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Ediacaran to lower Cambrian basement in eastern George V Land (Antarctica): Evidence from U Pb dating of gneiss xenoliths and implications for the South Australia- East Antarctica connection

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Abstract :

This study presents the first geochronological results on basement rocks from the Penguin-Bage-Webb (PBW) domain located east of the Neoarchean-Paleoproterozoic Terre Adélie craton, Antarctica. Investigated samples are paragneiss xenoliths hosted within early Paleozoic granitoids, which were emplaced during the Ross orogeny. Zircon UPb dating yielded ages ranging from the Archean to the Cambrian, with a dominant Ediacaran (550–635 Ma) population and maximum depositional ages around 570–575 Ma. U–Th–Pb analyses of monazite suggest that the metamorphic event that formed the gneiss samples occured at ca. 515 Ma, shortly prior to incorporation within the granitic magmas. The studied samples likely represent relics of the pre-Gondawana Pacific margin, which was subsequently deformed and metamorphosed during the early Paleozoic Ross orogeny. The obtained zircon UPb date distributions present similarities with those of the Kanmantoo and Nargoon sediments in Southern Australia and provide new constrains for the correlations between East Antarctica and South Australia before the opening of the Southern Ocean.

Highlights

► Zircon and monazite U—Pb ages of the gneiss xenoliths from eastern George V Land ► Inherited ages ranging from Archean to Cambrian with main Ediacaran population ► Relics of a pre-Gondwana pacific margin metamorphesed during the Ross orogeny

Keywords : Gondwana margin, Ross orogeny, George V Land, Antarctica-Australia connection, Zircon and monazite UPb dating

1/ Introduction

The initial configuration of Gondwana and its fragmentation are still debated because of the lack of consensus on the nature of major structures and geological domains that composed the super-continent. In East Gondwana, the region of Terre Adélie and George V Land (East Antarctica) is considered to represent southern extension of South Australia (Borg and DePaolo, 1994; Di Vincenzo et al., 2014; Flöttmann et al., 1993; Oliver and Fanning, 1997; Payne et al., 2009; Peucat et al., 2002, 1999; Reading, 2004; Talarico and Kleinschmidt, 2003a), Figure 1. In particular, the continuity of the Terre Adélie Craton in Antarctica with the western Gawler Craton (Australia), both being parts of the Neoarchean-Paleoproterozoic Mawson Continent, is well documented from geological (Fanning et al., 1999, 2003; Fitzsimons, 2003) and geophysical studies (Aitken et al., 2014). However, the continuity of the domains located east of the Mawson Continent needs to be refined because lacks and inconsistencies exist. For example, outcrops from the eastern Gawler Craton (Australia) characterized by 1.85 and 2.0 Ga ages (Hand et al., 2007), as well as Ediacaran-early Cambrian formations such as Kanmantoo group (Ireland et al., 1998) do not display correlatives neither in eastern George V Land (Antarctica) nor in the Terre Adélie Craton. Furthermore, the lack of geochronological data from eastern George V Land, more specifically on the Penguin-Bage-Webb block (close to the Terre Adélie Craton), is a key issue to better understand the Precambrian connections between Australia and Antarctica and subsequently the evolution of both the Mawson Continent and the Gondwana.

The aim of this contribution is thus to constrain the age of the Penguin-Bage-Webb basement block located east of the Terre Adélie Craton and separated from it by the Mertz Shear Zone (Di Vincenzo et al., 2007; Ménot et al., 2007). Up to now, only the cross-cutting granitoids of Penguin Point have been dated by zircon U-Pb analyses at 505 Ma (Fanning et al., 2002) and 508-510 ± 5 Ma (Goodge and Fanning, 2010), and by biotite Ar^{39}/Ar^{40} analyses at 487.7 ± 3.5 Ma (Di Vincenzo et al., 2007). The existence of gneiss xenoliths within the early Paleozoic granites offers a unique opportunity to clarify the age and nature of the underlying basement which have, up to now, never been addressed. In this study, we report the results of zircon and monazite U-Pb analyses performed on three gneiss xenoliths. The obtained dataset allows to discuss: (i) the potential extension of the Terre Adélie Craton eastward and the role of the Mertz Shear Zone to the tectonic evolution of the area, and, (ii) the correlation between the Penguin-Bage-Webb block and its presumably corresponding Australian formations.

2/ Geological setting

2.1/ Terre Adélie and George V Land

The Terre Adélie and the western George V Land constitute the Terre Adélie Craton (135 to 145°E), which is part of the Neoarchean-Paleoproterozoic Mawson continent (Fanning et al., 2003). The Terre Adélie Craton is divided into two domains: the Neoarchean basement and the Paleoproterozoic metasedimentary basins (Ménot et al., 2007, see Figures 1, 2). The Neoarchean basement (in green and brown on Figure 2) extends from 141°E (the Zélée shear zone, ZSZ) to 146°E (the MSZ) and is predominantly composed of felsic to mafic orthogneiss and granodiorites intruding siliciclastic metasediments with subordinate marbles and calc-silicates. This 2.55-2.44 Ga continental crust segment (Duclaux et al., 2008; Oliver and Fanning, 2002) exposes two distinct tectonic units that equilibrated under granulite and amphibolite facies conditions respectively, and then represent deep and intermediate crustal sections, respectively (Ménot et al., 2005). A thermal and tectonic event occurred at 1.7-1.5 Ga, as proposed by Di Vincenzo et al. (2007) on the base of Ar/Ar dating. According to Duclaux et al. (2008), the 1.7 Ga event is likely to be restricted to narrow fluid-bearing anastomosed shear zones, concentrated on the edges of the Neoarchean domain (Mertz and Zélée shear zones). Synchronously to this event, the Paleoproterozoic metasedimentary basins were formed (purple in Figure 2). They include the Dumont d'Urville (DDU) and Cape Hunter (CH) basins. DDU basin extends west from 141°E (the Zélée shear zone) and consists of dominant metapelitic migmatitic gneisses together with minor metagraywackes, silicic metavolcanics and mafic intrusions. The DDU formations experienced high-grade amphibolite-facies metamorphic conditions (Pelletier et al., 2005). The CH basin appears as a tectonic unit within the Neoarchean basement and it mainly consists of phyllites equilibrated in greenschist-facies conditions (Ménot et al., 2005).

The exposed edge of the Terre Adélie Craton to the east is marked by the MSZ, which could correspond to the southern extension, on the Antarctica continent, of the Kalinjila or of the Coorong shear zones (Gawler Craton, south Australia) before the Cretaceous opening of the Southern Ocean (Gibson et al., 2013; Talarico and Kleinschmidt, 2003b). The MSZ is several km-wide, and bears a steeply-dipping pervasive mylonitic foliation and a subhorizontal to 20° north-plunging lineation with predominantly dextral motion indicators (Kleinschmidt and Talarico, 2000). This suggests that the MSZ might represent a mid-crustal strike-slip fault that could have accommodated large horizontal displacements. Microstructural and thermo-barometric studies show that the MSZ deformation likely resulted in successive shear structures occurring under different metamorphic conditions from medium pressure amphibolite to greenschists facies up to 1.5 Ga (Duclaux et al., 2008; Lamarque et al., 2016; Talarico and Kleinschmidt, 2003b). Talarico and Kleinschmidt (2003a) highlighted undated brittle structures crosscutting the mylonic foliation and Ménot et al. (2005) suggest that a younger age (post-Ordovician ?) cannot be formally ruled out because Paleozoic rocks are found to the East of the Mertz Glacier.

The domain east of the MSZ (145°E to 148°E, in yellow on Figures 1 and 2) corresponds to eastern George V Land and to the Penguin-Bage-Webb block. It is characterized by outcrops of granitoids with U-Pb dates of 505 Ma (Fanning et al., 2002) and 508-510 ± 5 Ma (Goodge and Fanning, 2010). Granites from Penguin Point display a large amount of gneiss and mafic microgranular xenoliths. They are massive with a mean grain size around 0.2-0.3 cm and they mainly contain quartz, feldspars and large flakes of biotite. Feldspars plagioclase is more abundant than K-feldspar. When compared to the descriptions of Ravich et al. (1968) given for the granites from the Ainsworth Bay (now Desolation Bay), the Penguin Point granites seem to be close to those of Cape Bage (located about 15 km away to East, see Figure 1) and rather distinct to those of Cape Webb (more to the East, Figure 1).

The studied samples occur as spherical to elongated xenoliths of few tens of cm hosted within the Penguin Point granite (see xenoliths description in paragraph 3)

2.2/ South Australia

A large part of South Australia corresponds to the Gawler Craton, which is also part of the Mawson continent (Fanning et al., 2003). The Gawler Craton mainly consists of Archean to Paleoproterozoic basement that is overlain and intruded by Paleoproterozoic to Mesoproterozoic sedimentary, volcanic and intrusive rocks (Reid at al., 2014 and Figure 1). The Archean basement is comprised of two temporally and spatially distinct pieces of crust that have unrelated formation and/or metamorphic histories. Mesoarchean (*ca.* 3250-3150 Ma) gneisses compose the oldest rocks, which are outcropping in the southeastern Gawler Craton (Reid et al., 2014, pink in Figure 1). Neoarchean to earliest Paleoproterozoic domains include both the Sleaford Complex in the southern Gawler Craton (green in Figure 1) and the Mulgathing Complex in the north central part of the craton that are composed of felsic, mafic and ultramafic volcanics as well as metasedimentary lithologies representing portions of a single Late Archean belt, deformed and metamorphosed during the Sleafordian Orogeny between 2450 and 2420 Ma (Daly and Fanning, 1993; Swain et al., 2005). The Miltalie gneiss intruded the Sleaford Complex during its uplift and erosion around 2000 Ma (Fanning et al., 2007, 1988). Thereafter, the Hutchison Group (> 1850 Ma) overlained the eastern margin of the Gawler Craton (Daly and Fanning, 1993). This group includes a basal quartz-pebble conglomerate and quartzite which change to calcareous and aluminous metasediments at the top (Parker and Lemon, 1982). The Hutchinson Group is limited to the east by a major tectonic structure, the Kalinjala shear zone (KSZ), formed during the ca. 1730–1690 Ma Kimban Orogeny. The Kimban Orogeny completed the volcano-sedimentary basin development during the Paleoproterozoic and extensively reworked the Archean and Paleoproterozoic domains through the activation of transpressional shear zones, such as the

KSZ (Hand et al., 2007; Reid and Hand, 2012; Vassallo and Wilson, 2002). This later corresponds to a 4 - 6 km wide corridor showing subvertical mylonitic structures, associated magmatism as for example Middle Camp Granite and high-grade metamorphic assemblages (Parker, 1980; Vassallo and Wilson, 2002). However magmatic effect of the Kimban orogeny and relationships with large scale tectonic structures were mainly described across the central and northern Gawler craton (Hand et al., 2007). Thermal and mechanical effects of the high-strain zone activity could be observed in an area up to 100 km from the heart of the shear zone (see Figure 5 of Hand et al., 2007). The KSZ likely represents a palaeosuture zone, separating two crustal (or possible lithospheric-scale) blocks with compositional differences (Howard et al., 2006). East of the Kalinjala shear zone, outcrops reveal the presence of a small area of felsic orthogneiss basement dated at 3150 Ma and deformed around 2530-2510 Ma (Fraser et al., 2010). This basement did not suffer any Sleafordian deformation. The Paleoproterozoic igneous Donington Suite (1850 Ma) intrudes sedimentary rocks with distinct isotopic signature from those located west of the Kalinjala shear zone (Howard et al., 2009). The Myola volcanics occurred between 1765 and 1735 Ma (Daly et al., 1998) and overly the Donington Suite. Following the Kimban Orogeny, magmatism took place during the time period 1690-1575 Ma. Markers of this magmatic activity include (i) the post-orogenic intrusive Tunkillia Suite (1690-1670 Ma), which origin is still debated (Payne et al., 2010), (ii) the voluminous St Peter Suite (1620-1610 Ma), which shows subduction origin (Hand et al., 2007; Swain et al., 2008) (iii) the Gawler Range Volcanics (1600-1585 Ma) which constitutes a silicic-dominated large igneous province (Agangi et al., 2011) and, (iv) the Hiltaba Suite (1590-1575 Ma) that developed into upper-crustal syn-tectonic plutons occuring in a wide zone of crustal shearing (McLean and Betts, 2003).

The Neoproterozoic to Paleozoic formations of South Australia are represented by the Adelaide Geosyncline (Figure 1), which was fully described by Counts (2017). As a general overview, this rift complex is composed by successive (super)groups defined as (i) the Warrina supergroup which include both the Callanna group (minimum age around 802 ± 10 Ma) mainly composed of siltstone, sandstone, carbonates, evaporites and basalt; and the Burra group (~ 777 – 700 Ma) mainly consisting of siltstone, shale, sandstone and dolomite (Forbes et al., 1981; Krieg et al., 1991), (ii) the Heysen supergroup which include both the Umberatana group (~ 700-620 Ma) made up of tillite, sandstone, siltstone, arkose, dolomite, quartzite, conglomerate, shale and greywacke; and the Wilpena group (~ 588-566 Ma) mainly composed of siltstone with laminated quartzite, dolomite, marble and sandy marble (Knoll et al., 2006), and, (iii) the Moralana supergroup which include, among others, the Normanville (~ 526-515 Ma) made of limestone; sandstone; shale and volcanics; the Kanmantoo (~ 522-514 Ma) including marine metasandstone, phyllite, schist, gneiss, minor calcsilicate and marble; and the Lake Frome groups (~ 523 – 498 Ma) composed of sandstone, siltstone, shale, limestone and conglomerate (Zang et al., 2004). Study of detrital-zircon ages in the Adelaide fold belt (Ireland et al., 1998) shows an abrupt change in zircon population at the base of the Cambrian Kanmantoo Group. It is dominated by Ross-Delamerian (600–500 Ma) and Grenvillean ages (1200–1000 Ma) whereas zircons from Neoproterozoic sedimentary rocks (Normanville and older groups) mainly derived from the Australian cratons with ages progressively changing from Mesoproterozoic to Neoproterozoic and only few zircon that are close to the depositional age. Further east, the Murray Basin overlies these formations. The outcropping Glenelg River Complex (Figure 1) as well as the Nargoon Group sampled from stratigraphic drill-hole, both within the Murray Basin, were described as correlative formations of Kanmantoo Group (Haines et al., 2009; Lewis et al., 2016, respectively). From geophysical data, Gibson et al. (2013) defined the previously unmapped Coorong Shear zone (see Figure 1). The authors proposed that the Coorong shear zone represent the correlative structure of the Mertz shear zone located in Antarctica, as they are both aligned with the

George V Land Facture Zone located in the Southern Ocean, thus challenging the generally accepted Kalinjala-Mertz correlation (Di Vincenzo et al., 2007; Kleinschmidt and Talarico, 2000; Talarico and Kleinschmidt, 2003a).

3/ Sample description

We studied three gneiss samples hosted within the early Paleozoic granites of Penguin Point (146°E), which constitutes the westernmost outcrop of granites from Penguin-Bage-Webb area. The gneiss samples display sharp boundaries with the host granites (Figure 3) and distinct petrographic features. Sample 12GL04 is a banded leucocratic gneiss with alternating centimetric thick (up to 5 cm) quartz-feldspar layers and thin (up to 2 mm) biotite beds. It could correspond to the "fine-grained feldspathic quartzite" described by Ravich et al. (1968). Sample 12GL01 is a homogeneous biotite -rich gneiss. Samples 12GL01 and 12GL04 display rather comparable textures and mineralogy. They mainly differ by the grain size of minerals (quartz, feldspars, biotite) being larger in 12GL01 than in 12GL04. They are granoblastic to grano-lepidoblastic with equigranular (0.2 to 0.3 mm-large in 12GL04 and 1.1 to 1.2 mm in 12GL01) undeformed quartz and feldspar mosaic suggesting a late static recrystallization which would be more developed in 12GL01 compared to 12GL04. Andesine plagioclase is more widely present than K-feldspar. Biotite flakes (0.2 to 1.2 mm-long) clearly mark the foliation; they enclose a lot of inclusions such as zircon and Fe-oxides (mainly ilmenite). Muscovite was occasionally observed.

Sample 12GL02 corresponds to a migmatitic gneiss with quartz-feldspar leucosomes occuring as lenses and small dykelets intruding the melanocratic layers, and presenting a granular texture. The melanocratic layers consist of poikiloblastic garnet crystals (up to several mm in size) that contain alignments of biotite and Fe-oxides, which consist of ilmenite grains generally elongated (up to 0.8mm-long and 0.4 mm-wide). Thus, biotite and ilmenite mark a former foliation.

In all three samples, the zircon grains are mainly included within biotite crystals, but few occur as intergranular isolated grains within the matrix. The high modal proportion of biotite and the presence of garnet are consistent with a sedimentary origin for the protoliths, which likely corresponded to greywackes.

4/ U-Pb zircon data

4.1/ Analytical techniques and data processing

Rock samples were crushed using standard procedure (jaw, crusher, disc mill) and sieved to <500 µm. Zircon and monazite grains were separated using heavy liquids, an isodynamic Frantz separator, and then handpicked under a binocular microscope to obtain a representative selection of all components present in the zircon population. Selected zircon grains were mounted in epoxy resin and polished to an equatorial grain section. Analytical work was carried out in the Laboratoire Magmas et Volcans (Clermont-Ferrand, France). Minerals were imaged by cathodoluminescence (CL) using a JEOL JSM-5910 SEM to document their internal structure, resorption surfaces, and overgrowths (Hanchar and Miller, 1993; Vavra, 1990). The analyses involved the ablation of minerals with a Resonetics M-50 Excimer laser system operating at a wavelength of 193 nm. Spot diameters of 26µm (zircon) and 9 µm (monazite) were associated to repetition rates of 3 Hz (zircon) and 1 Hz (monazite) and fluency of 4.5 J/cm^2 (zircon) and 8 J/cm^2 (monazite). The ablated material was carried into helium and then mixed with nitrogen and argon before injection into the plasma source of an Agilent 7500cs ICP-MS (Paquette et al., 2014). The analytical method for isotope dating with laser ablation ICPMS is reported in (Hurai et al., 2010; Paquette et al., 2017). Data are corrected for U-Pb fractionation occurring during laser sampling and for instrumental mass bias by standard bracketing with repeated measurements of GJ-1 zircon standard (Jackson et al., 2004) and C83-32 monazite standard (Corfu, 1988). The occurrence of common Pb in the sample was monitored by the evolution of the ^{204}(Pb+Hg) signal intensity, but no common Pb correction was applied owing to the large isobaric interference from Hg. Repeated analyses of 91500 zircon (Wiedenbeck et al., 1995) and Trebilcock monazite (Kohn and Vervoort, 2008) standards treated as unknowns yielded concordia ages of 1067 ± 3 Ma ($MSWD_{(C+E)}$=0.45; n=69) and 271 ± 2 Ma ($MSWD_{(C+E)}$=1.2; n=20), independently control the reproducibility and accuracy of the corrections. Data reduction was carried out with the software package GLITTER® from Macquarie Research Ltd (Van Achterbergh et al., 2001). Calculated ratios were exported and Concordia ages and diagrams were generated using Isoplot/Ex v. 3.7 Excel macro package by Ludwig (2008). The concentrations in U-Th-Pb were calibrated relative to the certified contents of GJ-1 zircon (Jackson et al., 2004) and Moacyr monazite (Gasquet et al., 2010) standards, respectively.

Results of U-Pb analyses for all samples are summarized in Table 1 (supplementary data).

4.2/ Results

Most zircon grains analyzed in the course of this study are light yellow, but a population of bigger dark brown grains was found in sample 12GL02, some of which being metamict. Cathodoluminescence images of representative grains are presented in Figure 4. They are characterized by elliptical to rounded shapes (aspect ratio ranging from 0.3 to 1 with mean value of about 0.6). Core-rim relationships are common and most core and rim domains feature oscillatory to patchy zoning. Narrow CL-bright rims (<10 µm large) are also observed. Secondary textures include healed cracks and fractures. In some cases, only part of the zircon grain is preserved and do not show any core-rim structure. The variety of internal growth structures and the wide range of Th/U ratios between 0.01 and 5.78 support derivation from various igneous and/or metamorphic protoliths, consistent with a metasedimentary origin of the gneiss samples.

Results of zircon U-Pb dating are presented in Wetherill diagrams for each sample in Figure 5a,b and 6a. Zircon date distributions are reported as Kernel Density Estimates (Fig. 5e,f) following Vermeesch(2012). The comprehensive analytical dataset for all grains is provided in Table S1 (supplementary data). In the following, quoted dates are $^{206}Pb/^{238}U$ dates when younger than 1.2 Ga. Otherwise, the $^{207}Pb/^{206}Pb$ dates are preferred.

Sample 12GL02

A total of 76 U-Pb analyses were performed on 62 zircon grains. Sixty-two analyses are concordant at 90 – 110 % (with concordance defined as $^{206}Pb/^{238}U$ date / $^{207}Pb/^{206}Pb$ date x 100). Following Vermeesch (2004), it entails that we can be confident at 95% that no fraction representing more than 8% of the sample has been missed. 12GL02 is typified by (i) a dominant Ediacaran (549-628 Ma) zircon population (N=27; Fig. 5a,c); (ii) a subordinate population (N=4) with Cryogenian-late Tonian dates (693-784 Ma); (iii) grains yielding dates scattered between the early Tonian and the Stenian (0.9 to 1.2 Ga; N=10); (iv) an important Archean population (N=21), clustering at c. 2.7 and 3.1 Ga (Fig. 5c). Besides, four discordant analyses show $^{207}Pb/^{206}Pb$ dates in excess of 2.6 Ga. Importantly, zircon grains showing Ediacaran and Archean dates display a very large range of Th/U ratios (from 0.01 to 2.39, Tab. S1) and textural patterns. In contrast, the early Tonian-Stenian population mostly consists of grains with oscillatory zoning textures and elevated Th/U ratios (mostly between 0.3 and 0.8, Tab. S1). The 16 youngest Ediacaran grains showing overlapping $^{206}Pb/^{238}U$ dates at 2σ allowed calculation of a weighted average date of 569.4 ± 5.0 Ma (Fig. 5e). Finally, one single CL-dark, low Th/U (0.03) and U-rich (2600 ppm) zircon crystal yielded a Cambrian $^{206}Pb/^{238}U$ date of 514 ± 18 Ma.

Sample 12GL04

Thirty-four measurements were performed on 27 zircon grains and 23 yielded U-Pb dates concordant at 90–110%, meaning that no fraction representing more than 18% of the sample has been missed (at 95% confidence). Sample 12GL04 also features a dominant Ediacaran population (569–622 Ma, N=9, Fig. 5b,d) with again a large variety of internal growth structures and a wide range of Th/U ratios between 0.11 and 5.78 (Tab. S1). Two grains yielded Tonian dates of 848 ± 29 and 910 ± 31 Ma. One grain show a date of 1200 ± 40 Ma, i.e. at the Stenian-Ectasian boundary. Notably, 12GL04 differs from 12GL02 by the presence of a Paleoproterozoic zircon population defining sub peaks at c. 1.9 and 2.4 Ga (N=5). Grains of that age feature oscillatory zoning patterns and a narrow range of Th/U ratios (0.33 to 0.52, Tab. S1). One grain has the oldest concordant $^{207}Pb/^{206}Pb$ date retrieved in the course of this study (at 3.4 Ga). Finally, a weighted average date of 575.2 ± 8.3 Ma can be calculated considering the 6 youngest Ediacaran grains showing overlapping $^{206}Pb/^{238}U$ dates at 2σ (Fig. 5f).

Sample 12GL01

Only 15 zircon grains were extracted from this sample and 16 U-Pb analyses were performed out of which 9 are concordant at 90–110%. Two grains show Ediacaran dates of 575 ± 21 and 633 ± 22 Ma. Three grains yielded Stenian-late Ectasian dates (at 1.1–1.2 Ga) and four grains Archean dates spanning between 2.6 and 3.3 Ga. In addition, 7 monazite grains were also retrieved from this sample. Seven out of 8 analyses are equivalent (Fig. 6b) and allow calculation of a robust Concordia date at 514.6 ± 5.2 Ma ($MSWD_{(C+E)}$ = 1.07).

notably, when all three samples are considered together, zircon date distributions evidence a tendency toward younger ages for the rims (blue) and older ages for the cores (red), both populations recording similar age patterns (Fig. 7).

5/ Discussion

5.1. Interpretation of the U-Pb results

As the investigated xenoliths are interpreted to be metasediments, the new U-Pb dataset can place constraints on the maximal depositional ages of the sedimentary protoliths. Those were calculated based on the robust YC2σ(3+) estimator of Dickinson and Gehrels (2009), i.e. the weighted mean age of the youngest zircon population of at least three grains showing overlapping $^{206}Pb/^{238}U$ dates at 2σ. This approach is particularly suited in the absence of distinctive correlations between zircon date and U content or Th/U ratios, as observed among the Ediacaran populations of samples 12GL02 and 12GL04. Calculated maximal depositional ages are 569.4 ± 5.0 Ma and 575.2 ± 8.3 Ma, respectively (Fig. 5c,d). No depositional age was obtained for 12GL01 as only 2 Ediacaran dates were retrieved and do not overlap (Fig. 6a). As the enclosing granites are ca. 505 Ma-old, the protoliths of the paragneiss xenoliths are unambiguously of Ediacaran – Lower Cambrian age.

The monazite date of 514.6 ± 5.2 Ma most probably constrains the timing of metamorphism experienced by the xenoliths, before incorporation in the granitic magmas. This age is identical to the Cambrian $^{206}Pb/^{238}U$ date of 514 ± 18 Ma measured on a zircon grain from sample 12GL02, suggesting that this grain possibly (re)crystallized or got its U-Pb system reset during high-grade metamorphism, in agreement with its low Th/U ratio of 0.03 (Rubatto et al., 2001). Metamorphism and plutonic activity at 515-500 Ma can be related to the Ross orogeny (Boger, 2011) which affected several segments of Antarctica and Australia. In that sense, the paragneiss xenoliths of eastern George V Land most probably represent relics of the paleo-Pacific margin of eastern Gondwana that was deformed and metamorphosed during the Ross orogeny.

5.2/ Relationships between the PBW block and the Terre Adélie-Gawler Cratons

U/Pb ages in the Terre Adélie Craton Paleoproterozoic domain have been published by Peucat et al. (1999). They show (i) that the Dumont d'Urville basin contains two populations of inherited zircon grains bearing SHRIMP ages of about 1.73-1.76, 2.6 and 2.8 Ga and (ii) that a major partial melting event, marked by newly formed zircon and monazite grains, occurred at around 1.69 Ga. In the Neoarchean domain of the Terre Adélie Craton, U-Pb ages were obtained by Oliver et al. (1983); Oliver and Fanning (2002); Ménot (in press). They range between 2.4 and 2.5 Ga and indicate a major period of magmatism and of high grade metamorphism.

Importantly, there is a clear mismatch between the ages recorded in the Terre Adélie craton and the zircon U-Pb date distribution of paragneisses from the PBW block (Figure 8). In the latter, grains with dates between 1.6 and 1.8 Ga are lacking and only 4 grain domains show dates in the range 2.4 – 2.6 Ga. A similar conclusion can be drawn when the Gawler craton is considered (Fig. 8). These results clearly indicate that the source of older-than-1 Ga zircon grains in the Ediacaran – Lower Cambrian detritus does not originate from the Terre Adélie/Gawler craton. In terms of geodynamic reconstruction, it implies that either (i) an old basement similar to the Terre Adélie/Gawler Cratons is present beneath the PBW block but was not exposed at the time of sediment deposition (Ediacaran to Lower Cambrian) so that it was not reworked as detritus feeding the Ediacaran-Lower Cambrian basins, or (ii) the lack of Terre Adélie/Gawler Cratons signature reflects the presence of a different basement in the PBW block. We favor the second hypothesis because seismic investigations (Lamarque et al., 2015), aeromagnetic exploration (Aitken et al., 2014; Ferraccioli et al., 2009; Finn et al., 2006) and gravity data (Jordan et al., 2013) support that the MSZ is a major continental scale tectonic structure that clearly separates two distinct lithospheric domains of probably contrasted ancestries.

5.3. Correlations with South Australia

In order to better constrain the relationships between Antarctica and South Australia before the opening of the Southern Ocean, we attempt to identify the correlative formation(s) of our samples in South Australia. We thus compare in Figure 9 the detrital zircon U-Pb age distribution of Penguin Point paragneisses to those of the Kanmantoo, Normanville, Adelaidian and Nargoon (meta)sedimentary formations, all deposited in the Ediacaran to Lower Cambrian. From a graphical observation (Fig. 9), the zircon U-Pb date distribution of eastern George V Land paragneisses clearly resembles that of the Kanmantoo and Nargoon group sediments. Indeed, they are all characterized by a dominant Ediacaran (≈ 550-630 Ma) zircon population which is notably lacking in the of Normanville and Adelaidian formations (Fig. 9). The latter instead encompass a prominent Mesoproterozoic zircon population not observed in our samples. The match between PBW paragneisses and Kanmantoo/Nargoon sediments is not perfect as: (i) Tonian-Stenian zircon grains are rather scarce in PBW but common to abundant in the Kanmantoo/Nargoon sediments; (ii) the peak at ca. 2.7 Ga typical of the PBW paragneisses is lacking in the Kanmantoo/Nargoon sediments. Because they are of same age (Ediacaran to Lower Cambrian), present a similar zircon date distribution and are (at least for PBW and Kanmantoo) intruded by Paleozoic granitoids formed during the Ross-Delamerian orogeny (see Figure 1, Di Vincenzo et al., 2007; Foden et al., 2002), we regard the PBW paragneisses as being lateral equivalents to the Kanmantoo/Nargoon sedimentary formations. The above-mentioned discrepancies between their U-Pb date distributions likely reflect lateral variations in the nature of the detritus.

6/ Conclusion

Zircon and monazite U-Pb dating of paragneisses from the eastern George V Land region reinforces the geological correlations between South Australia and the Terre Adélie-George V Land regions and support the previous geodynamical reconstructions, which were synthetized by Boger (2011). In particular, we have shown that:

(i) Zircon and monazite ages suggest that the studied gneisses are relics of the pre-Gondwana margin, which had been deformed and metamorphosed during the early Paleozoic Ross orogeny.

(ii) Zircon date distributions of the studied samples present strong similarities with the Ediacaran to Lower Cambrian Kanmantoo and Nargoon groups of South Australia, arguing for a correlation between these formations. This has implications for correlations between the east Mertz Shear Zone area in East Antarctica and the eastern terrains of the Gawler Craton in South Australia before the opening of the Southern Ocean.

(iii) There is a clear mismatch between the date distribution of older-than-Mesoproterozoic zircon grains recovered from the paragneisses and the geological record of the adjacent Terre Adélie (and Gawler) cratons. This observation brings into question the actual source of the Paleoproterozoic to Archean detritus that fed the Ediacaran to Lower Cambrian basins of the PBW domain.

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Figure captions

Figure 1: A/ General map of Antarctica and Australia. B/ Simplified geological map of the Gawler Craton and juxtaposed terrains (modified from Foden et al., 2002; Haines et al., 2009; Howard et al., 2006; Milnes et al., 1977; Reid et al., 2014). C/ Synthetic geological map of study area, modified from Ménot et al. (2005). The green area represents the Terre Adélie Craton, whereas the yellow area is related to the Ross orogeny. The red circle represents the studied outcrop (Penguin Point). Note that the geological maps of south Australia and Terre Adélie-George V Land (B and C) are juxtaposed for graphical purpose but this is not representative of any paleo-reconstruction.

Figure 2: **A:** Location of Terre Adélie and George V Land in the Antarctic continent. **B:** Link between south Australia and Antarctica. TAC = Terre Adélie Craton, GC = Gawler Craton, MSZ = Mertz shear zone, KSZ = Kalinjala shear zone, CSZ = Coorong shear zone. **C:** Synthetic geological map of the Terre Adélie Craton (after Ménot et al., 2007). Purple areas are Paleoproterozoic terrains, which correspond to the Dumont d'Urville and Cape Hunter basins; green and brown areas are Neoarchean terrains, green being intermediate to upper amphibolitic crust and brown granulite facies crust. Orange area represents the Paleozoic crust, mainly composed of granitoids. Darkest colours correspond to outcrops. MSZ denotes the Mertz shear zone and ZSZ denotes the Zélée shear zone. Directions of field-measured structures are drawn in black. Locations of studied samples are marked by red stars. See also Ménot et al. (2007) and Ménot (to be published) for more complete geological description.

Figure 3: A, B/ Photographs of xenoliths in the field, and their relations with the host granite. C/ Thin-section photograph of sample 12GL01. D, E/ Thin-section photograph of sample 12GL02. F/ Thin-section photograph of sample 12GL04.

Figure 4: Cathodoluminescence images of selected zircon grains from paragneiss xenoliths12GL01, 12GL02 and 12-GL04. The circles represent the locations of laser spots

and the obtained dates (in Ma) together with their uncertainties (at 2σ). $^{206}Pb/^{238}U$ dates are reported when younger than 1.2 Ga. For older dates, the $^{207}Pb/^{206}Pb$ dates are preferred. This applies to all figures in the contribution.

Figure 5: Zircon U-Pb results for the East George V Land paragneiss xenoliths 12GL02 and 04. (a,b) Wetherill diagrams. Error ellipses are quoted at 2σ level of uncertainty. (c,d) Average ages calculated for the youngest concordant zircon population following the YC2σ(3+) estimator of Dickinson and Gehrels (2009). (e,f) Zircon U-Pb date distribution represented as Kernel Density Estimates. Only analyses discordant at less than 10% are displayed. All Kernel Density Estimates were plotted with the Density Plotter program of Vermeesch (2013).

Figure 6: Zircon and monazite U-Th-Pb results for the George V Land paragneiss xenolith 12GL01. (a) Wetherill diagram showing zircon U-Pb data. Error ellipses are quoted at 2σ level of uncertainty. (b) $^{206}Pb/^{238}U$ versus $^{208}Pb/^{232}Th$ diagram for the analyzed monazite grains. Error ellipses are quoted at 2σ level of uncertainty.

Figure 7: U–Pb date distribution of zircon grain cores and rims from all samples, represented as Kernel Density Estimates. Only analyses discordant at less than 10% are displayed.

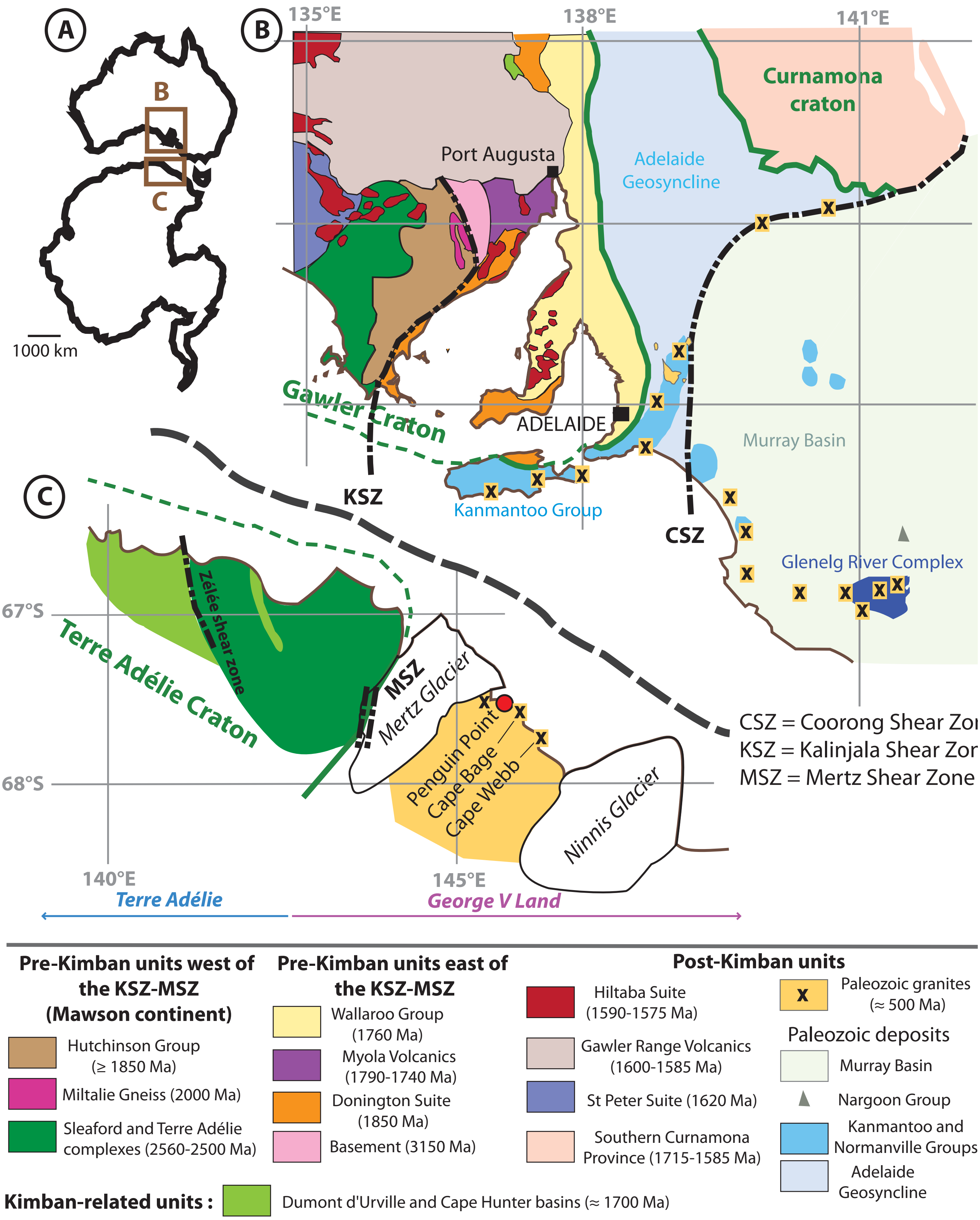
Figure 8: Zircon U-Pb date distributions of the George V Land paragneiss xenoliths compared to the main periods of geological activity (magmatism/metamorphism) in the Terre Adélie craton (see text for references and discussion). Is also depicted an histogram summarizing available intrusion ages for the Gawler craton (meta)igneous rocks. For paragneisses zircon data, only analyses discordant at less than 10% are displayed. Data for the Gawler craton are from the Geochron database of the Australian Geological Survey.

Figure 9: Detrital zircon U-Pb date distributions of the George V Land paragneiss xenoliths compared to those of several Ediacaran to Lower Cambrian (meta)sediments from the Delamerian segment of Australia, all represented as Kernel Density Estimates. Only analyses

discordant at less than 10% are displayed. Data sources: Ireland et al. (1998) for Kanmantoo, Normanville and Adelaidian sediments; Geochron database from the Australian Geological Survey for the Nargoon group sediments (East Victoria).

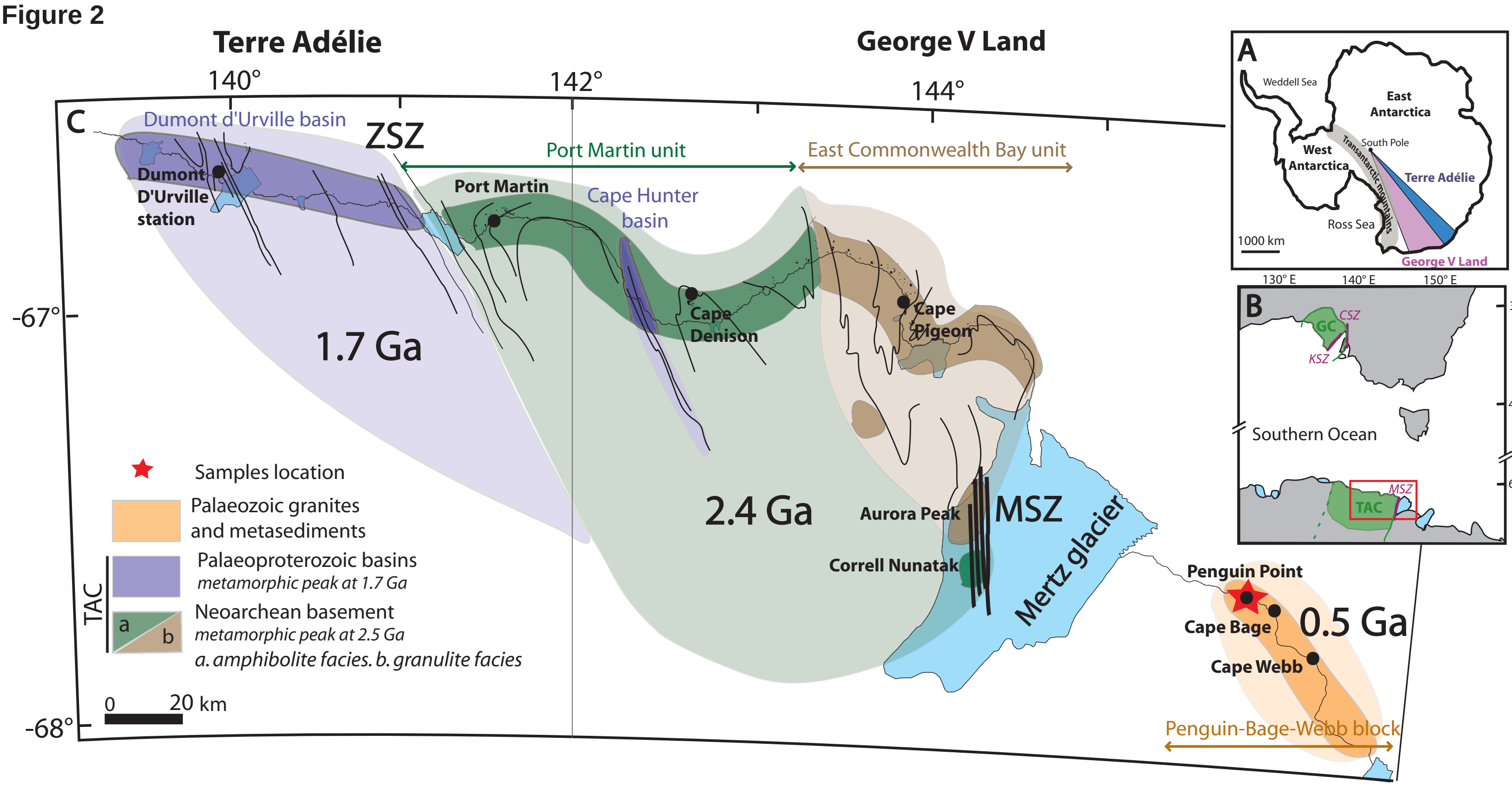
Supplementary material

Table 1: Results of zircon and monazite U-Pb dating performed on gneiss xenoliths from Eastern George V Land.



A
B
C
1000 km
135°E
138°E
141°E
Curnamona craton
Port Augusta
Adelaide Geosyncline
Gawler Craton
ADELAIDE
Murray Basin
KSZ
Kanmantoo Group
CSZ
Glenelg River Complex
67°S
68°S
Zélée shear zone
Terre Adélie Craton
MSZ
Mertz Glacier
Penguin Point
Cape Bage
Cape Webb
Ninnis Glacier
CSZ = Coorong Shear Zo
KSZ = Kalinjala Shear Zor
MSZ = Mertz Shear Zone
140°E
145°E
Terre Adélie
George V Land
Pre-Kimban units west of the KSZ-MSZ (Mawson continent)
Hutchinson Group (≥ 1850 Ma)
Miltalie Gneiss (2000 Ma)
Sleaford and Terre Adélie complexes (2560-2500 Ma)
Pre-Kimban units east of the KSZ-MSZ
Wallaroo Group (1760 Ma)
Myola Volcanics (1790-1740 Ma)
Donington Suite (1850 Ma)
Basement (3150 Ma)
Post-Kimban units
Hiltaba Suite (1590-1575 Ma)
Gawler Range Volcanics (1600-1585 Ma)
St Peter Suite (1620 Ma)
Southern Curnamona Province (1715-1585 Ma)
Paleozoic granites (≈ 500 Ma)
Paleozoic deposits
Murray Basin
Nargoon Group
Kanmantoo and Normanville Groups
Adelaide Geosyncline
Kimban-related units :
Dumont d'Urville and Cape Hunter basins (≈ 1700 Ma)

Figure 2



Terre Adélie
George V Land
140°
142°
144°
-67°
-68°
C
Dumont d'Urville basin
ZSZ
Port Martin unit
East Commonwealth Bay unit
Dumont D'Urville station
Port Martin
Cape Hunter basin
Cape Denison
Cape Pigeon
1.7 Ga
2.4 Ga
Aurora Peak
Correll Nunatak
MSZ
Mertz glacier
Penguin Point
Cape Bage
Cape Webb
0.5 Ga
Penguin-Bage-Webb block
Samples location
Palaeozoic granites and metasediments
TAC
Palaeoproterozoic basins
metamorphic peak at 1.7 Ga
Neoarchean basement
metamorphic peak at 2.5 Ga
a. amphibolite facies. b. granulite facies
0 20 km
A
Weddell Sea
East Antarctica
West Antarctica
South Pole
Transantarctic mountains
Terre Adélie
Ross Sea
George V Land
1000 km
130° E
140° E
150° E
B
GC
CSZ
KSZ
30° S
40° S
66° S
Southern Ocean
TAC
MSZ

Figure 3
Click here to download high resolution image

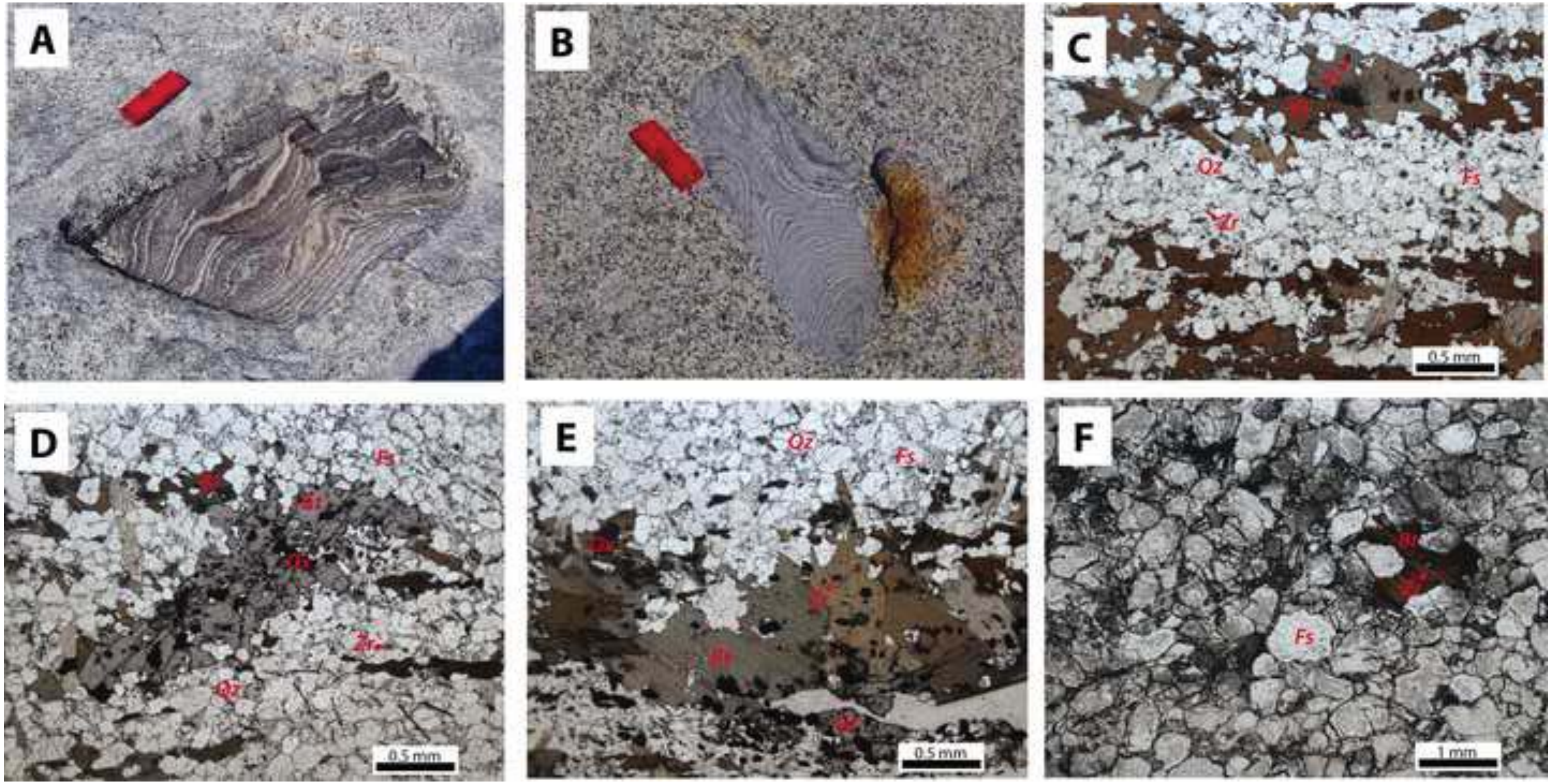


Figure 4

Click here to download high resolution image

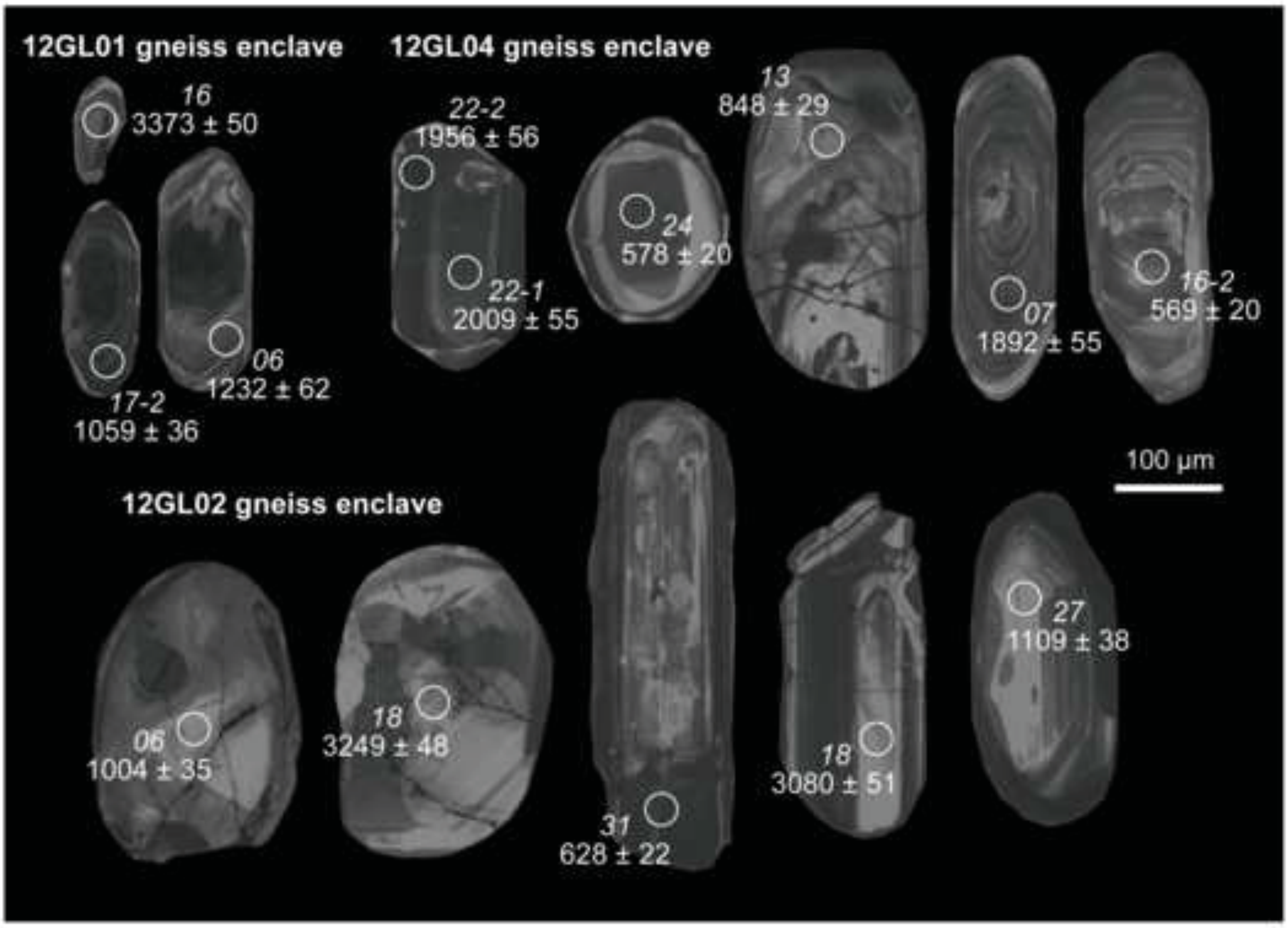
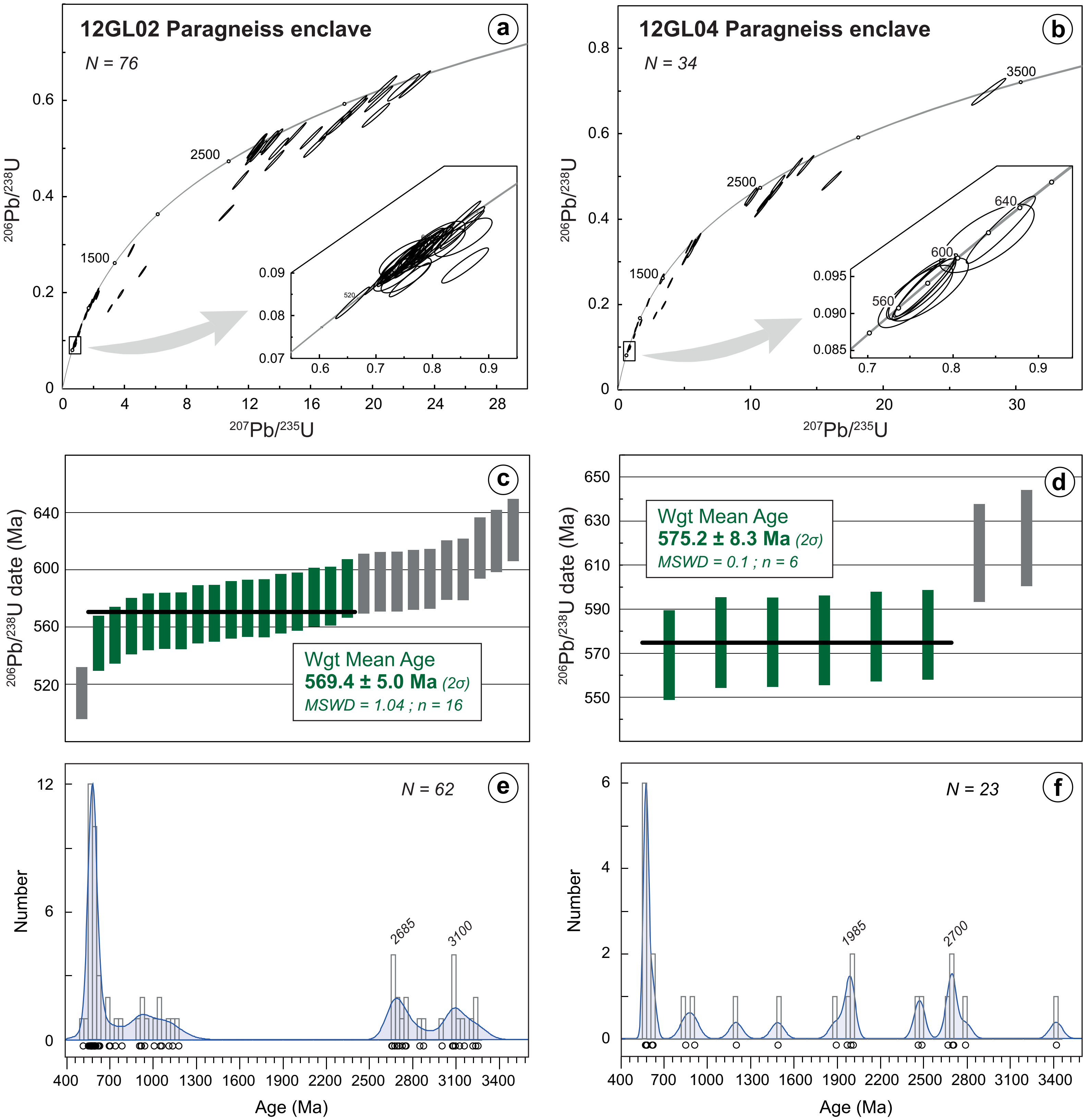
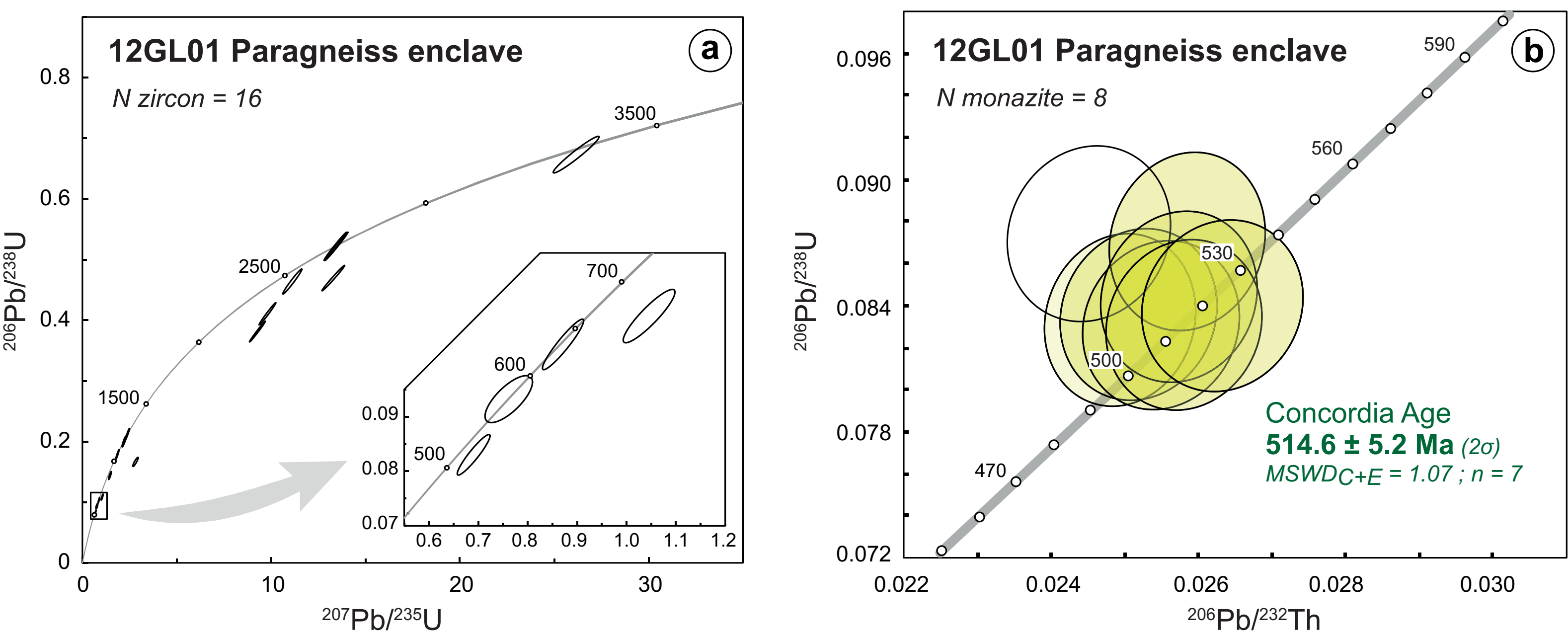


Figure 5



12GL02 Paragneiss enclave
a
N = 76
2500
1500
0.09
0.08
0.07
0.6
0.7
0.8
0.9
206Pb/238U
207Pb/235U
12GL04 Paragneiss enclave
b
N = 34
3500
2500
1500
640
600
560
0.095
0.090
0.085
c
Wgt Mean Age
569.4 ± 5.0 Ma (2σ)
MSWD = 1.04 ; n = 16
206Pb/238U date (Ma)
d
Wgt Mean Age
575.2 ± 8.3 Ma (2σ)
MSWD = 0.1 ; n = 6
e
N = 62
2685
3100
Number
Age (Ma)
f
N = 23
1985
2700

Figure 6



12GL01 Paragneiss enclave
a
N zircon = 16
3500
2500
1500
700
600
500
0.09
0.08
0.07
0.6
0.7
0.8
0.9
1.0
1.1
1.2
0
0.2
0.4
0.6
0.8
0
10
20
30
206Pb/238U
207Pb/235U
12GL01 Paragneiss enclave
b
N monazite = 8
590
560
530
500
470
0.096
0.090
0.084
0.078
0.072
0.022
0.024
0.026
0.028
0.030
206Pb/238U
206Pb/232Th
Concordia Age
514.6 ± 5.2 Ma (2σ)
MSWDC+E = 1.07 ; n = 7

Figure 7

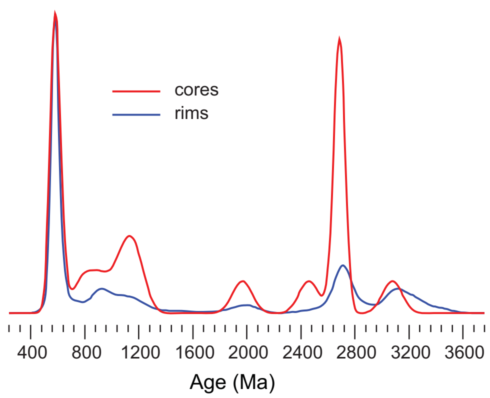


Figure 8

Figure 8

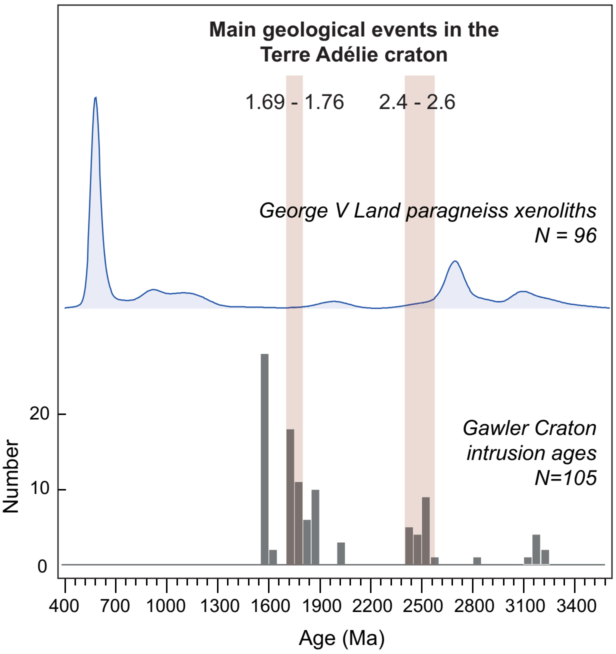
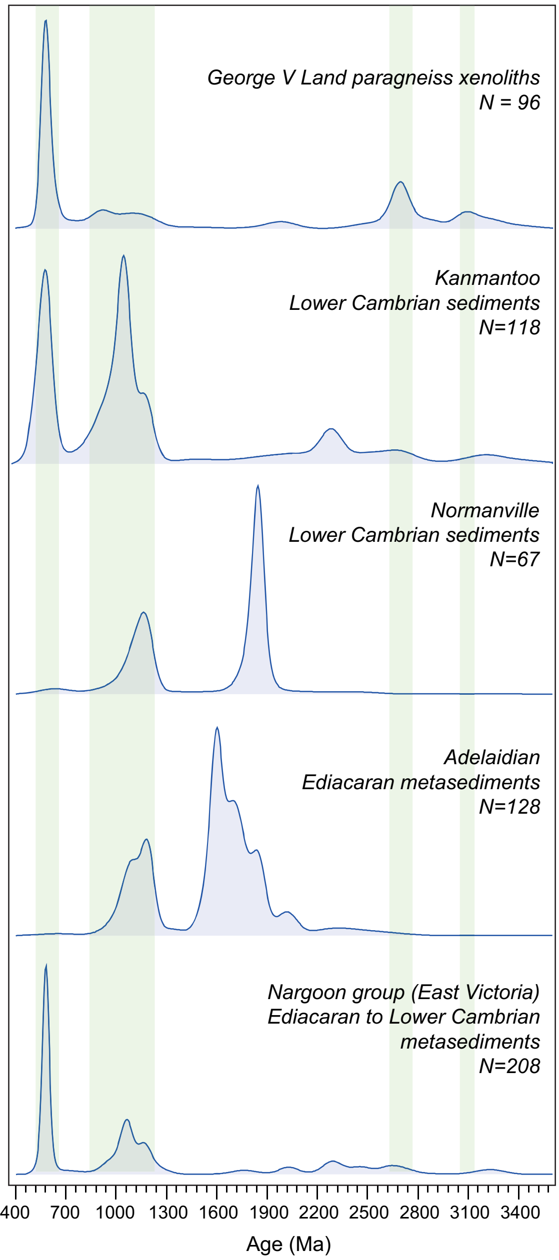


Figure 9



George V Land paragneiss xenoliths
N = 96
Kanmantoo
Lower Cambrian sediments
N=118
Normanville
Lower Cambrian sediments
N=67
Adelaidian
Ediacaran metasediments
N=128
Nargoon group (East Victoria)
Ediacaran to Lower Cambrian
metasediments
N=208
400
700
1000
1300
1600
1900
2200
2500
2800
3100
3400
Age (Ma)

Background dataset for online publication only
Click here to download Background dataset for online publication only: supplementary-data.xlsx