

# Differentiating between Inherited and Autocrystic Zircon in Granitoids

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## ABSTRACT

Inherited zircon, crystals that did not form *in situ* from their host magma but were incorporated from either the source region or assimilated from the wall-rock, is common but can be difficult to identify. Age, chemical and/or textural dissimilarity to the youngest zircon fraction are the primary mechanisms of distinguishing such grains. However, in Zr-undersaturated magmas, the entire zircon population may be inherited and, if not identifiable via textural constraints, can lead to erroneous interpretation of magmatic crystallization age and magma source. Here, we present detailed field mapping of cross-cutting relationships, whole-rock geochemistry and zircon textural, U–Pb and trace element data for trondhjemite, granodiorite and granite from two localities in a complex Archean gneiss terrane in SW Greenland, which reveal cryptic zircon inheritance. Zircon textural, U–Pb and trace element data demonstrate that, in both localities, trondhjemite is the oldest rock ( $3011 \pm 5$  Ma,  $2\sigma$ ), which is intruded by granodiorite ( $2978 \pm 4$  Ma,  $2\sigma$ ). However, granite intrusions, constrained by cross-cutting relationships as the youngest component, contain only inherited zircon derived from trondhjemite and granodiorite based on ages and trace element concentrations. Without age constraints on the older two lithologies, it would be tempting to consider the youngest zircon fraction as recording crystallization of the granite but this would be erroneous. Furthermore, whole-rock geochemistry indicates that the granite contains only  $6 \mu\text{g g}^{-1}$  Zr, extremely low for a granitoid with  $\sim 77$  wt%  $\text{SiO}_2$ . Such low Zr concentration explains the lack of autocrystic zircon in the granite. We expand on a differentiation tool that uses Th/U ratios in zircon versus that in the whole-rock to aid in the identification of inherited zircon. This work emphasizes the need for field observations, geochemistry, grain characterization, and precise geochronology to accurately determine igneous crystallization ages and differentiate between inherited and autocrystic zircon.

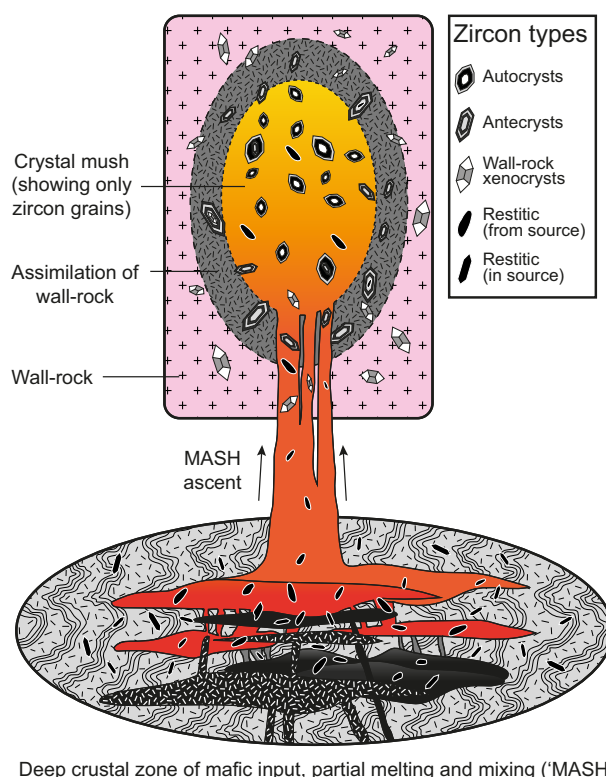
**Key words:** antecryst; autocryst; xenocryst; Akia Terrane; Archean; trace element

## INTRODUCTION

The mineral zircon— $\text{ZrSiO}_4$ —is arguably the gold standard in geochronology (Krogh, 1973; Harley & Kelly, 2007). Zircon is a ubiquitous trace mineral in felsic and, to a lesser extent, intermediate and mafic rocks and, very rarely, in ultramafic rocks (Speer, 1980; Corfu *et al.*, 2003). Its success in geochronology stems from its physical and chemical properties, including its relative durability, hardness, chemical inertness, incorporation of trace amounts of U and Th (Bea, 1996), negligible common-Pb content (Watson *et al.*, 1997; Harley & Kelly, 2007) and high closure temperature to Pb ( $>900^\circ\text{C}$ ; Lee *et al.*, 1997; Cherniak & Watson, 2001). Owing to the ability of zircon to survive crustal anatexis, particularly in dry systems (Harrison & Watson, 1983; Villaros *et al.*, 2009; Yakymchuk & Brown, 2014), it can retain age and other isotopic information (e.g. Hf, O) in cores as well as commonly formed new zircon overgrowth rims. Although the survival of zircon in igneous systems is useful to understand the development of magmatic plumbing systems (Claiborne *et al.*, 2010; Nasdala *et al.*, 2014; Pack *et al.*, 2016), its endurance can also be a hindrance, particularly when attempting to determine magma crystallization ages (Roddick & Bevier, 1995; Clarke, 2007; Simon *et al.*, 2008).

In igneous systems, which are supposed to have short-lived crystallization times ( $<10\text{ Myr}$ , even for the most long-lived plutons and batholiths; Matzel *et al.*, 2006; Miller *et al.*, 2007), enigmatically older crystals of zircon are commonly encountered that are not related to an eruption or final pulse of magma crystallization (e.g. Wotzlaw *et al.*, 2013; Broderick *et al.*, 2015; Samperton *et al.*, 2017). Miller *et al.* (2007) stated ‘it is no exaggeration to say that hundreds of zircon geochronologic studies have shown this to be true’. By now, there are probably thousands of studies that have yielded zircon grains that are older than their magmatic crystallization age. These appreciably older crystals—referred to as ‘inherited’—can be a major obstacle in assigning a crystallization age to igneous rocks. Inherited zircon grains can themselves be subdivided into three basic categories (Fig. 1): (1) restitic zircon, originating from the source (Pidgion & Aftalion, 1978; Chappell *et al.*, 1987; Eliasson & Schöberg, 1991; Jeon & Williams, 2018); (2) xenocrystic zircon, incorporated into the melt via wall-rock assimilation and delivering foreign (i.e. xeno-) zircon into the magmatic plumbing system (Johnson, 1989; Kemp *et al.*, 2005); (3) antecrystic zircon, grains formed in antecedence to the final crystallization phase but still part of the same magmatic plumbing system (Charlier *et al.*, 2005; Smithies *et al.*, 2015).

The identification of inherited zircon is most commonly made via age data (e.g. Siégl *et al.*, 2018), aided by textural (e.g. Corfu *et al.*, 2003), geochemical (e.g. Belousova *et al.*, 2002; Kirkland *et al.*, 2015) or other isotopic parameters (Valley, 2003; Siebel *et al.*, 2009; Liu *et al.*, 2014). Although age discrepancies are the most



Deep crustal zone of mafic input, partial melting and mixing ('MASH')

**Fig. 1.** Schematic image of zircon types in a magmatic plumbing system, modified from Miller *et al.* (2007). MASH, melting, assimilation, storage and homogenization (Hildreth & Moorbath, 1988).

common technique, zircon antecrysts and occasionally xenocrysts may show negligible difference in age from the youngest fraction of zircon grains as a consequence of insufficient dating precision. In situations where there is negligible age difference, the presence of inherited zircon may be evidenced by resorbed grain cores with strong chemical differences from zircon overgrowths (Mundil *et al.*, 2004; Siégl *et al.*, 2018).

All the above scenarios assume that the youngest concordant fraction of zircon grains in a given igneous sample represents the crystallization phase of that melt. However, it has long been recognized that certain igneous rocks (e.g. ultramafic rocks, kimberlite; Hatch, 1908) can lack zircon that crystallized in the final stages of magma solidification—termed autocrysts (Miller *et al.*, 2007). The tendency to crystallize zircon directly from the melt is a function of temperature, Zr concentration in the melt, volatile content (especially  $\text{H}_2\text{O}$ ) and bulk magma composition, with hotter, Zr-depleted and drier melts less likely to develop zircon autocrysts and instead likely to become dominated by xenocrystic or restitic zircon (Watson & Harrison, 1983, 2005; Boehnke *et al.*, 2013; Kirkland *et al.*, 2015; Siégl *et al.*, 2018). Although ultramafic and mafic magmas rarely crystallize zircon, a lack of auto- or antecrystic zircon grains may also occur in intermediate to felsic rocks. In the absence of textural evidence (e.g. resorbed cores) or chemical data (which may not be collected during

routine U–Pb analysis), is it possible to determine that the youngest zircon fraction is inherited (i.e. cryptic zircon inheritance)?

In this contribution, we present detailed field mapping, petrography, whole-rock geochemical data and zircon U–Pb, trace elements and textures of three igneous units from two proximal localities in the Mesoarchean Akia Terrane in SW Greenland that bring this issue into focus. It is feasible that cryptic zircon inheritance is relatively common in the geological record and that, if undiagnosed, it could lead to assignment of erroneously older crystallization ages to igneous rocks. Using petrography, zircon textures, zircon trace elements and whole-rock chemical data, we show that granitoid ages can be confidently assigned, which would have been impossible to address using U–Pb geochronology alone. We also describe a novel mechanism to differentiate autocrystic from inherited zircon grains via Th/U ratios in zircon crystals versus whole-rock. Finally, we evaluate the causes and mechanisms of cryptic zircon inheritance in granitoids. Ultimately, we emphasize the importance of detailed geological mapping, sampling, whole-rock and zircon trace element analysis in conjunction with routinely collected zircon textural and U–Pb age data to aid in the identification of cryptic zircon inheritance.

## GEOLOGICAL SETTING OF THE AKIA TERRANE, SW GREENLAND

The North Atlantic Craton in southern West Greenland contains an important crustal block that tracks crustal history from at least 3.8 to 2.5 Ga (Fig. 2; Friend *et al.*, 1988; Nutman & Collerson, 1991). The craton extends west into Canada (Bridgwater & Schiotte, 1991) and SE into southeastern Greenland (Kalsbeek *et al.*, 1993) and northwestern Scotland (Friend & Kinny, 2001). The surface of the North Atlantic Craton exposed at present is dominated by felsic to intermediate orthogneisses intercalated with remnants of supracrustal belts and mafic to ultramafic and anorthositic plutonic rocks (see reviews of the North Atlantic Craton in West Greenland by Henriksen *et al.*, 2009; Windley & Garde, 2009; Polat *et al.*, 2015).

The North Atlantic Craton in SW Greenland comprises various terranes, of which the Akia Terrane (situated north of the capital city Nuuk) is a major constituent (Fig. 2). The Akia Terrane dominantly comprises rocks with crystallization ages that fall into two distinct age groupings, ~3230–3190 Ma and 3070–2970 Ma (Garde, 1997; Garde *et al.*, 2000; Friend & Nutman, 2005), with the latter being significantly more voluminous. Following major c. 3050–2970 Ma diorite and tonalite–trondhjemite–granodiorite (TTG) magmatism and associated high-grade metamorphism, at least a portion of the supracrustal rocks in the Akia Terrane were deposited between 2877 and 2857 Ma onto the Mesoarchean basement (Kirkland *et al.*, 2018a). These supracrustal rocks were subsequently buried to >30 km

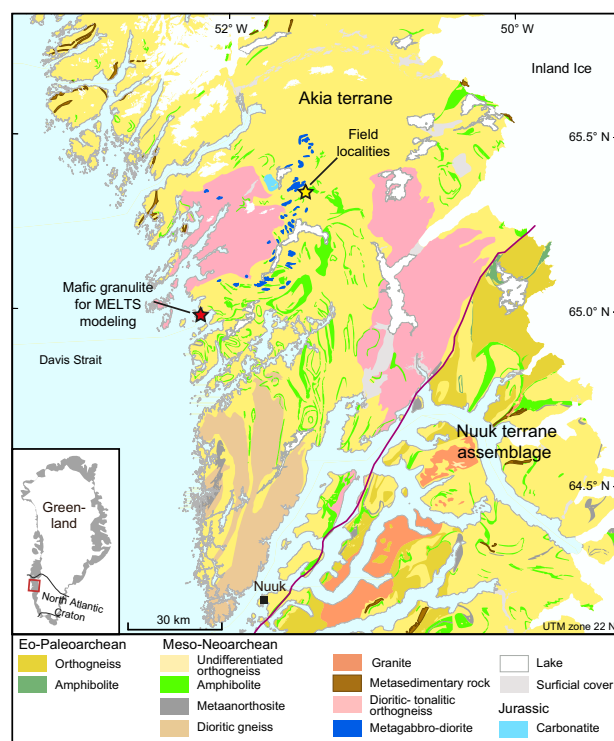


Fig. 2. Simplified geological map of the Akia Terrane, modified from Gardiner *et al.* (2019b), with sampling locality region labelled.

depth, where they partially melted between 2857 and 2700 Ma. The timing and nature of this Neoproterozoic metamorphism along the edges of the Akia Terrane is consistent with similar conditions in surrounding terranes in West Greenland, implying a wide commonality of thermal conditions and linking of crustal elements at least by this time. Further greenschist- to amphibolite-facies metamorphic events at c. 2630 Ma and 2540 Ma are recorded by metamorphic zircon overgrowths and neoblastic apatite (Kirkland *et al.*, 2018b), and titanite (Kirkland *et al.*, 2020), respectively.

## FIELD MAPPING AND SAMPLE SELECTION

The present study was part of a structural, geochronological and geochemical investigation in the Maniitsoq region, southwestern Greenland, undertaken in 2016–2017 by the Ministry of Mineral Resources, Government of Greenland. Two localities (Table 1), situated within 30 m of each other, expose three generations of igneous rocks that are similarly affected by regional deformation (Fig. 3).

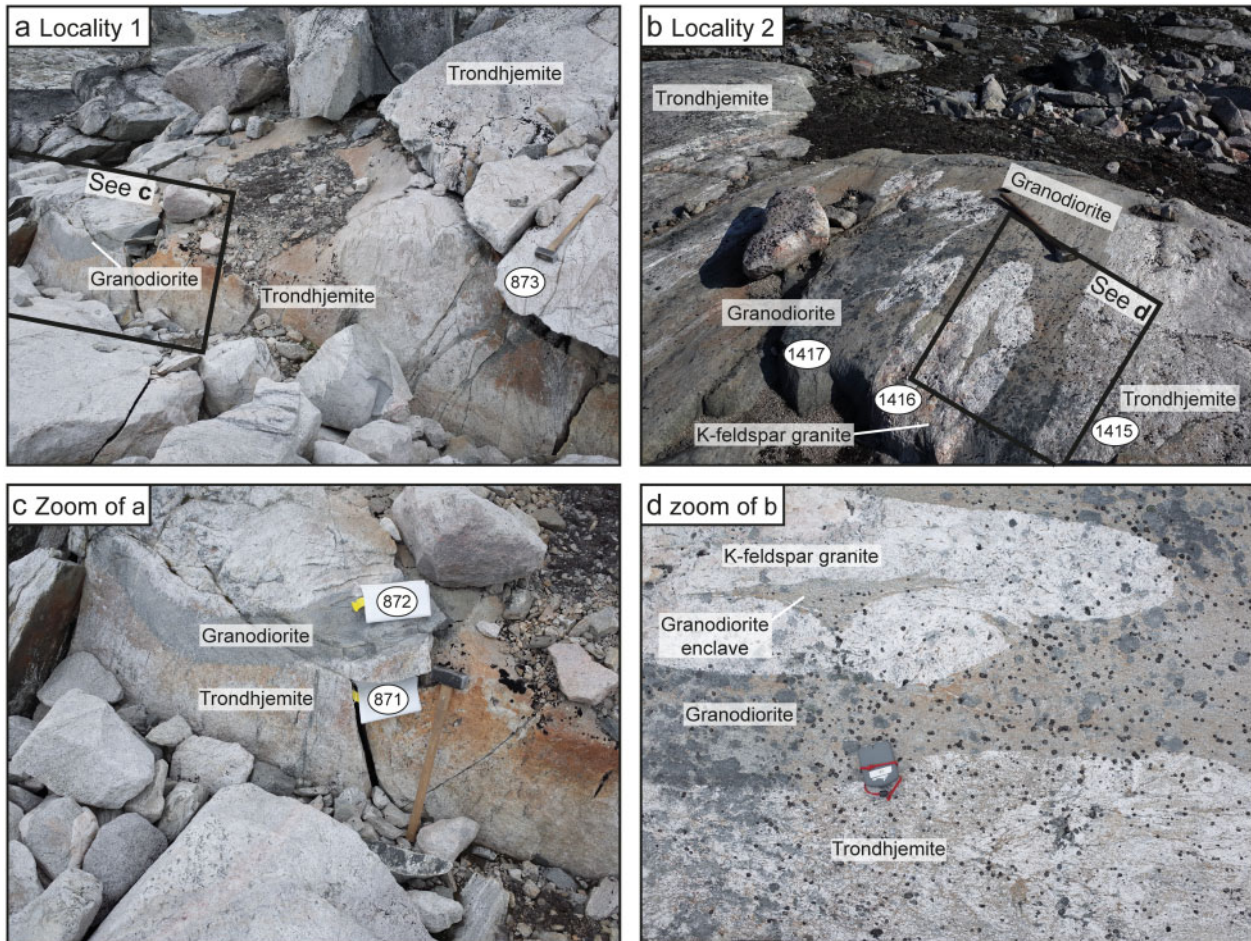
In both localities, a regional, beige-coloured, coarse-grained porphyritic trondhjemite is intruded by up to 1 m wide grey, equigranular, medium-grained granodiorite dykes (Fig. 3a and b). In places, the trondhjemite has a moderately developed foliation (058/70°S) defined by mafic mineral layers, but this foliation is not always evident where mafic layers are lacking (Fig. 3).



**Table 1:** Locations, petrographic descriptions and modal abundances

Sample:	871*	873*	1415	872*	1417	1416
Latitude:	65-35283	65-35283	65-35283	65-35283	65-35283	65-35283
Longitude:	-51-44170	-51-44170	-51-44106	-51-44170	-51-44106	-51-44106
Lithology:	Trondhjemite	Trondhjemite	Trondhjemite	Granodiorite	Granodiorite	K-feldspar-rich trondhjemite
Quartz	32	34	28	26	32	26
Orthoclase	1.6	16	9.8	0.02	10	15
Albite	2.2	13	6.9	2.1	9.3	18
Oligoclase	59	29	48	57	33	39
Anorthite	1.4	0.90	0.74	1.9	2.9	0.25
Muscovite	1.7	3.9	1.7	1.5	2.3	0.40
Biotite	0.84	0.89	1.8	9.0	4.9	0.00
Calcite	0.37	0.10	0.00	0.03	0.00	0.00
Apatite	0.02	0.01	0.02	0.18	0.14	0.00
Magnetite	0.03	0.15	0.09	0.02	0.62	0.01
Ilmenite	0.01	0.00	0.01	0.00	0.08	0.00
Titanite	0.02	0.00	0.00	0.12	0.54	0.00
Zircon	0.01	0.01	0.01	0.01	0.02	0.00
Allanite-(La)	0.01	0.01	0.05	0.07	0.09	0.00
Unclassified	1.5	2.3	2.4	2.4	4.4	1.1

\*Samples were taken from the same location as location 8 of (Garde et al., 2012). Modal abundances are from automated mineralogy data on the entire thin section.



**Fig. 3.** Field photographs showing the cross-cutting relationships at both localities. Sample numbers are indicated in ellipses.

In locality 1, a tabular granodiorite dyke cross-cuts the trondhjemite, almost perpendicular to the foliation in the trondhjemite (Fig. 3c). In locality 2, an irregular-shaped

granodiorite body cross-cuts the trondhjemite host rock (Fig. 3b). The granodiorite is generally homogeneous and fine-grained, and does not display a noticeable fabric,

other than larger scale open folding. However, the contacts between the granodiorite and the hosting trondhjemite commonly display protrusions of the former into the latter as small veinlets parallel to the foliation (e.g. Fig. 3d).

In locality 2 only, the granodiorite is cross-cut by a ptgmatically folded, equigranular, very coarse-grained, K-feldspar-rich granitic pegmatite with occasional thin granite veins into the granodiorite (Fig. 3b and d). The ptgmatically folded granite also appears to enclose small enclaves of granodiorite (Fig. 3d) but the folded nature of the outcrop implies that the granodiorite is still connected in three dimensions (Fig. 3b).

Field mapping of localities 1 and 2 demonstrates that the relative chronology, from oldest to youngest, is trondhjemite, granodiorite dykes and (in locality 2 only) K-feldspar-rich granite (Fig. 3). Three samples were selected from locality 1, including two from relatively undeformed trondhjemite (871 and 873) and one from the cross-cutting granodiorite (872), the latter being equivalent to sample 524254 of Scherstén & Garde (2013). Three samples were selected from locality 2, one each from the trondhjemite (1415), granodiorite (1417) and K-feldspar-rich granite (1416).

## ANALYTICAL TECHNIQUES

### Thin section preparation

A segment of each of the rock samples was mounted on glass slides, cut back and polished down to 30 µm thickness. Polished thin sections were imaged in transmitted light (plane- and cross-polarized) using an Axio Imager II at Curtin University for entire thin section images (Supplementary Data Fig. A; supplementary data are available for downloading at <http://www.petrology.oxfordjournals.org>). All thin sections were carbon coated and the full thin section was analyzed using a Tescan Integrated Mineral Analyzer (TIMA) at the John de Laeter Centre (JdLC), Curtin University. Backscatter electron readings were taken every 3 µm and energy-dispersive X-ray spectrometry (EDS) readings were taken every 27 µm or when the back-scattered electron signal changed.

### Whole-rock geochemistry

All samples were trimmed to remove regolith crust and a subset was sent to ALS (Ireland) and/or Genalysis Ltd (Perth, Western Australia) for major and trace element analysis. All samples were crushed using a jaw crusher and pulverized using a low-chrome steel mill to yield particles with sizes <75 µm.

To determine major and most trace element concentrations, a prepared aliquot (0.200 g) was added to lithium metaborate flux (0.90 g). The sample-metaborate flux was put in a platinum crucible, mixed well and placed in a fusion machine to heat the mixture until molten to form a single homogeneous hot liquid at 1000 °C. The resulting melt was then cooled into a fused

disc. At ALS, the fused disc was dissolved in 100 ml of 4% HNO<sub>3</sub>–2% HCl. Major elements were analyzed by inductively coupled plasma optical emission spectroscopy (ICP-OES) at ALS and X-ray fluorescence (XRF) at Genalysis. Trace elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) using a single-collector quadrupole for all elements except Sc, V, Cr, Ni, Cu and Zn, which were analyzed by ICP-OES. Results were subsequently corrected for spectral inter-element interferences. For major elements, oxide concentration was calculated from the determined elemental concentration and the result is reported in that format (Table 2, Supplementary Data Table A).

Base metal determination utilized a four-acid digest instead of lithium metaborate fusion on an aliquot of the sample. Many sulfides and some metal oxides are only partially decomposed by the borate fusion and some elements such as cadmium and zinc can be volatilized. A prepared aliquot (1.0 g) was weighted directly into a 125 ml Teflon beaker and a concentrated four-acid digest was added (5 ml HCl, 5 ml HNO<sub>3</sub>, 2.5 ml HClO<sub>4</sub> and 15 ml HF). The samples were placed on a hotplate at 200 °C and evaporated until dry. The residue was then re-dissolved in 10% v/v HCl and returned to the hotplate at 100 °C. When the residue was completely dissolved, the samples were cooled and transferred to 50 ml storage tubes. One ml of 0.5% w/v H<sub>3</sub>BO<sub>3</sub> was added to each tube to complex HCl and mitigate ICP degradation. The four acid-sample solution was analyzed by ICP-MS and corrected for spectral inter-element interferences.

Loss on ignition (LOI) was determined by placing a prepared aliquot (1.0 g) in an oven at 1000 °C for 1 h, followed by cooling and then re-weighing. The per cent loss on ignition was calculated from the difference in mass.

To aid in quality control, repeat major element analysis of sample 1417 revealed a <10% discrepancy between analyses in all major element determinations (Supplementary Data Table A). Sample 1416 was duplicated for trace element analysis and revealed a <5% discrepancy between analyses for most trace elements present at >5 µg g<sup>-1</sup> abundance, with the exception of Ce, Ba and Ga, which yielded differences of 6–13% (Supplementary Data Table A). Elements close to the detection limit often showed significant discrepancies (Supplementary Data Table A). Further quality control was assured by co-analyzing standards with the unknowns, including OREAS 24b, OREAS 46 (both from the Ore Research & Exploration, Australia) and SY-4 from Natural Resources Canada. All standard analyses overlap with certified values at 2σ (Supplementary Data Table A).

### Zircon separation and imaging

Approximately 5 kg of each sample was crushed and the resultant slurries were put through a Jasper Canyon Research concentrating shaker table for initial

**Table 2:** Whole-rock geochemistry for new samples from the Akia Terrane

Rock type:	Trondhjemite	Trondhjemite	Trondhjemite	Granodiorite	Granodiorite	K-feldspar-rich granite
Sample:	871	873	1415	872	1417	1416
<i>wt%</i>						
SiO <sub>2</sub>	73.9	75.2	74.0	69.1	70.9	76.8
Al <sub>2</sub> O <sub>3</sub>	14.7	14.2	14.8	16.2	15.0	13.5
Fe <sub>2</sub> O <sub>3</sub>	1.20	0.82	1.07	2.92	2.65	0.62
MgO	0.13	0.14	0.20	0.92	0.66	0.05
CaO	1.81	1.51	1.70	2.84	2.31	1.19
Na <sub>2</sub> O	4.5	4.4	5.4	5.5	4.3	5.1
K <sub>2</sub> O	2.99	3.06	2.34	1.32	3.12	2.42
TiO <sub>2</sub>	0.07	0.06	0.12	0.40	0.34	0.01
P <sub>2</sub> O <sub>5</sub>	0.02	0.02	0.01	0.11	0.08	0.01
MnO	0.01	0.01	0.01	0.04	0.03	<0.01
LOI	0.64	0.57	0.41	0.69	0.64	0.27
Total	100	100	100	100	100	100
<i>ppm</i>						
Li	8.8	10.1	9.8	29.6	19	2.8
Be	0.72	0.42	0.61	1.06	1.07	2.29
Sc	0.8	0.7	1.2	4.2	3.2	<10
V	17	11	7	41	22	<10
Cr	11	12	10	12	8	213
Co	1.5	1	1.3	6.4	4.2	0.6
Ni	2	1.5	2.1	5	3.4	4.4
Cu	5.4	2.9	1.8	1.8	0.5	3.7
Zn	17	15	21	70	48	3
Ga	17.6	16.1	17.9	21.4	19.5	23.6
Ge	0.34	0.33	0.05	0.37	0.35	1.24
As	<0.2	1.6	<0.2	1.4	0.7	0.9
Se	<1	<1	<1	<1	<1	<0.5
Rb	52.4	48.5	57.1	57.3	86	60.1
Sr	423	479	449	411	264	78
Y	1.2	1	1.8	7.3	5.9	1.3
Zr	60	63	64	178	203	6
Nb	0.7	0.6	1.9	3.9	4.7	1.2
Mo	0.21	0.12	0.24	0.17	0.19	1.4
Ag	0.08	0.02	0.04	0.02	0.04	0.05
Cd	<0.02	<0.02	<0.02	0.03	<0.02	0.13
In	<0.005	0.005	0.005	0.017	0.015	<0.01
Sn	0.3	0.2	0.4	0.8	1	<1
Sb	<0.05	<0.05	0.05	<0.05	<0.05	0.08
Te	<0.05	<0.05	<0.05	<0.05	<0.05	<0.2
Cs	0.24	0.3	0.6	0.9	0.8	0.5
Ba	1390	1745	1050	258	1205	106.1
La	9.5	21.8	19.1	34.7	56.4	4
Ce	14.1	32.8	35.7	59.8	93.3	6.1
Pr	1.47	2.99	3.08	5.99	8.87	0.6
Nd	4.8	9.4	9.5	20	27.1	2.1
Sm	0.75	1.07	1.07	3.12	3.88	0.7
Eu	0.55	0.73	0.4	0.66	0.73	0.4
Gd	0.57	0.69	0.96	2.6	2.36	0.3
Tb	0.04	0.05	0.04	0.33	0.25	<0.1
Dy	0.25	0.23	0.4	1.65	1.23	0.2
Ho	0.04	0.03	0.06	0.28	0.21	<0.1
Er	0.15	0.08	0.12	0.65	0.44	0.1
Tm	<0.01	<0.01	<0.01	0.08	0.11	<0.1
Yb	0.12	0.07	0.1	0.61	0.47	0.1
Lu	0.02	0.01	0.01	0.09	0.07	<0.1
Hf	1.8	1.8	1.7	4.4	5.3	0.2
Ta	<0.1	<0.1	<0.1	0.1	0.1	0.4
W	0.1	0.1	0.1	0.1	0.1	2
Re	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Tl	0.29	0.28	0.3	0.39	0.56	0.31
Pb	22.5	22.2	21	16.3	20.8	23.8
Bi	<0.01	<0.01	0.01	0.01	0.01	<0.01
Th	5.89	5.78	12.05	7.99	11.65	1.7
U	0.32	0.21	0.51	0.8	0.57	0.3
K <sub>2</sub> O + Na <sub>2</sub> O	7.52	7.44	7.69	6.82	7.40	7.52
K <sub>2</sub> O/Na <sub>2</sub> O	0.66	0.70	0.44	0.24	0.73	0.47
(La/Yb) <sub>cn</sub>	44.2	208.0	144.2	36.2	64.1	28.7
(La/Sm) <sub>cn</sub>	7.1	13.6	13.5	7.1	7.8	4.1
(Eu/Eu*) <sub>cn</sub>	2.6	2.6	1.2	0.71	0.74	2.67

(continued)



Table 2: Continued

Rock type:	Trondhjemite	Trondhjemite	Trondhjemite	Granodiorite	Granodiorite	K-feldspar-rich granite
M	1.52	1.53	1.53	1.51	1.51	1.37
$T_{\text{ZircSat}}$ (°C)	600.4	560.5	643.2	688.0	681.7	491.1
Zr/Hf	33.3	35.0	37.6	40.5	38.3	30.0
Th/U	18.4	27.5	23.6	10.0	20.4	5.7

concentration of heavy minerals and subsequently through LST heavy liquids at  $2.9 \text{ g cm}^{-3}$ . The heavy fraction was isolated using a Frantz isodynamic magnetic separator. Heavy mineral grains were subsequently hand-picked from the non-magnetic fraction, mounted in 25 mm epoxy rounds together with zircon reference standards and polished to approximately half grain thickness to expose grain interiors.

Each mount was imaged using transmitted and reflected light to provide internal grain textural information. Cathodoluminescence (CL) imaging was conducted using a Mira3 field emission gun SEM (FEG-SEM) at the JdLC, Curtin University. Imaging was conducted with a nominal working distance of 17 mm, a beam current of 935 pA, spot size of 14 nm and an accelerating voltage of 12 kV. CL images were used to document internal zonation patterns (e.g. oscillatory, sector, patchy), identify recrystallization textures and recognize the presence of any crystal rims. These identification procedures aid in elucidating whether grains were originally magmatic (igneous), metamorphic or experienced recrystallization (e.g. Corfu *et al.*, 2003). A compendium of all mounted zircon grains may be found in [Supplementary Data Fig. B](#).

### Zircon U–Pb geochronology and trace element geochemistry

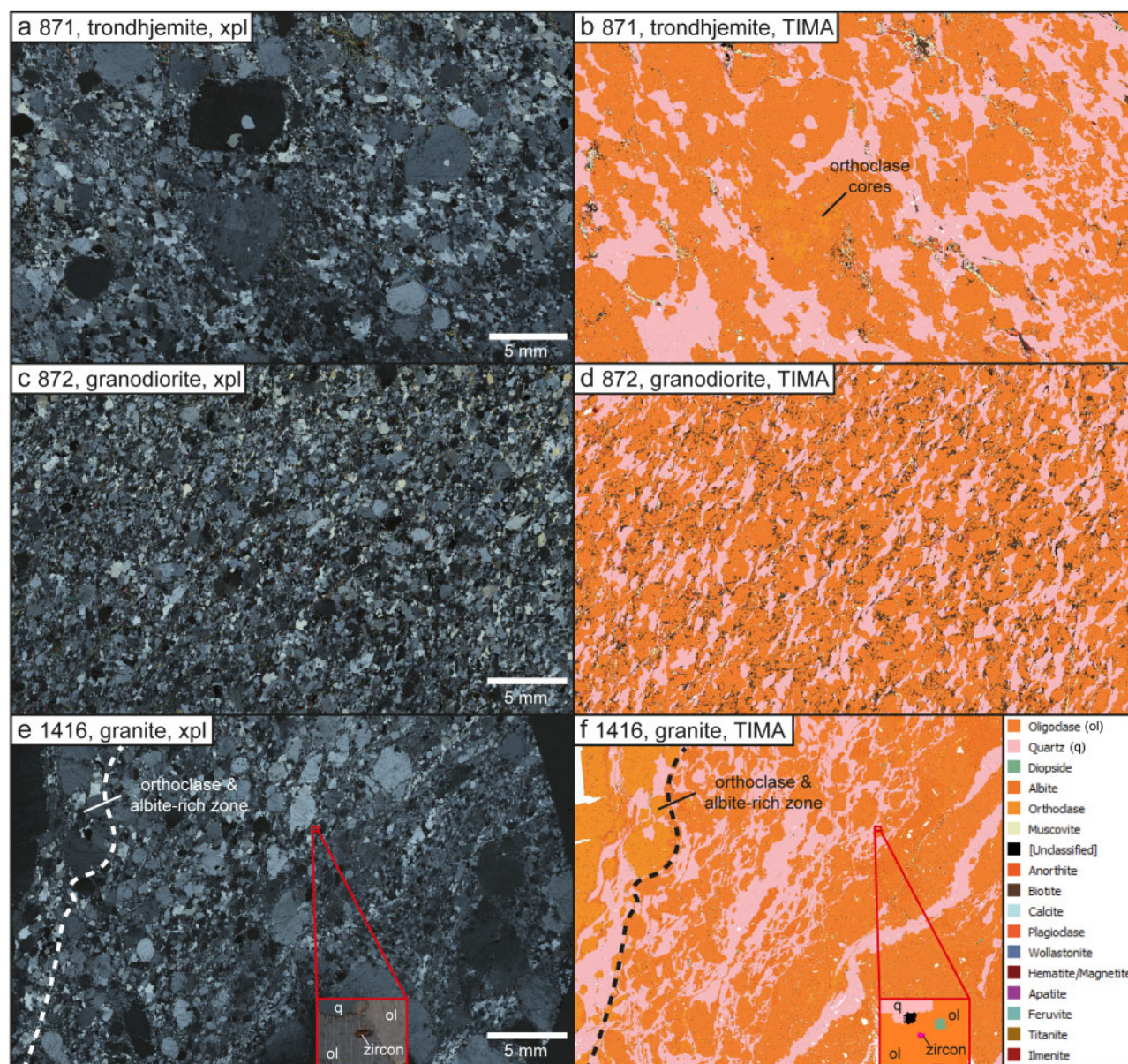
Zircon U–Pb and trace element data were collected at the GeoHistory Facility, JdLC, Curtin University. Most samples were analyzed in the first analytical session, with a second session performed to acquire additional analyses from sample 1416. Where possible, multiple spots were collected from both grain cores and rims. An overview of operating conditions is given here but more detail has been given by Spencer *et al.* (Spencer *et al.*, 2017). The excimer laser (RESOLUTION LR 193 nm ArF with a Lauren Technic S155 cell) spot diameter was  $33 \mu\text{m}$ , on-sample energy was  $2 \text{ J cm}^{-2}$  with a repetition rate of 5 Hz for 30 s of total of analysis time and  $\sim 50$  s of background capture. All analyses were preceded by two cleaning pulses. The sample cell was flushed by ultra-high purity He ( $0.68 \text{ l min}^{-1}$ ) and  $\text{N}_2$  ( $2.8 \text{ ml min}^{-1}$ ).

U–Pb data were collected on an Agilent 8900 triple quadrupole mass spectrometer with high purity Ar as the carrier gas (flow rate  $0.98 \text{ l min}^{-1}$ ). Analyses of every  $\sim 20$  unknowns were bracketed by analyzing a standard block containing the primary zircon reference materials OG1 ( $3465.4 \pm 0.6 \text{ Ma}$ ; Stern *et al.*, 2009) and 91500 ( $1062.4 \pm 0.4 \text{ Ma}$ ; Wiedenbeck *et al.*, 1995), which were used to monitor and correct for mass fractionation and instrumental drift. The standard block also contained Plešovice ( $337.13 \pm 0.37 \text{ Ma}$ ; Sláma *et al.*, 2008), GJ-1

( $601.95 \pm 0.40$  to  $608.5 \pm 1.5 \text{ Ma}$ ; Jackson *et al.*, 2004; Horstwood *et al.*, 2016) and Maniitsoq ( $3008.70 \pm 0.72 \text{ Ma}$ ; Marsh *et al.*, 2019; all uncertainties at  $2\sigma$ ), which were used as secondary standards to monitor data accuracy and precision. When reduced to an appropriate primary standard, all secondary standards yielded weighted mean ages within  $2\sigma$  of the published ages, including Plešovice ( $337.7 \pm 1.3$  and  $337.8 \pm 1.2 \text{ Ma}$ ), GJ-1 ( $603.7 \pm 1.5$  and  $605.6 \pm 1.6 \text{ Ma}$ ) and Maniitsoq ( $3005 \pm 5$  and  $3005 \pm 7 \text{ Ma}$ ). Data were reduced using Lolite 3 (Paton *et al.*, 2011) and in-house Excel macros. Zircon analyses are considered concordant where the error ellipses at  $2\sigma$  generated by the  $^{207}\text{Pb}/^{206}\text{Pb}$  and  $^{206}\text{Pb}/^{238}\text{U}$  ratios overlap the inverse concordia curve, excluding uncertainties on the decay constant (i.e. assuming the concordia curve is a line rather than a zone). Uncertainties on the primary reference materials were propagated in quadrature to the unknowns and secondary zircon reference materials. All zircon dates are presented as  $^{207}\text{Pb}/^{206}\text{Pb}$  ages owing to their superior precision at the typical ages of c. 3 Ga. Common-Pb was not corrected for as almost all concordant analyses have  $f_{206}$  of  $<0.1\%$  (Supplementary Data Table B).

Trace element data (Si, Ti, Y, Nb, Yb and Hf) were collected simultaneously with U–Pb data in the first analytical session only. International reference glass NIST610 was utilized as the primary reference material for concentration determination and to correct for instrument drift (using  $^{91}\text{Zr}$  as the internal standard element and an assumed stoichiometric 43.14 wt% Zr in zircon). NIST SRM 612 was run as a secondary standard and yielded recommended values within 3% for all elements using NIST 610 as the primary reference material.

Ti-in-zircon temperatures were calculated using the method of Ferry & Watson (2007). Titanite (and/or ilmenite) and quartz are commonly observed to coexist in the analyzed samples, except samples 873 (trondhjemite) and 1416 (granite), where titanite is  $<0.01 \text{ vol}\%$  (Fig. 4, Table 2). Given the lack of rutile, the activation energy of  $\text{TiO}_2$  ( $\alpha_{\text{TiO}_2}$ ) is lower than unity. Given the plausible limits of  $\alpha_{\text{TiO}_2} = 0.5$  in crustal rocks (Ferry & Watson, 2007; Hayden & Watson, 2007), the maximum likely overestimation of crystallization temperature would be  $\sim 30^\circ\text{C}$  at temperatures of  $\sim 700$ – $900^\circ\text{C}$  and 0.5–1.0 GPa [estimates of temperature and pressure for the Akia Terrane at c. 3.0 Ga from Kirkland *et al.* (2020) and Yakymchuk *et al.* (2020)]. As it is likely that the temperature and pressure did not significantly change for the age window in which the trondhjemite to granite was emplaced, we use a constant pressure of 0.5 GPa



**Fig. 4.** Representative thin section photomicrographs of (a, b) trondhjemite, (c, d) granodiorite, and (e, f) granite. xpl, transmitted, cross-polarized light; TIMA, automated mineral analysis image taken using Tescan Automated Mineral Analyzer. Insets in (e) and (f) show zircon grain enclosed in oligoclase crystal. Insets are  $\sim 200\ \mu\text{m} \times 150\ \mu\text{m}$ . High-resolution, full thin section photomicrographs in transmitted plane- and cross-polarized light, and TIMA images may be found in [Supplementary Data Fig. A](#).

for all data. Temperature estimates may be overestimated by up to  $\sim 30^\circ\text{C}$  owing to the absence of rutile, and underestimated by up to  $30^\circ\text{C}$  owing to potential higher pressures (up to 1.0 GPa). Thus, the zircon crystallization temperatures may be in error by up to  $60^\circ\text{C}$ .

Full zircon isotopic and trace element data for the samples are given in [Supplementary Data Table B](#).

## RESULTS

### Thin section petrography and rock classification

The dominant country rock at both localities is a coarse-grained, leucocratic, porphyritic trondhjemite gneiss that chiefly comprises  $\sim 2$ –5 mm oligoclase phenocrysts

set within a coarse-grained matrix of oligoclase and quartz (Figs 4 and 5, Table 1). Samples 871, 873 and 1415 were collected from this rock type. Oligoclase phenocrysts commonly show cores or inclusions of orthoclase and albite, which range from rare in sample 871 to common in sample 873 (Fig. 4). Gneissic banding is poorly defined by layers of oligoclase + orthoclase (42–61 vol%) and quartz (28–34 vol%; Fig. 4, Table 1). Minor interstitial muscovite (1.5–2.5 vol%) and biotite (0.8–1.8 vol%), and trace amounts of calcite, zircon, apatite, titanite and allanite are also present (Table 1).

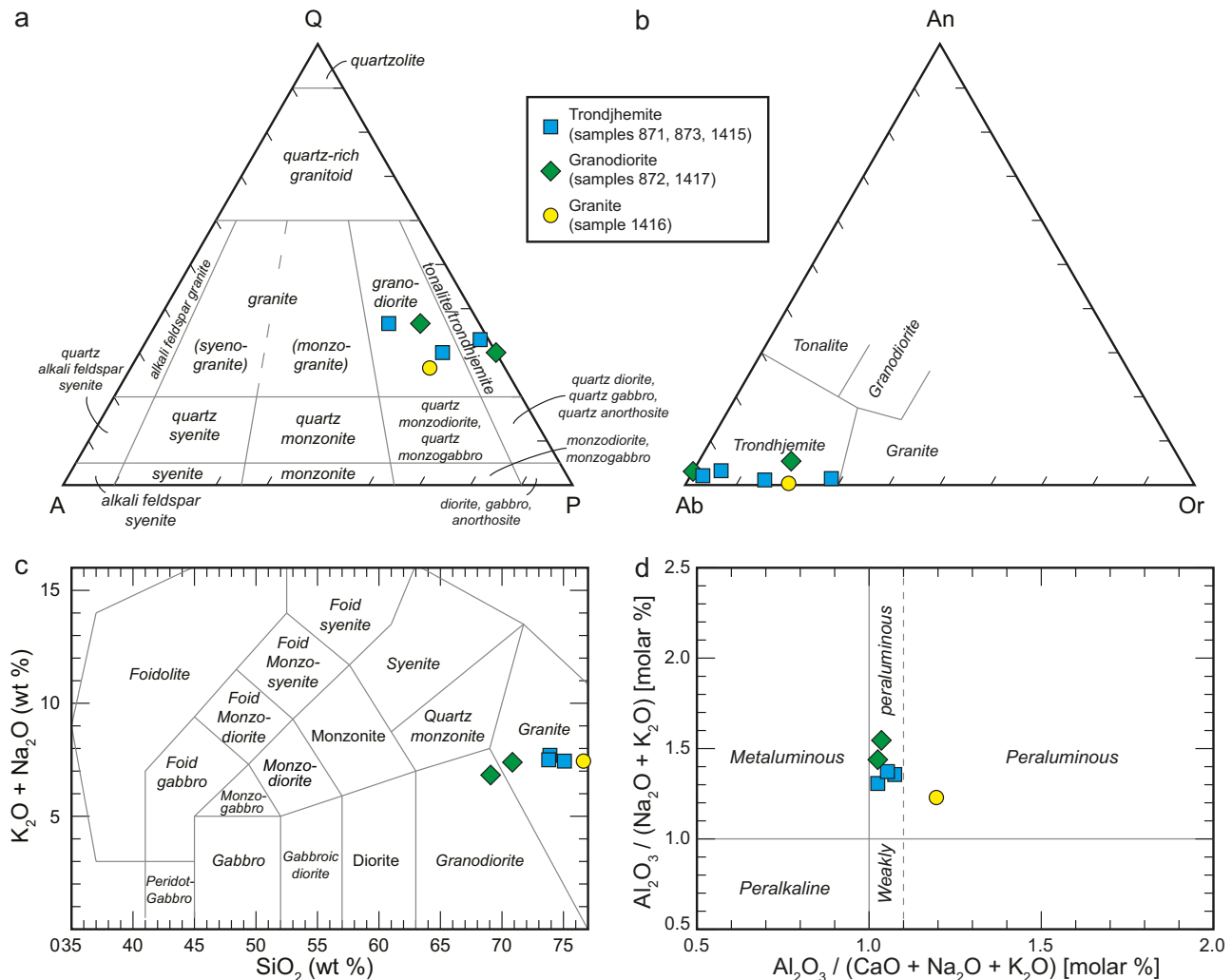
The trondhjemite gneiss is intruded by equigranular, mesocratic, fine- to medium-grained trondhjemitic to granodioritic gneisses. Samples 872 and 1417 were



collected from this lithology. Given that the thin sections are not fully representative of the coarse-grained lithologies, these trondhjemitic to granodioritic gneisses are hereafter referred to as mesocratic granodiorite for the purposes of differentiating them from the leucocratic trondhjemites. The granodiorites have similar proportions of feldspar (52–61 vol%) and quartz (26–32 vol%) to the leucocratic trondhjemites but contain an order of magnitude more biotite (~5–9 vol% compared with 0.8–1.8 vol%) that, together with their finer grain-size, yields darker coloured rocks. Minor muscovite and the same trace minerals as in the leucocratic trondhjemites are also present.

The ptlygmatically folded K-feldspar-rich granitoid is a coarse- to very coarse-grained, equigranular, folded, leucocratic granitic gneiss. Sample 1416 was collected from this lithology. Parts of the granitic gneiss are similar to the trondhjemite, comprising oligoclase- ( $\pm$  orthoclase) and quartz-rich layers that define the foliation. However, other

gneissic layers comprise orthoclase cores with albite rims. Thus, despite the fact that orthoclase and albite modal abundances are similar in samples 1416 (granite) and 873 (trondhjemite; see Table 1), their distributions within the rocks are different (Fig. 4); in sample 1416, orthoclase and albite are located in only the left area of the thin section (Fig. 4f), whereas in 873, orthoclase and albite are relatively evenly distributed throughout (Supplementary Data Fig. A). The granitic gneiss approaches granite compositions but plots in the range of granodiorite on a QPA diagram in the trondhjemite field on an Ab–An–Or diagram (Fig. 5b). Owing to their high Si content (see section ‘Whole-rock major and trace element geochemistry’) and high concentrations of albite and K-feldspar, we hereafter refer to the leucocratic granitic gneiss as granite to differentiate it from the other two lithologies. Trace minerals in the granite are less abundant than in other rock types, including less titanite (0.005 vol%), zircon (0.007 vol%) and apatite (0.010 vol%; Table 1).



**Fig. 5.** Petrographic and whole-rock geochemical classification of granitoid samples. (a) Quartz (Q)–alkali feldspar (A)–plagioclase (P) classification diagram (Streckeisen, 1967). (b) Anorthite (An)–albite (Ab)–orthoclase (Or) diagram (Barker, 1979). (c) Total alkali (weight  $Na_2O + K_2O$ ) vs silica (weight  $SiO_2$ ) diagram for intrusive rocks (Le Bas *et al.*, 1986; Middelmost, 1994). (d) Aluminium saturation index: molar  $Al_2O_3 / (Na_2O + K_2O)$  vs molar  $Al_2O_3 / (CaO + Na_2O + K_2O)$  (Shand, 1927; Zen, 1986).

## Whole-rock major and trace element geochemistry

All granitoid samples have negligible alteration as indicated by LOI in all samples <0.2 wt% (Table 2). Thus, all their major and trace elements are considered to be unaffected by deuteric alteration. Major and trace elements from this study (Fig. 6) are shown together with other regional samples from the Akia Terrane to facilitate geochemical modelling (see Discussion), with samples ranging from mafic amphibolites to andesites and TTG (Garde, 2007; Gardiner *et al.*, 2019b; Yakymchuk *et al.*, 2020).

The trondhjemites from this study are SiO<sub>2</sub>-rich (73.7–75.0 wt%) and weakly peraluminous with moderate K<sub>2</sub>O (2.3–3.1 wt%), low K<sub>2</sub>O/Na<sub>2</sub>O (0.44–0.70), low CaO (1.5–1.8 wt%) and low MgO (0.13–0.20 wt%; Fig. 6; Table 2). The granodiorites are more primitive with less SiO<sub>2</sub> (69.0–70.8 wt%), more MgO (0.66–0.92 wt%), more FeO<sup>T</sup> (2.6–2.9 wt%) and more CaO (2.3–2.8 wt%) but are otherwise similar in major element composition to the leucocratic trondhjemites (Fig. 6; Table 2). The granite sample is the most evolved with very high SiO<sub>2</sub> (~76.9 wt%), and extremely low FeO<sup>T</sup> (0.6 wt%), MgO (0.05 wt%) and TiO<sub>2</sub> (0.01 wt%; Fig. 6, Table 2). Most major elements show evolution trends with SiO<sub>2</sub>, consistent with liquid lines of descent, except Na<sub>2</sub>O, K<sub>2</sub>O and equivalent +1 and +2 cation trace elements (e.g. Rb, Sr; Fig. 6, Table 2).

All samples show similar highly negatively sloping rare earth element [REE, (La/Yb)<sub>cn</sub> = 36–208, where cn indicates chondrite normalized with values from Sun & McDonough (1989)] and incompatible element (IE) plots with notable negative Cs, Rb, U, Nb and P anomalies relative to primitive mantle (Figs 6 and 7). Europium anomalies are consistently positive for both trondhjemites and granite [(Eu/Eu\*)<sub>cn</sub> = 1.2–2.7, where Eu\* =  $\sqrt{(\text{Sm} \times \text{Gd})}$ ] but consistently negative for granodiorites [(Eu/Eu\*)<sub>cn</sub> = 0.71–0.74; Fig. 6].

Zirconium concentrations in all samples are below continental crustal averages of 145–165 µg g<sup>-1</sup> for Archean rocks (Fig. 6; e.g. Condie, 1993; Martin *et al.*, 2005). Granodiorite concentrations are approximately two-thirds of average continental crust at ~99–107 µg g<sup>-1</sup>, whereas trondhjemite samples have significantly lower Zr concentrations at ~22–65 µg g<sup>-1</sup> (Fig. 6; Table 2). Given the major element concentrations, the low Zr concentrations in the trondhjemites and granodiorites yielded zircon saturation temperatures ( $T_{\text{ZircSat}}$ ) of ~580–650 °C and ~690 °C, respectively [calculations using formula of Boehnke *et al.* (2013)]. The granite yielded an extremely low Zr concentration of ~6 µg g<sup>-1</sup>, equivalent to a  $T_{\text{ZircSat}}$  of ~490 °C. Such temperatures are well below the wet granite solidus. Zircon saturation calculations are most robust when applied to glasses and thus problematic for plutonic rocks (Harrison *et al.*, 2007; Boehnke *et al.*, 2013; Gervasoni *et al.*, 2016). Thus, these zircon saturation temperatures are unrealistic.

## Zircon morphology and textures

The zircon grains from all six samples can be subdivided into five main groups (Groups 1–5; Fig. 8, Table 3) on the basis of their external morphology, habit and size, internal CL zonation, trace element chemistry (see section 'Zircon U–Pb isotopes and trace element data') and U–Pb dates (see section 'Zircon U–Pb isotopes and trace element data').

Zircon grains in Group 1 are anhedral to euhedral, 80–200 µm long and have aspect ratios of 1:1 to 2:1 (Fig. 8a and b). In CL, internal zircon textures are commonly homogeneous, with occasional faint oscillatory or sector zoning (Fig. 8a and b). The only difference in Group 1 grains is that in the granodiorite and granite Group 1 grains are typically rounded cores that are always overgrown by oscillatory-zoned zircon (Fig. 8b), whereas in the trondhjemite Group 1 grains show no core–rim relationships (Fig. 8a).

Group 2 grains occur in granodiorite and granite (Fig. 6c and d) and comprise zircon crystals that are euhedral to subhedral, 75–150 µm long and have aspect ratios of 1:1 to 4:1 (Fig. 8c and d). In CL, Group 2 grains show well-developed oscillatory zoning with occasional thin, bright rims (<15 µm wide; Fig. 8c and d). Crystals in Group 2 have similar internal textures to Group 1 but have significantly different ages (see section 'Zircon U–Pb isotopes and trace element data', Table 3).

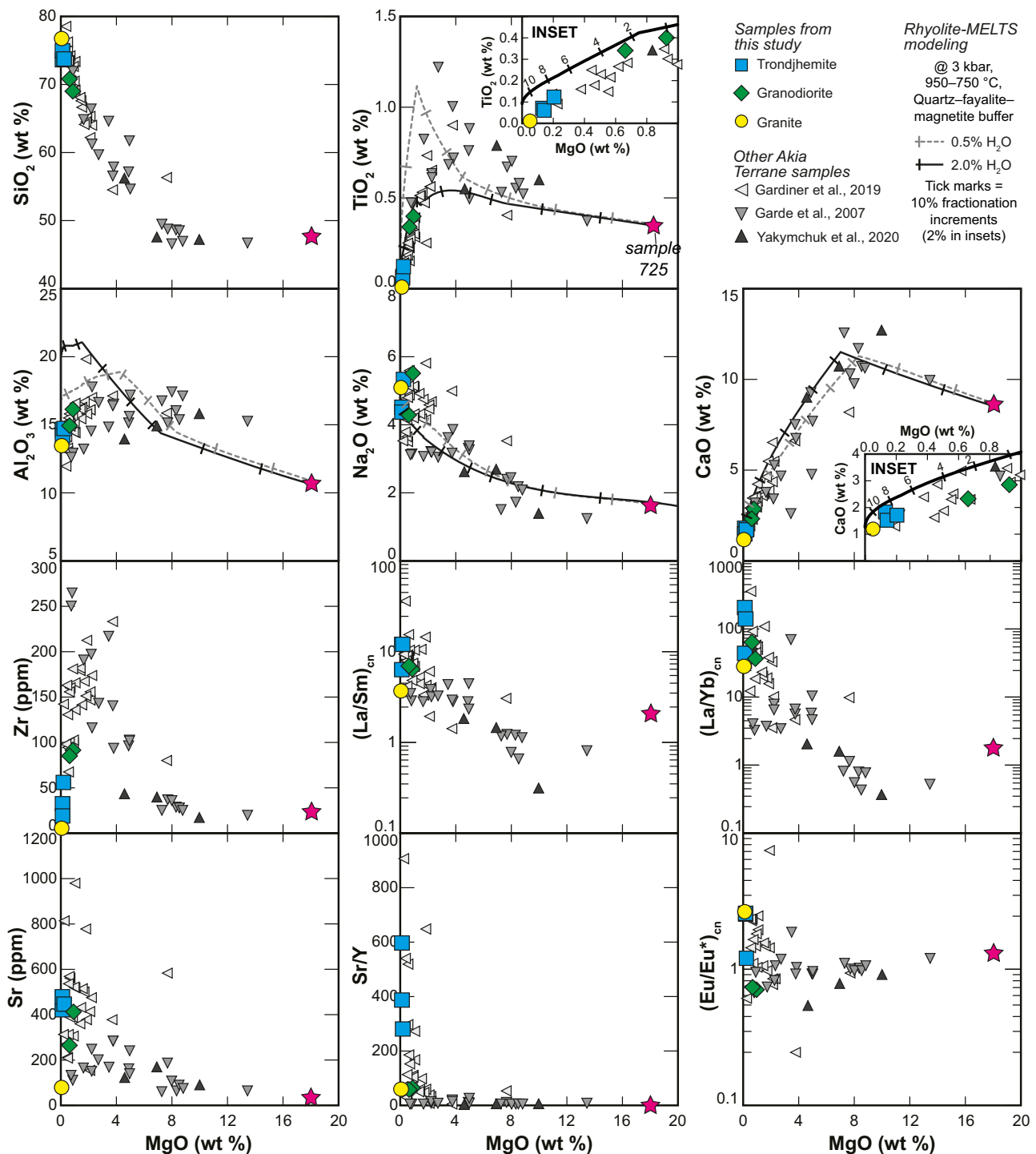
Group 3 grains also occur in granodiorite and granite samples. These grains are morphologically similar to Group 2, being euhedral to subhedral, 120–150 µm long and with length to width ratios of 1:1 to 3:1 (Fig. 8e and f). They differ from Group 2 in CL, displaying well-developed oscillatory and sector zoning with internal zones that are significantly brighter than those for any of the other groups (Fig. 8e and f). However, oscillatory zoning towards the edge of the grains is commonly darker in CL (Fig. 8e and f). There are also thin rims (<25 µm) present on Group 4 grains that are equally bright in CL in sample 1416 (e.g. Fig. 8i, far right grain 17), and these may be equivalent to Group 3.

Group 4 is present in every sample except 1417. Group 4 comprises anhedral to subhedral zircon grains, ~150–400 µm long with aspect ratios of 2:1 to 4:1 (Fig. 8g–i). Zircon grains from Group 4 tend to be larger and more elongated than crystals from other groups. In CL, Group 4 crystals show variable degrees of mottling in the core and rim, which commonly overprints oscillatory zonation (Fig. 8g–i). Bright rims also occasionally occur on anhedral cores (Fig. 8i).

Group 5 is present in most samples and comprises anhedral to euhedral, ~200–300 µm long zircon grains with aspect ratios of 2:1 to 3:1 (Fig. 8j). In CL, zircon grains show extremely mottled to occasionally near-homogeneous internal textures (Fig. 8j).

## Zircon U–Pb isotopes and trace element data

Analyses and ages for each of the samples may be found in Fig. 9. Analyses that do not overlap with the

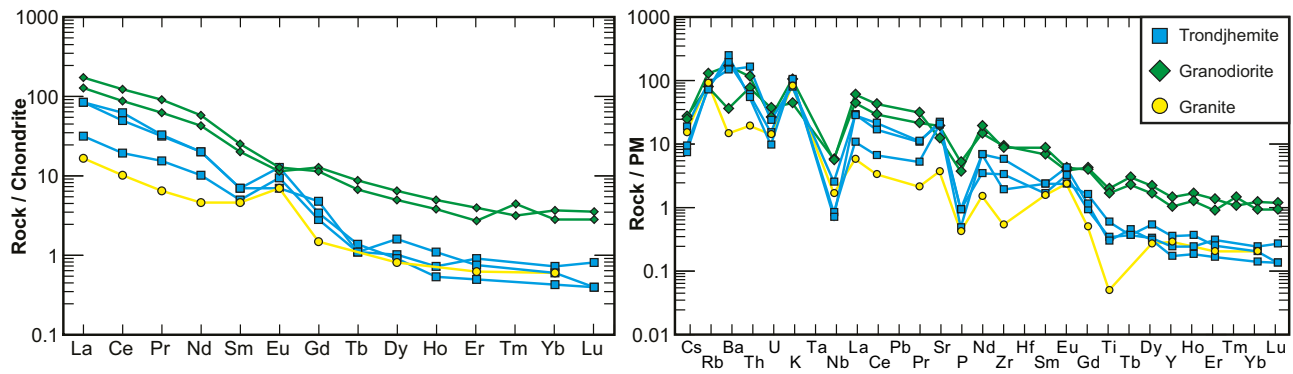


**Fig. 6.** Harker diagram plots of selected major and trace element (ratios) vs MgO, including published data from mafic amphibolites, andesite and TTG suites from the Akia Terrane (Garde, 2007; Gardiner *et al.*, 2019b; Yakymchuk *et al.*, 2020). Rhyolite-MELTS v1.0.2 modelling (Gualda *et al.*, 2012) curves shown for MgO against major elements using for scenario 1 (see Discussion): (1) sample 725 from Yakymchuk *et al.* (2020) as a starting composition, (2) constant pressure = 3 kbar and adiabatic cooling from 950 to 750 °C, (3) 0.5–2.0 wt% H<sub>2</sub>O concentration, (4) a quartz–fayalite–magnetite buffer. Insets in TiO<sub>2</sub> and CaO vs MgO relate to scenario 3 (see Discussion) and are close-up views of the same MELTS model. Numbers in insets represent fractionation amounts in per cent starting from the most primitive granodiorite sample (872). It should be noted that the SiO<sub>2</sub> curve is not shown owing to quartz buffer, which means that quartz cannot fractionate. Chondrite-normalization (cn) after Sun & McDonough (1989).

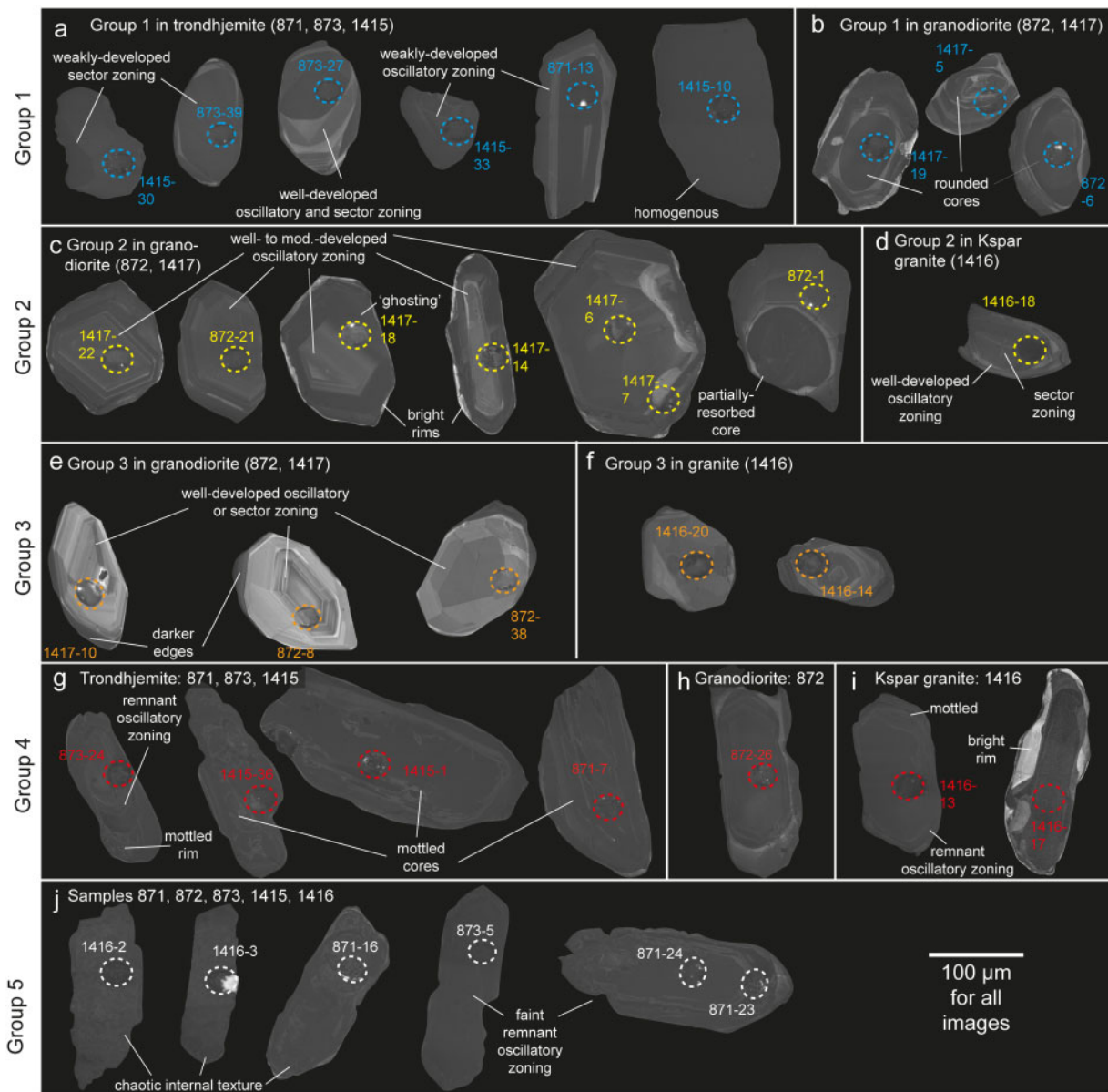
concordia or are mixed core–rim ablations are not considered further. On the basis of characteristic textural, chemical and U–Pb characteristics (Table 3), we present

all U–Pb data per textural grouping (Fig. 10) and report the differences between groupings below. All analyses reported below are from grain cores; analyses of thin,





**Fig. 7.** Rare earth element and incompatible element spider diagrams. Chondrite and primitive mantle normalization after Sun & McDonough (1989).



**Fig. 8.** Representative CL images of zircon grains. All images are shown at the same scale, and were taken at the same operating conditions. Dashed circles and adjacent numbers correspond to 30 µm laser ablation spots. A full compendium of all zircon CL images may be found in [Supplementary Data Fig. B](#).

**Table 3:** Classification of zircon fractions using grain habit, internal textures, trace element concentrations and U–Pb dates

	Group 1	Group 2	Group 3	Group 4	Group 5
Samples	All	872, 1417, 1416	872, 1417, 1416	All except 1417	871, 873
Lithologies	All	Granodiorite, granite	Granodiorite, granite	All	Trondhjemitite
Shape	Eu- to anhedral	Eu- to subhedral	Eu- to subhedral	An- to subhedral	An- to euhedral
Size ( $\mu\text{m}$ )	80–200	75–150	120–150	150–400	200–300
Aspect ratio	1:1–2:1	1:1–4:1	1:1–3:1	2:1–4:1	2:1–3:1
CL texture	Homogeneous to faint oscillatory or sector zoning	Oscillatory zoning	Oscillatory and/or sector zoning	Mottling + weak oscillatory zoning	Highly mottled, chaotic to near-homogeneous
Texture of rims	Oscillatory-zoned	<15 $\mu\text{m}$ , bright	<25 $\mu\text{m}$ , bright	Bright	n.a.
No. of concordant analyses	34	29	14	31	17
Th/U range	0.28–7.2	0.80–2.4	1.2–5.0	0.03–2.1	0.03–0.15
Th/U median	1.9	1.2	1.7	0.34	0.07
U range (ppm)	66–385	82–449	27–82	102–1538	1275–3378
U median (ppm)	123	183	51	721	1777
$T_{\text{ZircTi}}$ range ( $^{\circ}\text{C}$ )	628–797	605–925	674–774	616–865	603–804
$T_{\text{ZircTi}}$ median ( $^{\circ}\text{C}$ )	724	656	714	718	727
Date range (Ma)	3027–2986	2991–2957	3014–2959	3066–3005	3020–2832
Age $\pm 2\sigma$ (Ma)	3010 $\pm$ 4	2974 $\pm$ 4	2982 $\pm$ 10	3039 $\pm$ 5	n.a.

n.a., not applicable.

bright rims in sample 1416 were attempted (e.g. 1416-17 in Fig. 8i) but failed to yield any concordant analyses (Supplementary Data Table B). All uncertainties presented in the text are at  $2\sigma$  internal for individual analyses and 95% confidence for weighted mean ages.

Zircon grains from Group 1 yielded  $^{207}\text{Pb}/^{206}\text{Pb}$  dates from  $3027 \pm 25$  Ma to  $2986 \pm 23$  Ma (Table 3, Fig. 10a, Supplementary Data Table B). All grains from Group 1 in the trondhjemitite and granodiorite or granite yielded  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted mean ages of  $3011 \pm 5$  Ma ( $n=21$ , MSWD=0.61,  $P=0.91$ ) and  $3008 \pm 6$  Ma ( $n=13$ , MSWD=0.96,  $P=0.48$ ), respectively, which overlap at  $2\sigma$  confidence. Zircon grains in Group 1 have low to moderate U concentrations ( $66\text{--}385 \mu\text{g g}^{-1}$ , median =  $123 \mu\text{g g}^{-1}$ ) and variably low to high Th/U ratios (0.28–7.2, average = 1.9; Fig. 11). Ti-in-zircon temperatures are between  $628 \pm 22$  and  $797 \pm 80$   $^{\circ}\text{C}$  (median =  $724$   $^{\circ}\text{C}$ ).

Zircon grains from Group 2 yielded  $^{207}\text{Pb}/^{206}\text{Pb}$  dates from  $2991 \pm 21$  Ma to  $2957 \pm 22$  Ma, (Table 3, Fig. 10b, Supplementary Data Table B). Analyses from Group 2 in the granodiorite and granite yielded  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted mean ages of  $2976 \pm 4$  Ma ( $n=25$ , MSWD=0.76,  $P=0.79$ ) and  $2966 \pm 9$  Ma ( $n=4$ , MSWD=0.30,  $P=0.82$ ), respectively, which overlap at  $2\sigma$  confidence. U concentrations ( $82\text{--}449 \mu\text{g g}^{-1}$ ) and Th/U ratios (0.80–2.4) are similar to those for Group 1 albeit with a slightly larger spread in Th/U (Fig. 11). Ti concentrations are more variable, with most analyses between 1.7 and  $59 \mu\text{g g}^{-1}$ , yielding Ti-in-zircon temperature estimates of  $605\text{--}925$   $^{\circ}\text{C}$ .

Zircon grains from Group 3 yielded relatively imprecise  $^{207}\text{Pb}/^{206}\text{Pb}$  dates from  $3014 \pm 31$  Ma to  $2959 \pm 27$  Ma (Table 3, Fig. 10c, Supplementary Data Table B). Group 3 grains from the granodiorite and granite yielded  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted mean ages of  $2984 \pm 15$  Ma ( $n=9$ , MSWD=2.0,  $P=0.04$ ) and  $2979 \pm 20$  Ma ( $n=5$ , MSWD=1.7,  $P=0.16$ ), respectively, which overlap at  $2\sigma$  confidence and overlap with the

ages from Group 2. All these grains have low U concentrations ( $27\text{--}82 \mu\text{g g}^{-1}$ ) and moderate to high Th/U ratios (1.2–5.0), which explains their relatively imprecise U–Pb dates (Fig. 11). Ti concentrations are consistently low ( $4.4\text{--}14.5 \mu\text{g g}^{-1}$ ) that translate to Ti-in-zircon temperatures of  $674 \pm 67$  to  $774 \pm 15$   $^{\circ}\text{C}$ .

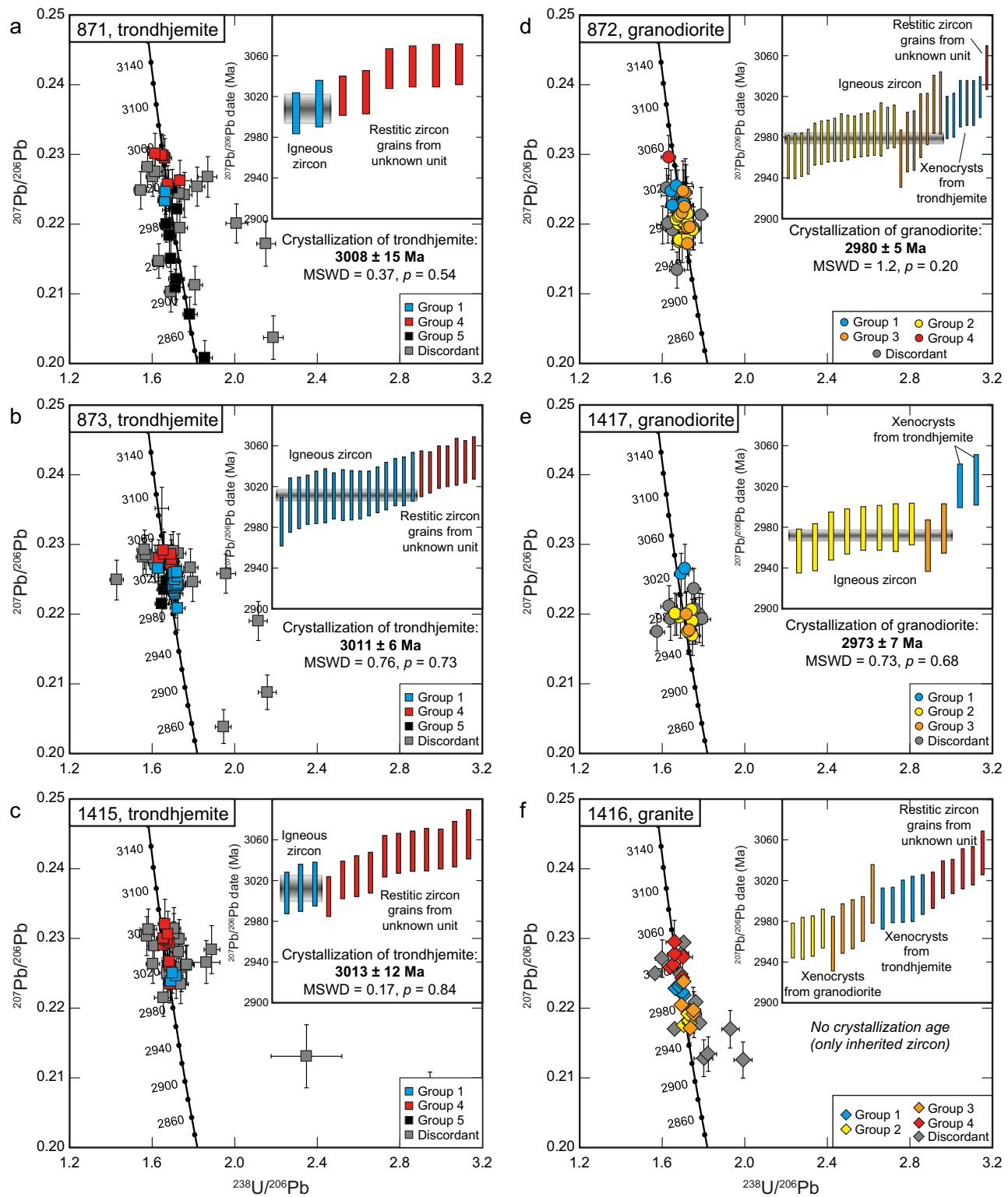
Group 4 grains, which show various degrees of mottling and partial resorption, yielded  $^{207}\text{Pb}/^{206}\text{Pb}$  dates from  $3066 \pm 24$  Ma to  $3005 \pm 19$  Ma across five of the six samples (Table 3, Fig. 10d, Supplementary Data Table B). The Group 4 grains yielded a  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted mean age of  $3037 \pm 5$  Ma ( $n=31$ , MSWD=2.0,  $P=0.001$ ) but we note that this is not statistically valid for a single dataset. Zircon grains in Group 4 have moderate to very high U concentrations ( $102\text{--}1538 \mu\text{g g}^{-1}$ , median =  $718 \mu\text{g g}^{-1}$ ) and very low to moderate Th/U ratios (0.03–2.1, median = 0.34; Fig. 11). Ti concentrations also vary by two to three orders of magnitude, from 2.6 to  $35 \mu\text{g g}^{-1}$  ( $n=25$ , with three outliers at 124, 195 and  $611 \mu\text{g g}^{-1}$ ), which yield Ti-in-zircon temperature estimates of  $635 \pm 64$  to  $865 \pm 15$   $^{\circ}\text{C}$  (median =  $726$   $^{\circ}\text{C}$ , excluding the three outliers).

Group 5 grains have variable  $^{207}\text{Pb}/^{206}\text{Pb}$  dates from  $3020 \pm 20$  Ma to  $2832 \pm 20$  Ma with no statistically significant mean (Table 3, Fig. 10e, Supplementary Data Table B). These grains have very high concentrations of U from  $1275$  to  $3378 \mu\text{g g}^{-1}$  that make these zircon grains particularly susceptible to metamictization and (partial) isotopic resetting.

## DISCUSSION

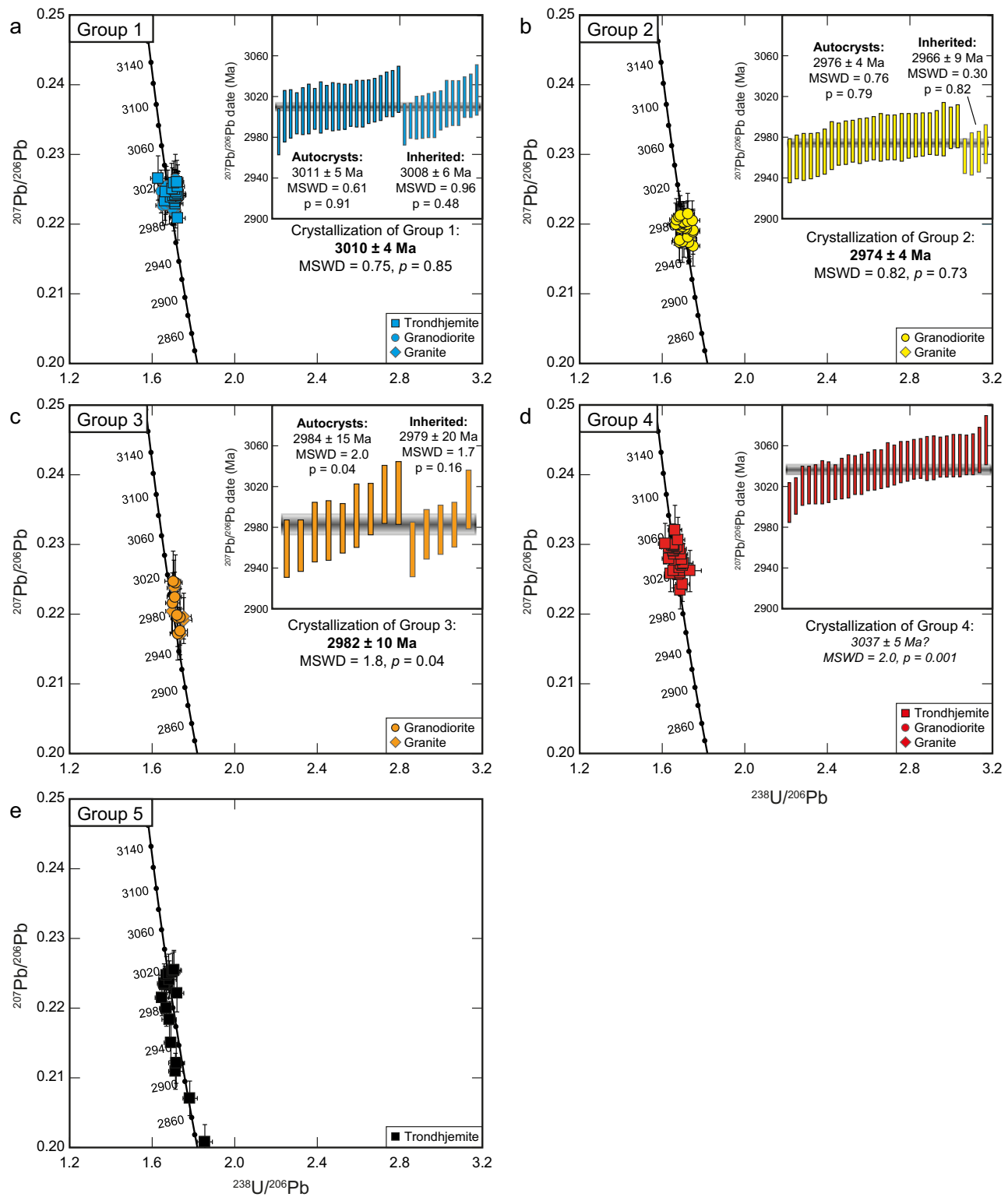
### Assigning absolute ages to granitoids

Field mapping has identified three distinct generations of granitoids, from oldest to youngest, trondhjemitite, granodiorite and granite (Fig. 3). These field observations are, to some degree, in agreement with the calculated



**Fig. 9.** Tera-Wasserburg U-Pb inverse concordia plots for zircon sorted by sample. (a–c) trondhjemite (squares); (d–e) granodiorite (circles); (f) granite (diamonds). Colors correspond to interpretations based on morphological analysis, CL response and zircon trace element data (see Table 3). It should be noted that a single highly discordant analysis from sample 1417 is not shown for reasons of clarity. Full U-Pb data tables may be found in Supplementary Data Table B.

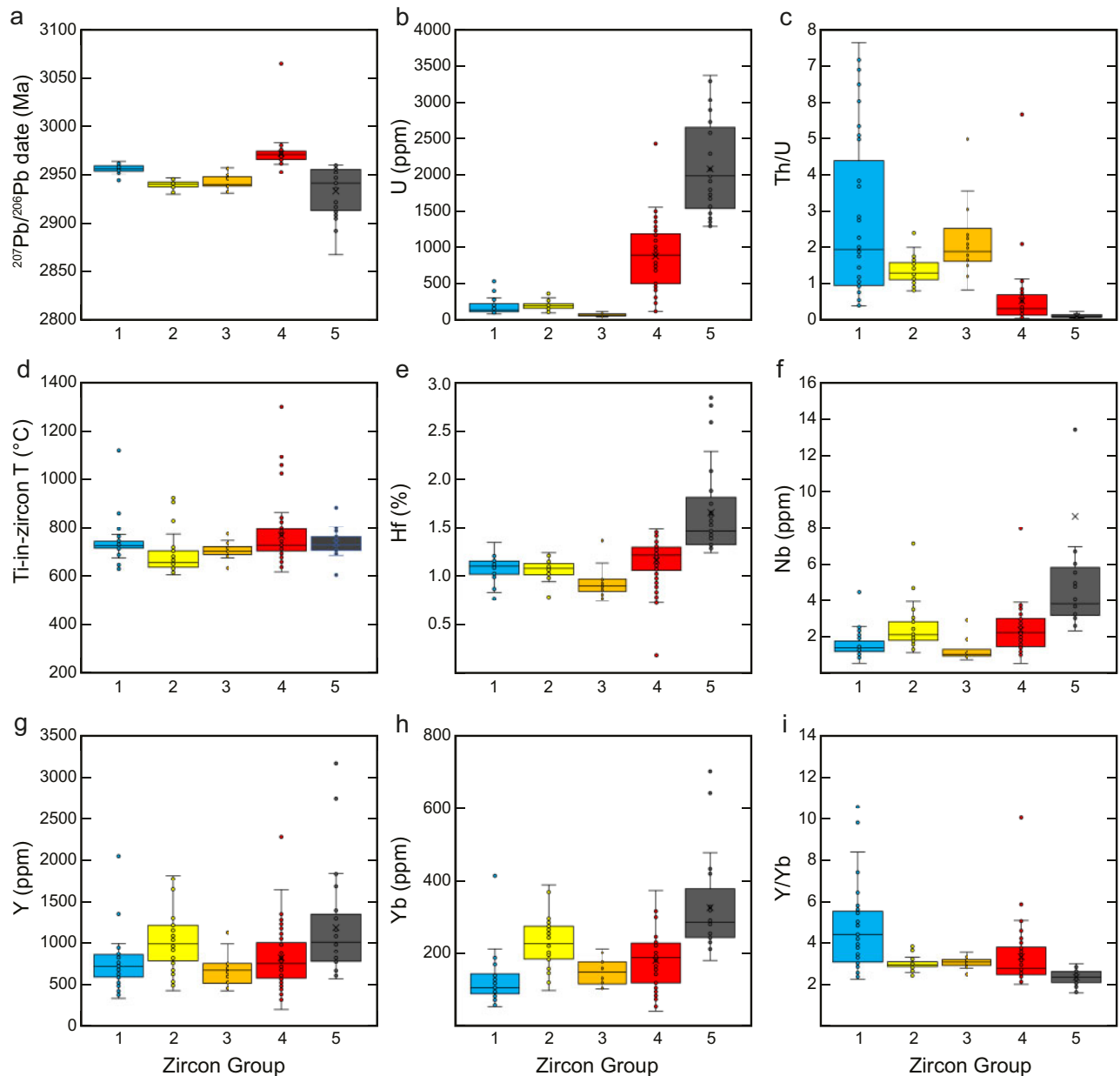




**Fig. 10.** Tera-Wasserburg U–Pb inverse concordia plots for zircon sorted by textural grouping. (a) Group 1; (b) Group 2; (c) Group 3; (d) Group 4; (e) Group 5. (For interpretation as autocrystic and inherited grains, see Discussion section ‘Assigning absolute ages to granitoids’.) Full U–Pb data tables may be found in [Supplementary Data Table B](#).

zircon U–Pb ages. However, none of the samples yielded a single statistically coherent fraction of zircon U–Pb dates (i.e.  $p \geq 0.05$ ) compatible with solely autocrystic origin (Fig. 9). We show below that the mixture of

zircon fractions can primarily be attributed to various inherited zircon reservoirs mixing with autocrystic fractions, where only the latter can be used to determine the timing of magmatic crystallization.



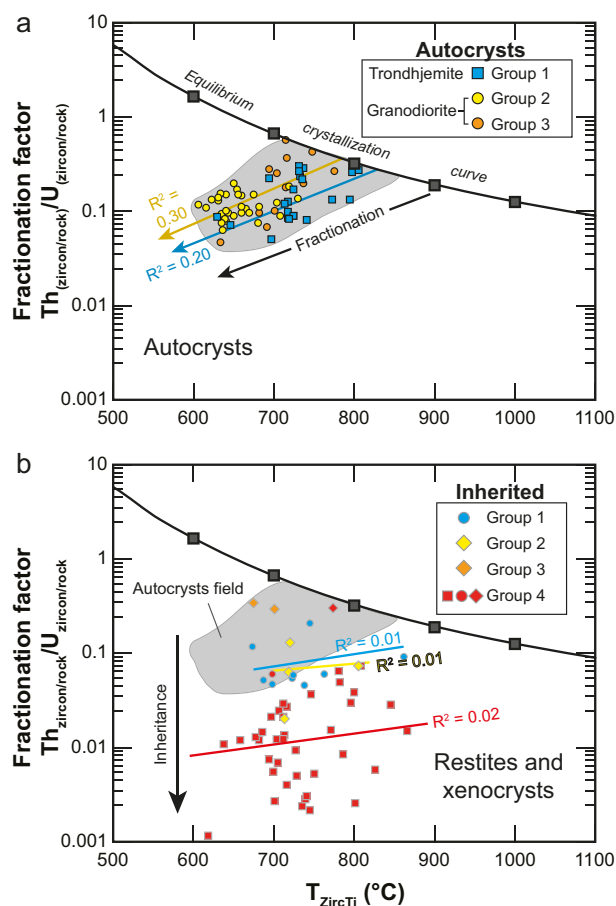
**Fig. 11.** Box-and-whisker plots for selected zircon U–Pb dates and trace elements in texturally classified groups.

#### *Groups 4 and 5—herited fractions*

In most samples, Group 4 shows textural and chemical evidence for being out of chemical equilibrium for at least some of its history within a silicate melt. Texturally, zircon grains show mottled textures, partial to complete destruction of oscillatory and sector zoning, and resorbed grain edges (Fig. 8g–i). Chemically, there is a significant disequilibrium between, for example, Th/U ratios in the zircon crystals versus that in the bulk-rock (see section ‘Th/U disequilibrium in inherited zircon grains’). The  $^{207}\text{Pb}/^{206}\text{Pb}$  dates for these zircon components range from  $3066 \pm 24$  Ma to  $3005 \pm 19$  Ma, statistically too varied for a single dataset with errors accounted for by analytical uncertainty alone (Fig. 10d).

The heterogeneity in zircon trace element concentrations also points to several different inherited zircon reservoirs (Fig. 11). Ultimately, zircon grains from Group 4 cannot be interpreted as autocrystic and therefore do not provide information on granitoid crystallization ages.

Group 5 is similar in texture to Group 4 but even more internally chaotic (Fig. 8j). Group 5 also often displays homogeneous CL textures because its extremely high U and Th concentrations suppress CL response (Nasdala *et al.*, 2003). The chaotic to homogeneous internal textures (Fig. 8j) and the extremely high U and Th concentrations (Fig. 11) are consistent with these grains developing high alpha doses and thus radiation



**Fig. 12.** Th/U tool for the identification of autocrystic, antecrystic and other inherited zircon grains. Figure is based on studies by Kirkland *et al.* (2015) and Siegel *et al.* (2018). (a) Fractionation factor, defined by  $\text{Th}_{\text{zircon/rock}}/\text{U}_{\text{zircon/rock}}$  vs  $T_{\text{ZircTi}}$ , with method from Kirkland *et al.* (2015). Autocrysts should plot along a fractionation trend below the equilibrium crystallization curve and antecrysts should plot above the curve. (b) Method for the identification of xenocrystic and restitic zircon grains, showing notable differences in the field of autocrystic grains defined in (a).

damage, leading to radiogenic Pb loss and isotopic resetting (Ashwal *et al.*, 1999; Cherniak & Watson, 2001). Given that the Akia Terrane has experienced upper amphibolite- and granulite-facies events (Garde *et al.*, 2000; Kirkland *et al.*, 2018a, 2018b; Kirkland *et al.*, 2020; Yakymchuk *et al.*, 2020), it is not surprising that Group 5 grains have undergone partial radiogenic Pb loss to younger apparent U–Pb dates as elevated temperatures, fluids and radiation damage facilitate Pb mobility (Cherniak & Watson, 2001; Geisler *et al.*, 2007; Cherniak, 2010; Peterman *et al.*, 2016). Like those of Group 4, U–Pb dates from Group 5 grains do not reflect the magmatic crystallization ages of their host rocks.

#### Trondhjemite—crystallization revealed by Group 1

With Groups 4 and 5 aside, it is now evident that the trondhjemite host rock (samples 871, 873 and 1415) comprises a single autocrystic zircon group (Group 1)

with a statistically valid  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted mean age of  $3011 \pm 5$  Ma ( $n = 21$ , MSWD = 0.61,  $P = 0.91$ ; Fig. 10a). The presence of oscillatory and sector zoning is indicative of magmatic crystallization processes (Fig. 8a and b). The lack of post-crystallization destruction of primary igneous zones, the lack of resorbed grain edges and the absence of grain rims indicate that this age of c. 3010 Ma represents the crystallization age of the trondhjemite.

#### Granodiorite—crystallization revealed by Groups 2 and 3

Granodiorite dykes (samples 872 and 1417) comprise three zircon fractions denoted as Groups 1, 2 and 3. The textural, morphological, trace element and U–Pb data for Group 1 grains indicate that this group is equivalent to Group 1 in the trondhjemite (Figs 8a, b and 10a, Table 3). Thus, Group 1 grains in the granodiorite represent inherited zircon from the trondhjemite that has been incorporated into the granodiorite melt.

Groups 2 and 3 in the granodiorite are two fractions distinguished via CL response (Fig. 8fc–d) and trace element concentrations (Fig. 11) but with similar U–Pb dates at  $2\sigma$  uncertainty (Fig. 10b and c). Group 2 has significantly higher concentrations of trace elements (e.g. Hf, Nb, U), which suppress the CL response and produce overall lower CL emission textures (Fig. 11). In all other aspects, Groups 2 and 3 are comparable. Similar Ti-in-zircon temperatures between Groups 2 and 3 imply that both zircon groups crystallized at approximately the same temperature (Fig. 11d). Similar incompatible element ratios (e.g. Y/Yb; Fig. 11i) imply that fractional crystallization, which has limited effects on ratios of similarly incompatible elements, is the primary reason for the differences in chemistry and texture of Groups 2 and 3.

With the above considerations, we suggest that both Groups 2 and 3 in the granodiorite are probably part of the same magmatic system, with zircon grains forming at slightly different times and from slightly different source chemical compositions (see Schaltegger & Davies, 2017). The magmatic system may have been partially open to magma recharge at various times, as implied by oscillatory-zoned zircon textures (Fig. 8c and d; Hoskin, 2000), but generally moving towards a closed system from the broad evolution of dark to lighter CL responses (Fig. 8c and d) and corresponding depletions in trace elements (Fig. 8c and d).

Ultimately, there is no noticeable difference in dates between Groups 2 and 3 and thus we cannot differentiate between ante- and autocrystic fractions. A combined  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted mean age of  $2978 \pm 4$  ( $n = 34$ , MSWD = 1.12,  $P = 0.29$ , Fig. 10b and c) for Groups 2 and 3 is considered the best age estimate for crystallization of the granodiorite dykes. This age is also comparable with the c. 2970 Ma age previously determined from granodiorite intrusions at locality 1 by Scherstén & Garde (2013; sample 524254).



### *K-feldspar granite—solely inherited crystals*

The K-feldspar-rich granite (sample 1416) is enigmatic in that it comprises only zircon grains with the same morphological, textural, chemical and age characteristics as those found in samples of the surrounding trondhjemite and granodiorite (Fig. 8–10). Although Group 4 shows evidence of inheritance (e.g. mottling, partial resorption; Fig. 8c), Groups 2 and 3 are texturally indicative of magmatic zircons (Corfu *et al.*, 2003), with no clear evidence of partial resorption or overprinting of primary oscillatory or sector zoning (Fig. 8g and i), yet the chemistry and U–Pb dates of Groups 2 and 3 in the granite can be clearly linked to the same groups in the granodiorite, overlapping in age (Figs 10 and 11).

Without the trondhjemite and granodiorite geochronology it would have been difficult, if not impossible, to ascertain that Groups 2 and 3 in the granite were inherited and not autocrystic. The age of the granite (sample 1416) would conceivably have been erroneously interpreted as the age of the youngest zircon fraction. Instead, all the analyses record zircon inheritance. Therefore, we can ascertain that the granite is younger than the granodiorite only on the basis of cross-cutting relationships (i.e. younger than c. 2978 Ma; Fig. 10b and c). As the magmatic rims did not yield concordant analyses, it is uncertain how much younger the granite is.

### **Th/U disequilibrium in inherited zircon grains**

Above, we have shown that sufficient textural, chemical and age evidence exists for differentiating inherited from autocrystic grains. In addition, there are indications that there is a significant imbalance of Th/U ratios in the zircon crystals versus the bulk-rock (Fig. 12). Work by Kirkland *et al.* (2015) on >10 000 magmatic zircon grains from Western Australia established a distinct relationship between Ti-in-zircon crystallization temperature and  $\text{Th}_{(\text{zircon/rock})}/\text{U}_{(\text{zircon/rock})}$ . Kirkland *et al.* (2015) predicted the  $\text{Th}_{(\text{zircon/rock})}/\text{U}_{(\text{zircon/rock})}$  ratio under equilibrium crystallization conditions and suggested that autocrystic zircon grains plot between the equilibrium crystallization curve—where zircon is in equilibrium with the silicate melt—and a fractionation trend with a high correlation coefficient towards lower  $\text{Th}_{(\text{zircon/rock})}/\text{U}_{(\text{zircon/rock})}$  (Fig. 12a). Conversely, antecrystic grains were suggested to plot above the equilibrium crystallization curve, indicating that these formed at high temperatures and prior to significant fractionation (Fig. 11a; Kirkland *et al.*, 2015). Siégl *et al.* (2018) found slightly different relationships in a zircon dataset from eastern Australia but produced a similar equilibrium crystallization curve, some 50 °C lower for a given  $\text{Th}_{(\text{zircon/rock})}/\text{U}_{(\text{zircon/rock})}$  at ~700 °C (see fig. 8B of Siégl *et al.*, 2018). Given the uncertainties associated with Th/U concentrations in whole-rocks (see below; Table 2), a 50 °C difference is within uncertainty of the modelling technique.

In our dataset, the autocrystic grains (i.e. Group 1 in the trondhjemite, Groups 2 and 3 in the granodiorite) mimic the autocryst fractionation trend identified by Kirkland *et al.* (2015) (Fig. 12a). There are minor differences in whole-rock Th/U ratios in the trondhjemite (18–28) and granodiorite (10–20) but these make little difference to the logarithmically plotted  $\text{Th}_{(\text{zircon/rock})}/\text{U}_{(\text{zircon/rock})}$  ratios (Fig. 12). Both the trondhjemite and granodiorite show moderate correlations ( $R^2 = 0.30$  and  $0.20$ , respectively), which intersect the equilibrium crystallization curve at temperatures of 830 and 780 °C, respectively (Fig. 12a). The spread in data is possibly a reflection of slight Th/U ratio differences between the individual fractionated crystals' melt composition and the measured whole-rock concentration (as a proxy for that melt). Thus, it is more conservative to estimate the crystallization temperature range from the full spectrum of data (i.e. positions where the grey field in Fig. 12a touches the equilibrium crystallization curve), which corresponds to a temperature range of ~720–860 °C (Fig. 12a). We see no data points plotting above the equilibrium crystallization curve and, thus, no evidence for antecrystic zircon grains (Fig. 12a).

One important implication carried with this form of evaluation of crystal geochemistry is how the Th/U ratio in zircon versus bulk-rock can be used to differentiate autocrystic versus xenocrystic and restitic zircon grains. Both xenocrystic and restitic grains are expected to be, on average, in significant disequilibrium with the silicate melt they reside in, irrespective of whether they were incorporated via partial melting of a restitic source or wall-rock assimilation. Diffusional equilibration of Th and U with the host melt is also expected to be negligible given the very slow diffusivity of actinides in zircon (Cherniak *et al.*, 1997). Furthermore, inherited zircon grains would be expected to display greater variability in  $\text{Th}_{(\text{zircon/rock})}/\text{U}_{(\text{zircon/rock})}$  as a function of their dissimilarity to primary melt composition (i.e. whole-rock composition). Thus, fractional crystallization regressions through inherited components would not be well defined (i.e. low  $R^2$ ) due to this source discrepancy. This hypothesis is corroborated by both poor overlap of the inherited fraction with the field defined by autocrystic grains and poor correlation trends of the inherited grain groups ( $R^2 < 0.02$ ; Fig. 12b).

The discrepancy between the inherited grains and the autocrystic field in Fig. 12a is especially notable for Group 4, interpreted to be derived from a restitic reservoir (Fig. 12b). Such extremely low fractionation factors are geologically unreasonable (Kirkland *et al.*, 2015), implying that the Th/U ratios in the restitic zircon grains cannot correspond to the Th/U whole-rock ratios of the trondhjemite, granodiorite or granite in which the restitic zircon grains reside. Other inherited groups (Group 1 in the granodiorite and granite, and Groups 2 and 3 in the granite) deviate less from the autocrystic field (Fig. 12b), indicating that the zircon Th/U ratios are more similar to the whole-rock Th/U ratios of the trondhjemite, granodiorite and granite (Table 2).

Nonetheless,  $R^2$  values of fits are still much lower than those from autocrystic components (Fig. 12b). This technique may provide another tool for identifying inherited zircon crystals, particularly if the parent zircon source has dissimilar bulk-rock Th/U ratios to the new silicate melt.

### Modelling the causes for inherited zircon in granitoids

With the ages assigned to the three sample lithologies, the addition of whole-rock geochemistry coupled with the above zircon data can be used to elucidate the processes that account for the lack of autocrystic zircon grains in the granite. The granite sample has extremely low Zr concentrations at  $\sim 6 \mu\text{g g}^{-1}$ ; granitoids with such low concentrations of Zr are rare in the Proterozoic and Phanerozoic (Barbey *et al.*, 1996) but more common in the Archean rock record (Van Kranendonk & Kirkland, 2013). The low Zr concentrations in the granite are consistent with its lack of autocrystic zircon (Fig. 9), and the paucity of zircon grains in the sample in general (Supplementary Data Fig. B). In any evolved granitoid such as granite sample 1416 with  $\sim 77 \text{ wt\% SiO}_2$ , it is necessary to have multiple stages of crystallization and partial melting to evolve a mantle-derived melt with  $\sim 45\text{--}50 \text{ wt\% SiO}_2$  to a rock with  $>75 \text{ wt\% SiO}_2$  (Fig. 12; Chappell, 1974; Soesoo, 2000; Clemens *et al.*, 2011; Gao *et al.*, 2016). The primary mechanism for reducing the Zr concentrations for highly evolved rocks is via fractional crystallization or partial melting of already Zr-depleted rocks (Lee & Bachmann, 2014; Wu *et al.*, 2017).

Three scenarios are considered for the inheritance of zircon grains in the granite: (1) extensive fractional crystallization of a lower crustal, mafic amphibolite, as is commonly invoked as the source for TTGs (Condie, 2005; Bédard, 2006; Næraa *et al.*, 2014; Gardiner *et al.*, 2019a), with additional local assimilation of wall-rock; (2) remelting of the granodiorite and/or trondhjemite to form the granite; (3) fractionation of the surrounding granodiorite and/or trondhjemite.

#### Scenario 1: extensive fractional crystallization of a mafic amphibolite

In the first scenario, we test whether extensive fractional crystallization of a less evolved source can generate the investigated samples by using the rhyolite-MELTS program (Gualda *et al.*, 2012). We employ adiabatic cooling of a variably hydrated, mafic granulite from 950 to 750 °C, whereby the final temperature corresponds approximately to the temperature of granite crystallization as predicted by Fig. 12. We use a mafic granulite sample (725) from Yakymchuk *et al.* (2020) as a starting composition as this sample is sufficiently primitive ( $\sim 48 \text{ wt\% SiO}_2$ ,  $18 \text{ wt\% MgO}$ , Fig. 6) and is proximal to the samples studied here ( $\sim 50 \text{ km}$  apart). Other magmatic samples with major and trace element data from the Akia Terrane (Garde, 2007; Gardiner *et al.*, 2019b; Yakymchuk *et al.*, 2020) are also shown to facilitate the

modelling. The incorporation of various degrees of granodiorite or trondhjemite assimilation is not modelled because of their compositional similarity to the granite (Fig. 6).

We find that fractionation at upper crustal conditions ( $\sim 3 \text{ kbar}$ ) at relatively low  $\text{H}_2\text{O}$  contents of  $\sim 2.0 \text{ wt\%}$  best fits the various major element patterns, although  $\text{Al}_2\text{O}_3$  is a better fit with lower water contents ( $\text{H}_2\text{O} = 0.5 \text{ wt\%}$ ; Fig. 6). We note that rhyolite-MELTS does not model quartz or magnetite fractionation as a quartz-fayalite-magnetite (QFM) buffer is assumed. Also, rhyolite-MELTS does not model trace elements but the MgO vs Zr trend is qualitatively similar to, for example, the modelled MgO vs  $\text{TiO}_2$  curve (Fig. 6), the latter being related to rutile, titanite or ilmenite fractionation. It should be noted that rhyolite-MELTS does not account for the breakdown of hydrous phases (e.g. amphibole). Thus, the water content will probably vary during cooling, and this is not encapsulated in our models.

Our models indicate that fractionation of up to 85% crystals is required to yield the highly depleted samples with  $>74 \text{ wt\% SiO}_2$  and  $<0.2 \text{ wt\% MgO}$  (Fig. 6). Such extreme fractionation volumes are unlikely as the efficacy of crystal fractionation in felsic liquids is inhibited by both their high viscosity and the similar densities of fractionated phases (e.g. plagioclase) from the residual melt (Clemens & Stevens, 2016).

#### Scenario 2: partial melting of surrounding granodiorite or trondhjemite

In the second scenario, partial melting of the granodiorite or trondhjemite modelling cannot produce the granite. Rare earth elements are often employed for melting or fractionation modelling as they are relatively insensitive to secondary processes such as alteration and metamorphism (Jourdan *et al.*, 2007; Olierook *et al.*, 2018). Partial melting of the trondhjemite or granodiorite would lead to, for example, an increase in the La/Sm and La/Yb ratios of the resultant melt. However, the granite has even lower La/Sm and La/Yb than the trondhjemite and granodiorite (Fig. 6). Thus, it is not possible to generate the granite from the trondhjemite or granodiorite.

#### Scenario 3: fractionation of the surrounding granodiorite or trondhjemite

In the third scenario, the presence or absence of autocrystic zircon may reflect the fractionation of anatectic melt in the deep crust. Anatectic melt in the deep crust is generated through partial melting of high-temperature metamorphic rocks mostly through reactions associated with the breakdown of hydrated minerals (e.g. Brown, 2013; Yakymchuk, 2019). In the Akia Terrane, high-temperature-low-pressure granulite-facies metamorphism associated with partial melting occurred at c. 3.05–2.97 Ga (Friend & Nutman, 1994; Garde *et al.*, 2000; Yakymchuk *et al.*, 2020).

Mesoarchean (c. 3.0 Ga) granitoids in the western Akia Terrane have zircon Hf isotope ratios that are consistent with being derived from Eoarchean metabasites (Gardiner *et al.*, 2019b) and have trace element compositions consistent with melt expected from partial melting of metabasites at 3–6 km below the current erosional level (Yakymchuk *et al.*, 2020). Therefore, rocks exposed at the current erosional level and from the deeper crust were part of the same anatectic system at c. 3.0 Ga in the western Akia Terrane. Melt may have been generated, transported and emplaced at various levels in the partially molten deep crust without necessitating discrete partial melting and crystallization episodes as is envisaged in the first two scenarios.

During anatexis, melt initially forms at the grain boundaries between reactants; once a critical volume is reached, low-density and weak felsic melt can be extracted (e.g. Rosenberg & Handy, 2005) and then ascend owing to buoyancy or travel to nearby dilational zones. In many migmatite terranes, the majority of melt generated is expected to stay in the anatectic crust (e.g. Morfin *et al.*, 2013; Yakymchuk *et al.*, 2013; Diener *et al.*, 2014; Carvalho *et al.*, 2016). Chemical differentiation of this melt can occur during extraction, transport, and emplacement as a result of crystal fractionation (Sawyer, 1987; Solar & Brown, 2001; Morfin *et al.*, 2014). Consequently, most granitoids in anatectic terranes do not have the compositions of initial anatectic melt. The two granodiorite samples (872 and 1417) that we investigated do not show strongly fractionated trace element patterns and are the closest approximation to the composition of initial anatectic melt expected to be generated from an anatectic metabasite (see Yakymchuk *et al.*, 2020). These rocks would be expected to have igneous zircon and variable amounts of restitic or xenocrystic zircon depending on the efficacy of extraction from the source (i.e. entrained material) and interaction with the wall rock during transport and emplacement (i.e. assimilation).

Many granitoids in migmatite terranes are cumulates that reflect the physical accumulation of early crystallized minerals and the loss of more fractionated melt (e.g. Sawyer, 1987; Brown *et al.*, 2016; Yakymchuk, 2019). Melt loss can be aided by syn-anatectic deformation (i.e. filter pressing; Brown *et al.*, 1995). Considering that zircon is expected to grow early from anatectic melt in the crystallization sequence (Kelsey *et al.*, 2008; Yakymchuk & Brown, 2014), these rocks are expected to contain autocrystic zircon. Three trondhjemites (871, 873 and 1415) from the Akia Terrane show positive Eu anomalies that suggest that they have more plagioclase than an initial melt composition and could be part of the cumulate suite (Fig. 7). These samples also contain autocrystic zircon as well as restitic zircon that could have been retained from the source.

The complementary fractionated melt to the cumulate-rich material in migmatites is granitoids that are leucocratic, SiO<sub>2</sub> and K<sub>2</sub>O rich, and can have low (<100 µg g<sup>-1</sup>) concentrations of Zr (Sawyer, 1987; Milord

*et al.*, 2001; Morfin *et al.*, 2014). These features reflect the physical separation of ferromagnesian minerals, plagioclase and potentially zircon from the anatectic melt prior to final emplacement and crystallization (e.g. Morfin *et al.*, 2014). Even if antecrystic zircon crystallized from this melt, it may have been physically separated during extraction and remained with the complementary cumulates. Zr/Hf ratios, an effective tool to test whether zircon has been extensively fractionated from the melt in granites (Claiborne *et al.*, 2006), show broadly chondritic Zr/Hf ratios of 33.3–40.5 for the trondhjemite and granodiorite samples (Table 2), indicative of negligible to modest zircon fractionation (Claiborne *et al.*, 2006). However, granite sample 1416 has a Zr/Hf ratio of 30.0 (Table 2), significantly lower than chondrite values, and probably reflects extensive zircon fractionation.

The final emplacement of this fractionated and Zr-depleted melt may be associated with the entrainment of xenocrystic zircon from the surrounding rocks and autocrystic zircon may be absent. Sample 1416 from this study has similar characteristics (high SiO<sub>2</sub>, high K<sub>2</sub>O, leucocratic, low Zr) to fractionated granite compositions in other migmatite terranes, contains xenocrysts with similar ages to those from the host granodiorite and trondhjemite (Fig. 10), and yielded no autocrystic zircon. Consequently, the early crystallization of anatectic melt and physical separation of the cumulate-rich material from the fractionated liquid may result in granitoids with very little autocrystic zircon.

To test the above ideas, we use the same MELTS model as in scenario 1 but start the fractionation from the most primitive sample in our study (granodiorite 872 with MgO = 0.92). Using the most primitive rock will provide the maximum fractionation expected to generate a granite. We show that the granite is best produced with ~10% fractionation of granodiorite sample 872 with 2.0 wt% H<sub>2</sub>O, pressures of 3 kbar and a QFM buffer (Fig. 4, insets in TiO<sub>2</sub> and CaO diagrams). If the granite was instead produced from further fractionation of one of the trondhjemites, the fractionation would be ~2–3% only. Irrespective of which scenario is correct, a maximum of 10% fractionation is far more feasible in crustal rocks than scenario 1, which involved starting with a mafic amphibolite and fractionating 85% in a single step. Thus, fractionation from the granodiorite or trondhjemite seems plausible to generate the granite.

One final point of interest is how a rock with ~6 µg g<sup>-1</sup> Zr managed to avoid complete dissolution of zircon crystals. A Zr-saturated melt is required for the zircon to remain stable and remain in the residue during anatexis; if the melt was undersaturated, any zircon would be dissolved. In thin section, the only observed zircon crystal in sample 1416 is situated within a large plagioclase crystal (insets in Fig. 4e and f). Thus, we propose that the zircon crystals were buffered in a major phase mineral that was also inherited. Zircon crystals that were entombed in feldspar grains would be exempt

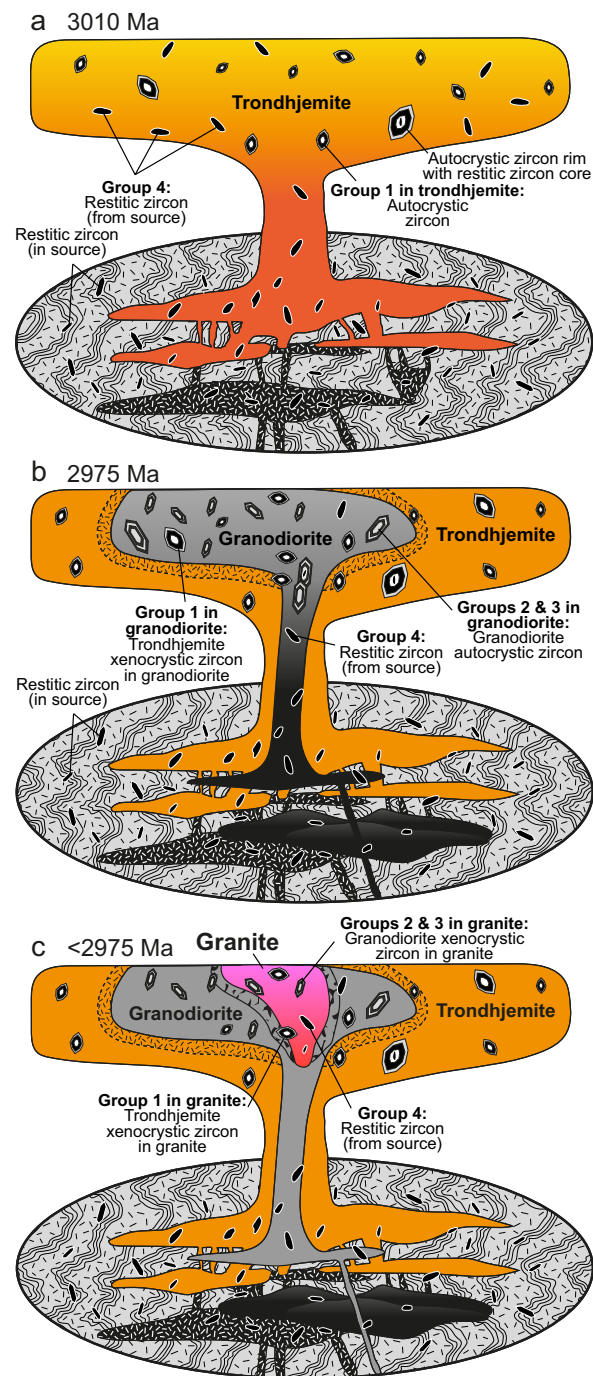


from interaction with fluids, thereby preserving zircon in a Zr-undersaturated melt.

### Mechanisms for inherited zircon delivery into magmatic plumbing systems

Our modelling indicates that the ultimate source or sources for the trondhjemites, granodiorites and granite samples in this study are all mafic amphibolites similar to sample 725 of Yakymchuk *et al.* (2020) (Figs 6 and 13), and this is also consistent with Hf isotopic data (Gardiner *et al.*, 2019a). However, extensive crystal fractionation (~85%) as presented in scenario 1 is unlikely, and a fractionation of the surrounding trondhjemite and/or granodiorite (<10%) in a partially molten deep crust (scenario 3) is a more plausible explanation. The question remains how abundant inherited zircon was specifically incorporated into these rocks. Two primary mechanisms for delivering inherited zircon into a new magma plumbing system have been proposed: (1) derivation from partial melting of a deep, restitic source, or (2) shallow-level wall-rock assimilation (i.e. xenocrysts; Fig. 1). We suggest that both modes have operated for delivering different zircon groups into different lithologies in our case study, and these are explored in more detail below.

Zircon found deep in the magmatic plumbing system and ascending is a common phenomenon but its unambiguous identification remains problematic (Figs 1 and 13; Miller *et al.*, 2007). Much like source-to-sink analysis of sedimentary rocks, analysis of both the restite and neocrystallized igneous rocks is a requisite for unequivocal identification of restitic zircon in neocrystallized rocks (Olierook *et al.*, 2019). In our samples, the largest fraction of inherited grains occurs in trondhjemite, with >50% of grains belonging to Group 4 (Fig. 9a and c). Such volumes of inherited zircon are difficult to incorporate into the partial melt via late-stage crustal assimilation because granitoid mushes are not hot enough to facilitate such extensive crustal assimilation (Spera & Bohrsen, 2001) and crustal assimilation is an energy-intensive and self-limiting process (Glazner, 2007). The mottled nature of the grains and textural evidence for partial resorption (Fig. 8) also point towards long-term magma interaction (e.g. Corfu *et al.*, 2003). Excluding two younger Group 4 dates, Group 4 grains of c. 3066–3022 Ma are common in orthogneisses across the Akia Terrane (Garde *et al.*, 2000; Gardiner *et al.*, 2019b), which may imply a widespread reservoir in the Maniitsoq region. Such a source has been found across several locations in the Akia Terrane (Fig. 13). Garde *et al.* (2000) reported ages of  $3050 \pm 7$  Ma and  $3035 \pm 7$  Ma for two retrogressed grey gneisses on the southern margin of the Akia Terrane. In the central part of the Akia Terrane, Garde *et al.* (2000) obtained an age of  $3044 \pm 7$  Ma for a diorite in Fiskefjord. Scherstén & Garde (2013) also reported a c. 3038 Ma age from a granitoid xenolith in a postkinematic intrusion in the northeastern part of the Akia Terrane. Thus, the source of these restitic grains is probably from less evolved gneissic rocks deeper within the Akia Terrane.



**Fig. 13.** Schematic illustration of the sequential formation of trondhjemite, granodiorite and high-silica granite in the Akia Terrane from similarly hydrated mafic amphibolite sources, with their incorporation of different types of zircon. (a) Formation of trondhjemite at c. 3010 Ma with autocrystic (Group 1) and restitic (Group 4) zircon grains. (b) Formation of granodiorite at c. 2975 Ma with autocrystic (Groups 2 and 3), xenocrystic (Group 1 from trondhjemite) and restitic (Group 4) zircon grains. (c) Formation of granite after c. 2975 Ma with xenocrystic (Group 1 from trondhjemite, and Groups 2 and 3 from granodiorite) and restitic (Group 4) zircon grains.

For the granodiorite and granite samples, wall-rock assimilation of xenocrystic zircon is a better explanation for the origins of inherited zircon grains than restitic

zircon (Fig. 13). The granodiorite samples contain only a single zircon analysis from Group 4 across both samples (Fig. 9d and e). Thus, it is unlikely that the Group 4 grains in the granodiorite were incorporated from a restitic reservoir, but rather came from crustal assimilation of the trondhjemitic wall-rock the granodiorite was intruding into. A crustal assimilation mechanism for the granodiorite melt also explains the presence of Group 1 grains that are interpreted to have been derived from the surrounding trondhjemitic. The zircon morphologies of Group 1 grains are relatively unmodified by long-term magma–crystal interaction (Fig. 8; Corfu *et al.*, 2003), which further supports the notion that these grains are xenocrystic rather than restitic. The lack of melt modification of zircon grains from Group 1 is probably due to the short duration of cooling and limited volume of melt, as demonstrated by the relatively thin width of the intrusions and fine to medium grain size of the granodiorite.

## CONCLUSIONS

Two field localities with up to three lithologies in the Akia Terrane contain complex zircon populations comprising both inherited and autocrystic grains. Using textural, and zircon U–Pb and trace element data, it is possible to differentiate inherited from autocrystic components and assign ages of  $3011 \pm 5$  Ma ( $2\sigma$ ) for the host trondhjemitic and  $2978 \pm 4$  Ma ( $2\sigma$ ) for the granodiorite intrusions, compatible with the relative chronology evident in field relationships. The granite is established as the youngest lithology from cross-cutting relationships but yielded exclusively inherited zircon grains sourced from the older two lithologies, with potentially the only magmatic zircon located in  $<15\mu\text{m}$  rims that could not be readily dated. Th/U ratios in zircon versus whole-rock can also serve as a novel tool for differentiating autocrystic from xenocrystic and restitic zircon grains. Whole-rock geochemistry shows that the granite is highly evolved with  $\text{SiO}_2$  contents of  $\sim 77$  wt% and exhibits extremely low concentrations of Zr ( $\sim 6\mu\text{g g}^{-1}$ ). It is likely that such low concentrations were caused by derivation from already Zr-depleted TTG suites, probably from continued fractionation of the surrounding trondhjemitic and/or granodiorite. We demonstrate that inherited zircon grains in the three lithologies were derived from both restitic reservoirs and via wall-rock assimilation. Ultimately, we emphasize the importance of detailed field mapping, adequate sampling of all lithologies, and auxiliary zircon trace element and whole-rock geochemical data to aid in the positive identification of inherited zircon.

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## SUPPLEMENTARY DATA

Supplementary data are available at *Journal of Petrology* online.

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