Research article

Reconnaissance thermochronology of southern Zealandia

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Abstract: We report new fission-track, (U–Th)/He and 40Ar/39Ar ages for minerals in surface, dredge and borehole cuttings samples from the southern South Island, Campbell Plateau and Chatham Rise regions of the Zealandia continent. Our results indicate that much of southern Zealandia underwent rapid cooling in the interval 105–80 Ma, probably during widespread intracratonic rifting before Zealandia split from Gondwana. The 108±11 Ma rapid exhumation of a zircon He retention zone in the Chatham Schist, however, may record cessation of long-lived subduction at the Gondwana margin owing to Hikurangi Plateau collision and/or the onset of the extensional rifting episode. Locally, basement rocks have been appreciably heated, and thermochronological systems reset, in response to deepening of the Great South Basin and by local Miocene intraplate volcanism. An apatite fission-track age of 179±17 Ma from a dredge sample of Precambrian granite at the southern tip of the Campbell Plateau indicates that it is probably ice-rafted, thus in situ Precambrian crust in Zealandia is still unconfirmed. In contrast, a zircon (U–Th)/He age of 99±9 Ma from a Precambrian metarhyolite from Iselin Bank at the conjugate Antarctic continental margin plausibly indicates an in situ position.

Supplementary material: Detailed analytical methods and raw data are available at: http://www.geolsoc.org.uk/SUP18886.

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Zealandia is the seventh largest geological continent and lies in the SW Pacific Ocean (Fig. 1). It has a basement of Cambrian to Early Cretaceous tectonostratigraphic terranes and Cordilleran batholiths that formed along the edge of southern Gondwana. In the Late Cretaceous, widespread intracratonic rifting, followed by seafloor spreading, broke up this Palaeozoic–Mesozoic Gondwanide orogen and formed the separate continents of Zealandia, Australia and Antarctica (Mortimer & Campbell 2014). A first-order Late Cretaceous to Holocene sedimentary systems tract, the Zealandia Megasequence, developed in several sedimentary basins as Zealandia became isolated by oceanic crust of the Tasman, SW Pacific and Emerald basins (Fig. 1; Sutherland 1999; Mortimer et al. 2014). With a change to transpressional Pacific–Australian plate motions at c. 25 Ma, Zealandia underwent substantial tectonic modification in the Neogene (e.g. Kamp et al. 1989; Sutherland et al. 2009; Jiao et al. 2014; Mortimer 2014). A continental collision zone today characterizes the highest elevation part of the Pacific–Australia plate boundary and divides Zealandia into northern and southern halves (Fig. 1).

Being 94% submerged, the 4.9 Mkm2 area of Zealandia has wide continental shelves, and crustal thickness is typically only 25–30 km. This makes Zealandia a natural laboratory for intracratonic rifting. A proven approach to study tectonic development in such crustal settings is to use low-temperature thermochronology to reveal thermal history. Low-temperature thermochronology uses temperature-sensitive isotopic dating methods, most notably the fission-track (e.g. Gleadow et al. 2002; Bernet 2009), (U–Th–Sm)/He (e.g. Farley 2002; Guenthner et al. 2013) and 40Ar/39Ar (e.g. Harrison & Zeitler 2005) methods, to reconstruct the thermal history of rocks and has proved important in constraining a wide variety of geological processes. The fission-track and (U–Th–Sm)/He methods applied to apatite (AFT and AHe respectively) and zircon (ZFT and ZHe respectively) typically record patterns of geological cooling at relatively low temperatures, c. 60–120°C for AFT, 40–80°C for AHe and 140–220°C for ZHe and 180–280°C for ZFT, the variation depending on factors such as cooling rate, grain size, mineral chemistry and radiation damage. Such relatively low temperatures are characteristic of the upper few kilometres of the Earth’s crust where changes are strongly influenced by tectonic and landscape evolution processes. The cooling histories of rocks often reflect rock transport towards the surface by mechanisms including surface denudation of uplifted areas and footwall exhumation along large normal faults. They may also respond to the direct influence of heating events where these are present. In sedimentary basins, the thermochronometers may be combined with burial history and thermal history analysis as well as modelling, to provide important constraints on the timing, magnitude and duration of heating and/or cooling events.

Low-temperature thermochronology has successfully been used to investigate Zealandia’s Neogene collisional orogen in the Southern Alps and Fiordland (e.g. Tippett & Kamp 1993; House et al. 2005; Sutherland et al. 2009). In contrast, only a few scattered studies have considered the history of Zealandia outside the Neogene transpression zone (e.g. Kamp 1991, 2001; Kamp & Liddell 2000; Reiners et al. 2004; Jiao et al. 2014; Ring et al. 2015).

The purpose of this paper is to present new results of a low-temperature thermochronological investigation of rock samples from southern Zealandia well outside the Neogene collision zone, especially from the Campbell Plateau and Chatham Rise (Fig. 2). It is important to establish the thermochronological history of this part of Zealandia because, in contrast to northern Zealandia, most of it appears to have experienced minimal tectonic modification since the Late Cretaceous. As such, southern Zealandia provides an essential thermochronological reference frame against which subsequent deformation in the continent can be measured. In this paper we report 16 fission-track ages, 16 helium ages (based on 56 single-grain ages) and four 40Ar/39Ar ages, and incorporate them with...
existing reference data to build a regional picture. Three research questions were posed at the start of the study. (1) At what time or times did the southern Zealandia continental crust become tectonically and thermally stable? (2) Can thermochronological signatures (i.e. apparent ages) be plausibly related to subduction cessation, intracontinental rifting and continent–ocean rifting episodes? (3) Can thermochronology data be used to test whether two Precambrian igneous rock dredges are in situ or ice-rafted? We address the three questions with varying degrees of success. It should be noted that our southern Zealandia dataset differs from classic thermochronological datasets in that the samples are very widely scattered and there are no altitudinal profiles. For this first-order reconnaissance study no thermal modelling has been carried out.

This paper builds on, develops and integrates themes from several earlier papers including the aforementioned studies of Zealandia basement, the basement geology and crustal structure of the Campbell Plateau (Challis et al. 1982; Beggs et al. 1990; Grobys et al. 2007, 2009; Adams 2008), Gondwana rifting and breakup (O’Sullivan et al. 2000; Kula et al. 2007, 2009; Gohl 2008), local sedimentary basin development (Cook et al. 1999) and Zealandia intraplate volcanism (Hoernle et al. 2006; Timm et al. 2010).

Geological background

Campbell Plateau and Chatham Rise are the names for two major bathymetric highs that dominate southern Zealandia and that lie east of the South Island and Stewart Island (Fig. 2). Southern Zealandia is the largest piece of continental crust on the Pacific Plate (the only other being the Salinian Block west of the San Andreas Fault). Rock outcrops are sparse, occurring only as surface exposures on the Chatham Islands and some of the Subantarctic Islands. Natural exposures are supplemented by rock samples from oil exploration boreholes, and research cruise dredges. Ocean Drilling Program boreholes in southern Zealandia have never penetrated to continental basement.

The regional basement geology has been outlined by Beggs et al. (1990) and Mortimer (2008). Two major features of the Mesozoic Gondwana orogen, Median Batholith and Haast Schist, can be extrapolated eastward from South Island to correlations in the Bounty and Chatham Islands (Fig. 2; Mortimer 2008, 2014). These represent a Mesozoic magmatic arc and its Mesozoic accretionary wedge, respectively. Between these two units lie weakly metamorphosed sedimentary Mesozoic forearc terranes. The southern part of Campbell Plateau is inferred to be underlain by Early Palaeozoic terranes intruded by Phanerozoic granitoids and, possibly, Precambrian granite (Beggs et al. 1990; Challis et al. 1982; Adams 2008). Many of the above have correlatives in formerly conjugate Antarctica and Australia. The continent–ocean boundary between the Chatham Rise and Hikurangi Plateau is the surface trace of the Mesozoic subduction zone (Davy et al. 2008; Davy 2014) to which the Haast Schist and Median Batholith were genetically related (Mortimer 2008). At some time in the Late Cretaceous interval 105–85 Ma, long-lived subduction at the Zealandia part of the Gondwana margin ceased and was replaced by a regime of intracratonic rifting and volcanism. The sedimentary basins of the Bounty Trough and Great South Basin developed post-100 Ma and Zealandia started to split away from Antarctica and Australia in the interval 85–80 Ma (Sutherland 1999; Davy 2006). Nonetheless our sample set does provide reasonable thermochronological data coverage of southern Zealandia, at least on a reconnaissance basis.

Sampling and methods

Most of the samples for this investigation were obtained from existing institutional collections at GNS Science (P and R prefixes) and Otago University (OU prefix), but five Chatham Islands and South Island samples were specifically collected for this study and given P numbers (P80686 to 82333). Many samples, particularly of borehole cuttings and dredges, were <100g and it was not possible to separate sufficient quantities of apatite from the Snares Islands, Auckland Islands or Stuttgart Seamount samples (Fig. 1). Nonetheless our sample set does provide reasonable thermochronological data coverage of southern Zealandia, at least on a reconnaissance basis.
**Fission-track and He dating**

Minerals were extracted from rocks using standard mineral separation techniques. AFT and ZFT samples analysed by Seward (Table 1) were prepared as follows. Polished grains were etched in 7% HNO₃ for 45 s at 21°C to reveal the fossil tracks. Neutron irradiation was carried out at the ANSTO facility, Lucas Heights, Australia. Samples were counted at ×1250 magnification for apatites and ×1600 under oil for zircons. Ages were determined using the zeta factor approach (Hurford & Green 1983). Zeta for apatite/CN5 is 355 ± 5 and for zircon/NBS612 is 338 ± 5. All ages are central ages (Galbraith & Laslett 1993) and errors were calculated according to Green (1981).

For AFT samples analysed by Kohn at the University of Melbourne a relatively new method was employed. This uses a combination of automated track counting (Gleadow et al. 2009) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS; Hasebe et al. 2004), the latter replacing conventional U determination via neutron irradiations. Methods for AHe and ZHe samples analysed by Kohn at the University of Melbourne follow those described by Tian et al. (2012, 2013).

**40Ar/39Ar dating**

Samples were analysed by Spell at the University of Las Vegas. Mineral separates were irradiated for 7h at the US Geological Survey TRIGA Reactor along with Fish Canyon Tuff sanidine, synthetic K-glass and optical grade CaF₂ to monitor neutron dosage (J-factor) and interfering neutron reactions on K and Ca. Repeated analysis of K-glass and CaF₂ fragments yielded correction values. Calculated J-factors assume an age of 28.02 Ma for Fish Canyon Tuff sanidine (Renne et al. 1998). J-values from analysis of Fish Canyon Tuff sanidine were determined by fusion (20W CO₂ laser) of 4–8 crystals from each standard location in the irradiation tube and interpolating J-values to the sample locations using the Matlab curve-fitting toolbox. Discrimination was determined by measured 40Ar/36Ar ratios of repeated analysis of atmospheric argon aliquots from an on-line pipette system. Samples were step heated in a double vacuum resistance furnace similar to the Staudacher et al. (1978) design. Prior to admittance to an MAP 215-50 mass spectrometer by expansion, reactive gases were removed by three GP-50 SAES getters. Peak intensities for argon isotopes 36–40 were measured using a Balzers electron multiplier by peak hopping through seven cycles for linear regression to the time of gas admittance. Plateau ages are defined as a segment of the age spectrum that consists of three or more steps, comprising >50% of the total gas released, that overlap in age at the ±2σ analytical uncertainty level.

**Results**

Our fission-track, helium and 40Ar/39Ar thermochronological data are summarized in Table 1. Weighted mean ages were calculated using the Isoplot Excel add-in (Ludwig 2003). All data have been...
Table 1. Summary of new thermochronology data for southern Zealandia

| Location Islands                      | Sample      | Latitude (deg.) | Longitude (deg.) | Elevation | Rock Protolith age | Mineral Method Analyst | Age (Ma ± 2σ) |
|--------------------------------------|-------------|-----------------|------------------|-----------|--------------------|-----------------------|---------------|
| **Bounty Islands**                   |             |                 |                  |           |                    |                       |               |
| Bounty Islands, Tunnel Is. sea level | R06182      | −47.7502        | 179.0500         | 0         | Granodiorite       | Rb–Sr1 Zircon He B.K.  | 140 ± 29      |
| Bounty Islands, Tunnel Is summit     | R06182      | −47.7502        | 179.0500         | 0         | Granodiorite       | Rb–Sr1 Zircon He B.K.  | 117 ± 26      |
| Bounty Islands, Depot Island         | R0721       | −47.7515        | 179.0331         | 10        | Granodiorite       | Rb–Sr1 Zircon He B.K.  | 92 ± 17       |
| Bounty Islands, Funnel Island        | R10730      | −47.7630        | 179.0417         | 10        | Granodiorite       | Rb–Sr1 Zircon He B.K.  | 136 ± 16      |
| Bounty Islands, Penguin Island       | R10731      | −47.7537        | 179.0189         | 10        | Granodiorite       | Rb–Sr1 Zircon He B.K.  | 78 ± 11       |
| **Chatham Rise region**              |             |                 |                  |           |                    |                       |               |
| Chatham Islands, Forty Fours         | P40482      | −43.9600        | −175.8330        | 10        | Greywacke          | 256 Ma det zc² Zircon He B.K. | 141, 155, 186, 212 |
| Chatham Islands, Cape Pattison       | P82333      | −43.7483        | −176.8035        | 0         | Greyschist TZ2A    | K–Ar wr3 Zircon He B.K. | 121 ± 26      |
| Chatham Islands, Tuhurangi Creek     | P80687      | −43.7504        | −176.2328        | 0         | Greyschist TZ2A    | K–Ar wr3 Zircon He B.K. | 107 ± 8       |
| Chatham Islands, Whangaweta CIx99    | P80697      | −43.7390        | −176.3457        | 0         | Sandstone          | 115 ± 1 Ma U-Pb det zc⁴ Zircon He B.K. | 111 ± 32     |
| Chatham Islands, Point Somes         | P82316      | −43.8450        | −176.8546        | 0         | Greywacke          | 115 ± 1 Ma U-Pb det zc⁴ Zircon He B.K. | 110 ± 10      |
| Wishbone Ridge dredge, 2900 m        | P67415      | −40.7607        | −169.8438        | 0         | Granite            | 115 ± 1 Ma U-Pb det zc⁴ Zircon He B.K. | 99 ± 7        |
| Takahe Seamount dredge, 2750 m       | P67437      | −40.6169        | −168.7539        | 0         | Granite            | 115 ± 1 Ma U-Pb det zc⁴ Zircon He B.K. | No interpretable ages |
| Stuttgart Seamount dredge, 4000 m    | P67458      | −45.8847        | −173.2612        | 0         | Greywacke          | 146 Ma Ar–Ar white mica³ Zircon He B.K. | 141, 155, 186, 212 |
| **Stewart, Snares and South Islands**|             |                 |                  |           |                    |                       |               |
| South Island, Porpoise Bay           | P80920      | −46.6467        | 169.1384         | 0         | Granite egl clast  | 188–172 Ma deposition³ Zircon He B.K. | 132 ± 19      |
| Stewart Island, Sisters Bay          | P75047      | −47.1813        | 167.7905         | 0         | Two-mica granite   | 188–172 Ma deposition³ Zircon He B.K. | 167, 440, 468 |
| Snares Islands, Station Point        | P63318      | −48.0225        | 166.6102         | 10        | Granite            | 109 Ma U–Pb zc³ Zircon He B.K. | 104 ± 1       |
| **Great South Basin**                |             |                 |                  |           |                    |                       |               |
| Kauai-1A borehole 3786 m             | –           | −48.9290        | 169.1011         | −3107     | Metagreywacke      | 298 ± 6 Ma K–Ar we⁶,⁸ Zircon He B.K. | 260 ± 36      |
| Pakaki-1 borehole 3661 m              | –           | −48.5856        | 170.1519         | −2780     | Two-mica granite   | 107 ± 3 Ma U–Pb zc³⁸ Zircon He B.K. | 16 ± 4        |
| Pakaki-1 borehole 3661 m              | –           | −48.5856        | 170.1519         | −2780     | Two-mica granite   | 107 ± 3 Ma U–Pb zc³⁸ Zircon He B.K. | 70 ± 20       |
| Pakaki-1 borehole 3667 m              | –           | −48.5856        | 170.1519         | −2780     | Two-mica granite   | 107 ± 3 Ma U–Pb zc³⁸ Zircon He B.K. | 15 ± 4        |
| Pakaha-1 borehole 3350 m              | –           | −48.5856        | 165.5949         | −2665     | Biotite granite    | 32 Ma U–Pb zc³⁶ Zircon He B.K. | 1.7 ± 0.6     |
| Pakaha-2 borehole 3360–3363 m         | –           | −48.5856        | 165.5949         | −2665     | Biotite granite    | 32 Ma U–Pb zc³⁶ K-fsp Ar–Ar T.S. | 99–127       |
| Tara-1 borehole 4374 m                | –           | −47.3183        | 169.1683         | −4247     | Conglomerate       | 100–84 Ma deposition³ Zircon He B.K. | 75 ± 11       |
| **Outer Campbell Plateau and Antarctica**|             |                 |                  |           |                    |                       |               |
| Campbell Island, Garden Cove         | R23636      | −52.5555        | 169.1355         | 10        | Greywacke          | 526 Ma Rb–Sr isochron¹ Zircon He B.K. | 9.3 ± 1.6     |
| Campbell Island, Complex Point       | R23627      | −52.5406        | 169.0695         | 60        | Greywacke          | 462 Ma Rb–Sr isochron¹ Zircon He B.K. | 8.5 ± 1.6     |
| Auckland Island, Crab Bay             | O21581      | −50.8095        | 166.0605         | 0         | Granite            | 36 Ma U–Pb zc³ K-fsp Ar–Ar T.S. | 34–89        |
| S Campbell Plateau, S100 dredge, 2370 m| R06865      | −54.8567        | 165.2250         | 0         | Granodiorite       | 117 ± 9 Ma U–Pb zc⁰ Zircon He B.K. | 178 ± 17      |
| Iselin Bank, Lee 17 dredge, 250 m     | P50867      | −73.7000        | −176.4667        | 0         | Metahalloysite     | 545 ± 73 Ma U–Pb zc¹ Zircon He B.K. | 160, 171, 215, 219 |

Protophyle ages from 1Adams (2008), 2Adams et al. (2008), 3Adams & Robinson (1977), 4Mortimer et al. (2006), 5Cook et al. (1999), 6Allbone & Tulloch (2004), 7Scott et al. (2015), 8Beggs et al. (1990), 9Adams et al. (2015) and 10Mortimer et al. (2011). Latitude and longitude WGS84 decimal degrees. Elev. elevation in metres above sea level for land samples, or below seabed for borehole and dredge samples; Tz, textural zone; cgl, conglomerate; w, whole-rock; d, detrital, zc, zircon. Ages in regular font are our reported helium and fission-track ages based on multiple grains and/or Ar–Ar plateau ages. Ages in italics are single helium grain ages that do not constitute a statistical population or are a range of Ar–Ar step heating ages.
lodge in the online Petlab geoanalytical database (http://pet.gns.cri.nz). Except where explicitly noted, all ages reported in the main text and diagrams of this paper are shown with 2σ errors or at the 95% confidence level.

**Bounty Islands**

The Bounty Islands are composed of an Early Jurassic granite (Adams 2008) with K–Ar biotite cooling ages ranging from 192 ± 3 to 177 ± 3 Ma (recalculated from Adams & Cullen 1978). There is no sedimentary cover. We analysed apatite and zircon from the granite for both fission-track and helium ages in five separate samples and these represent the most complete thermochronology dataset reported in this paper (Fig. 3a). The sample sites span only 40 m in elevation difference, and there are no AFT age differences with altitude. The weighted mean of our five ZFT ages is 105 ± 8 Ma. The weighted mean of our two AFT ages is 80 ± 6 Ma.

For both apatite and zircon, our fission-track ages are 20–30 m.yr younger than the central He ages (Fig. 3a). This is counter to conventional understanding of effective closure temperatures for fission tracks and He accumulation in these minerals. However, there are documented cases of apatite He ages being older than coexisting AFT ages, as discussed by Fitzgerald et al. (2006), Shuster et al. (2006), Brown et al. (2013) and Jiao et al. (2014). Among the reasons discussed by those researchers the effect of variation in grain size, accumulation of α-radiation damage and crystal breakage are arguably amongst the most important factors, which may lead to age dispersion of the order of 50–100%. Age variation owing to crystal breakage was not evaluated in those studies, but most grains do not preserve their original form. Since the advent of modern (U–Th)/He thermochronology, several studies have demonstrated the potential of ZHe dating (e.g. Reiners et al. 2004; Reiners 2005; Wolfe & Stockli 2010). Although thermally activated volume diffusion is thought to be central in controlling He migration, crystal defects and especially radiation damage are also considered important (Guenthner et al. 2013), but their precise role is not well understood. Furthermore, the possibility of U and Th zonation in crystals may also introduce uncertainties in age determinations when applying the α-ejection correction. Similar to the case with our Bounty dataset, Kohn et al. (2014) previously reported examples where ZHe ages are older than their coexisting ZFT ages. These findings of an apparent reversed age relationship suggest that factors controlling annealing of α-damage in relation to FT damage in apatite and zircon are not well understood and invite further investigation.

**Chatham Rise and Islands**

We carried out ZHe age determinations on six samples of schist and greywacke from the Chatham Islands; apatite was recovered in sufficient quantity in only one sample (Table 1; Figs 3b and 4). The sample sites are all at or near sea level and span a 90 km east–west baseline (simplified at the scale of Fig. 2). Despite the lack of an altitudinal gradient the samples were collected across a pronounced metamorphic gradient. The easternmost sample, P40482 from the Forty Fours, is an unfoliated greywacke of the accretionary wedge Rakaia Terrane and has a youngest detrital zircon U–Pb peak population age of 256 Ma. Samples P80686, 82333 and R23825 are from the so-called Matarakau Greywacke unit of Adams & Robinson (1977); however, in reality this is a weakly foliated (textural zone 2A) schist of distinctly higher metamorphic grade than the Forty Fours sample. P80687 is a slightly higher grade schist again (textural zone 2B) and one sample from westernmost Chatham Island, PS2316, is from the deepest structural and metamorphic levels of the exposed Chatham Schist: chlorite zone greenschist facies.

ZHe ages from the two lowest metamorphic–textural grade samples in the Chatham Islands did not give statistically valid pooled ages. Apparent single ZHe grain ages in these samples are in the range of c. 212–46 Ma and c. 167–139 Ma (Table 1; Fig. 4). Probably this is because these rocks experienced a weak thermal overprint that only partially reset detrital grain ages, but was not sufficient to completely reset ages during regional metamorphism. However, for greywacke sample P40482 there is also a clear α-radiation damage effect whereby reduction in age shows a general correlation with greater U and Th content. Therefore, we do not assign any significance to the single grain ages from these low-grade samples. In contrast, four higher grade Chatham Schists have ZHe ages ranging from 121 to 107 Ma irrespective of metamorphic grade (Fig. 4). The geometric array of age vs. grade reveals the presence of a partial He retention zone in the Chatham Schist (dashed envelope in Fig. 4). The weighted mean of the four ZHe ages is 108 ± 11 Ma and this can be regarded as the interval during which the entire Chatham Schist basement cooled below c. 180–200°C. A single AFT age of 80 ± 14 Ma was obtained from P80687. In contrast to the Bounty Islands, there are cover rocks (Zealandia Megasequence) resting unconformably on basement in the Chatham Islands. The Waihere Bay Group lies 60 km south of the nearest Chatham Schist outcrops. It is dated as Motuan (103–99 Ma) in age with upper parts as young as Teratan 90–86 Ma (Fig. 3b; Campbell et al. 1993). A Waihere Bay Group sandstone contains Permian detrital zircons, presumably derived from local greywacke or schist basement (Adams et al. 2008). Relatively rapid cooling of Chatham Schist can be inferred from the data plotted in Figures 3b and 4.

There are three other samples in our dataset from the general vicinity of the eastern Chatham Rise; protoliths of these samples were reported by Mortimer et al. (2006). AHe and ZHe ages from siliceous igneous and volcanioclastic rocks dredged from the Wishbone Ridge and Takahe Seamount are both within error of their protolith (U–Pb zircon) ages. In the case of the Wishbone volcanioclastic sandstone (not shown in Fig. 3), the AHe age of 110 ± 10 Ma indicates no demonstrable reheating or resetting by sedimentary burial since eruption of associated dacites at 115 ± 1 Ma. In the case of the 97 ± 1 Ma Takahe A-type granite from the eastern tip of Zealandia, the near-identical ZHe age of 99 ± 7 Ma and AHe age (101 ± 6 Ma) ages also suggest rapid cooling (Fig. 3b), which fits with the rift interpretation for the granite (Mortimer et al. 2006). The third sample is a greenschist–amphibolite-facies schist dredged from a water depth of 4000 m on Stuttgart Seamount, on the Southeast Chatham Terrace. A total of 27 apatite grains were examined from this sample and all showed very low U content, usually in the range 0.1–0.4 ppm, and most contained dislocations and inclusions. These characteristics rendered the sample unsuitable for apatite dating. Similar analytical issues, particularly the very low U content, have been noted for many Haast Schist metamorphic apatites in the South Island (e.g. Kamp et al. 1989; Tippett & Kamp 1993; Batt et al. 2000). Although these samples were not suitable for dating, our observations of unusually low-U apatites do further support previous correlation of this rock with Haast Schist (Mortimer et al. 2006).

**Stewart, Snares and South Islands**

Kula et al. (2007) described a Late Cretaceous metamorphic core complex, Sisters Shear Zone, straddling the SE coast of Stewart Island, and there has been some effort to characterize the thermal evolution of the hanging-wall and footwall blocks of this structure (Fig. 3c; Kula et al. 2007, 2009; Ring et al. 2015).

Muscovite was extracted from P75047, a two-mica granite in the hanging-wall block, <200 m structurally above the Sisters Shear Zone detachment fault. The granite is similar to the 115–105 Ma Campsite Pluton of Allibone & Tulloch (2004). Muscovite
from P75047 exhibits a flat, concordant age spectrum (Fig. 5a). The total gas age is 103.5 ± 1.0 Ma. Steps 2–13 (97% of the 39Ar released) define a statistical plateau age of 103.5 ± 1.1 Ma. There is no isochron defined by the data. The plateau age is the most reliable for this sample, which can be interpreted as having cooled rapidly through 350 ± 50°C at 103.5 Ma. This plateau age is intermediate between equivalent hanging-wall (K-feldspar) ages and the muscovite plateau ages reported for three footwall samples, P77057, P76106 and P77499, which are up to 7 km along-strike from P75047 in both directions (Kula et al. 2009). The Sisters Shear Zone is poorly mapped in this, its northeastern part, particularly near P75047. We suggest that the proximity of P75047 to the shear zone and hot footwall block explains its younger age compared with other hanging-wall samples (Fig. 3c).

Muscovite from Snares Island granite P63138 also exhibited a flat, concordant age spectrum (Fig. 5b). The total gas age is 99.6 ± 1.1 Ma. Steps 1–14 (99.9% of the 39Ar released) define a statistical plateau age of 99.8 ± 1.1 Ma. Steps 1–13 (99.7% of the 39Ar released) yield a well-defined, statistically valid isochron of 99.5 ± 0.8 Ma. The isochron gives an initial 40Ar/36Ar isotopic ratio for this sample of 295 ± 7 (indistinguishable from the atmospheric ratio), indicating that no excess argon is present. The isochron age is the most accurate and reliable for this sample, which can be interpreted as having cooled rapidly through 350 ± 50°C at 99.5 Ma. This compares with the Snares Granite protolith age of 109 Ma (Scott et al. 2015).

We obtained an AFT age of 133 ± 20 Ma age (based on analysis of three grains only) from a granite clast from Jurassic forearc basin strata exposed on the Catlins coast of the South Island (Figs 2 and 3c). This is the first published AFT age from the Murihiku Terrane of the South Island. AHe ages on three grains from the same sample produced much older ages (Table 1); these excess He ages could result from a number of factors (see above). Our 133 ± 20 Ma age is slightly older than but still within error of AFT ages reported by Kamp & Liddell (2000) from coeval strata.
in the same terrane c. 700 km along-strike in New Zealand’s North Island. Nine samples from the Kamp & Liddell (2000) dataset gave a pooled AFT age of 114 ± 12 Ma (Fig. 3c), a remarkable similarity given their spatial separation.

We have no new thermochronological data of our own from the Mesozoic accretionary wedge terranes elsewhere in the South Island but here summarize existing datasets in a southern Zealandia context. Tippett & Kamp (1993) and Kamp (2001) published AFT and ZFT results from transects in the Torlesse Terrane greywacke and Haast Schist of South Island (i.e. the equivalents of the Torlesse Terrane greywacke and schist). The Haast Schist in the Southern Alps has been very rapidly exhumed and yields AFT and Haast Schist of South Island (i.e. the equivalents of the Torlesse Terrane greywacke and schist). The Haast Schist in the Southern Alps has been very rapidly exhumed and yields AFT ages <1 Ma and ZFT ages 15–2 Ma (Fig. 2). Outside this zone of rapid exhumation, samples from the Rakaiwa, Waitai and Lindis regions (Fig. 2) give Early Jurassic to Early Cretaceous K–Ar ages, Early Jurassic to Late Cretaceous ZFT ages (Fig. 4) and Late Cretaceous to Paleocene AFT ages. K–Ar and ZFT ages show an inverse relationship with metamorphic grade (Adams 1985; Mortimer 2003).

Great South Basin

Our dataset includes basement samples from the bottom of Great South Basin wells Kauai-1, Pukai-1 and Pakaha-1, and a Late Cretaceous conglomerate from Tara-1 well, which was not drilled to basement. Most of these samples were obtained from 2600–3100 m below the sea bed with only Tara-1 basement being deeper (Fig. 6). Previously Kamp (1991) described AFT ages from Zealandia Megasequence cover in Canterbury Basin wells Endeavour-1 and Galleon-1 (Fig. 2).

Present-day temperatures at the bottom of Great South Basin wells are typically 130–150°C (Funnell & Allis 1996). Progressive downhole reduction in Endeavour-1 AFT ages was noted by Kamp (1991). As expected, our bottom-hole AFT ages are reset to near zero and ZFT ages show partial resetting (they are younger than any of the aforementioned Bounty Island or South Island ZFT ages).

K-feldspar from Pakaha-1 Carboniferous granite P57235 exhibited an extremely discordant age spectrum (Fig. 5c) and could not be modelled using the multi-domain diffusion (MDD) method. The initial c. 20% 39Ar released shows the effects of large amounts of excess argon, obscuring the lowest temperature thermal history. Beginning at step 16 ages are c. 100 Ma and exhibit a steep age gradient to 121 Ma followed by a decrease and increase in age to step 36 at 127 Ma. The remaining steps are above the melting point and thus do not record thermochronological information. There are no plateau or isochron ages defined by these data. The relatively flat age spectrum followed by a steep stair-step decrease between steps 16 and 36 could be interpreted as rapid cooling in the Early Cretaceous (c. 120 Ma) followed by slow cooling to c. 100 Ma.

Southern Campbell Plateau and Iselin Bank

Two Campbell Island basement samples are from low-grade schist, which has a youngest detrital U–Pb zircon peak of 524 ± 6 Ma (Adams 2008) and K–Ar age of 443 ± 6 Ma (Adams et al. 1979). This basement rock forms just two small inliers on Campbell Island, the geology of which is dominated by intraplate volcanic rocks of Late Miocene (11–7 Ma) age (Adams et al. 1979). We had planned to use ZHe and AFT ages to try to establish the Palaeozoic–Mesozoic cooling history of this part of the Campbell Plateau. However, the AFT (9.3 ± 1.6 Ma) and ZHe (8.5 ± 1.6 Ma) ages for Chatham Islands samples plotted against metamorphic–textural grade. Chathams K–Ar and U–Pb data from Adams & Robinson (1977) and Adams et al. (2008). South Island zircon fission-track (ZFT) reference data from Tippett & Kamp (1993) and Kamp (2001).

Fig. 4. ZHe ages for Chatham Islands samples plotted against metamorphic–textural grade. Chathams K–Ar and U–Pb data from Adams & Robinson (1977) and Adams et al. (2008). South Island zircon fission-track (ZFT) reference data from Tippett & Kamp (1993) and Kamp (2001).
An assortment of igneous cobbles was dredged from the southern tip of the Campbell Plateau (Figs 2 and 7) and reported by Challis et al. (1982). Most of the dredged rocks were interpreted as ice-rafted erratics but at least one granite block (S100a = R6865) was considered to possibly be in situ on the basis of its angularity. Challis et al. (1982) obtained Precambrian K–Ar ages from R6865, recently corroborated by a U–Pb zircon age of 1170 ± 9 Ma (Adams et al. 2015). An X-ray fluorescence analysis of the sample reveals an I-type to weakly A-type composition. We obtained an AFT age of 179 ± 17 Ma for R6865. The four AHe grain ages obtained from this sample were in the range 219–160 Ma (Table 1) but a statistically valid AHe age cannot be calculated. The Early Jurassic AFT age is clearly much older than any otherapatite age we have obtained from southern Zealandia (compare Fig. 3d with Fig. 3a–c). Jurassic AFT ages are reported from East Antarctica (see Fig. 7, and discussion below).

Another Precambrian rock, metarhyolite P50869, has been dredged from the Iselin Bank (Figs 2 and 7), a part of the West Antarctic continental margin that was formerly conjugate with Zealandia (Wong et al. 1987). A 545 Ma protolith age was reported by Mortimer et al. (2011). We obtained a ZHe age on this rock to shed light on whether it was plausibly in situ or not. The ZHe age of 99 ± 9 Ma is similar to both our Campbell Plateau–Chatham Rise ZHe datasets and also to limited ZFT data from West Antarctica (Figs 3d and 7; Adams et al. 1995).

Discussion

Because of the large lateral distances between our samples, the treatment of the ages is somewhat different from that in a standard regional thermochronological study, which routinely reports data from closely spaced samples, often in an altitudinal profile. Furthermore, we do not have sufficient and/or suitable data to carry out t–T modelling on these samples. As such, we focus on the regional map pattern and provide a broad interpretation where we adopt commonly used estimated closure temperatures for mineral systems as listed by Braun et al. (2006) as follows: AHe 75 ± 5°C, AFT 100 ± 10°C, ZHe 180–200°C, ZFT 240 ± 30°C, K-feldspar Ar 150–350°C, biotite Ar 300 ± 50°C and muscovite Ar 350 ± 50°C. However, it should be borne in mind that variations outside these temperature ranges are possible owing to different factors within each system, as mentioned above. Figure 8 is our synthesis of the thermotectonic framework of southern Zealandia.

Reset ages

Given the bottom-hole temperatures in the Great South Basin oil exploration wells, we predicted and found disturbed and/or reset AFT basement ages from 2 to 4 km below seabed. We had hoped to obtain clear Mesozoic age signals from apatite and zircon on Campbell Island and from K-feldspar on the Auckland Islands. Unfortunately, this was not the case, as our data show that conductive heat from Miocene volcanoes has affected these rocks. This prevented us from completing a 1500 km long Cretaceous thermochronological transect across southern Zealandia (Figs 8 and 9). Interestingly, even though the Chatham Islands have been the site of repeated Late Cretaceous, Eocene and Pliocene intraplate volcanism, our Chatham samples seem unaffected. Intraplate volcanic rocks are widespread across southern Zealandia (Fig. 8; Timm et al. 2010) and any future sampling in the region should be cognisant of the potential for resetting of low-temperature thermochronometers. Figure 8 also shows the Neogene AFT and AHe ages of the South Island mountains in context: most of Zealandia has not experienced such young exhumation.

Syntectonic stabilization

As mentioned above and is clear from Figures 3 and 9, the apatite and zircon ages from the Chatham and Bounty islands are similar both to each other and to equivalent Mesozoic accretionary wedge and batholith units along-strike in Stewart and South islands. Collectively, the Chathams, Bounty, Snares, Stewart and South Island data lead us to an interpretation of widespread cooling across southern Zealandia in the interval 105–80 Ma (early Late Cretaceous). Assuming a geothermal gradient of 20–30°C km⁻¹ this approximates to an extensive denudation of 6–10 km of the upper crust since c. 105 Ma (Kula et al. 2007). In the Chathams the presence of sedimentary cover ‘forces’ the cooling rate and denudation rate to be high (Fig. 3b), and rapid cooling possibly predicates.
95 Ma. Takahe Seamount granite, with AHe and ZHe ages within error of the 97 Ma U–Pb emplacement age, affirms such a rapid cooling scenario. Most rocks in the Takahe dredge were cut by mylonites and characterized by epidotized and/or hematized cooling scenario. Most rocks in the Takahe dredge were cut by mylonites and characterized by epidotized and/or hematized microfaults as well (Mortimer et al. 2006, supplementary data), supporting the proposition that the entire eastern Chatham Rise underwent wholesale intracontinental rifting in the Late Cretaceous (Wood et al. 1989). Tulloch et al. (2009) noted pulses of intraplate magmatism across Zealandia at c. 102, 97 and 88–82 Ma (Fig. 9). Our thermochronological resolution of 115–80 Ma tectonic events in southern Zealandia is, so far, too imprecise to be able to suggest a causative relationship with the magmatic pulses.

On Stewart Island, the better exposed geology and application of multiple thermochronometers (Fig. 3c) allowed Kula et al. (2007, 2009) to identify a metamorphic core complex (tectonic denudation) in which footwall cooling began at c. 94 Ma and accelerated in the interval 89–82 Ma (Fig. 9). Our contention that most denudation was tectonic, rather than erosional, has major implications for palinspastic reconstructions of Zealandia. A non-rigid, rather than rigid, Zealandia must be accommodated in plate reconstructions (Grobys et al. 2008; Mortimer 2014).

In summary, the metamorphic core complex geometry on Stewart Island (Kula et al. 2009), graben identified on the Chatham Rise (Wood et al. 1989), and widespread faulted basement, relatively thin synrift sedimentary isopachs and beta factors of up to two on parts of the Campbell Plateau (Cook et al. 1999) suggest to us that tectonic denudation (widespread normal faulting) was the main mechanism of thermotectonic stabilization of southern Zealandia.

**Pre-rift tectonic events**

There are a few signals in our dataset relating to events earlier than c. 105 Ma. One of them is from our South Island sample P80920 from the forearc basin Murikiu Terrane, between the Haast Schist and Median Batholith (Fig. 2). This gives an AFT age of 133 ± 19 Ma, similar to the 126–102 Ma AFT ages of Kamp & Liddell (2000). This cooling age, which is older than all of our other in situ southern Zealandia samples, is not unexpected because the very low metamorphic grade and fossiliferous Murikiu Terrane strata were never deeply buried and so did not experience the large amounts of cooling and denudation that have exposed the flanking Haast Schist and Median Batholith. A recent \(^{40}\text{Ar}/^{39}\text{Ar}\) study of Murikiu detrital K-feldspars revealed diagenetic ages of 190 Ma with one sample having undergone a recrystallization event at 135–125 Ma (Mortimer et al. 2012).

In the Haast Schist of the South Island, there is a strong relationship between K–Ar age, ZFT age, AFT age and structural depth in the schist pile (Mortimer 2003). A very similar relationship exists between ZFT and K–Ar ages and textural grade (= structural depth) in the Haast Schist of the Chathams (Fig. 4) indicating that in its metamorphic–exhumation history the Chatham Schist is similar to the Otago Schist. Tentatively, we interpret the c. 170–150 Ma age of the whole-rock argon partial retention zone as dating the timing of prograde regional metamorphism of the accretionary wedge.
and the 108 ± 11 Ma age of the ZHe retention zone as dating the commencement of rapid cooling and exhumation of the Chatham Schist. The Chatham Islands are c. 150 km from the continent–ocean boundary represented by the Chatham Rise–Hikurangi Plateau margin and about the same distance from the SE Chatham margin (Figs 2 and 8). Given its spatial location, it is plausible that the 108 ± 11 Ma exhumation of the ZHe partial retention zone could be dating the timing of collision of the Hikurangi Plateau with the Chatham Rise and therefore the end of a phase of subduction. If true, this would corroborate a 105 Ma age of Hikurangi Plateau collision (Davy et al. 2008; Davy 2014).

Although it is tempting to formulate a simple two-process model of 108 ± 11 Ma end of subduction followed by 80 ± 14 Ma rifting, we cannot rule out another possible alternative. In this interpretation, the 108 ± 11 Ma Chathams ZHe exhumation age alternatively or additionally records the onset of the rifting phase of which the 80 ± 14 Ma Chathams AFT age represents a later and lower temperature part. Additional sample sites, and more precise thermochronology studies than presented here, are needed to test these models. In summary, it is still not entirely clear if schist exhumation was occurring while convergence (subduction) was continuing, if it represents a distinct episode on the termination of subduction (by plateau collision?) or if it is related to the onset of widespread rifting. This remains an important topic for continuing research.

Thermochronology as a test for ice-rafted samples

Our study is useful in helping assess whether two samples dredged at high southern latitudes were iceberg dropstones or in situ exposures. Our approach may well have wider application in circum-Antarctic and circum-Arctic regions, if distinctive combinations of protolith age and cooling age are present. Each major orogenic segment of Antarctica is characterized by reconnaissance geochronological
and thermochronological datasets, and distinctive combinations of protolith, cooling and flanking ocean crust ages can be outlined (Fig. 7). Near almost all Antarctic continent–ocean boundaries, AFT ages predate the age of oldest oceanic crust by tens of millions of years.

A 1170 Ma granite was dredged at the continental shelf edge break at 2370 m water depth on the southern tip of the Campbell Plateau (Challis et al. 1982). If it was in situ it would be expected to share the almost ubiquitous Late Cretaceous AFT ages shown by our intra-Zealandia samples and by samples from the formerly conjugate Antarctic and Australian continental margins (Figs 3 and 7). As it does not, an origin elsewhere seems likely, with iceberg transport to its collection site. The distinctive combination of Jurassic AFT ages and Grenville granite protolith ages is found in the Enderby Land–Lambert sector (Fig. 7) but other East Antarctic locations cannot be ruled out. Thus, at the time of writing, despite the possibility being raised by Adams et al. (2015), there has still been no proven in situ Precambrian rock reported from Zealandia.

Conclusions

A reconnaissance low-temperature thermochronological study of southern Zealandia basement rocks has revealed a variety of new information on this largely submerged continental area. Our efforts to obtain long baseline Cretaceous thermochronological information related to Gondwana subduction and breakup were hampered by the thermal resetting of apatite, zircon and K-feldspar by Miocene volcanism on Campbell and Auckland islands, and by low-U apatites in a dredged schist on the SE Chatham Terrace. Samples from the bottom of 2–4 km deep oil exploration boreholes, predictably, had reset AFT ages. On the basis of a much older than expected AFT age, we interpreted a dredged granite from the southern tip of the Campbell Plateau to be ice-rafted. Low-temperature thermochronology may help assess the in situ or dropstone origin of circumpolar dredged rocks in other situations.

We did obtain useful in situ Cretaceous thermochronological information from the Chatham Rise and Bounty Islands, which, despite being 550 km apart and in very different parts of the Mesozoic convergent margin, have very similar cooling histories to each other and to their along-strike correlative rock units in Snares, Stewart and South islands (Fig. 9). Across all of southern Zealandia, rhyolite has shared a common low-temperature thermotectonic history with the rest of the West Antarctic Marie Byrd Land margin and is therefore plausibly in situ (supporting shipboard observations by Wong et al. 1987).

Fig. 8. Overall interpretive summary map of southern Zealandia outlining main thermotectonic features based on thermochronology, sedimentary basin extent and water depth. Major normal faults from Cook et al. (1999), Kula et al. (2007) and Davy (2014).
relatively rapid 105–80 Ma cooling attests to widespread early Late Cretaceous denudation, probably rift-related tectonic denudation. However, more detailed work is needed to resolve single versus multiple events. A particularly strong signal in our dataset is the 108 ± 11 Ma age of rapid cooling and exhumation of a ZHe retention zone in the Chatham Schist. This can be attributed to subduction cessation via Hikurangi Plateau collision and/or to onset of the aforementioned Late Cretaceous rifting. The only significant thermal disturbances since 80 Ma in southern Zealandia have been scattered low-volume intraplate volcanism, thermal relaxation in sedimentary basin fill and the narrow yet prominent Neogene collisional orogen of onland (emergent) New Zealand. Our results provide a useful reconnaissance reference thermochronological dataset for stable southern Zealandia. They lay the foundation for more detailed work and invite a similar study of the more pervasively rifted and extended northern Zealandia continent.

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