims are not and would be destroyed after prolonged transport.

These data support the outcomes of an earlier study of diamonds from across Kalimantan that indicated the diamonds could have been derived from up to four different primary sources (Smith et al., 2009). These workers found that 68% of their sample-set were peridotitic diamonds and 32% were eclogitic diamonds. They also proposed that the diamonds resembled those that had been transported from the subcontinental lithospheric mantle to the surface by a kimberlite or lamproite. It is therefore likely that at least some of the diamonds from Cempaka (especially those with sharp resorption features, fine planar deformation striae and sharp negative crystal indents) were derived from a local source. This interpretation is further supported by the multi-modal grain-size distribution of diamonds from the deposit (Figure 16). We would expect a uni-modal grain-size distribution if all of the Cempaka diamonds were obtained from the same source. Also, the grain size distribution data indicates that fine grained (<1mm) diamonds exist in the Cempaka alluvium. These are associated with fine-grained ballas. Together, these would not survive multiple episodes of sedimentary recycling and metamorphism, indicating that these diamonds and ballas were derived from a local source.

There are two possible local sources: (1) the diamonds were sourced from ophiolites or high-pressure metamorphic rocks (e.g. eclogite) in the nearby Meratus Mountains, or (2) the diamonds were sourced from local, yet undiscovered diamondiferous diatremes (potentially associated with a period of high-K alkaline intrusive activity, e.g. the ~8 Ma Linhaisai Minette; Bergman et al., 1988). We discuss these models in more detail in the following section, along with hypotheses about the source of the more distal/reworked diamonds.

Insert Figure 16

6. Discussion

6.1 Assessing potential sources of Kalimantan's diamonds

6.1.1 Local Diatremes

Exploration companies have been searching for diamondiferous diatremes in Borneo for decades (van Leeuwen, 2014). Despite considerable effort none have been found to date. However, there have been some discoveries of ultrapotassic alkaline intrusions, such as the ~8 Ma Linhaisai Minette (Figure 1a) (Bergman et al., 1988). The Linhaisai Minette does not contain diamonds, but is significant in that it indicates that the tectonic regime at the time was conducive for the emplacement of ultrapotassic alkaline intrusions. Others have suggested Neogene potassic and ultra-potassic volcanic rocks that occur in various parts of Kalimantan could be a potential primary source of Neogene or younger alluvial diamonds (Simanjuntak and Simanjuntak 2000). Young high-potassic alkaline intrusions associated with this phase of magmatism in Borneo could be a candidate primary source for ~26% of the Cempaka diamonds with resorption features indicating that these were likely derived from a proximal source. The major challenge however is in finding relatively small intrusions in Borneo's heavily forested tropical rainforests. Exploration via mapping and stream sampling is particularly difficult with no guarantee of success. In addition, there is also a lack of high-resolution magnetic data collected with a line spacing conducive to finding weakly magnetic bodies of low surface area amongst strongly magnetic peridotites and their erosional products.

Other proximal, non-traditional diamond sources might also explain some of the diamonds in Borneo. For instance, recent work in Kamchatka has shown that there are micro-diamonds trapped within pumice ejected from arc volcanoes (Gordeev et al., 2014; Karpov et al., 2014). No macrodiamonds such as those found at Cempaka have been recovered from the Kamchatka volcanics, but if future work is able to identify macrodiamonds in these eruptive sources, then these could be a possible explanation for some of the Cempaka diamonds.

However, a relatively young local source only explains some of the diamonds, as our results also indicate that ~74% of the Cempaka diamonds do not have resorption features and are characterized by radiation burns and percussion marks, so there must be another source. This other source is probably older than Late Cretaceous as some of Kalimantan's diamonds are found in Upper Cretaceous conglomerates (e.g. the basal sequences of the Manunggul Formation (Katili, 1978; Sikumbang, 1990; Spencer et al., 1998; Guntoro, 1999).

6.1.2 Ophiolitic Source

A potential primary ophiolitic source for Borneo's diamonds was proposed by Nixon and Bergman (1987) and Bergman et al. (1987). This model was proposed after the realization that the Pamili Breccia could not be a primary diamond source (e.g. Bergman et al., 1987), and because some streams in SE Kalimantan are more diamondiferous where they flow over the base of an Upper Cretaceous sedimentary-volcanic unit that unconformably overlies ophiolitic rocks (e.g. the Pamali Breccia). This model was also proposed because of the proximity of the Cempaka alluvial deposit to the Meratus and Bobaris ophiolites (Figure 1a) and because there are diamonds in the drainages emanating from both the west and southeast of Cempaka, with the Meratus Mountains representing an obvious source. This proximity is reflected in the large proportion of chromium-spinels and PGE minerals found within the Cempaka gravels (Zientek et al., 1992; Graham et al., 2014; this study). There are also intramontane basins containing diamondiferous fanglomeratic sediments derived from the erosion of the Manunggal Formation. A Meratus Mountains/ophiolitic source is also supported by the recent discovery of 5 microdiamonds (600-800 μm in diameter) from a stream sediment sample collected within an ultramafic cumulate complex on Sebuku Island, offshore SE Borneo (Swamidharma et al., 2015). These diamonds apparently show no signs of abrasion and the ophiolitic rocks that are exposed in the area are not covered by Cenzoic sedimentary rocks (Swamidharma et al., 2015).

Ophiolitic peridotites and podiform chromites are now widely recognized as a source of microdiamonds, particularly in China, Russia and Myanmar (e.g. Yang et al., 2014). These microdiamonds are typically 0.2-0.5 mm diameter inclusions within magnesiochromitite grains, are yellowish-green and have very distinctive light carbon isotopic compositions (Yang et al., 2014). They also commonly contain inclusions of Ni-Mn-Co alloy and this can be used to distinguish them from kimberlitic and metamorphic diamonds. We have not conducted these analyses on the Cempaka diamonds, but we are reasonably confident that an ophiolite model cannot account for the macrodiamonds reported from the Cempaka deposit.

Ophiolitic diamonds are considered to form due to the recycling of continental crust via subduction into the mantle transition zone, with water, carbon dioxide and other fluids being released from these subducted rocks and mixing with highly reduced mantle fluids to produce diamonds that can become encapsulated in chromite if the melts/fluids rise above depths of ~300km (Robinson et al., 2011). However, the mechanism of transportation of the diamond-within-chromite to the surface is unresolved. One idea is that transport is driven by plumes or superplumes (Yang et al., 2014). Another possibility may be rapid exhumation of the diamond-bearing-chromite upper mantle rocks during crustal extension (e.g. Pownall et al., 2013, 2014), potentially followed by a phase of thrusting after a tectonic mode switch (e.g.

Lister and Forster, 2009). This tectonic scenario would not sensu-stricto equate to ophiolite obduction, and if correct would mean that the Meratus and Bobaris ophiolites represent peridotites rapidly exhumed from deep in the upper mantle. This is a possibility, but requires further investigation.

6.1.3 Subduction Source

Borneo's diamonds have also been said to form during UHP metamorphism within a subduction zone and later exhumed due to a process that did not involve a kimberlite intrusion (e.g. Figure 17) (Barron et al., 2008a). This model was proposed to explain similarities between the Cempaka diamonds and alluvial diamond deposits in eastern Australia (the Copeton and Bingara deposits) (Barron et al., 2008a,b). Diamonds from these deposits share: (1) similar nitrogen characteristics, (2) second order Raman spectroscopy peaks that are suppressed relative to the spectra obtained from cratonic diamonds, and (3) similar internal pressure estimates from inclusions (7.5 - 19 kb) (Barron et al., 2008a). Some of the Australian alluvial diamonds are also deformed and were also deposited near an uplifted and deformed continental volcanic arc (Scheibner and Basden, 1998; Barron et al., 2008a,b). Borneo's diamond deposits also contain significant amounts of igneous and metamorphic clasts and minerals (e.g. magnetite, muscovite and gold). Some workers have interpreted this to mean that the diamonds were derived from an igneous or metamorphic source (Burgath and Simandjuntak, 1983; Spencer et al., 1988). However, this mixture of diamonds with igneous and metamorphic minerals is not surprising considering all of Kalimantan's alluvial diamond deposits are located in close proximity to the Schwaner Granitoids and metamorphic rocks (e.g. Pinoh Metamorphics and Meratus Accretionary Complex) (Figure 1a).

Subduction-related metamorphic diamonds could represent either the local or distal source of diamonds that we have identified in this study. Diamonds associated with UHP metamorphic rocks are typically very small (<0.1 mm) ‘microdiamonds’. Such microdiamonds have been recovered from the Cempaka alluvium and the Meratus Mountains (van Leeuwen, 2014) and are small replicas of the macrodiamonds (e.g. average sizes between 0.1 to 2.0 carats, rare >5 carat, and rarer >20 carat diamonds) (Spencer et al., 1988; van Leeuwen, 2014). The microdiamonds are therefore quite possibly derived from the same source as the macrodiamonds. We therefore suspect that the Cempaka diamonds were not sourced from the UHP metamorphic rocks of the Meratus Accretionaty Complex as there are no reports of macrodiamonds being obtained from exhumed UHP metamorphic rocks, and no UHP mineral phases were recovered from the Cempaka alluvium (e.g. majoritic garnets or abundant rutile inclusions in clinopyroxenes).

Insert Figure 17

6.1.4 An Asian or Australian Source

It is not only Borneo that has alluvial diamonds with an unknown source. Several alluvial diamond deposits are spatially associated with Carboniferous-Permian glacial marine sedimentary units in Myanmar, Thailand and Sumatra (Figure 18) (Griffin et al., 2001; Win et al., 2001). These deposits have been referred to as “Sibumasu Diamonds” due to their distribution within the Sibumasu Terrane (van Leeuwen, 2014). They were originally considered as evidence of a connection between India and SE Asia, because diamonds were found in Permian glacial deposits in both Thailand and from Andraha Pradesh in India. This relationship was promoted in some tectonic reconstructions because of fortuitous fitting of coastline morphology and lithologies of similar age (Ridd, 1971). However, we now know that these tectonic reconstructions misposition the major continents and microcontinents relative to what has been determined from seafloor magnetic anomalies and paleomagnetic data (e.g. Hall, 2012; White et al., 2013). We also understand that the Sibumasu and SW Borneo terranes were part of Gondwana (located off the NW Australian margin) until the Early-Middle Permian and Late Jurassic respectively (Metcalfe, 1996; Hall, 2012). The discovery of diamonds across Australia in the late 20th century (e.g. Jaques et al., 1986; Atkinson et al., 1990; Jaques 1998), as well as an improved understanding of the tectonic configuration of Gondwana led to speculations that the Sibumasu and Borneo diamonds were possibly derived from crustal fragments of Australian/Gondwanan affinity rather than Indian/Gondwanan affinity (e.g. Taylor et al., 1990; Griffin et al., 2001; Metcalfe, 1996, 2011; Hall, 2012).

A strong case can be made for the Sibumasu diamonds being derived from an Australian/Gondwanan source as the alluvial diamonds are associated with Carboniferous-Permian diamictites and this combined with paleomagnetic data indicate Sibumasu was part of Gondwana at the time (e.g. Metcalfe, 1996), with the diamonds being deposited before or after Sibumasu was rifted from Gondwana during the Early Permian. By inference a similar origin can be postulated for (some of) the Kalimantan diamonds, which could have been incorporated into the SW Borneo or SE

Java blocks before they rifted from NW Australia in the Late Jurassic (Hall, 2012), or were emplaced in these crustal fragments sometime after they rifted (Figure 19).

Others have proposed that the Sibumasu-Kalimantan diamonds could have been derived from an Australian source based on similarities between particular diamond characteristics. For example, fourier transform infrared (FTIR) spectra from diamonds from Kalimantan, northwestern Australia [Argyle (1.2 Ga: Pidgeon et al., 1989), Ellendale-4 and Ellendale-9 pipes (18-22 Ma: Jaques et al., 1986; Smit et al., 2010; Evans et al., 2013)] and eastern Australia [Copeton] indicates that some of these diamonds share similar mantle residence times and thermal histories (Taylor et al., 1990). This was taken to indicate that the diamonds shared a common origin and may have survived in remnant subcontinental lithospheric mantle beneath Gondwana that was later sampled before or after microcontinents (e.g. SW Borneo) were rifted from Gondwana (Taylor et al., 1990) (this point is discussed further in section 6.2). However, these conclusions are based on relatively common diamond features that are insufficient to show that the Sibumasu-Kalimantan diamonds were obtained from the same source as diamonds in Australia.

A Gondwanan source of diamonds is plausible in terms of possible sediment transport distances and plate tectonic processes, but such models have been difficult to validate without information on the potential provenance of the material within Borneo's alluvial diamond deposits. The presence of Proterozoic and Archean zircons in the Cempaka deposit and Barito Basin (Figure 9) is a good indication that very old resistant mineral grains such as diamond could have been transported by surficial processes (e.g. alluvial, fluvial transport) or volcanic processes (e.g. xenocrysts brought to the surface during igneous intrusions or eruptions). This is supported by other geochronological studies that have reported inherited Proterozoic and Archean zircons in East Java (due south of Cempaka) (Smyth et al., 2005, 2007) as well as in northwestern and eastern Sulawesi (van Leeuwen et al., 2007; White et al., 2014; Hennig et al., in press). These age data combined with well data and interpretations of offshore seismic data also indicate that Cretaceous or older continental basement extends offshore, north and south of East Java (Emmet et al., 2009; Deighton et al., 2011; Granath et al., 2011).

Our current understanding of Mesozoic tectonic evolution is that the SE Asian region grew progressively due to the addition of continental fragments over time (e.g. Metcalfe, 1996; Hall, 2012) (e.g. Figure 4). This is particularly well-documented in western Indonesia and more recent work indicates that this is also the case in many parts of eastern Indonesia, such as large parts of west Sulawesi, the Makassar Straits, East Java Sea and East Java (e.g. Metcalfe, 1996; Hall, 2012; Hall and Sevastjanova, 2012).

The growing body of geochronological data (including this study) indicate that the SW Borneo and East Java blocks (Hall, 2012) potentially have Proterozoic to Archean basement and/or sedimentary units that were derived from the erosion of ancient crust (Smyth et al., 2005, 2007; van Leeuwen et al., 2007; White et al., 2014; Hennig et al., in press). This provides support for the idea that Kalimantan's alluvial diamonds could have been emplaced in thick, ancient crust and/or derived from a distal source, with transport occurring before these terranes were rifted from Gondwana (e.g. Figure 19). It also lends support to the idea that these rifted fragments may represent old, thick crustal fragments in which diamonds may have been emplaced via kimberlites or lamproites that were later reworked and deposited in Kalimantan.

6.2 Multiple diamond sources

We have based our interpretations of the multiple diamond sources primarily on secondary textures (proximal: no wear and tear; distal: a lot of wear and tear). Smith et al. (2009) however, identified five different populations of diamonds across Kalimantan on the basis of primary features in the diamonds, and argued that resorbed, rounded stones were less prone to mechanical abrasion as they were already rounded and hence have the appearance of a proximal stone. Our interpretations differ, but it is agreed that there are diamonds derived from multiple primary igneous sources in Kalimantan (e.g. Smith et al., 2009; van Leeuwen 2014 and references therein). Despite this, one question that remains unanswered is when these diamonds were brought from the sub-continental lithospheric mantle to the shallow crust. A comparative study of several diamonds from the Cempaka deposit with several diamonds from the Australian Ellendale and Copeton deposits addresses this point (Taylor et al., 1990). The Ellendale diamond(s) are associated with lamproites that were brought to the upper crust during the Miocene (18-22 Ma) (Evans et al., 2013). Taylor et al. (1990) compared the results of nitrogen aggregation analyses of Kalimantan, Copeton and Ellendale diamonds. They proposed that diamonds from Kalimantan, Copeton and Ellendale-9 must have been extracted from the mantle at a similar time (150 – 5 Ma) in order for them to plot on the same isotherm. However, subsequent measurements of diamonds from the Copeton and Bingara alluvial deposits indicates that Copeton and Bingara were each derived from distinct sources of different age (Carboniferous and Triassic respectively) (Barron et al., 2011).

Further characterization of the Kalimantan diamonds is required to determine how long the diamonds resided in the mantle and to identify possible times when they were brought to the surface. Such information could identify feasible mechanisms for diamond emplacement.

Stratigraphic relations at least provide some information about the relative timing of emplacement as diamonds are found in the basal sequences of Upper Cretaceous to Lower Paleogene sediments (e.g. the Manunggal Formation: Spencer et al., 1988; Guntoro, 1999) in Kalimantan. This requires that some of the Cempaka diamonds must have been emplaced and eroded before the deposition of these units. This implies a local SW Borneo/SE Java source of diamonds during the Cretaceous and/or an older source(s) of diamonds. However, since SW Borneo rifted from Australia in the Late Jurassic (Hall, 2012), diamonds that were brought to the surface after this time (e.g. the model of Taylor et al., 1990) must have been emplaced in a kimberlite or lamproite and could not be alluvial diamonds sourced from the Australian Plate. The lack of diamond indicator minerals around intrusions such as the ~8 Ma Linhaisai Minette (Bergman et al., 1988) indicates they are unlikely to be the source of diamonds but similar undiscovered young potassic or ultrapotassic alkaline volcanics and dykes (Simanjuntak and Simanjuntak, 2000) are a potential local source.

We favour models where Kalimantan's alluvial diamonds were derived from a local source and were also possibly transported from Gondwana on fragments that were rifted from Gondwana during the Late Jurassic (e.g. SW Borneo / SE Java blocks) (Metcalfe, 1996, 2011; Hall, 2012; Hall and Sevastjanova, 2012) (Figure 19). The diamonds were unlikely to have been sourced from the Sibumasu Terrane by transport along major Asian fluvial systems because parts of Sundaland (e.g. the Tin Belt and western Borneo) have been elevated at least since the Late Cretaceous (Figure 18). It is more likely that the material in the Cempaka alluvium was derived from the erosion of nearby rocks in the Schwaner and Meratus mountains and in the Barito Basin, along with material being transported from paleo-highs such as the Karimunjawa Arch to the south which provided material that was originally the sedimentary cover to the SW Borneo and East Java blocks (e.g. Witts et al., 2011). Future studies should test these ideas further, and one way to do this would be to characterise the age and morphology of diamonds, zircons and other heavy minerals from the Manunggal Formation to determine if the 'younger', less reworked diamonds that are present at Cempaka are also found in these older sediments.

7. Conclusion

Geochronological and geochemical data provide new evidence on possible sources of clastic material that accumulated in Kalimantan's Cempaka alluvial diamond deposit. Our results show that the Cempaka diamonds can be divided into two groups, one (A) that was transported from a distal source and/or were recycled several times indicating a long history in the secondary environment, the other (B) was not. The presence of diamonds in Upper Cretaceous paleo-alluvials indicates that at least some of the diamonds were already present in Borneo in the Early Cretaceous or earlier. Group A diamonds are obvious candidates and were most likely emplaced in the SW Borneo fragment and reworked several times, or were transported from NW Australia to the SW Borneo fragment before it rifted from Gondwana in the Late Jurassic.

Group B diamonds are unlikely to have been sourced from the erosion of nearby ophiolites or ultra-high pressure metamorphic rocks exposed in the nearby Meratus Mountains, because of the high proportion of macrodiamonds and because no mineral phases indicative of UHP metamorphism have been found within the Cempaka alluvium. However, the widespread occurrence of Miocene alkaline igneous bodies in the central part of Borneo indicates that the Neogene tectonic environment was conducive for the emplacement of diamondiferous diatremes or mantle-penetrating faults that could tap diamond-bearing material. These could explain the Group B diamonds that show little evidence of reworking.

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Figure Captions

Figure 1. (a) Map of Borneo showing the location of Cempaka and other alluvial diamond deposits across Kalimantan (modified from Smith et al., 2009), as well as the location of geological units discussed in this study. (b) An example of one of the conglomeratic units in which the Cempaka alluvial diamonds are found.

Figure 2. Schematic diagram showing the tectonic setting of diamond formation. Diamonds are stable at depths of approximately 150 km and are typically sourced from sub-continental lithospheric mantle beneath thick continental crust (a 'craton'), where they are brought to the surface as xenocrysts in kimberlite and lamproite intrusions. They may also be generated at similar depths in subducted oceanic crust and potentially brought to the surface with UHP metamorphic rocks (modified after Shirey et al., 2013).

Figure 3. Two tectonic reconstructions of SE Asia during the Lower Cretaceous [(a) 130 Ma and (b) 120 Ma] to show Borneo's position at the time with respect to Australia, Sundaland and other parts of what is now SE Asia. SWB = South West Borneo Block, EJWS = East Java/West Sulawesi Block; Sc.P. = Scott Plateau; Ex. P. = Exmouth Plateau; East C-T = East Ceno Tethys. Images taken from Hall (2012).

Figure 4. Regional map showing the location of Sundaland and the various crustal blocks that define it as well as when each of the fragments were rifted from Gondwana and when these accreted to the Asian margin (modified from Metcalfe, 1996, 2011; Hall and Sevastjanova, 2012).

Figure 5. Provenance of Cempaka spinels (grey diamonds) compared with the 50th and 30th percentiles of a global spinel composition database (Barnes and Roeder, 2001) for ophiolites excluding chromite seams (blue), kimberlite (yellow) and lamproites (red). These data show that the Cempaka spinels are dominantly sourced from an ophiolite, rather than a kimberlite or lamproite. Note, for simplicity only three geological environments are shown here. Readers are directed to the global spinel database (Barnes and Roeder, 2001) for more details about the compositional ranges of other settings.

Figure 6. Conventional U-Pb concordia plots of the results obtained from SHRIMP U-Pb isotopic analyses of Cempaka detrital zircons, showing (a) the full range of age data obtained, and (b) the majority of age data, which are less than 600 Ma.

Figure 7. CL imagery of Cempaka detrital zircons as well as the location and result of each SHRIMP analysis, marked with yellow and red circles. This data shows that the majority of zircons are primarily oscillatory zoned igneous zircons, some also showing sector zoning and generally lack overgrowths (i.e. rims). The zircons that are younger than ~120 Ma are predominantly angular, euhedral grains or angular grain fragments (shown with yellow circles), whereas older grains are generally rounded to angular, indicating that many such grains have been reworked.

Figure 8. Secondary electron SEM images of non-polished zircon grains, including: (a-c) rounded and sub-rounded grains which are indicative of transport in a high energy environment for some time; and (d-i) euhedral angular grains, many of which preserve primary growth textures [e.g. (e) and (f)], preserved mineral inclusions [e.g. (d)] or zones where mineral inclusions have been chemically or mechanically removed [e.g. (g) and (i). These features would not be preserved with prolonged transport in a high energy environment.

Figure 9. Relative frequency plots of zircon ages obtained from (a-b) Cempaka (this study) compared with zircon ages obtained from the (c-d) Schwaner Granitoids (modified from Davies et al., 2014); (e-f) Pinoh Metamorphics (modified from Davies et al. 2014); (g-h) Barito Basin (Witts et al., 2011, 2012), and (i-j) the Khorat Plateau Basin (Carter and Moss, 1999; Carter and Bristow, 2003).

Figure 10. Relative probability-frequency plot of age zircon fission-track age data obtained from twenty detrital zircons from the Cempaka alluvial deposit. The plot shows the results of zircon fission track analyses of two size fractions of zircons (<1 mm and >1mm).

Figure 11. Comparison of the mode (white dot) and range (red line) of trace element results obtained from LA-ICPMS analyses of zircon from (a) Cempaka, compared with average compositions of zircons reported from (b) lamproites*; (c) kimberlites*; (d) basalts*; and (e) granitoids* [*Data from Belousova et al., (2002)]. The trace element data also indicates that different compositional groups can be identified, particularly when the trace element data is plotted according to different grain-size

populations and when age data can be incorporated into the interpretation [e.g. (f) Hf vs. Ce plot].

Figure 12. Photomicrographs of Cempaka diamond morphologies: (a) modified colourless tetrahexahedron with fine plastic deformation lamellae (4 mm), (b) relatively flattened colourless octahedron (i.e. macle) with graphite inclusions (3 mm), (c) twinned cubo-octahedron with pronounced brown radiation spots (4 mm), and (d) partially resorbed dodecahedron (2 mm).

Figure 13. Photomicrographs of Cempaka semi-opaque to opaque diamonds: (a) semi-opaque cubo-octohedral diamond with polished window (2 mm); (b) close-up view of (a) through the polished window showing distinctive platy black graphite aligned along crystallographic planes (FOV ~0.1 mm); (c) modified cubo-octahedra opaque diamond (2 mm), and (d) anhedral semi-ovoid rough-textured ballas (3 mm).

Figure 14. Photomicrographs of (a) Cempaka diamonds with radiation “spots”, and (b-d) cut “windows” showing the internal structure of Cempaka diamonds. (a) The green outer colour is due to the presence of green-coloured radiation “spots” (this diamond has a length of 2 mm). (b) Cut window through semi-opaque coated diamond showing its transparent interior (FOV is ~0.2 mm); (c) Cut window through semi-opaque coated diamond showing abundant near-surface inclusions (FOV is ~0.3 mm), and: (d) Brightly illuminated close-up of (c), showing that this diamond is in fact transparent (FOV is ~0.3 mm).

Figure 15. Photomicrographs of Cempaka diamonds showing surface features and growth features: (a) partially resorbed diamond with pronounced negative crystal indents (3 mm); (b) pronounced dark brown radiation burns (2 mm); (c) large surface micro-disks (2mm), and; (d) zoning seen with polarized light (2 mm).

Figure 16. Histogram and cumulative frequency of relative diamond grain-size distribution from 8863 diamonds from the Cempaka paleoalluvium showing a multimodal grain size distribution. The data used to produce this plot are presented in Supplementary data table 5.

Figure 17. Schematic diagram of a continent-continent collision zone and the process by which diamonds associated with anhydrous UHP metamorphic rocks could be brought to the surface. This process was proposed as a primary source of the Cempaka diamonds due to their proximity to the Meratus-Bobaris ophiolites and Meratus Accretionary Complex. In reality, such a process would probably involve multiple tectonic mode switches driving phases of crustal extension and shortening as discussed by Lister and Forster (2009).

Figure 18. Map of the Sundaland region showing the distribution of major alluvial diamond deposits and districts. Alluvial diamonds in Sundaland are associated with Permian glacial marine diamictites. Kalimantan's diamonds are not likely to be derived from major fluvial systems reworking the Sundaland deposits and carrying these diamonds to Borneo as the Malayasian tin belt and Schwaner Mountains have been elevated regions since the Cretaceous and would have impeded any such drainage from the west (figure adapted from van Leeuwen, 2014).

Figure 19. (a) Map showing the present-day location of the Cempaka alluvial diamond deposit, the SW Borneo, East Java and Banda Embayment blocks as well as the location of various diamond deposits in northern and western Australia. (b) A rigid-plate reconstruction shows the current-day location of the Cempaka alluvial deposit rotated relative to an arbitrarily fixed Australian Plate and the possible transport direction of diamonds via major fluvial systems. This provides a maximum estimate of the transport distance between the Borneo terranes and Australian mainland as this reconstruction does not account for crustal extension in the NW Shelf. The Borneo fragments are rotated using the rotation poles of Hall (2012). Greater India is rotated relative to Australia as per White et al. (2013). The location of the Australian diamond deposits was taken from Jaques (2005).

Supplementary Data Captions

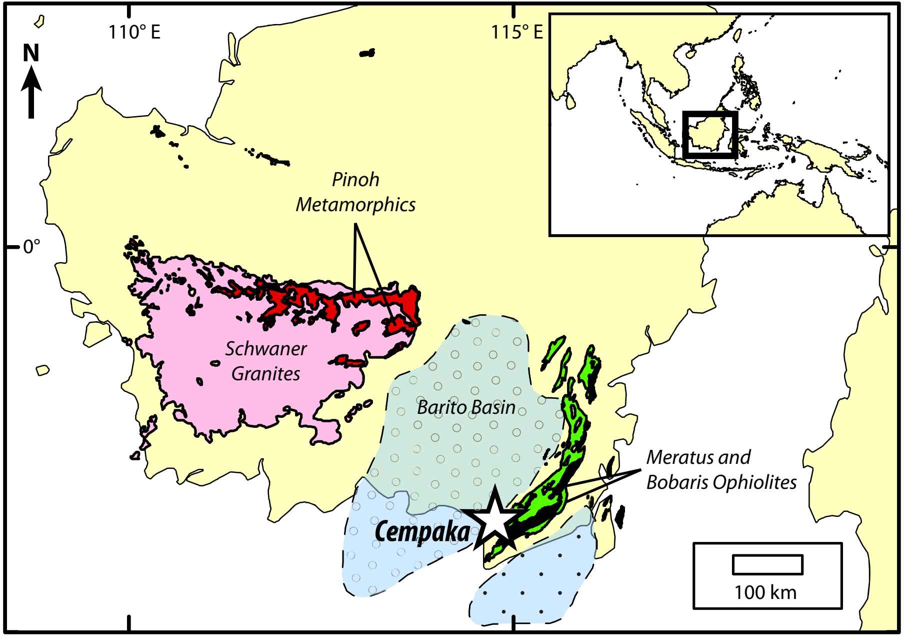
Supplementary Data Table 1: Results of spinel major element mineral chemistry obtained from EMP analyses

Supplementary Data Table 2: Results of SHRIMP U-Pb isotopic analyses of detrital zircon from the Cempaka alluvial deposit

Supplementary Data Table 3: Age results obtained from zircon fission-track analyses

Supplementary Data Table 4: Zircon trace element chemistry obtained from LA-ICPMS analyses

Supplementary Data Table 5: Size distribution data of diamonds from the Cempaka alluvium

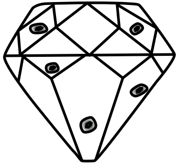


CEMPAKA ALLUVIAL DEPOSIT CONTAINS AT LEAST TWO SOURCES OF DIAMONDS WITH DIFFERENT TECTONIC HISTORY

GROUP A:

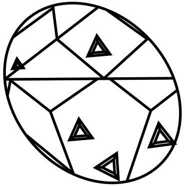
BROUGHT TO SURFACE BEFORE THE UPPER CRETACEOUS.

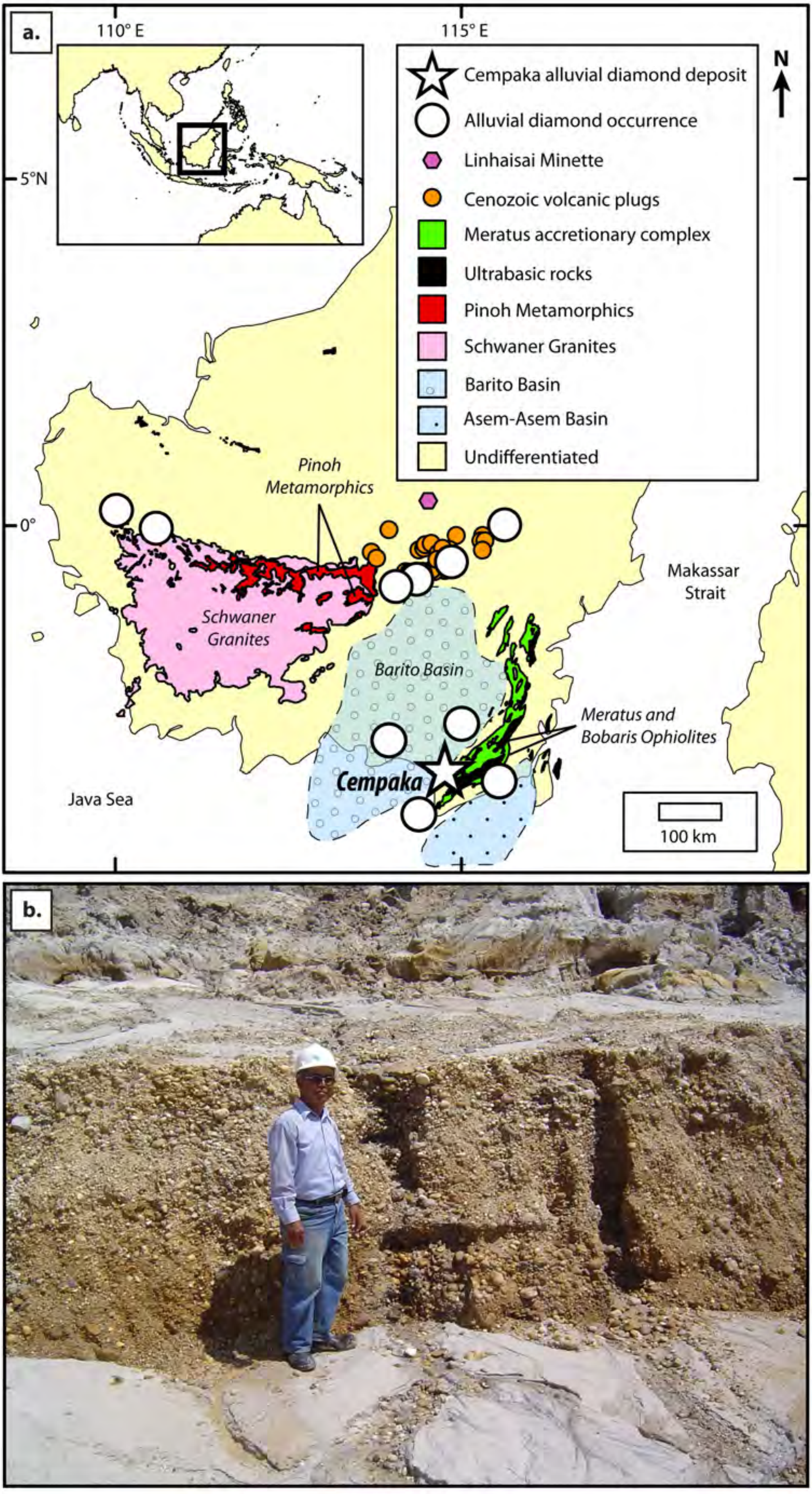
MANY SHOW FEATURES SUCH AS RADIATION BURNS AND HAVE BEEN REWORKED SEVERAL TIMES.

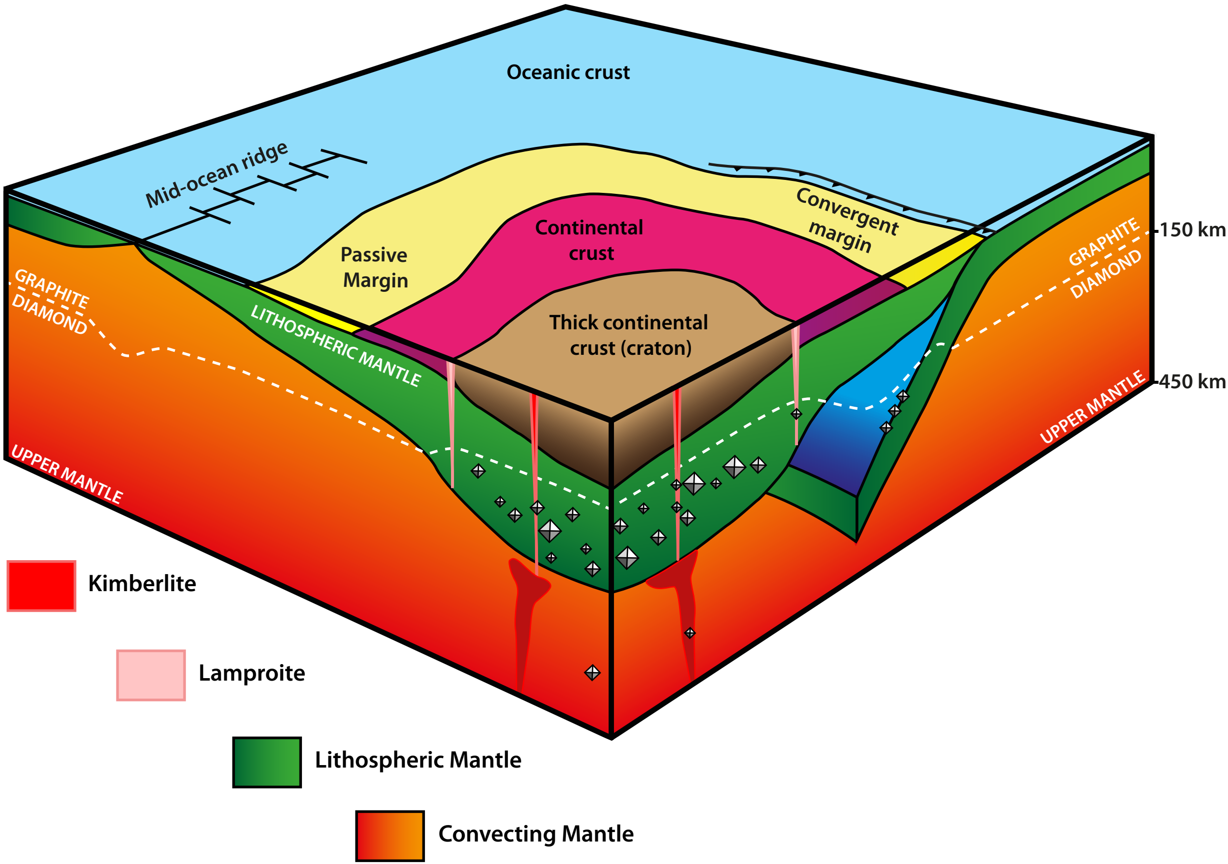


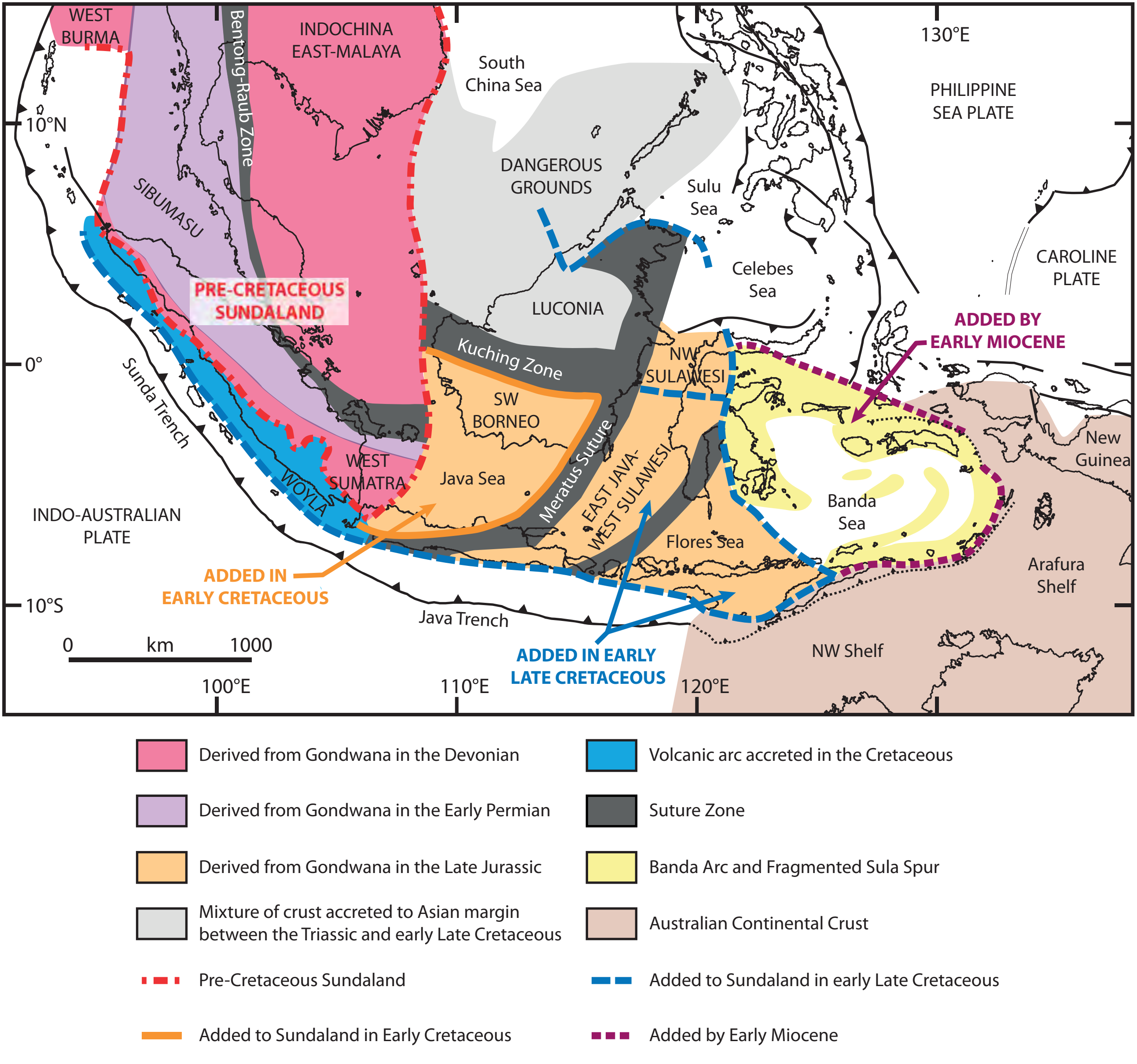
GROUP B:

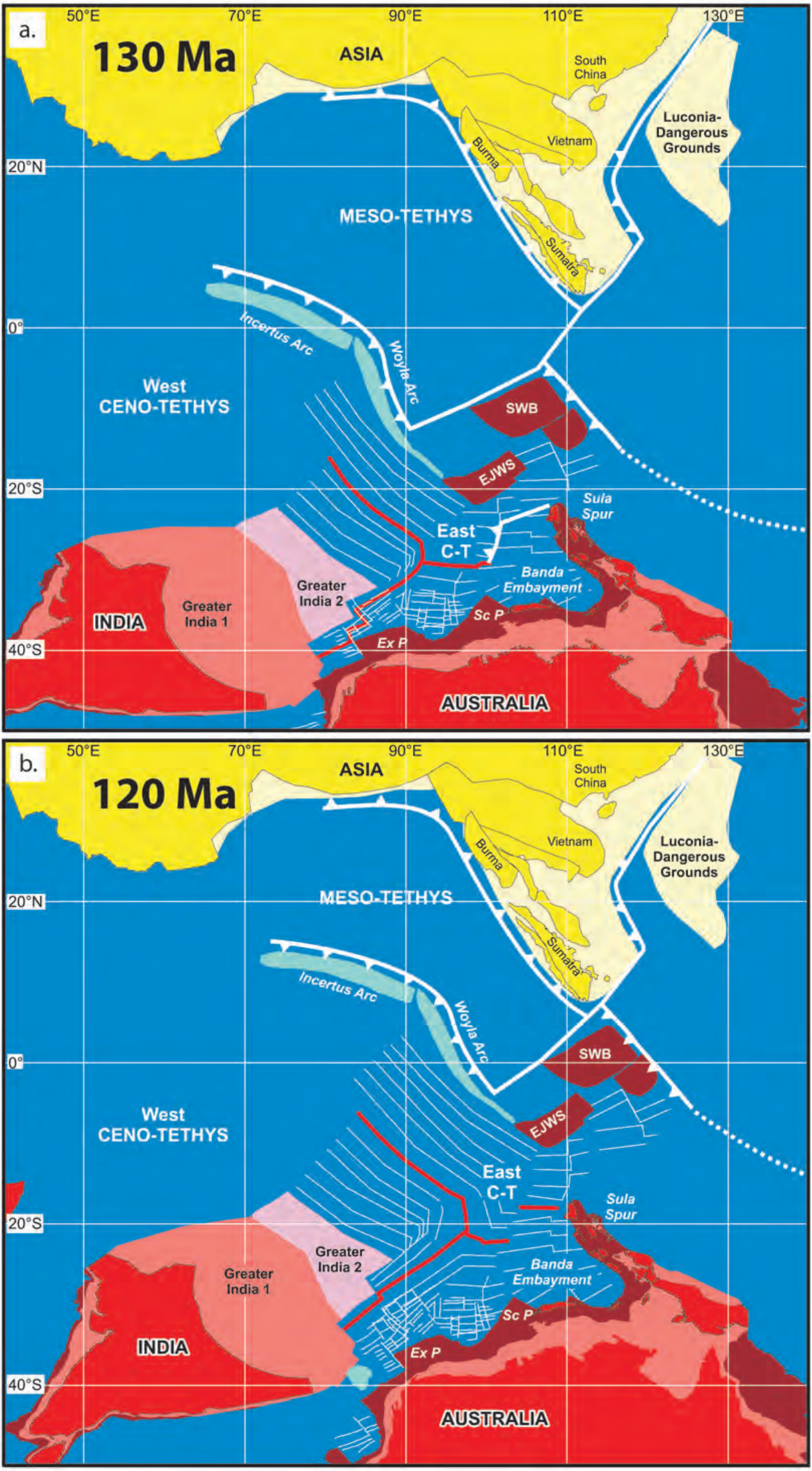
ROUNDED DIAMONDS, BUT COULD NOT HAVE BEEN TRANSPORTED LONG DISTANCES AS THEY SHOW SHARP RESORPTION TEXTURES ON THE GRAIN SURFACE.

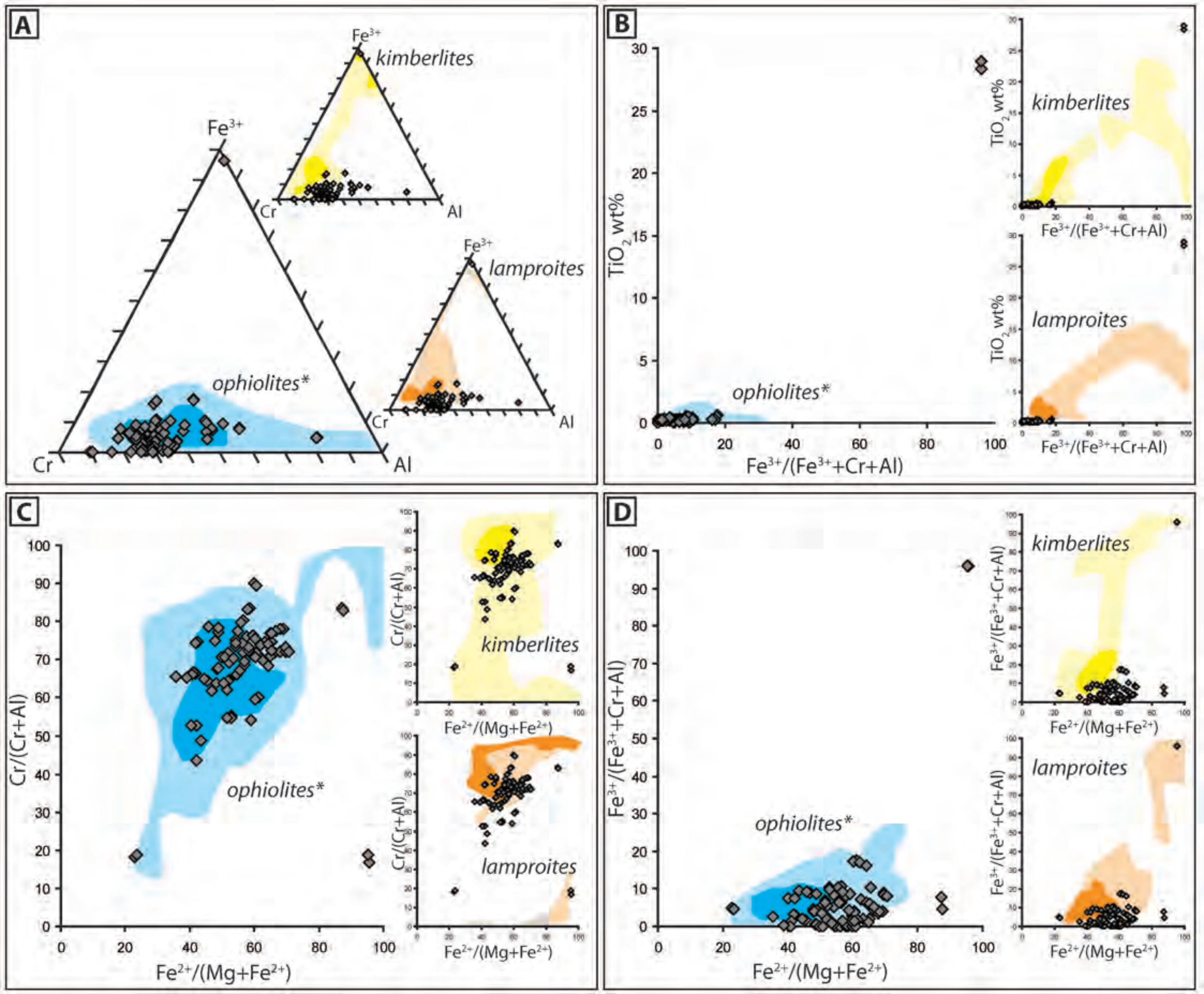


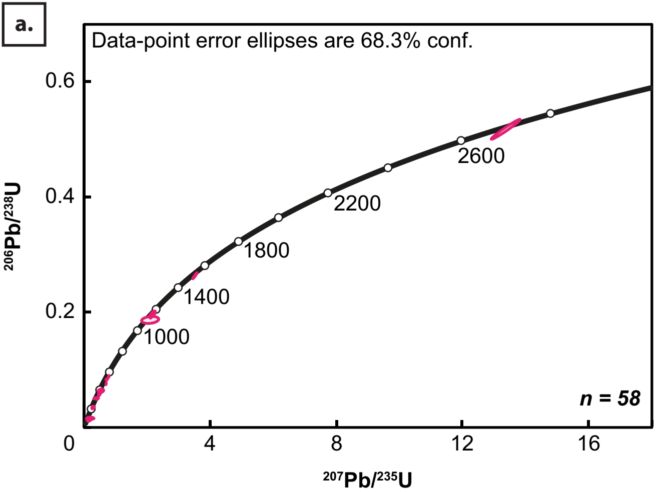

a.
110° E
115° E
5°N
0°
N
Cempaka alluvial diamond deposit
Alluvial diamond occurrence
Linhaisai Minette
Cenozoic volcanic plugs
Meratus accretionary complex
Ultrabasic rocks
Pinoh Metamorphics
Schwaner Granites
Barito Basin
Asem-Asem Basin
Undifferentiated
Pinoh Metamorphics
Schwaner Granites
Barito Basin
Makassar Strait
Meratus and Bobaris Ophiolites
Cempaka
Java Sea
100 km
b.

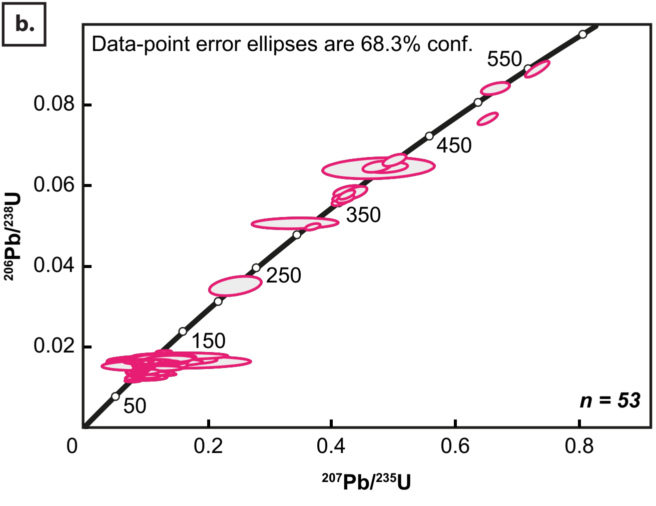

Oceanic crust
Mid-ocean ridge
Passive Margin
Continental crust
Convergent margin
Thick continental crust (craton)
GRAPHITE
DIAMOND
LITHOSPHERIC MANTLE
UPPER MANTLE
GRAPHITE
DIAMOND
UPPER MANTLE
150 km
450 km
Kimberlite
Lamproite
Lithospheric Mantle
Convecting Mantle

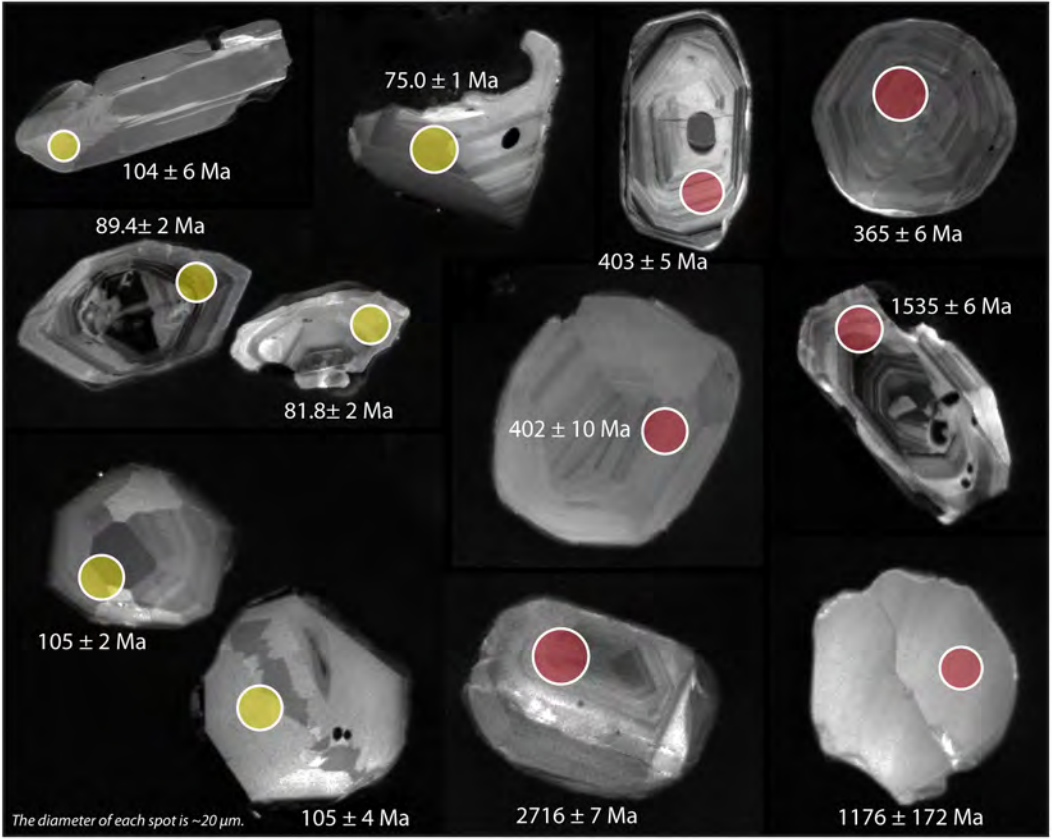

WEST BURMA
INDOCHINA EAST-MALAYA
Bentong-Raub Zone
SIBUMASU
PRE-CRETACEOUS SUNDALAND
South China Sea
DANGEROUS GROUNDS
LUCONIA
Sulu Sea
Celebes Sea
PHILIPPINE SEA PLATE
CAROLINE PLATE
130°E
10°N
0°
10°S
Kuching Zone
SW BORNEO
Meratus Suture
NW SULAWESI
EAST JAVA-WEST SULAWESI
ADDED BY EARLY MIOCENE
WEST SUMATRA
WOYLA
Sunda Trench
Java Sea
Flores Sea
Banda Sea
New Guinea
Arafura Shelf
NW Shelf
INDO-AUSTRALIAN PLATE
ADDED IN EARLY CRETACEOUS
ADDED IN EARLY LATE CRETACEOUS
Java Trench
0 km 1000
100°E
110°E
120°E
Derived from Gondwana in the Devonian
Derived from Gondwana in the Early Permian
Derived from Gondwana in the Late Jurassic
Mixture of crust accreted to Asian margin between the Triassic and early Late Cretaceous
Pre-Cretaceous Sundaland
Added to Sundaland in Early Cretaceous
Volcanic arc accreted in the Cretaceous
Suture Zone
Banda Arc and Fragmented Sula Spur
Australian Continental Crust
Added to Sundaland in early Late Cretaceous
Added by Early Miocene

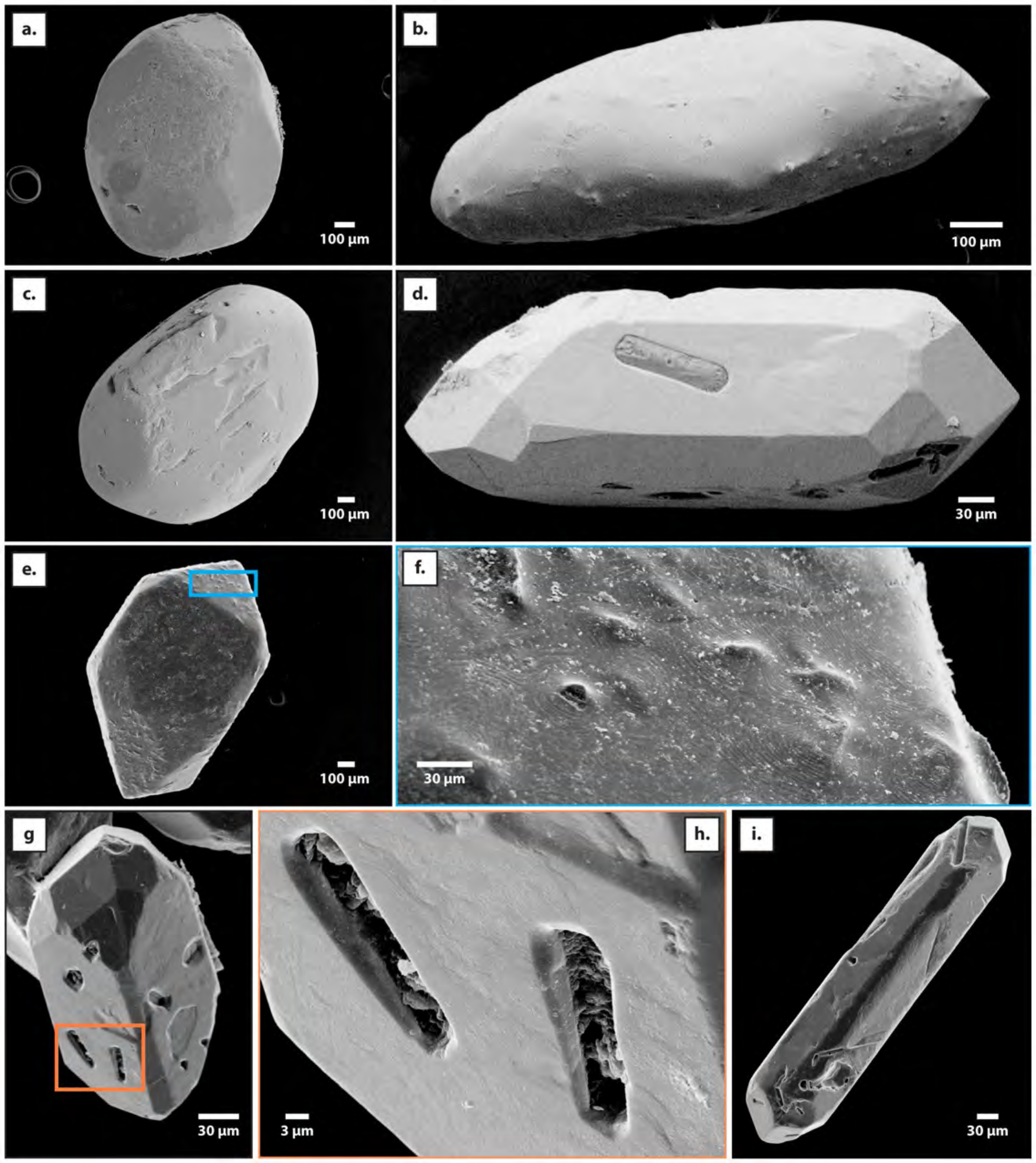

a.
130 Ma
50°E
70°E
90°E
110°E
130°E
ASIA
South China
Vietnam
Burma
Luconia-Dangerous Grounds
20°N
MESO-TETHYS
Sumatra
Incertus Arc
Woyla Arc
0°
West CENO-TETHYS
SWB
EJWS
20°S
Sula Spur
East C-T
Banda Embayment
Greater India 2
Greater India 1
INDIA
Sc P
Ex P
40°S
AUSTRALIA
b.
120 Ma
50°E
70°E
90°E
110°E
130°E
ASIA
South China
Vietnam
Burma
Luconia-Dangerous Grounds
20°N
MESO-TETHYS
Sumatra
Incertus Arc
Woyla Arc
0°
SWB
West CENO-TETHYS
EJWS
East C-T
Sula Spur
20°S
Greater India 2
Greater India 1
Banda Embayment
Sc P
INDIA
Ex P
40°S
AUSTRALIA


A
Fe3+
Cr
Al
kimberlites
lamproites
ophiolites*
B
TiO2 wt%
Fe3+/(Fe3+ +Cr+Al)
C
Cr/(Cr+Al)
Fe2+/(Mg+Fe2+)
D
Fe3+/(Fe3+ +Cr+Al)
Fe2+/(Mg+Fe2+)

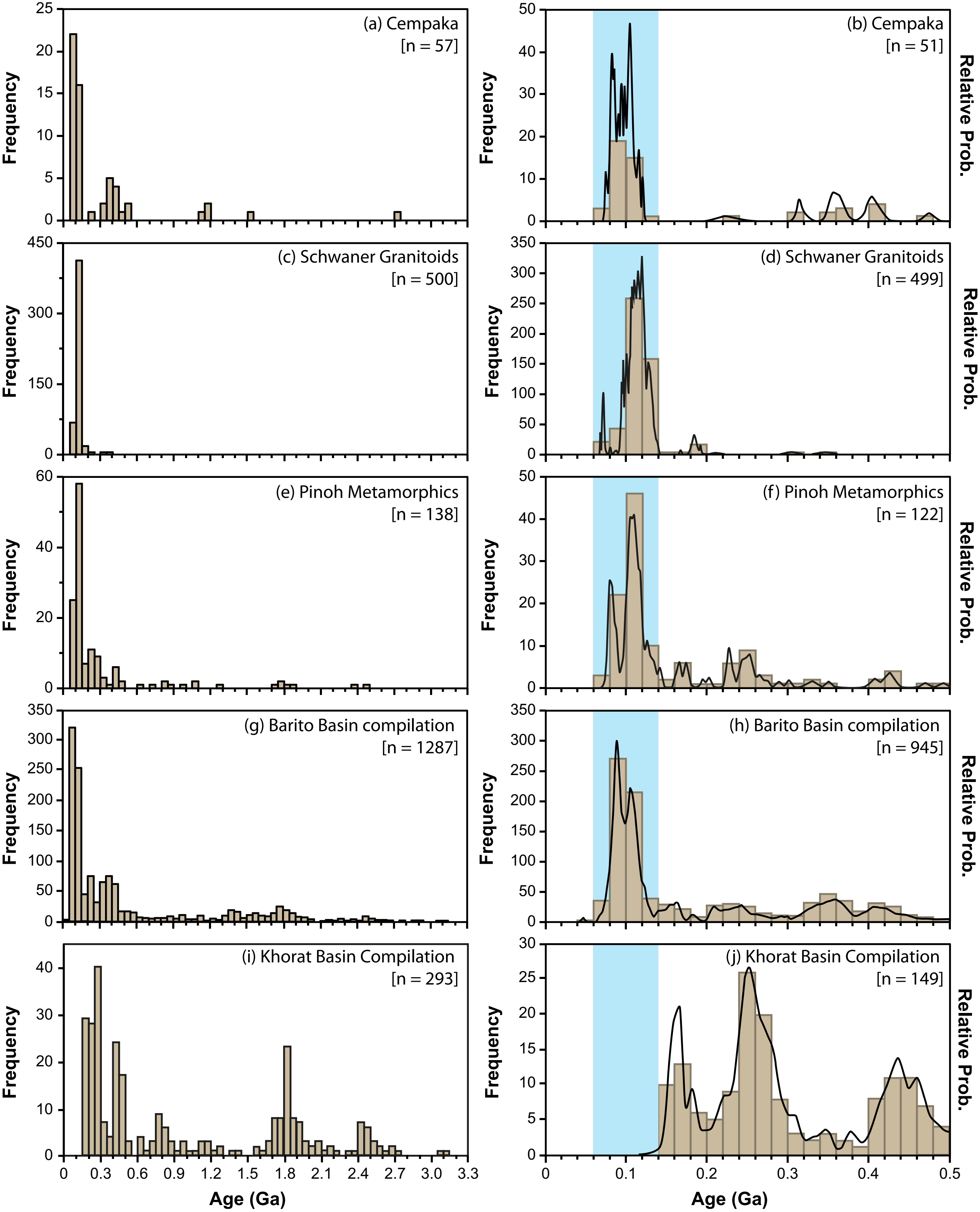

a.
Data-point error ellipses are 68.3% conf.
0.6
0.4
0.2
0
4
8
12
16
2600
2200
1800
1400
1000
n = 58
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$


b.
Data-point error ellipses are 68.3% conf.
0.08
0.06
0.04
0.02
0
0.2
0.4
0.6
0.8
550
450
350
250
150
50
n = 53
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$

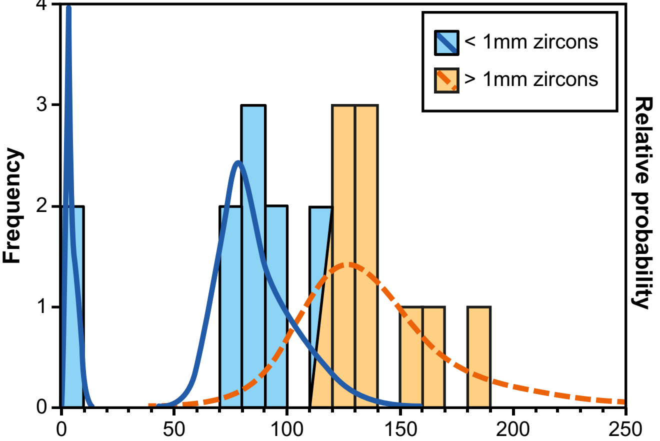

75.0 ± 1 Ma
104 ± 6 Ma
403 ± 5 Ma
365 ± 6 Ma
89.4± 2 Ma
81.8± 2 Ma
402 ± 10 Ma
1535 ± 6 Ma
105 ± 2 Ma
105 ± 4 Ma
2716 ± 7 Ma
1176 ± 172 Ma
The diameter of each spot is ~20 µm.



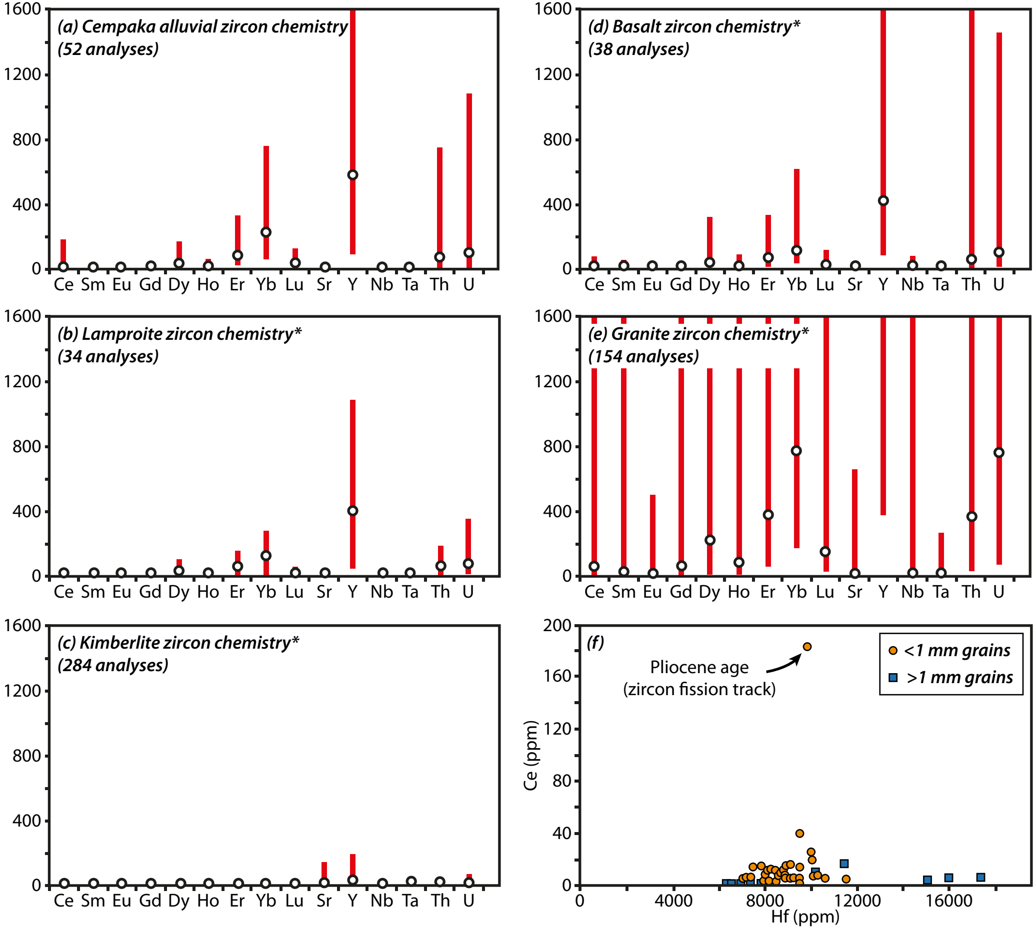
a.
100 µm
b.
100 µm
c.
100 µm
d.
30 µm
e.
100 µm
f.
30 µm
g
30 µm
h.
3 µm
i.
30 µm



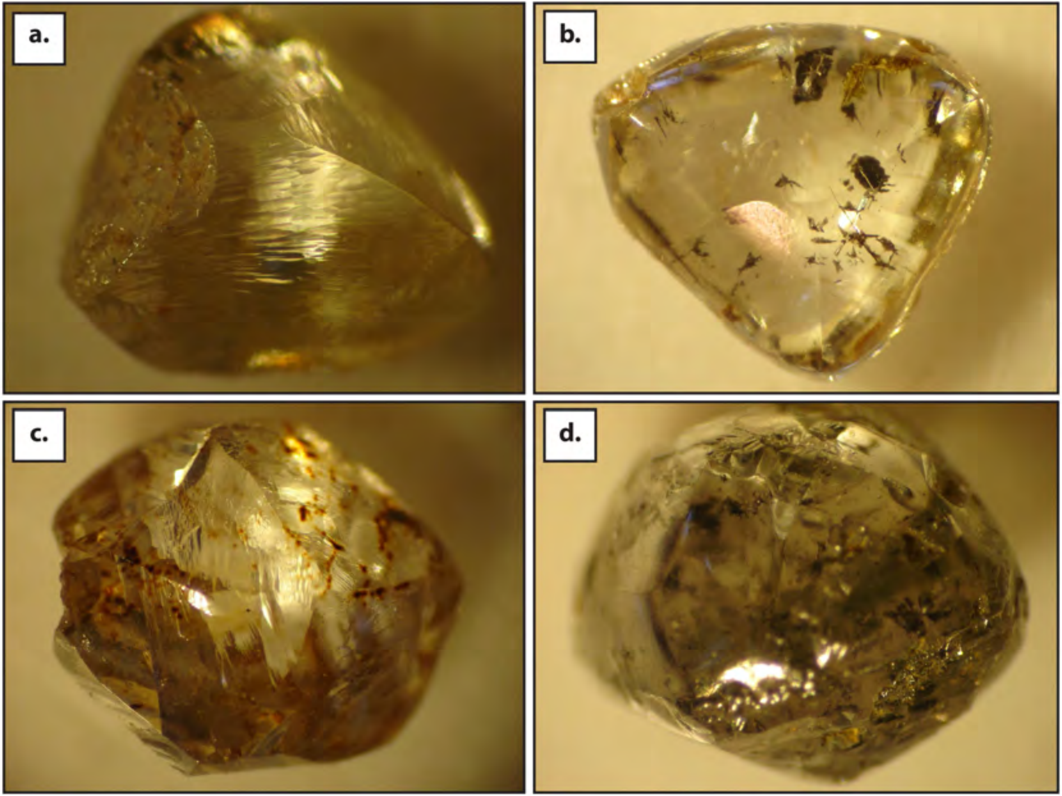
(a) Cempaka
[n = 57]
(b) Cempaka
[n = 51]
(c) Schwaner Granitoids
[n = 500]
(d) Schwaner Granitoids
[n = 499]
(e) Pinoh Metamorphics
[n = 138]
(f) Pinoh Metamorphics
[n = 122]
(g) Barito Basin compilation
[n = 1287]
(h) Barito Basin compilation
[n = 945]
(i) Khorat Basin Compilation
[n = 293]
(j) Khorat Basin Compilation
[n = 149]
Frequency
Relative Prob.
Age (Ga)

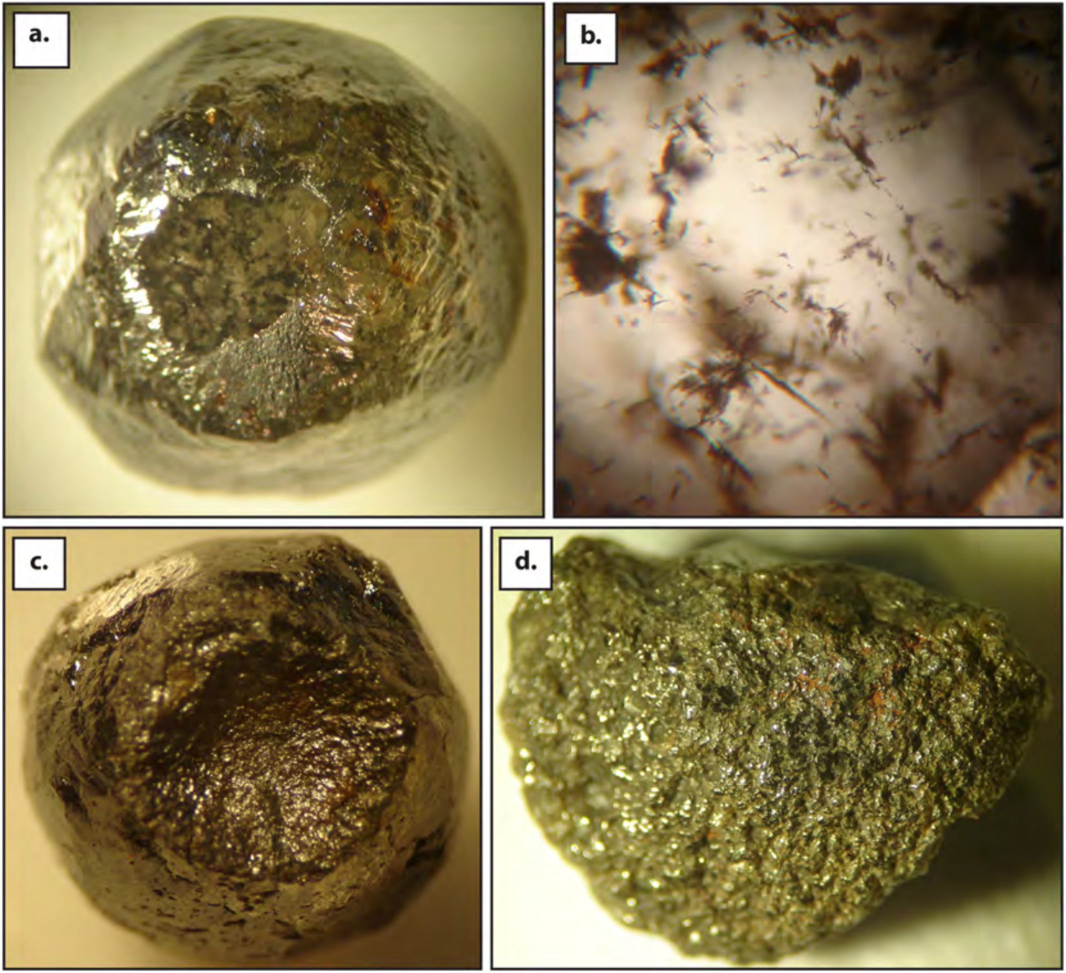


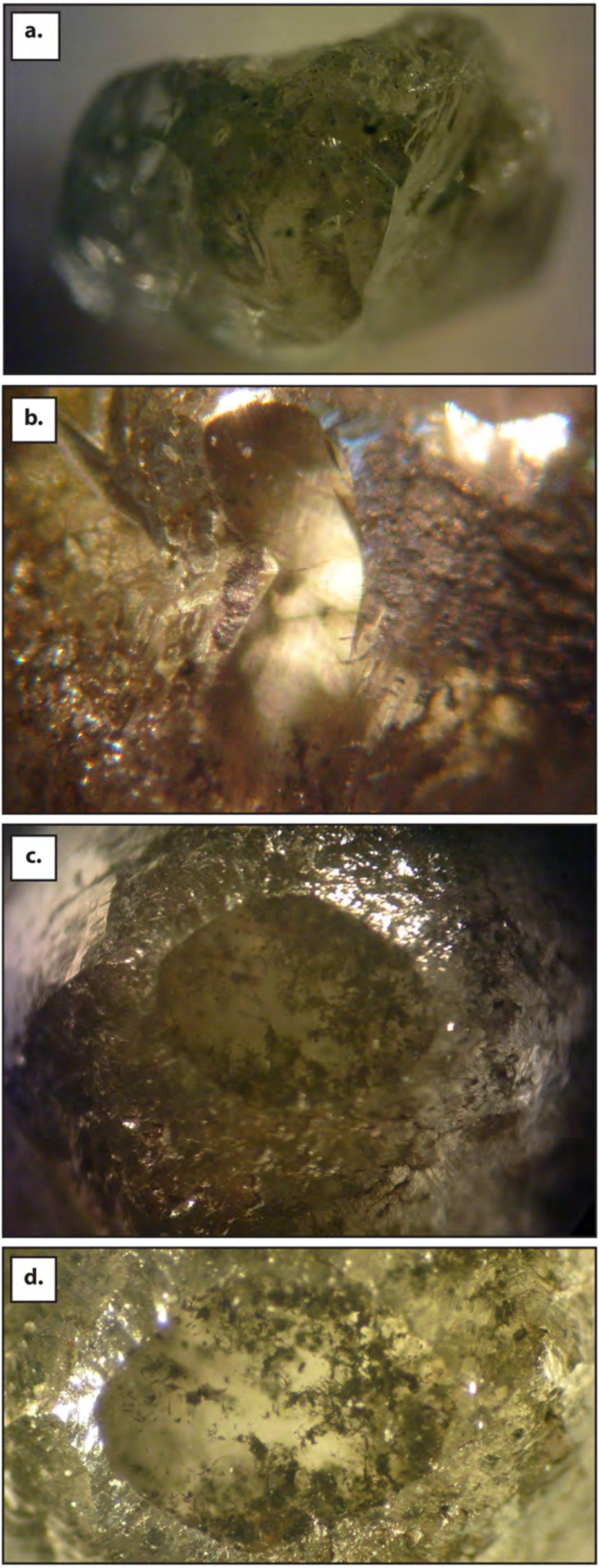
< 1mm zircons
> 1mm zircons
Frequency
Relative probability
0
1
2
3
4
0
50
100
150
200
250

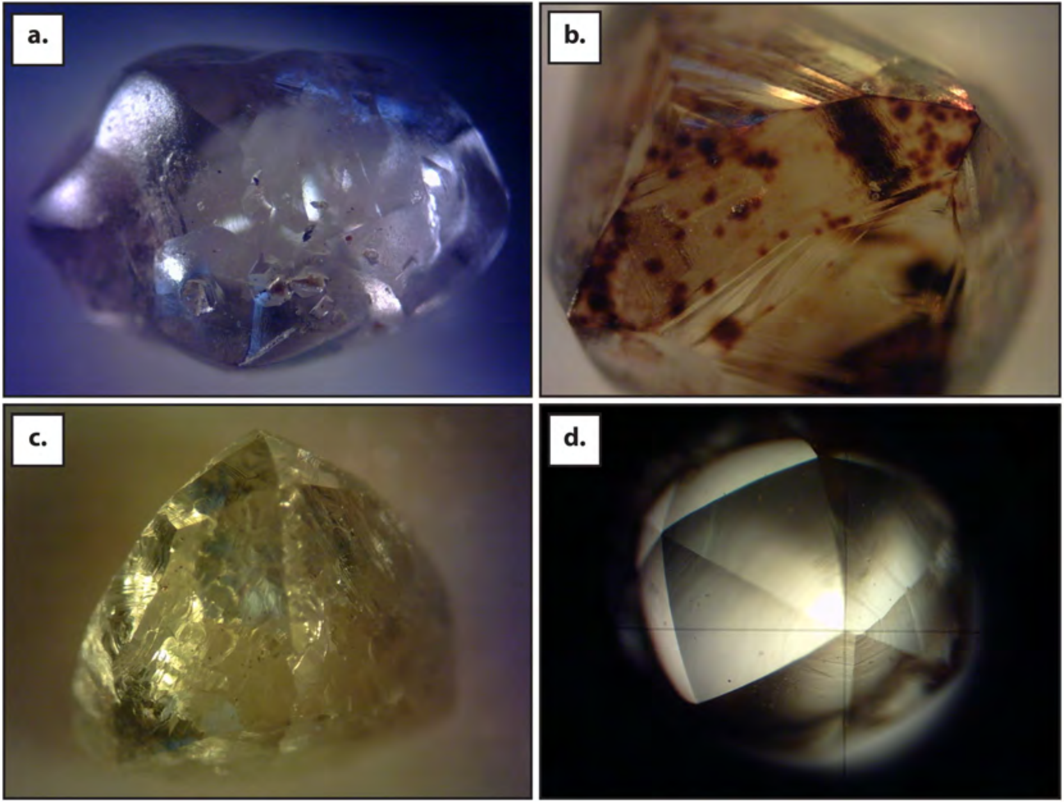


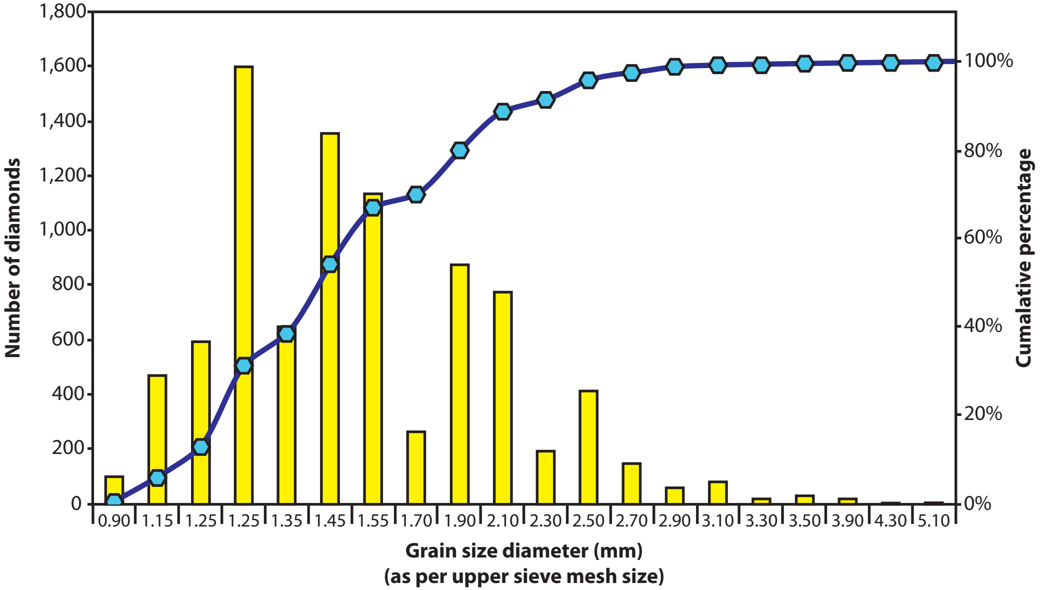
(a) Cempaka alluvial zircon chemistry
(52 analyses)
(b) Lamproite zircon chemistry*
(34 analyses)
(c) Kimberlite zircon chemistry*
(284 analyses)
(d) Basalt zircon chemistry*
(38 analyses)
(e) Granite zircon chemistry*
(154 analyses)
(f)
Ce Sm Eu Gd Dy Ho Er Yb Lu Sr Y Nb Ta Th U
0
400
800
1200
1600
Pliocene age
(zircon fission track)
<1 mm grains
>1 mm grains
Ce (ppm)
Hf (ppm)
0
40
80
120
160
200
4000
8000
12000
16000

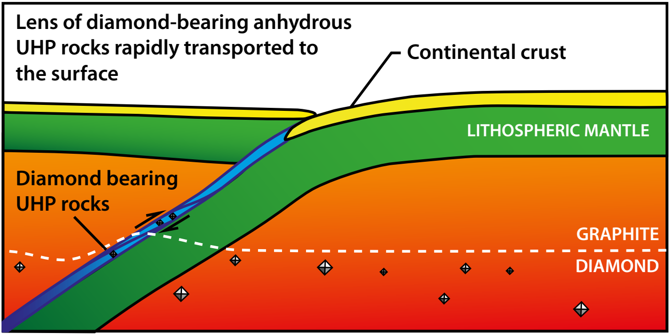

a.
b.
c.
d.

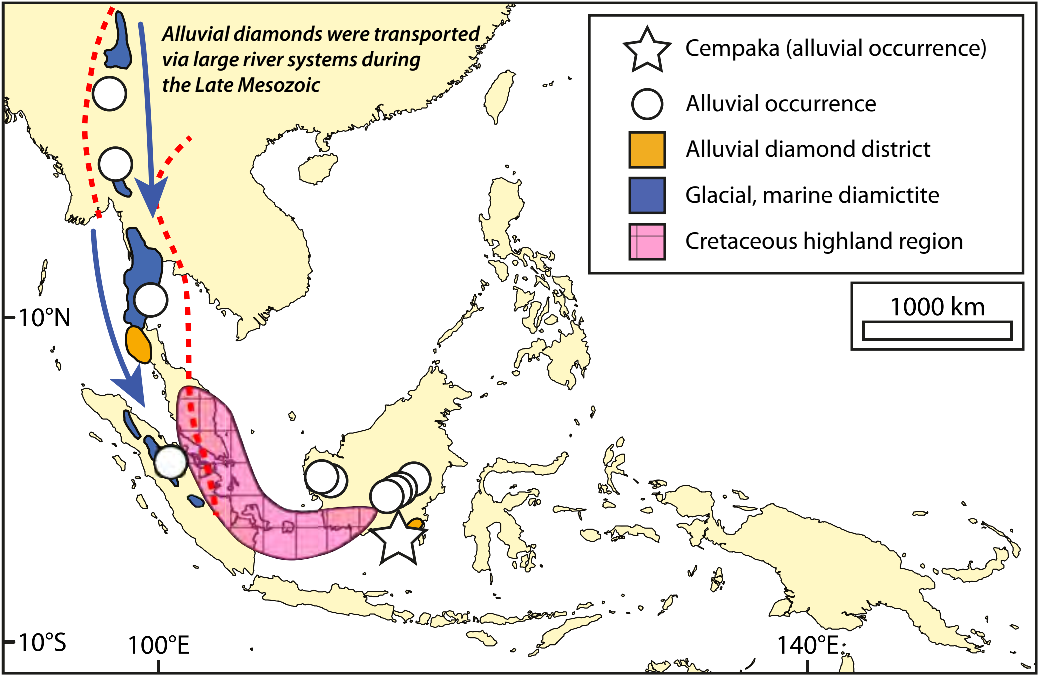

a.
b.
c.
d.

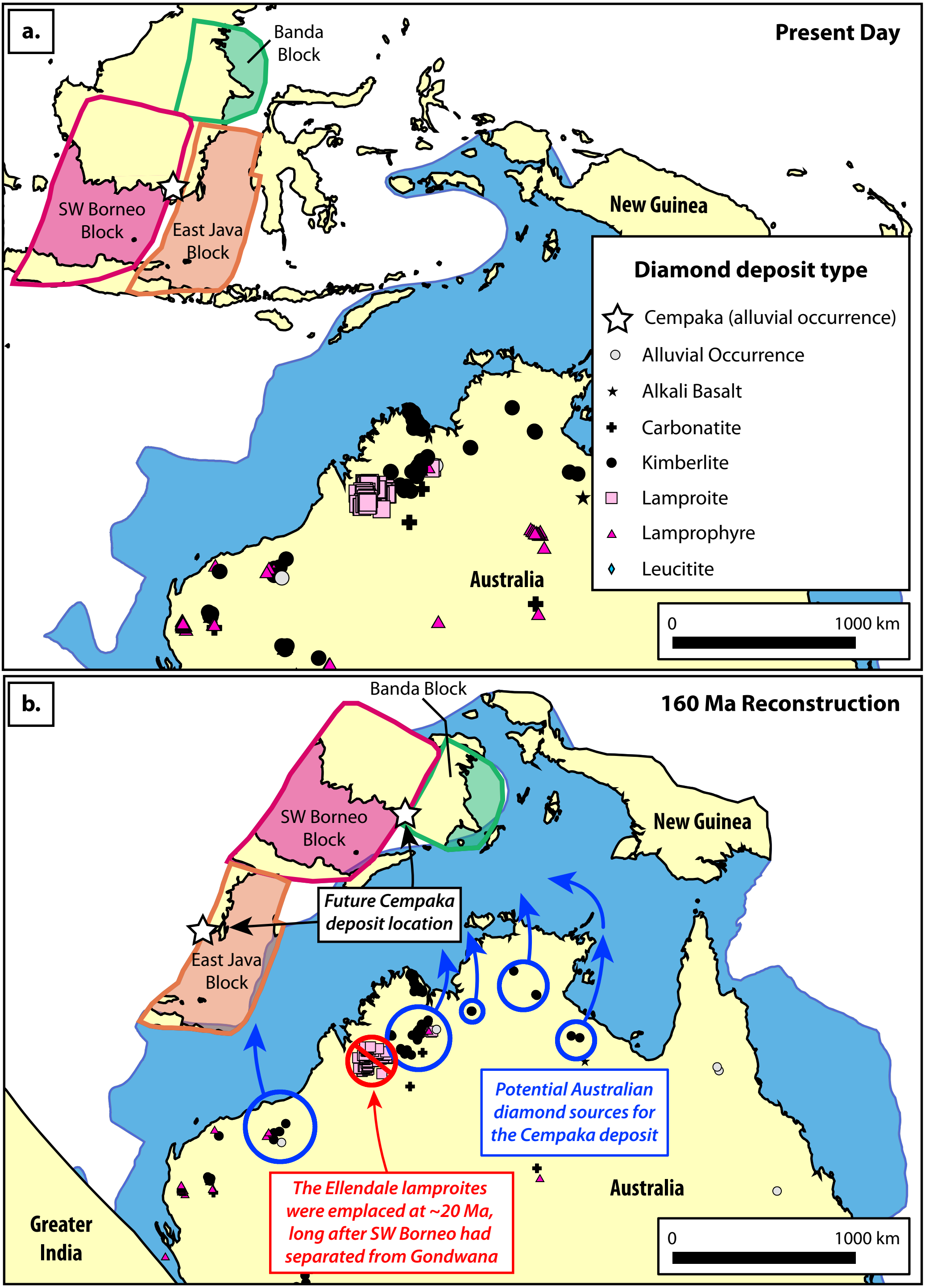

a.
b.
c.
d.




1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
Number of diamonds
100%
80%
60%
40%
20%
0%
Cumalative percentage
0.90
1.15
1.25
1.25
1.35
1.45
1.55
1.70
1.90
2.10
2.30
2.50
2.70
2.90
3.10
3.30
3.50
3.90
4.30
5.10
Grain size diameter (mm)
(as per upper sieve mesh size)


Lens of diamond-bearing anhydrous UHP rocks rapidly transported to the surface
Continental crust
LITHOSPHERIC MANTLE
Diamond bearing UHP rocks
GRAPHITE
DIAMOND


Alluvial diamonds were transported via large river systems during the Late Mesozoic
Cempaka (alluvial occurrence)
Alluvial occurrence
Alluvial diamond district
Glacial, marine diamictite
Cretaceous highland region
1000 km
10°N
10°S
100°E
140°E



a.
Present Day
Banda Block
SW Borneo Block
East Java Block
New Guinea
Australia
Diamond deposit type
Cempaka (alluvial occurrence)
Alluvial Occurrence
Alkali Basalt
Carbonatite
Kimberlite
Lamproite
Lamprophyre
Leucitite
0
1000 km
b.
160 Ma Reconstruction
Banda Block
SW Borneo Block
East Java Block
Future Cempaka deposit location
New Guinea
Potential Australian diamond sources for the Cempaka deposit
The Ellendale lamproites were emplaced at ~20 Ma, long after SW Borneo had separated from Gondwana
Australia
Greater India
0
1000 km