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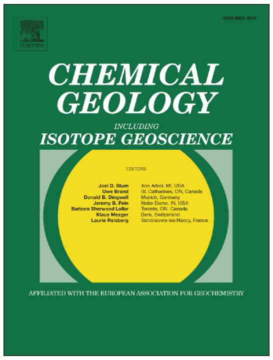

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Trace inheritance – clarifying the zircon O-Hf isotopic fingerprint of I-type granite sources: Implications for the restite model

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Abstract

Early to mid Carboniferous I-type granites distributed in a broad meridional belt west of Sydney, southeastern Australia, represent the last phase of granite magmatism in the southern Lachlan Fold Belt. Rare inherited zircon in the granites, in combination with zircon precipitated from the melt phase of the magmas, provides direct evidence of the nature and age of the source rocks from which the granites were derived, and the isotopic compositions of those rocks. Most granites from the north and central parts of the belt, represented by the Wuuluman, Home Rule, Oberon and Lett plutons (334 ± 3, 328 ± 4, 339 ± 2 and 328 ± 2 Ma, respectively), are characterized by scarce inherited zircon dominantly of Siluro-Devonian age, consistent with all being derived from a common zircon-poor source rock of mid to late Devonian age. Based on the isotopic compositions of the igneous zircon rims, that source was relatively homogeneous and immature ($\delta^{18}O_{zrn}$ 6–7‰, εHf(t) 0–+4). Two samples of the Tarana pluton (331 ± 2 Ma), near the centre of the belt, show evidence for heterogeneity in that source and the presence of a more evolved component that is also more zircon rich. Together with the Lett pluton from the same geochemical suite, their zircon rim compositions define a mixing array between more and less evolved end members ($\delta^{18}O_{zrn}$ 5.5–9.5‰, εHf(t) -4–+4). Only in the southern Chapmans Creek pluton (327 ± 3 Ma) is there clear evidence that the source of the granite also contained a minor component with a similar older protolith to the LFB early Palaeozoic sediments that host most of the LFB pre-Carboniferous granites. Presence of that component, which overwhelmingly dominates the inheritance in the pre-Carboniferous granites, is also reflected in a slightly elevated whole rock initial $^{87}Sr/^{86}Sr$ (> 0.7050) and igneous $\delta^{18}O_{zrn}$ (ca. 7.5‰), but not in the igneous zircon εHf(t) (ca. +2). The amount of restitic zircon in granite is determined by not only the proportion of restite present but also the zircon contents of the various source rock components. The process of restite unmixing does not necessarily mean that more mafic, restite-rich granites will contain more inherited zircon.

Keywords: I-type granites; Lachlan Fold Belt; O isotopes; Hf isotopes; restite model; zircon inheritance

1. INTRODUCTION

Inherited zircon in granites, namely zircon that predates the magmatism, provides valuable information about the processes involved in magma generation. Inherited zircon from the source rock of a granite preserves chemical and isotopic evidence of the composition of the source rock from which it was, in turn, derived. Inheritance entrained from wall rocks provides evidence of the nature and extent of crustal assimilation during magma genesis. Determining the origin of zircon inheritance can be difficult, however.

S-type and I-type are the terms commonly used to distinguish granites derived from predominantly sedimentary (or supracrustal) and igneous (or infracrustal) source rocks, respectively (Chappell and White, 1974). S-type granites commonly contain abundant inheritance, probably residual from their sedimentary sources. In contrast, I-type magmas, in which dissolution of inherited zircon is enhanced by the metaluminous magma compositions and higher temperatures, have been supposed to contain rare or no inherited zircon (Watson and Harrison, 1983). Thus, it has been suggested that the inherited zircon found in I-type granites is derived from the host rocks, not from the source rocks of the granite magma (e.g. Collins, 1998; Kemp et al., 2005; Lackey et al., 2005), particularly in the Lachlan Fold Belt (LFB), southeastern Australia, where the inheritance age patterns in spatially associated, but not necessarily contemporaneous, S- and I-type granites are similar (Williams, 1992).

It has been proposed by some researchers that host rock contamination played a significant role in the petrogenesis of the Silurian to Devonian I-type granites in the eastern LFB (Collins, 1998; Keay et al., 1999; Kemp et al., 2005). Inherited zircon is scarce but ubiquitous in those granites and, as in the S-type granites, the age pattern of the inheritance is indistinguishable from that of the detrital zircon in the host regional Ordovician turbidites (Williams, 1992). The argument, based on this similarity, is that the inheritance was not from the sources of the granites, but derived from the country rocks by crustal assimilation. Although this mixing model might explain some of the isotopic data in isolation, it is inconsistent with the observed relationships between the isotopic and chemical compositions of the granites (Chappell, 1994; Chappell et al., 1999).

Chappell and his co-workers have argued for a process of restite unmixing whereby, when the source rock of a granite is partially melted, residual unmelted material (restite) is carried in the magma together with the melt fraction. Differences in igneous rock compositions are attributed to different degrees of restite separation, producing linear chemical trends similar to those of mixtures (Chappell et al., 1987), but retaining isotopic similarities in related rocks. In the restite model, the inherited zircon in the I-type granites is interpreted as being restite, just as it obviously is in the S-types, providing strong evidence in support of the model (Chappell et al., 1987) and for low-temperature, zircon saturated, magmatism (Chappell et al., 2000).

Mixing and restite unmixing models cannot be distinguished just from the bulk-rock chemical compositions of granites, so it has long been debated which process was involved in the petrogenesis of the Palaeozoic granites in the LFB. Here we report newly-measured age patterns for inherited zircon cores, and O and Hf isotopic compositions for melt-precipitated zircon rims, from six Carboniferous I-type granites located at the northeastern edge of the LFB, and discuss the granite petrogenesis and the origin of the inherited zircon. The inheritance study provides critical information in terms of the magma genesis that could not be provided by the O and Hf isotopes alone. We also show how such a study provides a test of the applicability of the restite model to particular granite suites.

2. REGIONAL GEOLOGY

The LFB Carboniferous granites (LCG; ca. 350–320 Ma) are exposed in a region along the easternmost edge of the LFB from south of Nowra to north of Gulgong that cuts approximately NNW across the structural zones formed during earlier deformations (Fig. 1). The outcrop area is bounded by the Sydney Basin in the east, but the granites extend beneath the basin, as evidenced by granite exposed in some basement windows and intersected by deep drilling. The LCG are the youngest granites in the LFB, all I-types, and distinguished from the other Lachlan pre-Carboniferous granites by having K-feldspar megacrysts, high K and Sr, and low Y (Shaw and Flood, 1993; Chappell, 1994). They are relatively unevolved in Sr isotopic composition, with initial $^{87}Sr/^{86}Sr$ ratios of 0.7040–0.7055 (S. Shaw, unpublished data; age corrected using zircon U-Pb dates). The LCG are distributed in two main intrusive complexes, the Bathurst and Gulgong Batholiths, with small dispersed satellite plutons that occupy the central and northern area, and more than 15 small scattered plutons in the south (Fig. 1). The central-northern LCG are compositionally well grouped into several suites with initial $^{87}Sr/^{86}Sr$ ratios mostly less than 0.7050, whereas the southern LCG are more diverse, with slightly higher initial $^{87}Sr/^{86}Sr$ ratios (S. Shaw, unpublished data).

The central-northern LCG in part are intrusive into late Silurian to Devonian marine sedimentary and volcanic rocks (Hill End Trough and Capertee High) (Pogson and Watkins, 1998; Barron et al., 1999). The southern LCG mostly intrude Ordovician turbidites, the typical host rocks of most of the pre-Carboniferous granites in the LFB (Pogson and Watkins, 1998; Glen, 2005).

2.1. Granite samples and their host rocks

Six plutons were sampled to encompass the north-south range of the LCG (Fig. 1). Descriptions below of each granite and their host rocks are mainly based on the Explanatory Notes for the Dubbo and Bathurst 1:250,000 sheets (Pogson and Watkins, 1998; Barron et al., 1999) and the 1:1,250,000 map of granites and related rocks of the LFB (Chappell et al., 1991).

Chapmans Creek (OG37), one of the southern LCG, is a medium-grained biotite-hornblende monzogranite with no K-feldspar phenocrysts. It intruded Ordovician turbidite and late Silurian (Coven Creek Formation) to Mid-Late Devonian (Bindook Group) sedimentary and volcanic rocks.

Five samples were collected from three plutons of the central LCG: Oberon, Tarana and Lett. Oberon is a medium to coarse-grained, equigranular biotite-hornblende granodiorite, and the northernmost pluton of the LCG that does not contain pink K-feldspar megacrysts. It intruded Middle to Late Ordovician turbidites (Adaminaby Group) and the Late Ordovician Rockley Volcanics. Two samples were collected from the zoned Oberon granodiorite, one from the central region (OG16) and the other within about 500 m of the pluton margin (OGY). This provided a test of whether the presence of inherited zircon in the Oberon pluton was due to contamination of the magma by assimilation of its host sedimentary rocks.

The Tarana and Lett monzogranites are part of the Tarana Suite. Their common textural, mineralogical and compositional characteristics (B. Chappell, unpublished data) are consistent with their being derived from the same source, or sources of the same composition. Sample HB83, collected from the central region of the Tarana body, is a pink, coarse-grained, equigranular biotite monzogranite with K-feldspar phenocrysts (≤ 30 mm long). Tarana is the largest granite body of the LCG, and was emplaced as a zoned pluton or series of plutons in sequence from west to east. A second sample of more mafic Tarana granite (HB82) is coarse-grained biotite-hornblende monzogranite containing pale pink K-feldspar phenocrysts (≤ 20 mm long). The Tarana monzogranite intruded a series of Late Ordovician (Rockley volcanics), Silurian (Bells Creek Volcanics and Campbells Formation) and Devonian (Crudine Group) volcanic and sedimentary rocks.

Lett (sample HB11), the easternmost pluton of the Tarana Suite, is a medium-grained, pink K-feldspar megacryst-bearing biotite-hornblende monzogranite. Little of the contact between the monzogranite and country rock is exposed, and the eastern side of the pluton is overlain by Permian sedimentary rocks of the Sydney Basin (Shoalhaven Group). It is likely, however, that the granite at least in part intruded terrestrial sedimentary rocks of the late Devonian Lambie Group.

Samples were collected from two plutons of the northern LCG: Home Rule and Wuuluman. The Home Rule (HG21), a part of the Gulgong Batholith, is an equigranular biotite quartz monzonite containing large pink K-feldspar megacrysts (up to 50 mm diameter). It intruded Silurian volcanic rocks (Dungeree Volcanics) and Mid to Late Ordovician sedimentary rocks (Tucklan Formation).

Wuuluman (HG03) is the northwesternmost pluton of the LCG. It is a quartz monzodiorite containing large K-feldspar megacrysts (sometimes surrounded by white plagioclase, i.e. rapakivi texture) up to 50 mm diameter and greenish plagioclase. It intruded Silurian (Gleneski Formation) and Devonian volcanic and sedimentary rocks (Cuga Burga Volcanics, Cunningham Formation, Waterbeach Formation, Crudine Group and Guroba Formation).

3. METHODS

Measurements of the O, Pb, Th and U isotopes were carried out using a Sensitive High Resolution Ion Microprobe (SHRIMP) at the Australian National University. Measurements of the Hf isotopes were carried out using the ANU ThermoFinnigan Neptune multi-collector Laser Ablation Multi-collector Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICPMS). Details of the technical conditions for each type of analysis and data reduction procedures are same as those described by Jeon et al. (2014) and outlined in the supplementary documentation (Electronic Appendix 1).

To determine the zircon inheritance age patterns, representative aliquots of approximately 3000–4000 unsorted zircon grains from the eight individual Carboniferous granite samples were mounted in epoxy and sectioned to expose the grain centres. Separate mounts were prepared for each sample, except for the zircon from the two samples of the Oberon pluton, which was mounted on the same disk so that analytical conditions for both were identical. Possible cores, recognized by their discordant zoning (3–10% of most zircon populations), were identified by cathodoluminescence (CL) using a Hitachi S-2250N scanning electron microscope and preferentially targeted to date the inherited components (Electronic Appendix 2).

To measure the age of zircon crystallized from the melt phase of the magma (zircon rims), clear, euhedral zircon grains were hand-picked from the eight LCG samples under a binocular microscope. Approximately 200–300 grains were mounted on 35 mm megamounts separate from those prepared for the inheritance study. The spots selected for rim analysis were mostly on the margins of the zircon grains, where there was simple oscillatory zoning and no inclusions or fractures. After those spots had been dated by U-Pb and proved to be free of inheritance they were analysed for O and Hf isotopes. None of the zircon from the inheritance study was analysed for O or Hf. The isotopic data for the zircon rims (U-Th-Pb, O, Hf) and cores (U-Th-Pb only) are listed in Electronic Appendices 3 and 4, respectively.

4. RESULTS

Zircon inheritance age patterns, and rim ages and O-Hf isotopic compositions were determined for the eight granite samples (Electronic Appendices 1, 3 and 4). The U-Th-Pb dates, O and Hf isotopic ratios for the zircon rims are fully described in Electronic Appendix 1, summarized in Table 1 and illustrated in Figures 2 and 3. Initial εHf values [εHf(t)] were calculated based on the individual or mean zircon rim ages for each sample. All O and Hf isotopic compositions described and discussed in this study are for the zircon grains from the granite samples: when the O isotopic compositions of granite whole rocks are discussed, the notation $\delta^{18}O_{WR}$ is used. Unless noted otherwise, the term ‘core’ used in this study (‘apparent’ core in particular) refers only to a texturally discordant central zone in a zircon grain. A few of the dated cores proved to be detectably older than the granite magmatism, i.e. were clearly inherited. Only those cores are considered in the following discussion. Detailed descriptions and analytical results for zircon cores can be found in Electronic Appendix 1 and inheritance age patterns are illustrated in Figure 4.

5. DISCUSSION

5.1. A common Devonian source rock for the central-northern LCG

Of the eight granite samples studied from the length of the LCG, a similar, characteristic inheritance age pattern was found in six from the central-northern LCG: the Oberon granodiorite, Tarana (two samples) and Lett monzogranites, Wuuluman quartz monzodiorite and Home Rule quartz monzonite. It featured Silurian-Devonian dates and a lack of Archaean-Meosoproterozoic dates (Fig. 4). This inheritance pattern is distinct from those of the pre-Carboniferous granites, and the pattern of detrital zircon ages in Ordovician turbidites from the LFB, which typically show a strong peak in dates around 600–500 Ma, a second peak around 1.2–1.0 Ga, and a range of older dates into the Palaeoproterozoic and Archaean (see the background histogram in Fig. 4a; Williams, 1992; 2001).

Regardless of their origin, it might be argued that the few inherited cores from the LCG are the remnants of a much larger older zircon population, with the majority of the older (pre-magmatic) zircons being resorbed under conditions of zircon undersaturation during magma formation. The LCG are low-temperature granites, however, with zircon saturation temperatures (Watson and Harrison, 1983; Hanchar and Watson, 2003; Boehnke et al., 2013) of at most ~ 800ºC (if not negligible, slightly overestimated due to the presence of inheritance; Table EA5), and Zr concentrations that show a consistent decrease with increasing SiO_2, indicative of continuous zircon saturation during magma genesis (Fig. EA6; B. Chappell, unpublished data, summarized in Table EA 5). The rare inherited zircon grains will have been chemically stable since their incorporation into the Carboniferous magmas, either from the protolith or the wall/host rocks. For the purposes of the present discussion, it has been assumed that the inherited zircon age spectra mainly reflect the relative abundance of zircon in the source of the granites, although the mechanics of magma segregation and transport and/or other possible magmatic processes might influence this as well.

The inheritance in the central-northern LCG (except the Tarana Suite discussed below) originated either from the source rock from which the magma formed, or from host rocks that contaminated the magma during emplacement. The Oberon granodiorite samples provide a test for wall rock assimilation. The Oberon zoned pluton was emplaced into Ordovician turbidites, but there was no significant difference in the abundance or dates of the inherited zircon between the inner (OG16) and outer (OGY, closer to the host rock) samples of the pluton. The outer sample, in fact, contained Silurian-Devonian zircon cores which cannot be derived from the Ordovician host rock. The inherited zircon cores must have come from the granite's source rocks.

For the northern LCG, the surrounding Devonian volcanic and/or sedimentary rocks are potential sources of the rare inheritance. Based on the data in OZCHRON Geochronology Database (Geoscience Australia, 2007), however, those rocks are not zircon-poor. OZCHRON lists the ages of several host rocks ranging from andesite, dacite to rhyolite to sandstone based on multiple zircon analyses (431–407 Ma), indicating an abundance of zircon in the Silurian-Devonian age range. It is concluded, therefore, that the inheritance in most of the studied LCG was derived from the basement, the source rock of those granites, rather than from wall-rock contamination.

The growth textures of the zircon grains containing inherited cores also argue against country rock contamination. If the inheritance was entrained into the magma at a shallow level, it would have resided in the magma for a relatively short time before emplacement, so the cores should be overgrown by only thin melt-precipitated rims. Thin rims might also be explained by the magma becoming zircon saturated at a late stage, but this was not the case. The Carboniferous granite magmas were always zircon saturated, and the cores observed in the Oberon granodiorite, Wuuluman quartz monzodiorite and Home Rule quartz monzonite are surrounded by thick rims (Electronic Appendix 2), indicating that the inherited zircon was present in the magma from an early stage of magma genesis.

The range of Hf and O isotopic compositions preserved in the zircon rims provides evidence that the zircon-poor, Mid–Late Devonian source rocks for the granite magmas were not isotopically uniform (Fig. 5). Except for Tarana monzogranite sample HB82, the Hf and O isotopic compositions of the zircon rims from each sample are homogeneous, but the mean compositions of the rocks differ. Plotting $\delta^{18}O_{zrn}$ vs. εHf(t) for the three granite samples from the Tarana Suite (HB11, HB82, HB83), however, shows a broad linear correlation consistent with the mixing between relatively less (ca. $\delta^{18}O_{zrn}$ 6‰ and εHf(t) +2) and more mature (ca.

$\delta^{18}O_{zrn}$ 9‰ and Hf(t) -3, similar to the Oberon granodiorite) components.

5.2. Heterogeneous source rock for Tarana Suite

Tarana monzogranite sample HB83 contained much more inherited zircon (Fig. 4c) than other samples of the Tarana Suite or the nearby Oberon granodiorite. Conceivably the monzogranite sampled by HB83 was derived from a different source from that of the other central-northern LCG. On the other hand, HB83 must have shared the same source rock as the other comagmatic granites in the Tarana Suite (Tarana HB82 and Lett HB11), and hence as the Oberon granodiorite and the northern LCG. The more abundant inherited zircon in HB83 therefore needs to be explained in another way, for example by crustal contamination, magma mixing or source rock heterogeneity.

A clue to the character of the monzogranite HB83 source rock is provided by the isotopic composition of the zircon rims. The O and Hf isotopic compositions of the HB83 rims are less juvenile ($\delta^{18}O_{zrn}$ = 7.0 to 9.5‰; εHf(t) = -1 to -3) than those of the other studied LCG (Fig. 5), although the rim compositions of the two other samples of the Tarana Suite (HB82, HB11) overlap at least partly with those from the Oberon granodiorite. The Tarana Suite appears to be the product of mixing two isotopically different components, one of which is the same as the source rock of the Oberon granodiorite emplaced nearby. The Bathurst Suite, which adjoins the Tarana Suite, also has a very similar isotopic composition to the Oberon granodiorite (Fig. 5b, unpublished data), consistent with a common source rock for the granites throughout the central region.

Given that the more juvenile end member of the linear isotopic trend is probably the common source rock of the central-northern LCG, the other, more evolved end member ($\delta^{18}O_{zrn}$ ≈ 9.0‰, εHf(t) ≈ -3) is likely to be the component that provided the abundant inherited zircon to the Tarana monzogranite (HB83). Considering the large difference in zircon rim isotopic composition between HB83 and the other samples, a significant amount of that component was incorporated into the primary magma. The mixing could have occurred externally through magma mixing or crustal contamination, but there is no correlation between silica content (65–75% SiO_2) and isotopic composition over the five granites in the Tarana Suite (Fig. 6, data from this study and B. Chappell unpublished data), indicating that the mixing did not occur during magma differentiation. Neither did it involve end members with very different SiO_2 contents. Further, the rims that mantle the inheritance are thick, indicating that the inherited zircon cores have been present in the magma for most, or all, of the period of igneous zircon growth (Electronic Appendix 2). It is most likely that the Tarana monzogranite sampled by HB83 came from a mixed source rock containing a component that was zircon-rich and isotopically evolved.

As most of the inheritance in Tarana monzogranite sample HB83 was derived from the isotopically evolved component, the zircon age distribution of that component can be inferred by subtracting the age pattern of the rare inherited zircon from the common source rock of the LCG (represented by the combined inheritance pattern of the Oberon, Wuuluman and Home Rule granites) from the Tarana (HB83) pattern. The resultant inferred core age pattern (Fig. 7a) resembles those from the Pre-Carboniferous LFB granites and the Ordovician turbidites (Williams, 1992; 2001), except for the presence of some Silurian-Devonian dates.

Assuming that all the Silurian-Devonian cores were derived from the primary Devonian source rock (the juvenile component), the subordinate source rock might be a LFB-like component. Given the high proportion of Silurian-Devonian cores compared to the other granites, however, it is more likely that the second source component with an isotopically mature composition is also of Devonian age. If it is assumed to be a separate source rock with a different composition, its relatively large contribution should have affected the chemical composition of the Tarana Suite, but it has not. The chemical composition of the Tarana Suite is similar to those of the Bathurst and Oberon Suites (Fig. EA7; B. Chappell, unpublished data). It is thus geologically more logical to consider isotopic heterogeneity within a source rock, rather than to postulate a separate, coeval (Devonian) and chemically similar component with different isotopic compositions (lower εHf and higher $\delta^{18}O$). Incomplete isotopic homogenization of the source is evidenced by the range of zircon rim compositions, particularly from the other Tarana monzogranite sample HB82 (Fig. 5). Isotopic heterogeneity of the source rock for the LCG could also explain the O-Hf isotopic range and trends observed throughout the LCG.

5.3. Relationship between source rock composition and inherited zircon abundance in the Tarana Suite

The Lett monzogranite (HB11) has the least evolved zircon O and Hf compositions of the studied Tarana Suite granites. Seven inherited zircon cores were found, three of which were mantled by only thin rims (Electronic Appendix 2), a feature not observed in zircon from the other Tarana Suite granites. The cores with thin rims probably resided in the magma for a relatively short time, that is, they originated from late crustal contamination at a shallow level. Despite this textural evidence of contamination, the Lett monzogranite shows no significant offset from the zircon O-Hf isotopic trend defined by the other central-northern LCG (Fig. 5) and no offset from the trends in chemical composition of the other granites in the Tarana Suite (B. Chappell, unpublished data). The level of contamination is therefore too low to have played a significant role in the magma genesis.

There is a broad correlation between the isotopic compositions of the granites (represented by zircon rim composition) and the amount of zircon inheritance. Disregarding the cores with thin rims, Lett granite HB11 had four cores inherited from the source rock that is common to the central-northern LCG, ~ 0.25% of the zircon population. In Tarana monzogranite HB82, with zircon O and Hf compositions intermediate between Lett (HB11) and Tarana (HB83), ~ 1% of the zircon grains contained inheritance. In Tarana monzogranite HB83, the most isotopically evolved granite in the Tarana Suite, ~ 1.5% of zircon grains had an inherited core. This could indicate that the more juvenile part of the heterogeneous Devonian source rock was relatively zircon poor (source of the Lett and Oberon), and the more evolved part was relatively zircon rich (source of Tarana HB83; Fig. 5). The source of Tarana HB82 was intermediate in isotopic composition and zircon content.

5.4. The LFB sedimentary component in the southern LCG

The Chapmans Creek monzogranite (OG37) contained a similar high abundance of inherited cores to Tarana monzogranite HB83, but much less Silurian-Devonian zircon and much more zircon of Proterozoic and Archaean age. At least some of the inheritance in the Chapmans Creek must have come from a different source from that in the Tarana and other central-northern LCG. Nevertheless, the Chapmans Creek monzogranite had a similar range of zircon εHf(t) (+1 to +3) to, and only slightly heavier $\delta^{18}O_{zrn}$ (7–9‰) than, those of the central-northern LCG (Table 1 and Fig. 5).

It could be argued from the zircon rim Hf and O isotopic compositions that the Chapmans Creek monzogranite had the same source rock as the other LCG, implying that the LCG share a common Devonian source throughout the whole area from north to south. The difference in inheritance age patterns, however, shows that another source of pre-magmatic zircon is required. It is notable that the melt-precipitated rims on several of the inherited zircon cores were thin (Electronic Appendix 2), implying that those cores originated from crustal contamination at a shallow level. The dates of those cores (n = 11) ranged from Ordovician to Late Archaean, and significantly, included all the Archaean-Proterozoic cores older than 1.6 Ga (Fig. 4a). Due to their small number, the 11 thin-rimmed cores do not define a distinctive pattern of dates in themselves, but their dates are consistent with the cores having originated from LFB Ordovician turbidite—Archaean-Proterozoic inheritance was not found in any of the other LCG samples. The presence of an Ordovician sedimentary contaminant picked up at shallow level is consistent with Ordovician turbidites becoming increasingly abundant amongst the host rocks to the LCG in the southern part of the region (Fig. 1).

A third component is required to explain the abundant inheritance in the Chapmans Creek monzogranite. The zircon age distribution of that component can be inferred by subtracting the average inheritance pattern of the Oberon, Wuuluman and Home Rule granites, and the 11 cores with thin rims (Fig. 7b). The age pattern of the remaining zircon population is similar to that of typical LFB rocks (Pre-Carboniferous granites and Ordovician turbidites; Williams, 1992). The third zircon source was an LFB component that, given the thick rims that mantle that inheritance, probably resided in the source of the granite magma at depth (Electronic Appendix 2).

The Chapmans Creek monzogranite was derived primarily from the same Devonian source rock as the other LCG, but included LFB components incorporated both at deep and shallow crustal levels, the only one of the six granite bodies sampled for this study to have done so. Other evidence for the presence of an LFB component in the southern LCG is their having slightly but distinctly higher initial $^{87}Sr/^{86}Sr$ (≥ 0.7050) than the northern-central LCG (< 0.7050, S. Shaw, unpublished data). As the Hf isotopic compositions of the Chapmans Creek monzogranite were not affected by the isotopically distinct LFB components (most LFB I-type granites have εHf(t) values in the range -10 to -1, and the S-type granites are -10 to -8, Ickert, 2010; and the sediment values are probably even lower) and were similar to those of the Oberon granodiorite (the closest central LCG), the amount of LFB material incorporated in the magma was probably very small. The relatively high abundance of LFB inheritance is probably explained by the high abundance of zircon in the LFB sedimentary rocks.

To model the increase in initial $^{87}Sr/^{86}Sr$ of the Chapmans Creek monzogranite with the minimum amount of contaminant, it can be assumed that the LFB component was early Palaeozoic sedimentary rocks (McCulloch and Chappell, 1982; McCulloch and Woodhead, 1993; Gray and Webb, 1995). Assuming that the Chapmans Creek monzogranite was primarily derived from Devonian source rock with a similar isotopic composition to the source of the Oberon Suite, with a minor contribution from LFB sediments, the amount of sediment can be approximated. Assuming an initial source composition of 0.7045 (mean value of the Oberon Suite, Table 2), a $^{87}Sr/^{86}Sr$ of 0.7344 (at 327 Ma) and a mean Sr concentration of 248 ppm in the LFB clastic sediments, to produce the initial $^{87}Sr/^{86}Sr$ of the Lockyersleigh Suite to which the Chapmans Creek monzogranite belongs (0.7053), the primary magma would require the addition of about 6% sediment from the LFB. Given that the $\delta^{18}O_{WR}$ of sediment is typically about 15‰, this amount of LFB sediment could also explain why the $\delta^{18}O_{WR}$ of the Chapmans Creek monzogranite is slightly higher than that of the Oberon granodiorite. Based on a simple calculation of O isotopic compositions, the contribution of LFB sediments to the Chapmans Creek is ca. 10%, which would produce the difference of 0.5–1.0‰ in $\delta^{18}O_{WR}$ between the two granites (Fig. 5).

Given the geographic distribution of contrasting initial $^{87}Sr/^{86}Sr$ in the LCG (S. Shaw, unpublished data), the significant involvement of LFB sediment appears to have been limited to the southern LCG. Although the incorporation of less than 6% sediment into the southern LCG seems too little to show up as a chemical distinction from the central-northern LCG (especially the Oberon Suite, the closest to the southern LCG), the slightly lower CaO of the southern LCG (average CaO of the Lockyersleigh and Isabella Suites, Mumbedah, Kanangra and Columba granites is 1.9%, compared to an average of 3.5% in the whole LCG; B. Chappell, unpublished data) might reflect that incorporation (Ca loss during feldspar weathering is a feature of the LFB Ordovician sedimentary rocks and the S-type granites sourced from them: Chappell, 1994).

5.5. Importance of the inheritance study

This inheritance study contributes more to understanding the genesis of the LCG than could have been learned from the O and Hf isotopic compositions of the igneous zircon alone. First, without the inheritance information, the $\delta^{18}O_{zrn}$-εHf(t) correlation within the Tarana Suite could easily be misinterpreted as mixing between two separate components, one relatively juvenile (the common source rock, compositionally similar to the source of the Oberon Suite) and the other a more evolved external 'contaminant'. However, the high proportion of Silurian-Devonian inheritance in the Tarana monzogranite (HB83), and the similarity in inheritance patterns between the Tarana Suite granites (HB82 and HB11) and the other northern-central LCG, shows that the evolved component was not an external component, but a part of the source rock that had a less juvenile composition and was more zircon rich. It demonstrates that the Devonian source rocks were heterogeneous in both isotopic composition and zircon abundance.

Second, from the distinct inheritance age pattern of the Chapmans Creek monzogranite, it has been shown that a small amount of LFB sediment was added to the southern LCG, which explains their having slightly higher initial $^{87}Sr/^{86}Sr$ and $\delta^{18}O_{zrn}$ values than the other LCG. As the sedimentary contribution is too small (< 6%) to change the Hf isotopic composition of the southern LCG, the minor sedimentary component would be hard to distinguish without dating the inheritance.

5.6. Source of inheritance in the I-type granites: insights into the restite model

As there is no evidence for significant late-stage crustal contamination, the zircon inheritance in the LCG must have been derived from the source rock at depth, not from the host rocks, except possibly in the case of the Lett and Chapmans Creek monzogranites. The preservation of inherited zircon derived from the source materials in the low-temperature and zircon-saturated granites is consistent with there having been other residual solid source components (restite) in the magmas. The relative proportions of melt and restite would determine the composition of each granite (restite model, Chappell et al., 1987).

According to the concept of the restite model, the more mafic granites contain the more abundant residual materials derived from the source rock. As the inherited zircon is a part of the restite, it has commonly been argued that the more mafic granites within a suite should contain more restitic zircon than the felsic ones, and this is certainly the case in the S-type granites of the LFB. It is a logical argument with the assumption of a homogeneous source composition and thus has been used to determine whether the restite model is applicable in a specific granite terrane (e.g. Black et al., 2010). The argument is not always correct if the source rock is not homogeneous, however, because the abundance of inherited zircon depends not only on the proportion of restite in the magma, but also on the zircon contents of the relatively mafic and felsic components of the source rock.

The three Tarana Suite samples studied here (HB11, HB82 and HB83) reveal the isotopic heterogeneity of the source rocks for those granites. The sequence from isotopically less evolved (higher εHf(t), lower $\delta^{18}O$) to more evolved (lower εHf(t), higher $\delta^{18}O$) source compositions is: HB11 < HB82 < HB83 (Fig. 5b). Based on the inherited zircon cores abundant in HB83 (1.5%) and rare in HB11 (0.25%), it is highly likely that the more juvenile part of the source rock was relatively zircon poor (for HB11) and the more evolved part was relatively zircon rich (for HB83). As a consequence, contrary to the common observation elsewhere, the most felsic sample (HB83; 74.4% SiO_2), which contains the least restite, contains the most inheritance, whereas in the more mafic sample (HB11; 69.1% SiO_2), which contains more restite, inheritance is the least abundant within the suite. The most mafic Tarana Suite sample HB82 (65.5% SiO_2), which must contain the most restite, had intermediate and heterogeneous zircon O and Hf isotopic compositions and also contained an intermediate relative abundance of inheritance (1%).

This is a critical implication for the restite model, meaning that mafic granite could contain less restitic zircon than felsic granite in the same suite. It is not inconsistent with the restite model already demonstrated for the LCG in the previous discussion (no assimilation during the granite differentiation), but rather illustrates the important fact that the amount/ratio of inheritance depends, not on the proportion of restite alone, but also on the zircon content of the heterogeneous source rock from which that restite was derived. Therefore, the presence of more inherited zircon in the more mafic rocks within a granite suite is not alone a valid test for the restite model.

6. CONCLUSIONS

Based on the predominant pattern of rare inheritance and the presence of Siluro-Devonian zircon cores in the Oberon, Wuuluman, Home Rule and two plutons in the Tarana Suite, it is proposed that the Lachlan Carboniferous granites have a common source rock that is Mid to Late Devonian in age and zircon poor. Although the Tarana monzogranite (HB83) contains the highest relative abundance of inheritance and its O-Hf isotopic compositions are distinct (less juvenile), the Tarana Suite shows a linear $\delta^{18}O_{zrn}$-εHf(t) trend implying the mixing of two isotopically different components, of which the more juvenile, considering its similar isotopic compositions, is probably the common Devonian source rock. The amount of the less juvenile material involved in the Tarana Suite magma seems to be significant, but there is no correlation between silica content (65–75% SiO_2) and isotopic compositions in the suite, implying that the mixing occurred in the source, before the magma differentiated. As the inferred second source component of the Tarana monzogranite contained a significant proportion of Silurian-Devonian zircon, that component cannot be the LFB Ordovician turbidites, but was probably also of Devonian age. It is concluded that there was isotopic heterogeneity within the common Devonian source rock. The more juvenile part of the source was relatively zircon poor, and the more evolved part more zircon rich. Although the Chapmans Creek monzogranite was probably also derived from the common Devonian source rock (based on the similar range of εHf(t) and just a slightly higher $\delta^{18}O_{zrn}$), its inheritance shows signs of crustal contamination by zircon-rich LFB material both at shallow and deep levels. As this had a minimal effect on the isotopic composition of the melt-precipitated zircon, the amount of the LFB component must be very small (≤ 10%).

To summarize, all the LCG, from north to south, were derived primarily from isotopically heterogeneous Devonian source rocks. Incorporation of a minor LFB sedimentary component was limited to the southern LCG, where the initial $^{87}Sr/^{86}Sr$ and $\delta^{18}O_{zrn}$ values are slightly higher, and older inherited zircon is present. As inheritance has provided key information for understanding the petrogenesis of the LCG, the use of inherited zircon to study granite sources and petrogenesis should be widely applicable to other granite terranes. This study also showed that the amount of restitic zircon is controlled by not only the silica content (restite proportion) but also the source rock heterogeneity. Therefore, the process of restite unmixing does not necessarily imply that more mafic granites will contain more inherited (restitic) zircon.

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SUPPLEMENTARY DATA

Supplementary data for this paper are available at Chemical Geology online.

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FIGURE CAPTIONS

Figure 1. Sketch geological map showing the distribution of Carboniferous granites and their host rocks in the northeastern LFB. Shading patterns discriminate the plutons belonging to different geochemical suites. Sample locations with emplacement ages are shown. Silurian-Devonian granites are not shown, but are mostly within the Ordovician turbidite. The inset

map shows the distribution of SE Australian granite and the dashed box represents the area of the LCG.

Figure 2. Tera-Wasserburg concordia plots of U-Pb analyses of zircon grains from the eight samples of the LCG. Two samples (OG16 and OGY) from the Oberon granodiorite are plotted together in (b). Grey filled ellipses are the data omitted from the calculation of mean zircon ages. Analytical uncertainties 1σ.

Figure 3. Oxygen ($\delta^{18}O_{zrn}$, left-y axis, upper plots) and Hf (εHf(t), right-y axis, lower plots) isotopic ratios of zircon rims from the eight granites from which zircon cores were dated. Points marked with a cross are outliers and were omitted from the calculation of the weighted mean composition of each sample.

Figure 4. Distributions of dates of inherited zircon cores: > 360 Ma for (a) Chapmans Creek (OG37), (b) Oberon (OG16 and OGY), (c) Tarana (HB83), (d) Tarana (HB82), (e) Lett (HB11) and (f) Wuuluman (HG03) and Home Rule (HG21) granites. The numbers of inherited cores are shown (numbers in brackets indicate total of the analysed cores). Some cores with high common Pb are counted, but not plotted as their ages could not be determined. The lightly dotted column throughout (a) to (f) corresponds to the Siluro-Devonian period. Inset figures are Wetherill concordia diagrams of the inheritance with 1σ uncertainties. Black solid bars in (a) and (c) indicate detrital zircon ages from the Ordovician turbidites in the LFB (I. Williams, 2001 and unpublished data) and the abundance (y-axis) for those is compressed by over 5 times. Probability density plots are shown in (a) and (c) to compare to the age distribution of Ordovician turbidites better.

Figure 5. Plot of εHf(t) versus $\delta^{18}O$ for zircon rims (a) from the five granites with the Tarana Suite compositions represented by a shaded area and (b) from the three granites in the Tarana Suite, the most felsic Tarana (HB83, 74.4% SiO_2), the mafic Tarana (HB82, 65.5% SiO_2) and Lett (HB11, 69.1% SiO_2) granites. The O-Hf isotopic compositions of the Oberon samples are shown for comparison, and the shaded and dotted areas correspond to the compositions of the Tarana and Bathurst (unpublished data) suites, respectively. Vertical and horizontal bars correspond to the CHUR εHf and mantle zircon $\delta^{18}O$ of 5.3±0.3 ‰ (Valley, 2003), respectively. Error bars are 1σ.

Figure 6. Oxygen ($\delta^{18}O$, left-y axis, upper plots) and Hf ($\varepsilon Hf(t)$, right-y axis, lower plots) isotopic ratios of zircon against SiO_2 from the five granites in the Tarana Suite (data from this study and present authors' unpublished data). There is no systematic change in isotopic compositions over a 10% range in SiO_2, but good coupling between $\delta^{18}O_{zrn}$ and $\varepsilon Hf(t)$.

Figure 7. Date distributions of zircon from extra source component(s) for (a) Tarana and (b) Chapmans Creek. These histograms are inferred by subtracting the average population of the common Devonian source rock and the dates of cores mantled by thin rims (in the case of the Chapmans Creek). Note that the histograms do not show the numbers of measurements and the bars could have non-integer fractions, as the subtracted average inheritance pattern of the source rock was calculated as one fourth of the sum of the inherited cores from the Oberon, Wuuluman and Home Rule granites. The numbers in brackets are the total number of analysed cores. Black solid bars in (b) indicate detrital zircon ages from the Ordovician turbidites in the LFB (I. Williams, 2001 and unpublished data). The abundance (y-axis) for those is compressed by ca. 8 times.

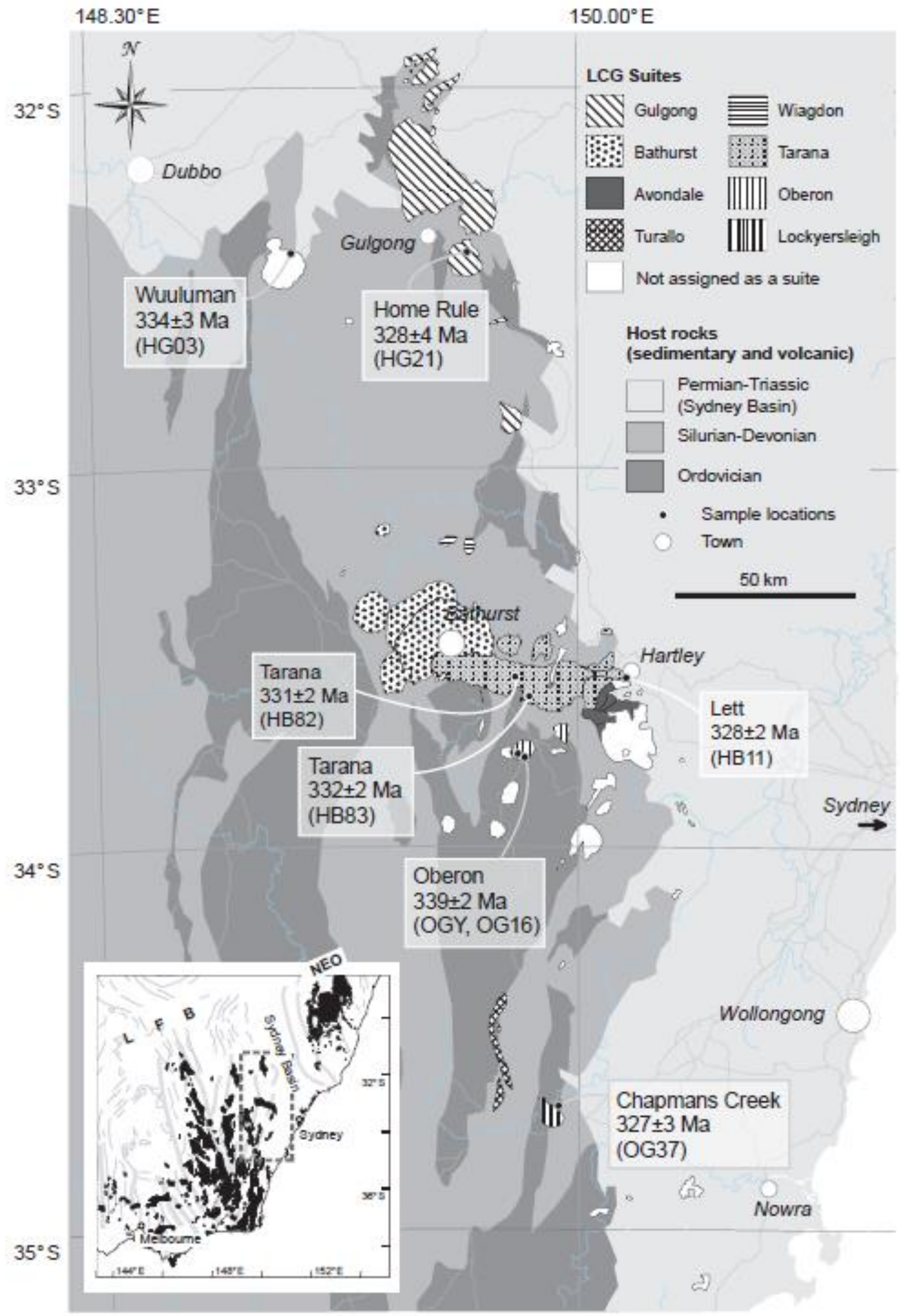
148.30° E
150.00° E
N
32° S
33° S
34° S
35° S
Dubbo
Gulgong
Wuuluman
334±3 Ma
(HG03)
Home Rule
328±4 Ma
(HG21)
LCG Suites
Gulgong
Wiagdon
Bathurst
Tarana
Avondale
Oberon
Turallo
Lockyersleigh
Not assigned as a suite
Host rocks
(sedimentary and volcanic)
Permian-Triassic
(Sydney Basin)
Silurian-Devonian
Ordovician
Sample locations
Town
50 km
Bathurst
Hartley
Tarana
331±2 Ma
(HB82)
Tarana
332±2 Ma
(HB83)
Lett
328±2 Ma
(HB11)
Sydney
Oberon
339±2 Ma
(OGY, OG16)
Wollongong
Chapmans Creek
327±3 Ma
(OG37)
Nowra
NEO
L F B
Sydney Basin
32° S
Sydney
36° S
Melbourne
144° E
148° E
152° E

Figure 1

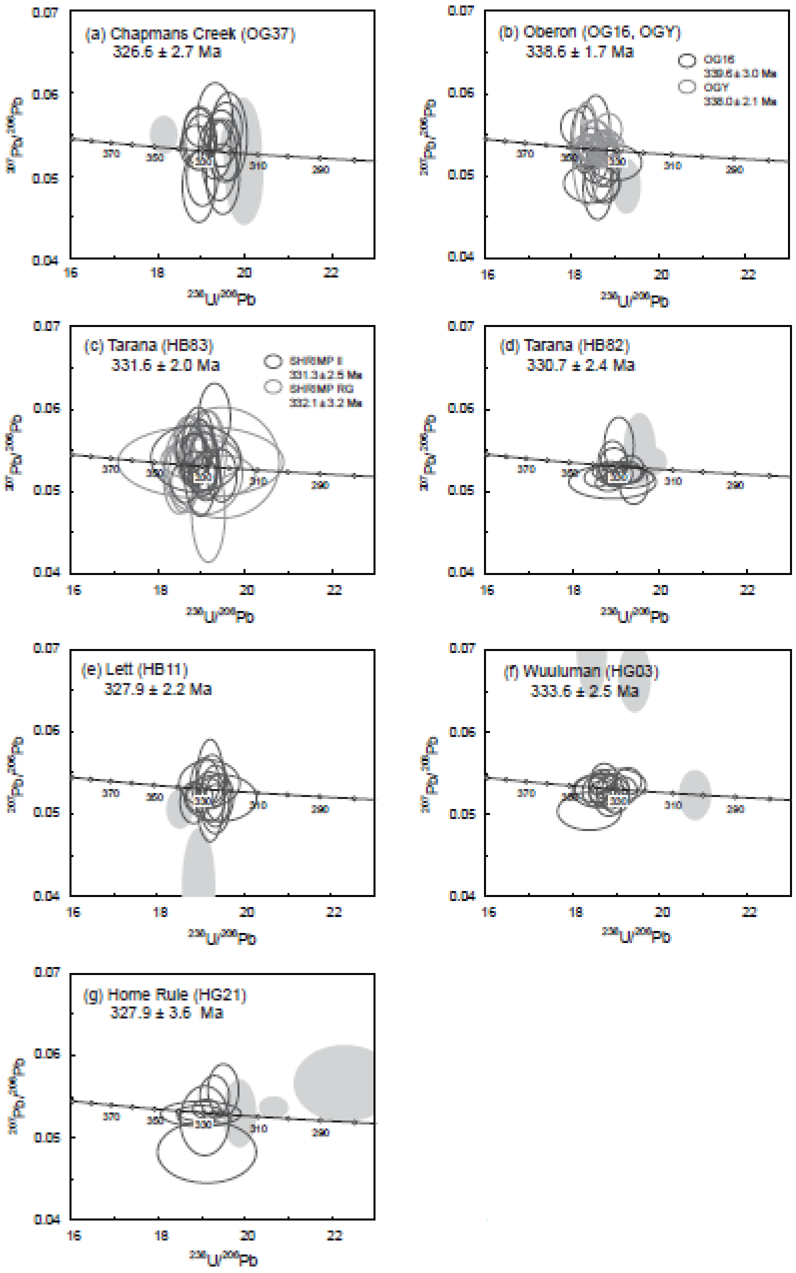
(a) Chapmans Creek (OG37)
326.6 ± 2.7 Ma
(b) Oberon (OG16, OGY)
338.6 ± 1.7 Ma
OG16
339.6 ± 3.0 Ma
OGY
338.0 ± 2.1 Ma
(c) Tarana (HB83)
331.6 ± 2.0 Ma
SHRIMP II
331.3 ± 2.5 Ma
SHRIMP RG
332.1 ± 3.2 Ma
(d) Tarana (HB82)
330.7 ± 2.4 Ma
(e) Lett (HB11)
327.9 ± 2.2 Ma
(f) Wuuluman (HG03)
333.6 ± 2.5 Ma
(g) Home Rule (HG21)
327.9 ± 3.6 Ma
370
350
330
310
290
0.07
0.06
0.05
0.04
16
18
20
22
$^{207}Pb/^{206}Pb$
$^{238}U/^{206}Pb$

Figure 2

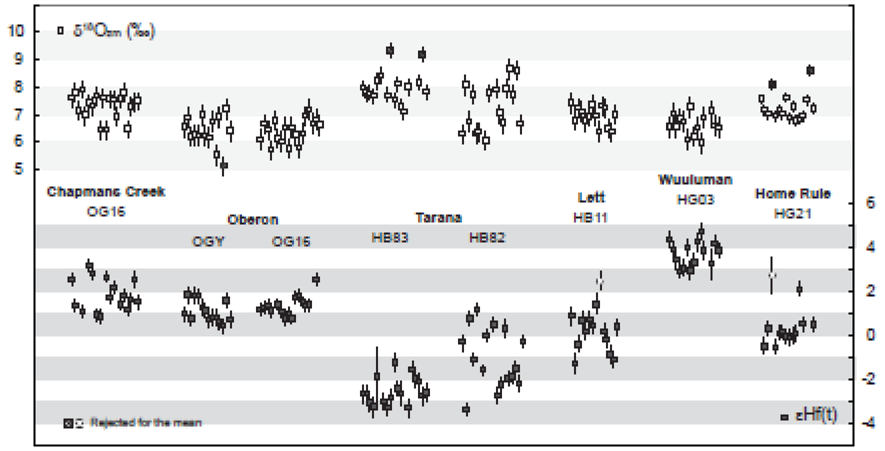
10
9
8
7
6
5
δ18Ozrn (‰)
Chapmans Creek
OG16
Oberon
OGY
OG16
Tarana
HB83
HB82
Lett
HB11
Wuuluman
HG03
Home Rule
HG21
6
4
2
0
-2
-4
εHf(t)
Rejected for the mean

Figure 3

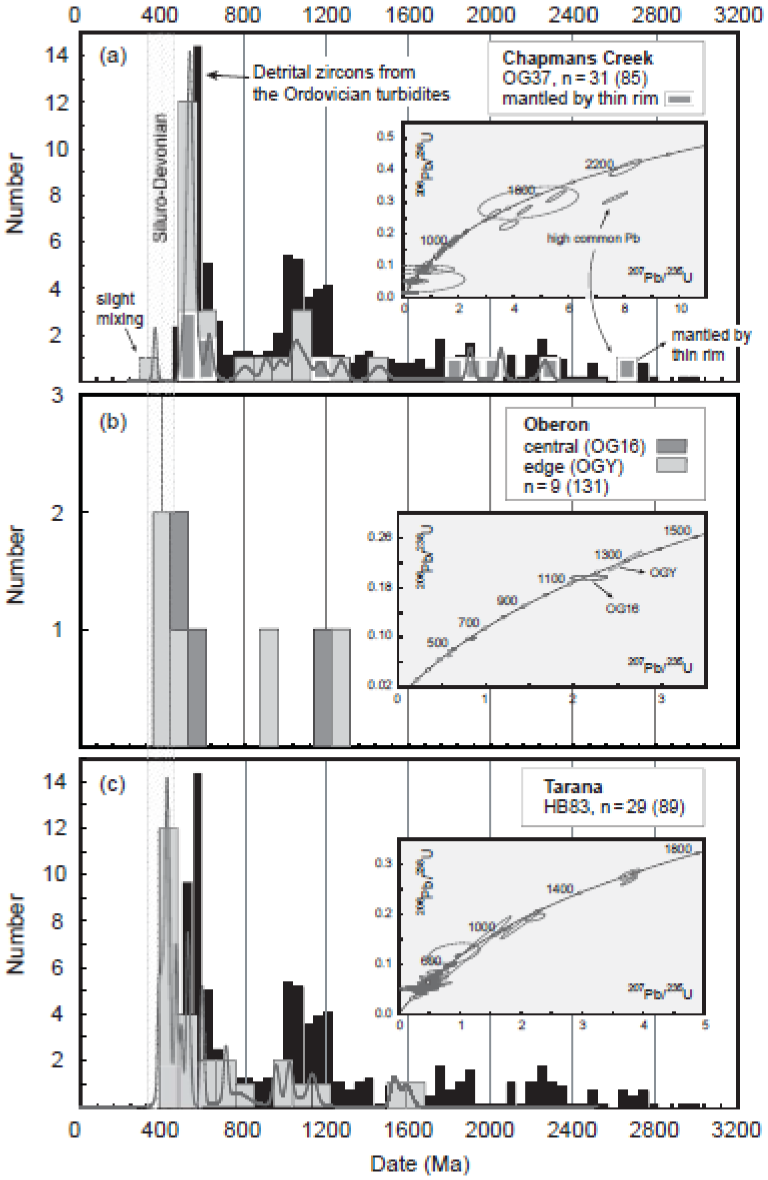
(a)
Chapmans Creek
OG37, n = 31 (85)
mantled by thin rim
Detrital zircons from the Ordovician turbidites
Siluro-Devonian
slight mixing
mantled by thin rim
high common Pb
(b)
Oberon
central (OG16)
edge (OGY)
n = 9 (131)
OGY
OG16
(c)
Tarana
HB83, n = 29 (89)
Number
Date (Ma)
^{207}Pb/^{235}U
^{206}Pb/^{238}U

Figure 4

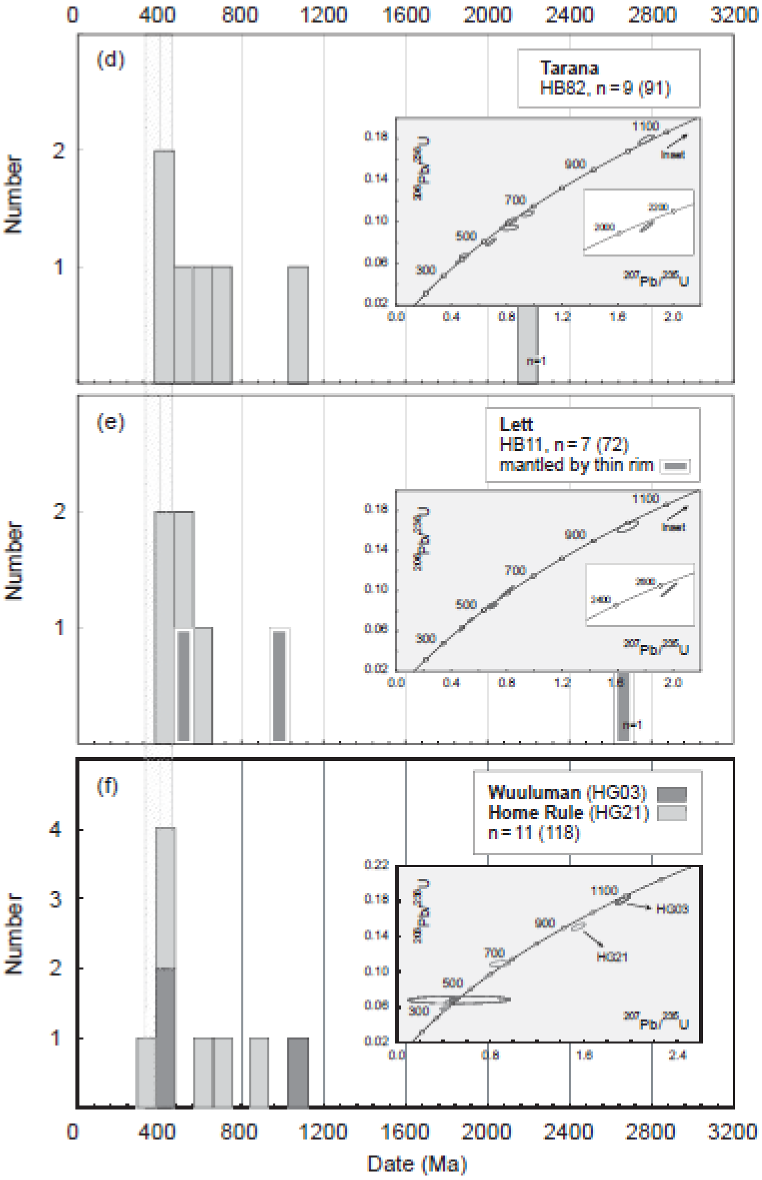

Figure 4 (continued).

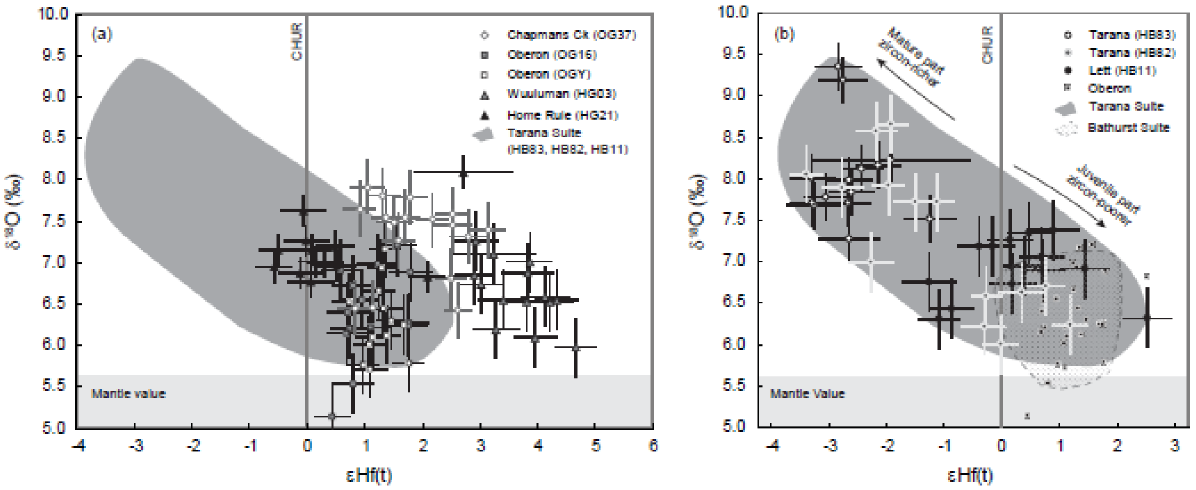
(a)
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
δ18O (‰)
CHUR
Chapmans Ck (OG37)
Oberon (OG16)
Oberon (OGY)
Wuuluman (HG03)
Home Rule (HG21)
Tarana Suite
(HB83, HB82, HB11)
Mantle value
-4
-3
-2
-1
0
1
2
3
4
5
6
εHf(t)
(b)
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
δ18O (‰)
Mature part
zircon-richer
CHUR
Juvenile part
zircon-poorer
Tarana (HB83)
Tarana (HB82)
Lett (HB11)
Oberon
Tarana Suite
Bathurst Suite
Mantle Value
-4
-3
-2
-1
0
1
2
3
εHf(t)

Figure 5

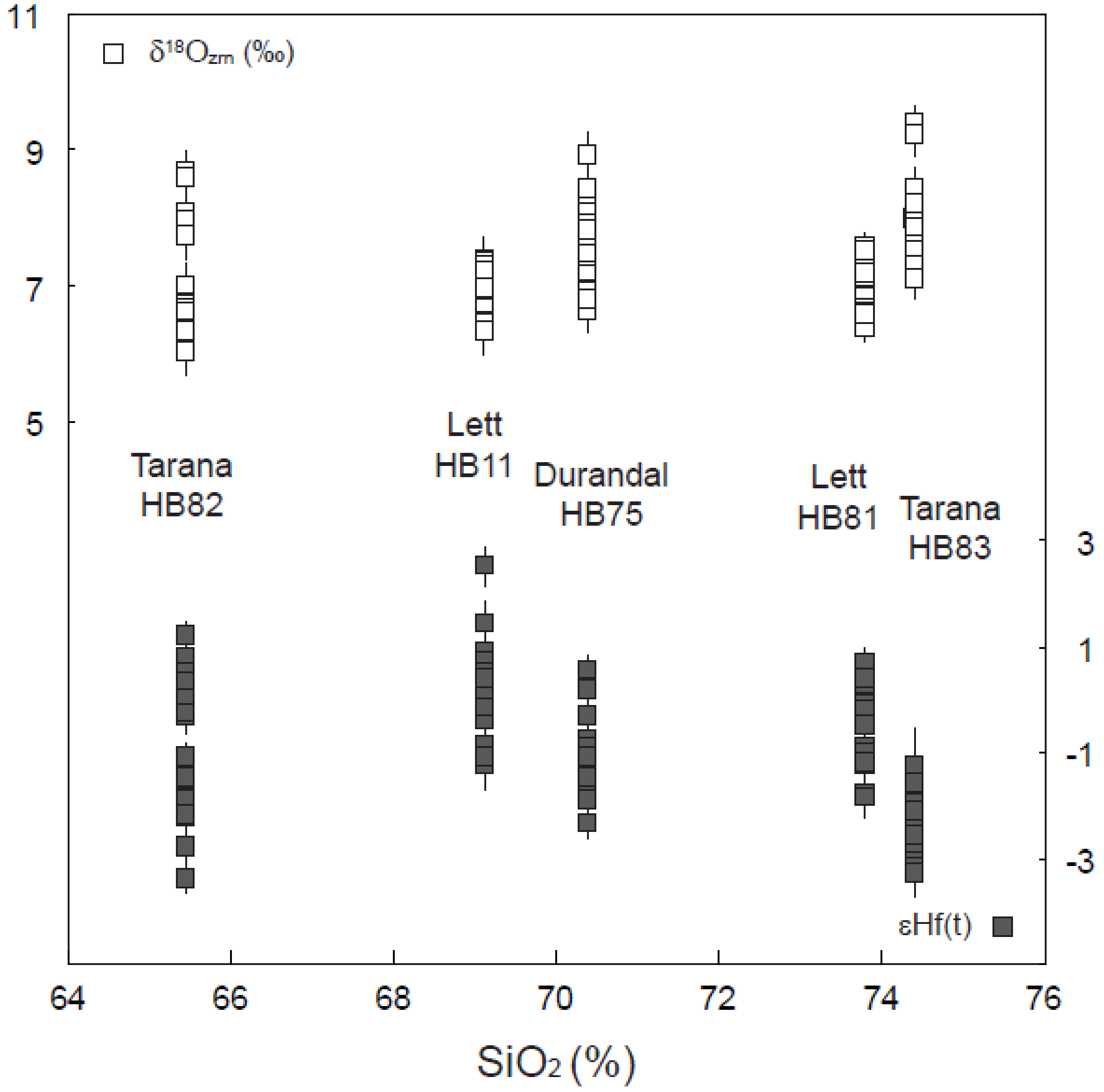
δ18Ozrn (‰)
Tarana HB82
Lett HB11
Durandal HB75
Lett HB81
Tarana HB83
εHf(t)
11
9
7
5
3
1
-1
-3
64
66
68
70
72
74
76
SiO2 (%)

Figure 6

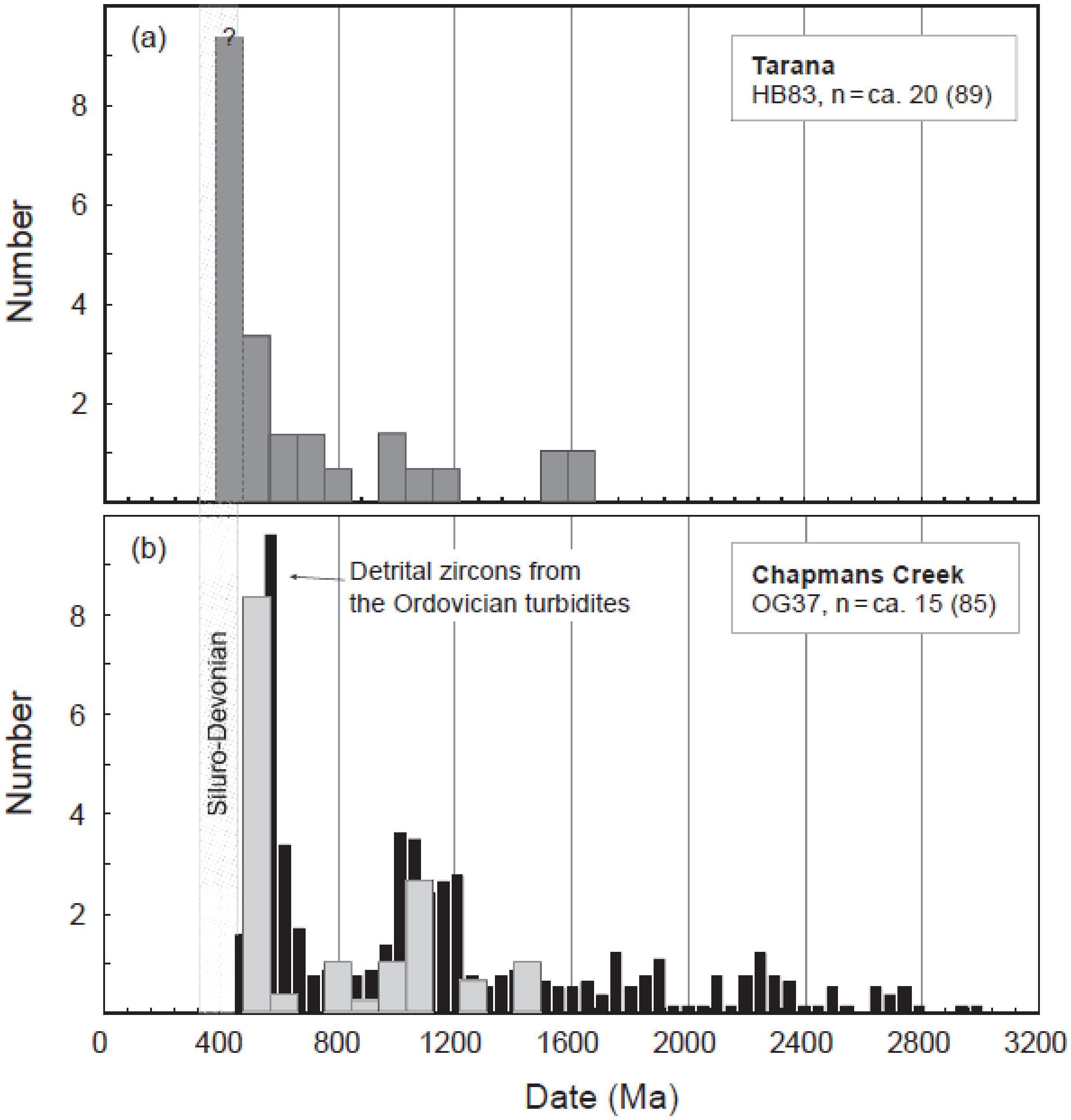
(a)
?
Tarana
HB83, n = ca. 20 (89)
Number
8
6
4
2
(b)
Detrital zircons from
the Ordovician turbidites
Chapmans Creek
OG37, n = ca. 15 (85)
Siluro-Devonian
Number
8
6
4
2
0
400
800
1200
1600
2000
2400
2800
3200
Date (Ma)

Figure 7

Table 1. Summary of O and Hf isotopic data for zircon rims from six granites of the LCG

Grain.spot	**Age [a] (Ma)**	**1σ**	**^{176}Hf/^{177}Hf(t)**	**εHf(t)**	**1σ**	**δ^{18}O (‰)**	**1σ**	**Notes**
Chapmans Creek (OG37)								
OG37-1.1	326.6 [b]	2.7	0.282651	2.52	0.28	7.59	0.32	age rejected
OG37-2.1	333.7	4.2	0.282612	1.31	0.28	7.81	0.32	
OG37-2.2	322.0	4.0				7.13	0.32	center [c]
OG37-3.1	319.7	4.4	0.282614	1.05	0.29	7.92	0.32	
OG37-4.1	325.4	4.2				6.98	0.32	
OG37-5.1	326.6 [b]	2.7	0.282669	3.15	0.29	7.40	0.32	age rejected
OG37-6.1	331.4	4.2	0.282656	2.80	0.30	7.32	0.32	
OG37-7.1	323.9	4.0	0.282607	0.91	0.26	7.65	0.32	
OG37-9.1	330.5	3.9	0.282601	0.84	0.30	6.45	0.32	center [c]
OG37-9.2	326.6 [b]					7.58	0.32	inner rim [c], no age information
OG37-9.3	326.6 [b]	2.7	0.282653	2.61	0.22	6.43	0.32	outer rim [c], no age information
OG37-10.1	320.1	3.8	0.282632	1.70	0.27	7.55	0.32	
OG37-11.1	333.0	4.0	0.282637	2.18	0.27	7.53	0.32	
OG37-12.1	323.9	4.4				6.90	0.32	core mixed?
OG37-13.1	322.5	4.1	0.282621	1.37	0.25	7.55	0.32	
OG37-14.1	331.8	4.1	0.282627	1.78	0.28	7.80	0.32	
OG37-15.1	326.6 [b]	2.7	0.282612	1.14	0.26	6.46	0.32	age rejected
OG37-16.1	326.6 [b]	2.7	0.282624	1.58	0.26	7.27	0.32	age rejected
OG37-17.1	324.0	7.6	0.282652	2.52	0.33	7.46	0.32	
OG37-18.1	324.2	4.3	0.282624	1.51	0.31	7.49	0.32	
Oberon (OG16)								
OG16-1.1	342.1	7.9	0.282597	0.95	0.31	6.55	0.35	
OG16-2.1	338.9	3.7	0.282623	1.81	0.35	6.89	0.35	
OG16-3.1	336.2	3.6	0.282595	0.75	0.32	6.21	0.35	
OG16-4.1	342.9	3.6	0.282619	1.77	0.35	6.27	0.35	
OG16-5.1	337.0	3.7	0.282623	1.76	0.33	6.24	0.35	
OG16-6.1	339.9	3.6	0.282606	1.23	0.34	6.99	0.35	
OG16-7.1	335.1	3.6	0.282606	1.11	0.33	6.22	0.35	
OG16-8.1	339.9	3.9	0.282591	0.69	0.33	6.15	0.35	
OG16-9.1	339.6 [b]	3.0	0.282594	0.81	0.35	6.73	0.35	age rejected
OG16-10.1	331.1	6.7	0.282599	0.80	0.34	5.53	0.35	
OG16-11.1	343.0	3.8	0.282586	0.59	0.33	6.91	0.35	
OG16-12.1	337.7	3.8	0.282585	0.44	0.31	5.14	0.35	
OG16-13.1	347.0	3.7	0.282611	1.56	0.34	7.21	0.35	
OG16-14.1	340.6	3.7	0.282590	0.70	0.35	6.40	0.35	
Oberon (OGY)								
OGY-1.1	342.0	3.7	0.282602	1.14	0.27	6.09	0.34	
OGY-2.1	343.3	3.6	0.282604	1.25	0.26	6.66	0.34	
OGY-3.1	340.7	3.6	0.282608	1.32	0.34	6.44	0.34	
OGY-4.1	344.1	3.6	0.282599	1.10	0.29	5.72	0.34	
OGY-4.2	332.7	3.6				6.75	0.34	center [c]

OGY-5.1	341.2	3.6	0.282609	1.39	0.22	6.12	0.34	
OGY-6.1	340.8	3.6	0.282601	1.07	0.25	6.01	0.34	
OGY-7.1	336.5	3.5	0.282594	0.73	0.27	6.53	0.34	
OGY-8.1	336.8	3.5	0.282601	0.98	0.26	5.77	0.34	
OGY-9.1	335.7	3.6	0.282595	0.74	0.23	6.52	0.34	
OGY-10.1	336.0	3.7	0.282621	1.68	0.27	6.25	0.34	
OGY-11.1	333.9	3.5	0.282625	1.77	0.25	5.79	0.34	
OGY-12.1	343.0	4.1	0.282611	1.48	0.24	6.30	0.34	
OGY-13.1	335.7	3.6	0.282611	1.30	0.24	6.94	0.34	
OGY-14.1	335.2	3.6	0.282612	1.36	0.24	7.17	0.34	
OGY-15.1	338.6	3.7				6.66	0.34	
OGY-16.1	337.8	3.6	0.282643	2.52	0.26	6.81	0.34	
OGY-17.1	332.5	3.5				6.63	0.34	
Tarana (HB83)								
HB83-1.1	331.0	3.7	0.282502	-2.66	0.41	7.98	0.27	
HB83-14.1	338.4	3.8	0.282497	-2.67	0.38	7.71	0.27	
HB83-2.1	332.8	3.8	0.282489	-3.06	0.35	7.79	0.27	
HB83-3.1	323.3	3.9	0.282489	-3.26	0.47	7.68	0.27	
HB83-15.1	331.2	4.1	0.282522	-1.93	1.36	8.23	0.27	
HB83-16.1	332.7	4.5				8.40	0.27	
HB83-17.1	331.3 [b]	2.5	0.282491	-3.02	0.35			no age information
HB83-4.1	333.9	4.6	0.282482	-3.29	0.37	7.71	0.27	
HB83-5.1	329.5	3.7	0.282497	-2.85	0.39	9.36	0.27	
HB83-9.1	332.7	11.9	0.282540	-1.26	0.45	7.52	0.27	
HB83-6.1	333.8	3.8	0.282506	-2.43	0.34	8.13	0.27	
HB83-10.1	333.7	3.6	0.282500	-2.65	0.52	7.28	0.27	
HB83-11.1	323.4	3.7				7.08	0.27	
HB83-12.1	329.4	3.8	0.282484	-3.30	0.39	8.02	0.27	
HB83-18.1	331.3 [b]	2.5	0.282532	-1.57	0.38			no age information
HB83-19.1	331.3 [b]	2.5	0.282521	-1.98	0.36			no age information
HB83-13.1	334.5	3.8	0.282514	-2.14	0.37	8.17	0.27	
HB83-7.1	330.9	4.0	0.282499	-2.76	0.41	9.20	0.27	
HB83-8.1	332.0	4.8	0.282502	-2.61	0.37	7.84	0.27	
Wuuluman (HG03)								
HG03-1.1	334.6	3.5	0.282697	4.34	0.36	6.56	0.35	
HG03-2.1	339.6	3.5	0.282681	3.88	0.37	7.01	0.35	
HG03-3.1	331.7	3.5	0.282673	3.41	0.42	6.55	0.35	
HG03-4.1	335.2	3.5	0.282656	2.91	0.31	6.85	0.35	
HG03-5.1	337.4	7.7	0.282658	3.02	0.36	6.74	0.35	
HG03-6.1	331.3	3.5	0.282688	3.96	0.36	6.10	0.35	
HG03-7.1	343.2	9.0	0.282652	2.93	0.38	7.27	0.35	
HG03-8.1	325.9	3.4	0.282673	3.29	0.39	6.20	0.35	
HG03-9.1	339.3	5.8	0.282691	4.22	0.38	6.53	0.35	
HG03-10.1	336.9	3.5	0.282705	4.67	0.35	5.98	0.35	
HG03-11.1	330.3	7.4	0.282685	3.83	0.44	6.88	0.35	
HG03-12.1	336.6	3.6	0.282665	3.24	0.70	7.11	0.35	
HG03-13.1	328.1	3.4	0.282696	4.14	0.41	6.59	0.35	
HG03-14.1	333.6	3.5	0.282683	3.81	0.34	6.53	0.35	

Home Rule (HG21)

HG21-1.1	325.1	3.7				7.54	0.18	core mixed
HG21-2.1	324.8	3.4	0.282567	-0.49	0.33	7.16	0.18	
HG21-3.1	335.6	3.5	0.282582	0.30	0.30	7.01	0.18	
HG21-4.1	327.9 [b]	3.6	0.282655	2.72	0.84	8.10	0.18	too thin, age rejected
HG21-5.1	321.5	3.8	0.282566	-0.58	0.32	6.95	0.18	center [c]
HG21-6.1	327.9 [b]	3.6	0.282581	0.07	0.34	7.16	0.18	age rejected
HG21-7.1	331.5	6.2	0.282581	0.16	0.29	7.01	0.18	
HG21-8.1	327.9 [b]	3.6	0.282577	-0.07	0.37	7.63	0.18	age rejected
HG21-9.1	330.1	6.5	0.282574	-0.12	0.36	6.88	0.18	
HG21-10.1	327.9 [b]	3.6	0.282578	-0.02	0.37	7.27	0.18	age rejected
HG21-11.1	328.9	3.5	0.282580	0.07	0.40	6.77	0.18	
HG21-13.1	330.8	12.8	0.282636	2.09	0.30	6.83	0.18	
HG21-14.1	331.3	10.6	0.282591	0.52	0.32	6.96	0.18	
HG21-15.1	327.9 [b]	3.6				7.52	0.18	age rejected
HG21-16.1	419.1	5.3				8.61	0.18	core [c]
HG21-17.1	327.9 [b]	3.6	0.282593	0.49	0.31	7.20	0.18	age rejected

All uncertainties are given at 1σ level

[a] SHRIMP ^{206}Pb/^{238}U zircon ages.

[b] Weighted mean age used for the spot with no age information or age rejected

[c] Analyzed zoning domain. All without designation " [c] " from rims

Table 2. Sr, O, SiO$_2$ compositions determined for Lockyersleigh Suite (that Chapmans Creek granite belongs) and its two main source components (source rock representative by Oberon Suite and LFB sediments)

Suite	sample id	Sr (ppm)	initial ^{87}Sr/^{86}Sr	$\delta^{18}O_{zrn}$	SiO$_{2\ WR}$[3]	$\delta^{18}O_{WR}$
Lockyersleigh	FS1167[1]	688	0.7056*			
Lockyersleigh	FS1168[1]	649	0.7050*			
Average (representative of Chapmans Ck)		**669**	**0.7053**	7.3 ‰	66.5%	8.9 ‰[4]
Oberon	FS1042[1]	688	0.7041^			
Oberon	D21[1]	525	0.7046^			
Oberon	D13[1]	685	0.7048^			
Average (representative of Oberon and/or Devonian source rock)		**633**	**0.7045**	6.4 ‰	63.6%	7.8 ‰[4]
Representative of LFB sediments[2]		**248[&]**	**0.7344[#]**			15.0 ‰

* recalcuated using Chapmans Ck age dated in this study

^ recalculated using Oberon age dated in this study

[&] average Sr concentration in the LFB clastic sediments

[#] recalculated using 327 Ma

[1] S. Shaw, unpublished data

[2] Champion et al., 2007; McCulloch and Chappell, 1982; Gray and Webb, 1995

[3] B. Chappell, unpublished data

[4] determined from $\delta^{18}O_{zrn}$ and SiO$_2$ using the equation of Lackey et al., 2008