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U-Pb zircon and titanite age of the Christiansø granite, Ertholmene, Denmark, and correlation with other Bornholm granitoids

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A granitic sample from the Danish island of Christiansø in the Ertholmene island group north of Bornholm is described petrographically and geochemically, and dated using U-Pb in zircon and titanite. Zircon systematics in the sample are complicated by abundant Pb loss and a large population of zircons interpreted as being inherited. Removal of highly disturbed zircons, imprecise analyses, and assumed inherited zircons yield an upper intercept date of 1500 ± 18 Ma (MSWD = 13, n = 58). Removal of zircons with high common Pb from this population yields an identical result of 1500 ± 22 Ma (MSWD = 8, n = 34). Zircons that are ≤3% discordant give a weighted average ^{206}Pb/^{238}U age of 1458 ± 12 Ma (MSWD = 3.0, n = 18), and a weighted average ^{207}Pb/^{206}Pb age of 1495 ± 14 Ma (MSWD = 4.7, n = 19). Titanites from the sample yield a lower intercept age of 1448 ± 15 Ma (MSWD = 6.8, n = 45). The sample contains a significant number of inherited grains indicative of ages around 1.7–1.8 Ga. The relatively large MSWDs for these age determinations indicate geological complexity, likely reflecting Pb loss, and the possible presence of inherited zircons which suffered major Pb loss during incorporation in the granitic magma. The zircon and titanite dates agree reasonably well with previous age determinations on felsic lithologies from the Bornholm mainland, as well as from the Blekinge Province of southern Sweden. Petrographically and geochemically, the Christiansø granite is indistinguishable from, and can be correlated with, the A-type granites and gneisses which occur on Bornholm. The high abundance of disturbed and inherited zircons (c. 1.7–1.8 Ga) may indicate that the granite was intruded into and assimilated a nearby region of unexposed Transscandinavian Igneous Belt rocks. The somewhat altered nature of the rock, and overall disturbance of U-Pb zircon systematics, suggest alteration associated with fluid-flow along nearby faults defining the northern margin of the Sorgenfrei–Tornquist Zone.

Keywords: Granite, Bornholm, Ertholmene, U-Pb zircon, titanite.

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Christiansø is a small island (*c.* 0.25 km^2) that is part of the island group Ertholmene, located *c.* 20 km northeast of Bornholm, in the southern Baltic Sea (Fig. 1A). The island group has a long and rich human history, and although it is generally acknowledged that the basement block making up Ertholmene is geologically related to Bornholm, to our knowledge no detailed geological investigations have been published on the rocks of the island group. The islands are the only emergent portion of a horst that forms part of the

Bornholm–Skåne segment of the Sorgenfrei–Tornquist Zone (Fig. 1A), a major intracontinental fault zone separating the East European Platform and the Baltic Shield in the north from the sedimentary rocks of the Danish–Polish Trough to the south (e.g. EUGENO-S Working Group 1987; Krzywieca *et al*. 2003; Graversen 2009). The islands of Christiansø and Frederiksø are dominated by a reddish granitic gneiss. Outcrops of dolerite dykes and green sandstone dikes, as also observed on Bornholm (e.g. Katzung 1996; Holm *et al*. 2010) have also been noted (Kofoed 1961). In this contribution, we present a petrographic description, geochemical analysis, and U-Pb zircon and titanite age for a representative granite sample collected from the southern end of Christiansø (Fig. 1B).

Methods

Whole rock geochemistry of the sample was determined at ACTLABs using the 4LithoRes protocol, a combination of lithium metaborate/tetraborate fusion ICP-OES and ICP-MS analysis for major and trace element analysis, respectively. U-Pb geochronology on titanite was carried out on a double-polished thin section by laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) at the Geological Survey of Denmark and Greenland (GEUS), using a NWR 213 frequency-quintupled solid state Nd:YAG laser system from Elemental Scientific Lasers (ESL) mounted with a standard TV2 ablation cell coupled to an ELEMENT 2 double-focusing single-collector magnetic sector-field

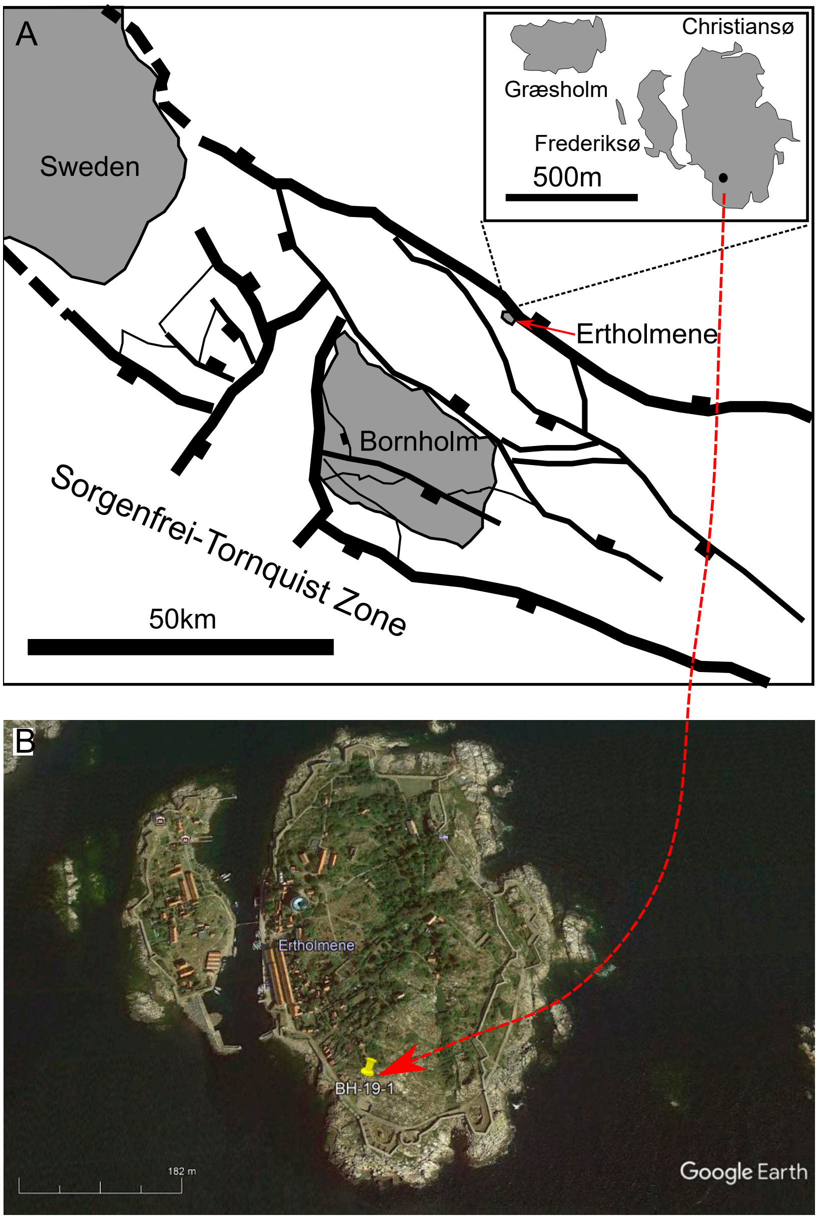

Fig. 1. A: Location map showing position of Bornholm and Ertholmene within the Sorgenfrei–Tornquist Zone (modified from Graversen 2009), tickmarks show downthrown side of fault blocks. **B:** Image of Christiansø and Frederiksø from Google Earth showing sample location.

ICPMS from Thermo-Fisher Scientific. The mass spectrometer is equipped with a new jet interface pump system and detector amplifier and employed Ni jet-type sampler and H-type skimmer cones. Operating conditions and data acquisition parameters are listed in the electronic appendix. Prior to loading, the thin section and standards were carefully cleaned with ethanol to remove surface contamination. To ensure stable laser output energy, the laser was heated prior to operation, providing a stable laser power and flat ablation craters by a 'resonator-flat' laser beam. The mass spectrometer was run for at least one hour before analysis to stabilise and minimise the background signal. The ablated material was swept by the helium carrier gas and mixed with argon gas *c.* 0.5 m before entering the mass spectrometer.

Before the start of analysis, the ICP-MS was optimised for dry plasma conditions through continuous linear ablation of the GJ-1 zircon standard. The signal-to-noise ratios for the heavy mass range of interest (i.e. ^{202}Hg to ^{238}U), emphasising on ^{238}U and ^{206}Pb, were maximised, while simultaneously opting for the lowest oxide production level by minimising the $^{254}UO_2/^{238}U$ ratio. To minimise instrumental drift, a standard-sample-standard analysis protocol was followed, bracketing 7–8 sample spots by 2–3 standard measurements. Standard analyses and results were validated by analyses of the natural titanite standards A1772 and A968 (provided by Y. Lahaye, GTK), the Seiland standard titanite (provided by Ø. Skår, NGU), and the Plešovice (Slama *et al.* 2008) and GJ-1 (Jackson *et al.* 2004) zircon standards, which all were analysed regularly throughout the analysis sequence. All standards demonstrated an averaged age accuracy within 3% deviation (2σ) from reference values, and internal uncertainties on individual spots of < 2–3% (2σ). Data processing was performed off-line using the software Iolite v. 2.5 (Hellstrom *et al.* 2008; Paton *et al.* 2010, 2011) with the VizualAge data reduction scheme (Petrus & Kamber 2012). Data were corrected for background, session drift and down-hole isotopic fractionation by using MKED1 as primary reference material (Spandler *et al.* 2016).

Data were acquired from single spot analyses using a laser spot size of 25 μm for the analyses and a pre-ablation spot size of 40 μm. A laser fluence of 3.5 to 4.4 J/cm^2 and a pulse rate of 5 Hz was applied. The acquisition sequence included 5 pre-ablation bursts followed by a 15 sec. background measurement, then laser ablation for 35 sec., and finally washout for 30 sec. Factory-supplied software was used for the acquisition of the transient data, obtained through an automated running mode of pre-set analytical locations. Analyses spots on the grains were placed at clear and inclusion-free locations free of cracks.

Titanites often contain a high proportion of common Pb, as shown by low $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios and compositions that plot above the concordia in Tera-Wasserburg plots. An assumption that the common Pb ratio is invariant will mean that any error in the isotope ratios assigned to common Pb will result in a consistent bias, rather than a random variation, of the calculated $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ radiogenic ratios (Ludwig 1998). Thus, using a "SemiTotal–Pb/U isochron" approach (Tera & Wasserburg 1972), the background- and session-drift corrected ratios can be plotted on a Tera-Wasserburg concordia diagram without correction for common Pb. If (and only if) the true $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ radiogenic isotope ratios represent comparable dates, the non-common Pb corrected data will be dispersed along a line whose lower intercept with the concordia curve defines the age of their crystallisation or resetting (Ludwig 1998; see for example Spencer *et al.* 2013 and Chew *et al.* 2014). This is the case for the titanite grains in this study, and thus the lower intercept age reported here for the titanites is not corrected for common Pb, and assumed to represent the U/Pb isotopic age of the titanite resulting from a specific geological event.

U-Pb dating of zircon was performed at GEUS by LA-ICPMS (same instrumentation as above) using methods described in detail in Waight *et al.* (2017). Common Pb corrections were made using the method of Andersen (2002). For both titanites and zircons, diagrams and statistical information were produced using Isoplot 3.70 (Ludwig 2008). All age data are plotted and presented at 2 sigma level.

Results

The sample (BH19-1) was collected from blasted outcrops near Kongens Bastion at the southern end of Christiansø (Lat. 55°19'6.10"N, long. 15°11'17.64"E). In outcrop, the rock is a reddish, leucocratic, fine to medium-grained, equicrystalline granitic gneiss (*sensu lato*) with a foliation defined by a weak alignment of mafic phases (Fig. 2). No significant variations in the texture or mineralogy of the granite were noted in reconnaissance investigations of Christiansø and Frederiksø.

In thin section, the sample comprises abundant subhedral to anhedral quartz and anhedral microcline-twinned alkali feldspar up to 1 mm in diameter (Fig. 3). Some granophyric intergrowths are also observed. Plagioclase occurs as larger but subordinate subhedral crystals up to 3 mm in length, showing weak albite twinning and common alteration with many inclusions of fine-grained epidote. No primary biotite is preserved in the rock, instead biotite has been altered to flakes of green chlorite up to 1 mm in length and showing anomalous purple interference colours. Rounded to square opaque phases (presumably magnetite) up to 0.5 mm in diameter are common, and often associated with anhedral titanite crystals of approximately the same size. Fine-grained hematite is evident along many grain boundaries and presumably contributes to the reddish colour of the rock.

A bulk geochemical analysis of the sample is presented in Table 1 and compared to analyses of granites and gneisses from Bornholm (Johansson *et*

Fig. 2. Close up of Christiansø granite from sampling location. Note the red colour which resembles leucocratic granite varieties on Bornholm (e.g. Hammer and Almindingen Granites).

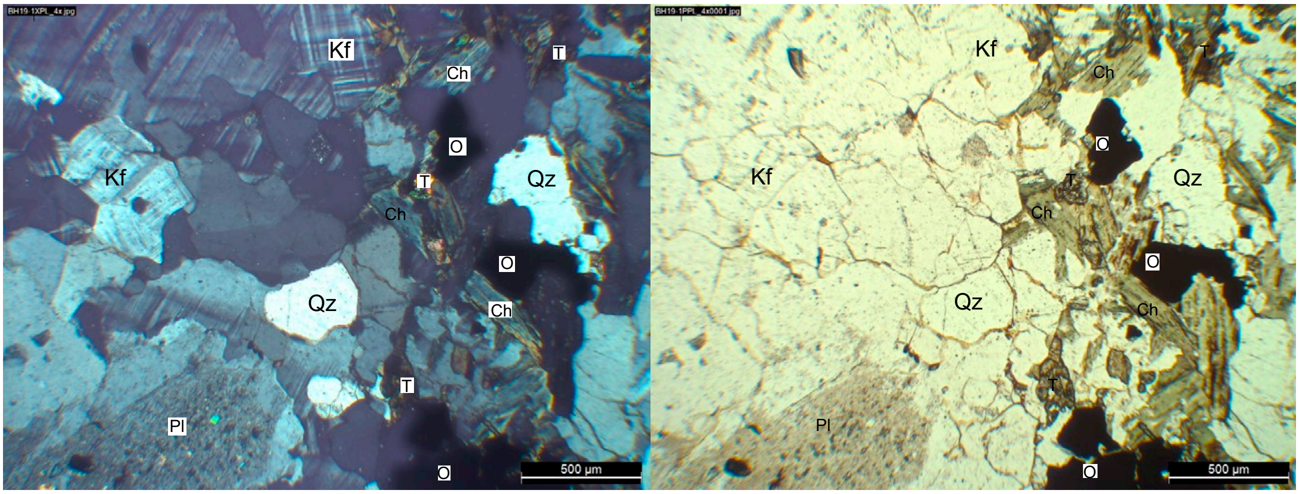

Fig. 3. Photomicrographs of sample BH19-1 (left = cross-polarised light, right =plain polarised light). Kf = alkali feldspar, Qz = quartz, Pl = plagioclase feldspar, T = titanite, Ch = chlorite, O = opaque.

Table 1. Geochemical analysis of sample BH19-1. Major elements are in weight percent, and trace elements in µg/g

SiO2	71.01	Sc	8	Sr	137	Ce	143	Lu	1.02
Al2O3	13.15	Be	4	Y	57.5	Pr	15.9	Hf	9.8
Fe2O3(T)	4.07	V	24	Zr	382	Nd	57.5	Ta	2.13
MnO	0.07	Cr	< 20	Nb	21	Sm	10.8	W	580
MgO	0.66	Co	75	Mo	< 2	Eu	1.94	Tl	0.6
CaO	1.67	Ni	< 20	Ag	0.9	Gd	9.2	Pb	25
Na2O	3.14	Cu	< 10	In	0.1	Tb	1.56	Bi	< 0.1
K2O	4.98	Zn	70	Sn	4	Dy	9.49	Th	21.4
TiO2	0.65	Ga	18	Sb	< 0.2	Ho	1.93	U	5.34
P2O5	0.16	Ge	1.5	Cs	1.2	Er	5.9		
LOI	0.78	As	< 5	Ba	1038	Tm	0.933		
Total	99.56	Rb	181	La	71.2	Yb	6.39		

al. 2016) in Fig. 4. The Christiansø granite has 71 wt.% SiO$_2$, plotting in the granite field in the total alkalies – silica diagram modified for plutonic rocks by Middlemost (1994; Fig. 4A). The rock is metaluminous (molar Al$_2$O$_3$/(CaO+Na$_2$O+K$_2$O) = 0.97), ferroan, and alkali-calcic (Figs 4B, C). The rock also shows similar trace element and rare earth element (REE) patterns as the granitoids and gneisses from Bornholm and is characterised by high field strength element (HFSE) enriched compositions such that it plots in the A-type / within-plate granite field in tectonic discrimination diagrams (Figs 4D, E, F).

A total of 137 zircons from the sample were analysed for U-Pb geochronology. The full data set is available as an electronic appendix to this article. Common Pb contents are variable, and a common Pb correction was applied when the estimated fraction of common Pb was over 0.05. Many of these analyses were subsequently discarded from age calculations on other grounds. The resultant data were highly scattered with many discordant analyses and evidence for open system behaviour and Pb loss. Consequently, filtering of the data was necessary. As the first part of this process, a purely mathematical approach was taken so as not to introduce any human-bias into the data sorting process. All analyses with negative correlation coefficients (n = 12) and/or internal errors on measured ^{207}Pb/^{235}U or ^{206}Pb/^{238}U greater than 10% (2 S.E.) (n = 47) were excluded from the data set. The data were separated visually into a group which we assume represent the original magmatic zircons (dark blue shaded and orange symbols in Fig. 5, n = 58), a second group we assume represents an inherited zircon population (green symbols in Fig. 5, n = 14), and a third group of highly discordant analyses likely also to represent older inherited zircons (possibly c. 2 Ga) that are excluded from further discussion (red symbols in Fig. 5, n=5). The first group yields a Model-2 upper intercept date of 1500 ± 18 Ma (MSWD = 13), with a lower intercept of *c.* 130 Ma (Fig. 5). These zircons have ^{207}Pb/^{206}Pb dates ranging from 1144 to 1596 Ma. Exclusion of zircons with a fraction of common Pb > 0.01 from this population (orange symbols in Fig. 5) yields an identical Model-2 upper intercept date of 1500 ± 22 Ma (MSWD = 8; n = 34 – blue shaded symbols in Fig. 5). The second presumed inherited population yields a Model 2 upper intercept date of 1727 ± 79 Ma (MSWD = 6.0), with a lower intercept also at *c.* 130 Ma (Fig. 5; green symbols) and is suggestive of an older population of zircons which have suffered partial lead loss. These zircons have ^{207}Pb/^{206}Pb dates ranging from 1672–1864 Ma. Those zircons within the first group that are within 3% of concordance yield a weighted average ^{207}Pb/^{206}Pb age of 1495 ± 14 Ma (MSWD = 4.7, n=19, Fig. 6A) and a weighted average ^{206}Pb/^{238}U date of 1458 ± 12 Ma (MSWD = 3.0, n = 18, Fig. 6B). The relatively high MSWDs for all these results clearly indicate a heterogeneous zircon population, which complicate determining a precise crystallisation age for this rock.

Fifty spot analyses were made in multiple grains of visually inclusion-free titanite in the polished section of BH19-1; the full data set is available as an electronic appendix to this article. These results define a line which plots above the concordia in a Tera-Wasserburg diagram, reflecting variable contents of common Pb. Following exclusion of six analyses (reflecting analytical challenges – i.e. have reverse slope of the semi-major axis on the ellipses and unusual eccentricity), and assuming an invariant initial Pb composition, the remaining analyses define a lower intercept date of 1448 ± 15 Ma (MSWD = 6.8, n = 44) (Fig. 7), which is in good agreement with the weighted average ^{206}Pb/^{238}U date for concordant, non-inherited zircons.

Discussion

U-Pb zircon analyses of granitoids and gneisses from Bornholm demonstrate that all felsic basement rocks were emplaced between 1470 and 1445 Ma (Zariņš &

Johansson 2009; Waight *et al.* 2012). No age distinction is possible between the largely undeformed granitoids and pervasively deformed gneisses within analytical uncertainty. However, ages for a gneiss sample of potentially supracrustal origin and a quartz-rich xenolith in the Svaneke Granite of *c.* 1480 Ma are slightly older and thus far the oldest ages determined for any rocks from Bornholm (Waight *et al.* 2017). The range of ages on Bornholm is in good agreement with age determinations of *c.* 1.45 Ga on granites in the Blekinge Province in southern Sweden and in the southern Baltic Sea (Åberg 1988; Kornfält 1993, 1996; Čečys *et al.* 2002; Čečys 2004; Obst *et al.* 2004; Krzeminska *et al.* 2021). Johansson *et al.* (2016) showed that the Bornholm granitoids and gneisses are ferroan, potassic rocks with features typical of A-type granitoids, and

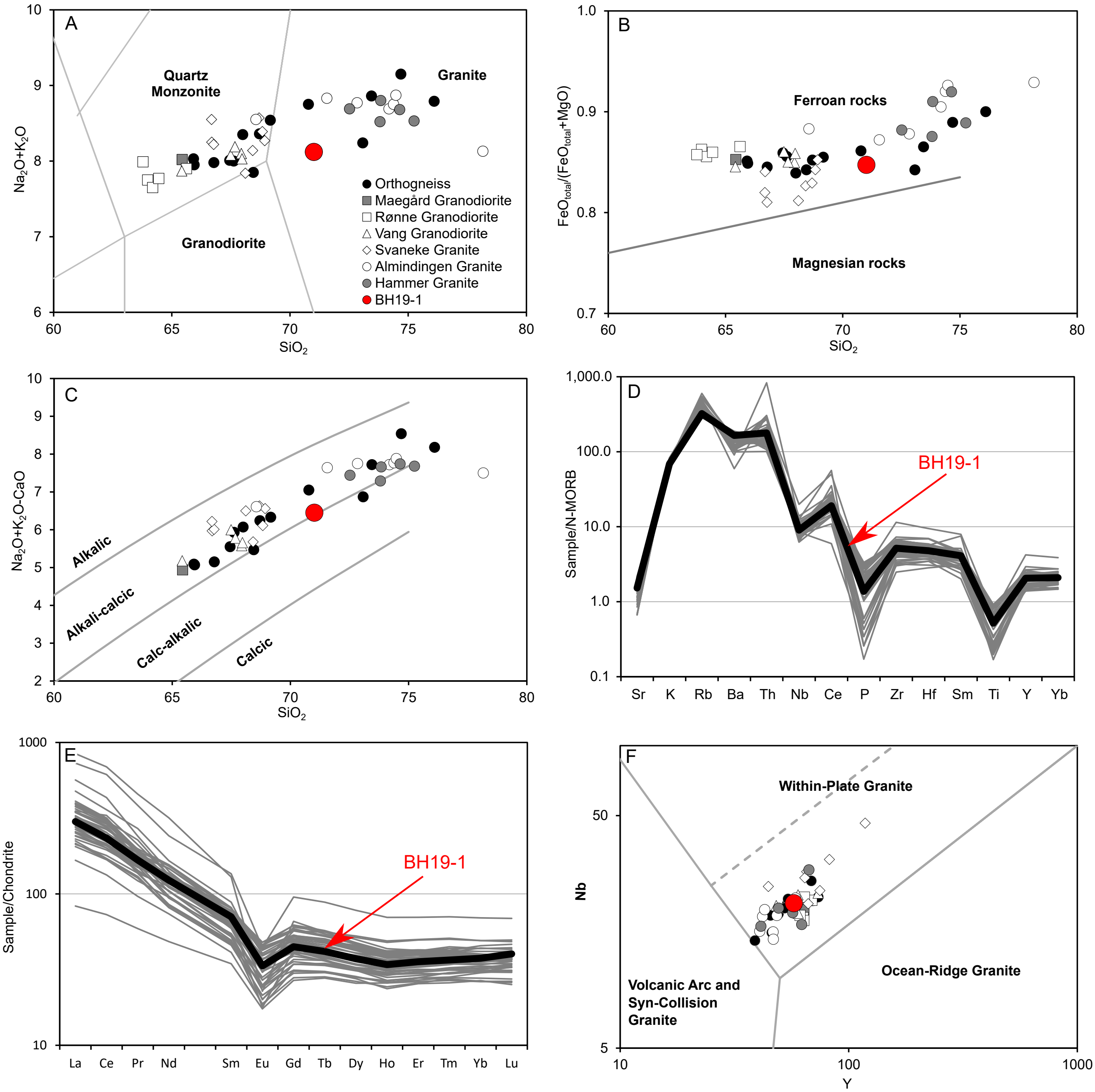

Fig. 4. Selected geochemical plots comparing Christiansø Granite (BH19-1) with granites and gneisses from Bornholm (data from Johansson *et al.* 2016). **A:** Total alkalies silica diagram from Middlemost (2003), **B:** FeO* vs SiO_2 classification plot of Frost & Frost (2008), **C:** Modified alkali-lime index classification plot of Frost *et al.* (2001), **D:** MORB-normalised multi-element diagram and **E:** Chondrite-normalised REE diagram (normalising values for MORB and Chondrite from Sun & McDonough (1989), various plutons are not distinguished for simplicity), **F:** Tectonic discrimination diagram of Pearce *et al.* (1984).

our new data indicate that the Christiansø granite has identical geochemical signatures. Combined, the geochronological and geochemical data indicate that the Bornholm and Blekinge Province rocks (including Christiansø) were generated in an intracontinental setting and are linked to the Danopolonian event in SE Sweden, Bornholm, Poland and Lithuania (e.g. Bogdanova *et al.* 2006). The relationship between this event and the penecontemporaneous tectonomagmatic Hallandian event in the Eastern Segment of the Sveconorwegian Orogen (e.g. Söderlund *et al.* 2002; Ulmius *et al.* 2015) remains unclear.

The complex nature of the U-Pb zircon data for the Christiansø granite complicate estimation of a precise crystallisation age. Both the weighted average zircon $^{206}Pb/^{238}U$ age of 1458 ± 12 Ma and the lower intercept titanite age of 1448 ± 17 Ma agree with the range of ages for granitoids and gneisses previously determined on Bornholm. However, we note that the weighted average $^{206}Pb/^{238}U$ date may have been moved to a somewhat younger date due to small amounts of Pb loss and discordance. The upper intercept zircon date of 1500 ± 18 Ma and the weighted average $^{207}Pb/^{206}Pb$ date of 1495 ± 14 Ma are significantly older than the ages obtained for other Bornholm granitoids and gneisses, although interestingly these dates are within error of the gneiss and xenolith ages presented in Waight *et al.* (2017). We note that we have made no attempt to remove potentially older zircons from the 'magmatic' population in sample BH19-1, and some of those zircons could represent potentially inherited zircon mineral grains (xenocrysts/restite) that lost large amounts of Pb during incorporation into the host magma. Incorporation of such zircons would shift results to slightly older ages. Because of the dominance of zircon analyses clustering towards the upper intercept, any geological significance of the lower intercept zircon ages for both the inherited and magmatic zircons is poorly constrained.

The Christiansø granite has a geochemical composition that is a perfect match for felsic basement rocks from Bornholm. The sample shows most petrographic and geochemical similarity to more silica-rich lithologies on Bornholm, specifically the Hammer and Almindingen granites and the more leucocratic red variants of orthogneisses present on Bornholm, to which the Christiansø granite also bears a strong physical resemblance. Therefore, we conclude that the basement rocks on Ertholmene can be confidently linked to basement rocks on Bornholm.

The relative abundance of potentially inherited zircons (19 out of 77 accepted analyses) in the Christiansø granite is unusual compared to most felsic basement rocks from Bornholm. In general, the abundance of inherited zircons on Bornholm is low (<5%). However, those that are found mostly have ages between 1.6 and

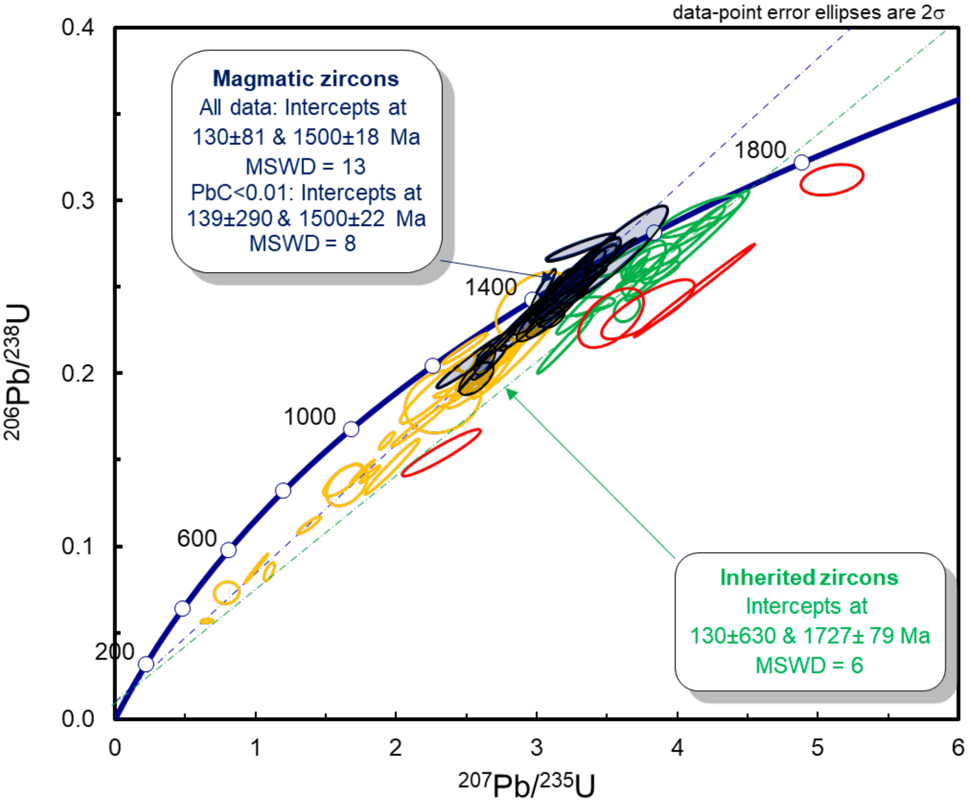

Fig. 5. Wetherill U-Pb Concordia diagram for zircons from sample BH19-1 (excessively discordant analyses, and all analyses with internal 2. S.E. errors > 10 % are excluded). Dark blue shaded ellipses (fraction of common Pb < 0.01) and orange ellipses (fraction of common Pb > 0.01) are interpreted as magmatic and are used to define the upper and lower intercept ages for the 'magmatic' zircons shown. Green ellipses are interpreted as inherited and are used to define the upper and lower intercept ages shown for inherited zircons. Red ellipses likely represent older (*c.* 2 Ga?) inherited zircons, but are not included in any age calculations. MSWD = the Mean Square of the Weighted Deviates (MSWD) for the isochron fit.

1.8 Ga (Waight *et al.* 2012), which is consistent with the involvement of Transscandinavian Igneous Belt rocks as an important source component (Johansson *et al.* 2016). We note that many zircons identified as potentially inherited in BH19-1 have U-Pb systematics consistent with dates of around 1.7–1.8 Ga, and subsequent relatively recent Pb loss (Fig. 5). No rocks of this timespan have been observed on Bornholm. However, they do occur to the north in the Blekinge Province (Johansson *et al.* 2006; Johansson 2016). The abundance of inherited zircons in the Christiansø sample suggests that this granite was emplaced into and contaminated by similar Blekinge or Transscandinavian Igneous Belt rocks.

The degree of disturbance of the zircon population in BH19-1 is also distinct from most felsic rocks from Bornholm where zircons are mostly relatively 'well-behaved', although zircons in a few samples show some evidence for Pb loss (Zariņš & Johansson 2009; Waight *et al.* 2012). We note that some zircons in the Almindingen sample (BH8) analysed by Waight *et al.* (2012) showed significant Pb loss. However, this Pb loss was relatively well-constrained to have occurred at around 400 Ma and likely reflected local disturbance related to intrusion of a nearby dike interpreted to be post-Silurian based on mineralogy and orientation (Jensen 1989). An additional sample from the same quarry dated by Zariņš & Johansson (2009) showed limited evidence for disturbance. Dated gneisses and granitoids from Bornholm are generally fresh and show only minor evidence for alteration (e.g. sericitisation of feldspars). We suggest that the more pronounced disturbance of the U-Pb isotopic system in the zircons from Christiansø, coupled with petrographic evidence for more extensive and higher temperature alteration (i.e. chloritised biotite and saussuritised plagioclase), is related to fluid flow along a nearby major fault, which defines the northern edge of the Christiansø Horst, and the northern margin of the Sorgenfrei–Tornquist Zone (Krzywiecka *et al.* 2003; Graversen 2009). Although poorly constrained and of uncertain geological significance, lower intercept ages are consistent with this disturbance occurring during Mesozoic or younger movement on the Sorgenfrei–Tornquist Zone (e.g., Mogensen & Korstgård 2003).

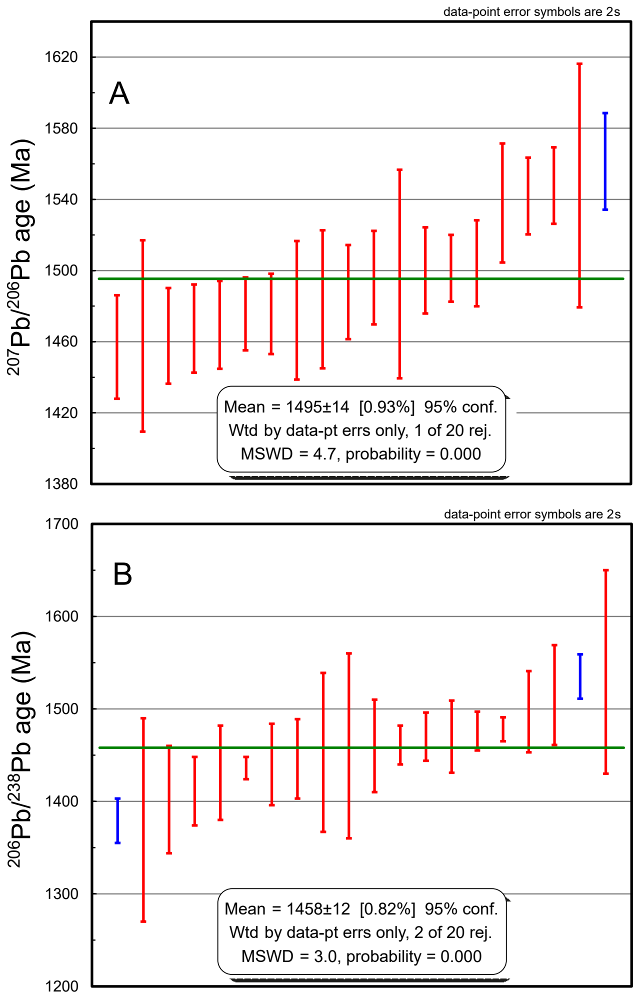

Fig. 6. Weighted mean of (**A**) ^{207}Pb/^{206}Pb and (**B**) ^{206}Pb/^{238}U dates for zircons that are within 3 % of concordance (Wetherill plot). Red bars are ages included in the mean, analyses in blue are excluded.

The general agreement in dates calculated for the near-concordant zircons and the titanites is evidence that both determinations are robust indicators of crystallisation age (albeit with relatively large uncertainties) and shows significant promise for expanded use of combining information from U-Pb in zircon and titanite as a geochronological tool. Titanite can provide important additional geological information due to its somewhat lower closure temperature (*c.* 500–650 °C; e.g. Cherniak 1993), a feature which has been used in for example cooling and metamorphic history studies (e.g. Willigers *et al.* 2001; Kirkland *et al.* 2017). We note, however, that several studies indicate that under some circumstances the closure temperature for Pb in titanite can be considerably higher (e.g. Kohn 2017; Hartnady *et al.* 2019) and thus it can also record crystallisation ages. Titanite can also form as a hydrothermal mineral, and can thus be used to constrain alteration and mineralisation events (e.g., Bell *et al.* 2017; Hart-Madigan *et al.* 2020). This is not the case on Bornholm and Christiansø where petrographic relationships indicate the titanite is a primary phase. U-Pb titanite dates from other felsic rocks from Bornholm are typically within error to 20 Ma younger than zircon dates from the same sample (Zariņš & Johansson 2009) and are consistent with initially rapid cooling, coupled with evidence from other geochronometers for subsequent relatively slow post-crystallisation cooling on Bornholm (Waight *et al.* 2012). Given the relatively large errors on both the titanite and zircon dates for Christiansø, it is not possible to evaluate any discrepancies related to cooling history and differences in closure temperature between zircon and titanite, but the ages are consistent with crystallisation followed by initially rapid cooling.

The abundant evidence for Pb loss and disturbance in the zircons is interestingly not observed in the titanites, suggesting that the latter phase is more robust to Pb loss. It is beyond the scope of this contribution to discuss this in detail; however, it has been noted that diffusion rates for Pb in titanite are relatively slow and ineffective at temperatures below *c.* 800°C (Kohn 2017) and we speculate that the robust age obtained here may reflect the larger grain size of the titanite crystals compared to zircon, such that the larger crystal volumes of titanite mean that any effects of Pb loss are restricted to smaller grains or the rims of larger crystals (Kirkland *et al.* 2016). We also suggest that the apparent robustness of titanite U-Pb systematics may also reflect generally lower U contents in titanite than zircon and thus less radiation damage. Diffusion experiments in zircon suggest that it should be robust to Pb loss by diffusion alone even at high temperatures (Cherniak & Watson 2001). However, this is clearly not the case at lower temperatures, as U-Pb discordance in zircons is commonly attributed to Pb loss and can be related to degree of radiation damage, particularly if the zircons have been at relatively low temperatures (below natural annealing temperatures of *c.* 360° C) for long periods (e.g., Cherniak & Watson 2001). This is consistent with Rb-Sr ages for mica indicating the Bornholm granites have not been at temperatures over 300–350°C since *c.* 1.37 Ga (Waight *et al.* 2012). Finally, higher common Pb contents in titanite compared with zircon likely reflect the crystal lattice of titanite being more accommodating for incorporation of Pb. Therefore, the radiogenic Pb produced by U decay in titanite is more tightly bound to the crystal lattice than in zircon and less prone to Pb loss.

Conclusions

A sample of the granite making up the small islands of Christiansø and Frederiksø north of Bornholm was investigated petrographically and geochemically and dated isotopically using U-Pb in zircon and titanite. The sample is a reddish, equigranular, leucocratic biotite granite with evidence for alteration (epidote in plagioclase and biotite altered to chlorite). The granite is ferroan, metaluminous, alkali-calcic and has essentially identical major and trace element characteristics to other felsic basement rocks on Bornholm.

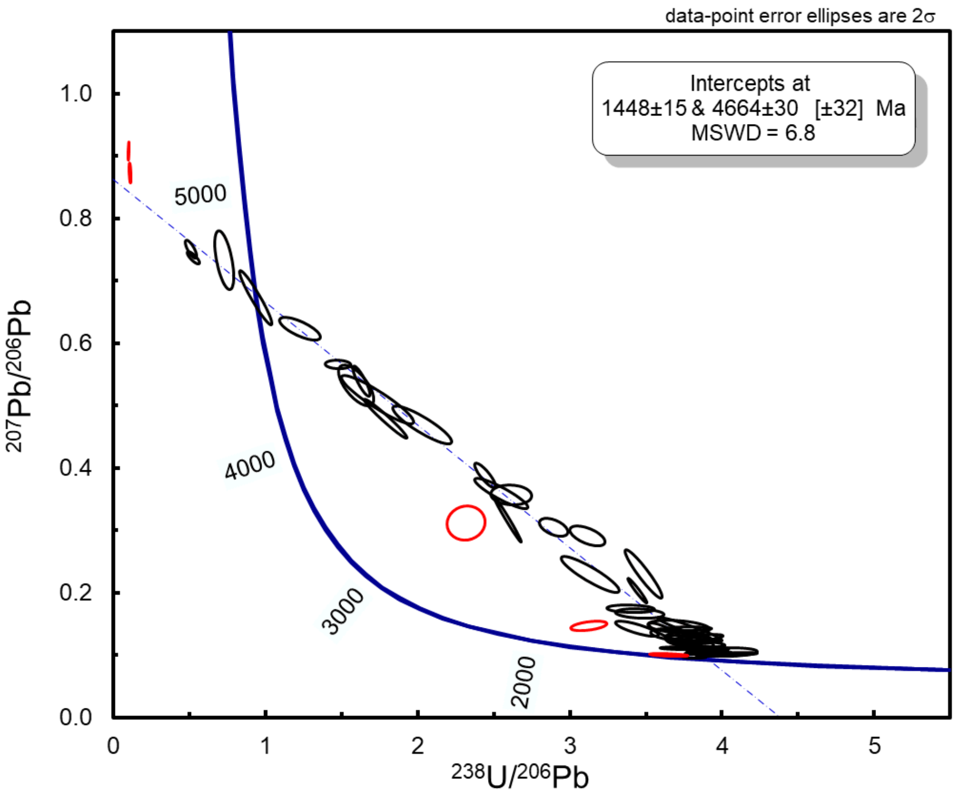

Fig. 7. Tera-Wasserburg plot for titanites from sample BH19-1. Black ellipses are used to define the lower intercept age shown, red ellipses are analyses excluded from the age calculation.

Zircon U-Pb systematics in the sample are complex, and include a significant number of zircon grains considered to be inherited. Many of the zircons have suffered relatively recent Pb loss. Removal of highly disturbed and imprecise analyses, and of inherited zircons, yields a poorly constrained upper intercept age of 1500 ± 18 Ma (MSWD = 13). Weighted average ages of 1495 ± 14 Ma (MSWD = 4.7) (^{207}Pb/^{206}Pb) and 1458 ± 12 Ma (MSWD = 3) (^{206}Pb/^{238}U) are obtained from those zircons that are within 3% of concordance. The discrepancy between these ages likely reflects inclusion of inherited zircons that suffered large degrees of Pb loss during incorporation in the host magma, and small amounts of Pb loss. U-Pb systematics in titanite yield an age of 1448 ± 15 Ma (MSWD = 6.8) that is within error of the weighted average ^{206}Pb/^{238}U zircon age. The disturbance of the zircons, and the alteration of the granite, are likely the result of the proximity to the major fault zone defining the northern edge of the Sorgenfrei–Tornquist Zone. Titanite does not show the same effects of Pb loss as zircon, suggesting that in this location it has been more robust during the Pb loss event. Most of the inherited zircons have suffered Pb loss, however they are mostly *c.* 1.7–1.8 Ga in age, consistent with inherited zircon ages observed on Bornholm. The greater abundance of inherited zircons compared to Bornholm may suggest intrusion into, and contamination by, nearby unexposed Transscandinavian Igneous Belt rocks.

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