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The ongoing search for the oldest rock on the Danish island of Bornholm: new U-Pb zircon ages for a quartz-rich xenolith and country rock from the Svaneke Granite

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Previous geochronological studies on the Danish island of Bornholm have not identified any rocks older than *c.* 1.46 Ga. New LA-ICP-MS U-Pb zircon ages are presented for a xenolith within, and the country rock gneiss adjacent to, the Svaneke Granite on Bornholm. The xenolith is fine-grained and quartz-rich and was likely derived from either a quartz-rich sedimentary protolith or a hydrothermally altered felsic volcanic rock. The relatively fine-grained felsic nature of the country rock gneiss and the presence of large zoned feldspars that may represent phenocrysts suggest its protolith may have been a felsic volcanic or shallow intrusive rock. A skarn-like inclusion from a nearby locality likely represents an originally carbonate sediment and is consistent with supracrustal rocks being present at least locally. Zircon data from the xenolith define an upper intercept age of 1483 ± 12 Ma (2σ, MSWD = 2.5) with a poorly defined lower intercept age of 474 ± 250 Ma, and a weighted average $^{207}Pb/^{206}Pb$ age of 1477.9 ± 4.6 Ma; both these ages are older than the host Svaneke Granite (weighted average $^{207}Pb/^{206}Pb$ age of 1465.0 ± 4.8 Ma). Zircons from the gneiss define an upper intercept age of 1477.7 ± 6.8 Ma when anchored at 0 Ma, and a weighted average $^{207}Pb/^{206}Pb$ age of 1475.4 ± 6.6 Ma which overlaps statistically with the Svaneke Granite age. These ages are currently the oldest ages determined for in situ rocks on Bornholm. Evidence for substantially older basement lithologies (e.g. 1.8 Ga as observed in southern Sweden) remains absent. The zircons display clear oscillatory zoning, have Th/U typical of magmatic zircons and in some cases preserve inherited cores, all of which suggest that the ages are robust and do not represent resetting due to incorporation within or intrusion by the Svaneke Granite. Inherited zircons are not common; they have ages (*c.* 1.6–1.8 Ga) that are similar to those observed in other felsic basement lithologies on Bornholm. These new results suggest that prior to intrusion of the Svaneke Granite, the upper crust on Bornholm was dominated, at least locally, by lithologies similar in composition to the currently exposed felsic basement. The protoliths to the two samples investigated here must have been buried to mid-crustal depths over a relatively short time period (*c.* 10 Ma) prior to intrusion of the Svaneke Granite. This suggests a dynamic tectonic environment and is consistent with evidence for broadly simultaneous magmatism and deformation in basement rocks at 1.46 Ga in southern Scandinavia and burial and metamorphism of sediments in southern Skåne.

Keywords: Zircon, geochronology, xenolith, granite, gneiss, provenance, Bornholm, Danopolonian Orogeny.

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Recent U-Pb zircon geochronological studies have demonstrated that the felsic basement rocks on Bornholm island crystallized over a relatively short period in the mid-Proterozoic, with age determinations indicating activity at 1.47–1.44 Ga (Zariņš & Johansson 2009; Waight *et al.* 2012). No age distinction can be made between deformed orthogneisses and undeformed granitoids within the analytical uncertainties of the methods used. Furthermore, the gneisses and granitoids cannot be distinguished geochemically or in terms of isotopic compositions (Johansson *et al.* 2016). The results indicate that magmatism and deformation on Bornholm must have occurred broadly simultaneously. Magmatism on Bornholm has been linked to regional igneous and tectonic activity in southern Scandinavia and eastern Europe referred to as the Danopolonian event (e.g. Bogdanova 2001; Bogdanova *et al.* 2008, 2014). Recent geochronological results contrast with earlier interpretations involving magmatism and metamorphism in the Gothian orogeny at around 1.8–1.6 Ga followed by younger granitic activity at around 1.4 Ga (Berthelsen 1989). Instead, the results are more consistent with the early conclusions of Callisen (1934) who suggested that Bornholm represented one large magma chamber. The nature of the country rocks to the Bornholm felsic basement lithologies is unknown but was probably similar to that observed in southern Sweden where age and chemical equivalents to the Bornholm granites intrude Blekinge Province basement consisting of felsic metavolcanics and metasediments, gneiss, orthogneiss (Tving granitoids) and leucogranites with ages between 1.8 and 1.7 Ga (Johansson *et al.* 2006). Recently, Bogdanova *et al.* (2014) have identified metasedimentary country rocks to the Tåghusa Granite. The latter has a similar age and geochemical signature to the Bornholm granites, and the sediments it intrudes were deposited around 1.5 Ga and derived from erosion of Gothian age (1.7–1.6 Ga) lithologies. No such older rocks have been identified on Bornholm, and the oldest rock identified to date is sample 95043/BH98 (Paradisbakke Migmatite) for which Zariņš & Johansson (2009) obtained a concordia age of 1469 ± 6 Ma. Inherited zircons in the Bornholm basement lithologies are relatively rare and have ages of around 1.7–1.9 Ga (Waight *et al.* 2012), consistent with geochemical data suggesting that lithologies of the 1.8 Ga Transscandinavian Igneous belt were the dominant crustal source during melting,

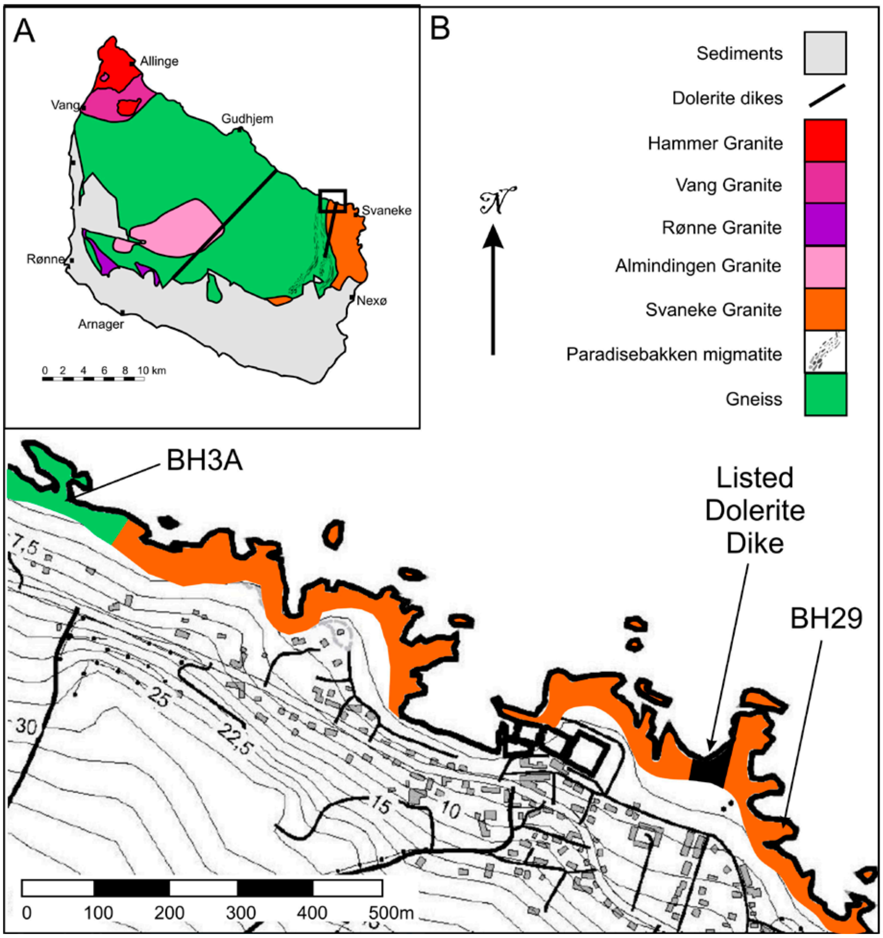

Fig. 1. **A**: Overview geology of Bornholm, showing the main granitoid bodies and extent of the gneiss and overlying sediments, and location of Svaneke Granite sample BH6 (modifed from Waight *et al.* 2012). Small square near Svaneke shows the location of B. **B**: Detailed map of the region near Listed where the two samples were collected. Sample coordinates are: BH29, inclusion in the Svaneke granite: 55.14477°N 15.1151°E; BH3A, banded gneiss adjacent to the intrusive contact with the Svaneke Granite: 55.1446°***N 15.1***152°E.

although a mantle-derived component is also required (Johansson *et al.* 2016).

In this contribution we present new LA-ICP-MS U-Pb zircon age determinations for two samples that, based on field relationships, represent clearly older and potentially supracrustal basement rocks into which the Bornholm granites were intruded. The two samples investigated are a quartz-rich xenolith included within the Svaneke granite (BH29), and a fine-to medium-grained leucocratic banded gneiss adjacent to the intrusive contact with the Svaneke Granite north-west of Listed (BH3A); sample locations are shown in Fig. 1. The aim of the study is to provide additional geochronological data contributing to our understanding of felsic magmatism on Bornholm, and provide constraints on some rocks that, based on field observations, are clearly older than the Svaneke Granite.

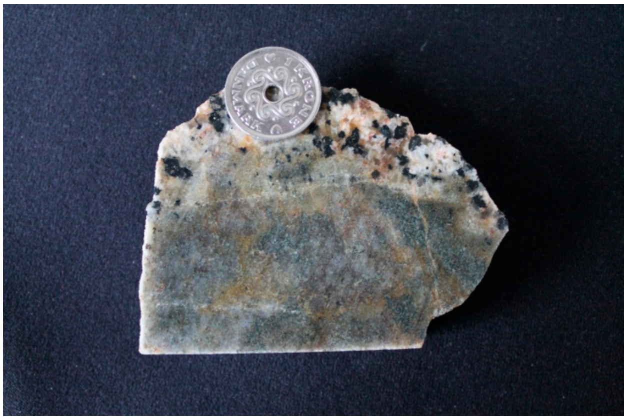

Fig. 2: Hand specimen of offcut from xenolith sample BH29, showing irregular sub-horizontal contact between the coarse-grained Svaneke Granite beneath Danish 1 krone coin (*c.* 2cm in diameter) and the darker, fine-grained quartz-rich xenolith.

Field description of samples and background

BH29

The xenolith sample is about fist-sized, rounded, fine-grained, quartz-rich and sampled from the Svaneke Granite in outcrops east of the Listed dolerite dike. Unfortunately, no field photo was taken when the sample was collected. A photo of an offcut from the hand specimen is presented in Fig. 2, illustrating its fine-grained and quartz-rich nature. Quartz-rich inclusions within gneisses and granitoids on Bornholm have also been described by Callisen (1956), Micheelsen (1961), Jørgart (1973) and Friis (1996).

BH3A

The gneiss immediately adjacent to the Svaneke Granite west of Listed is leucocratic and fine-to medium-grained. It exhibits a clear banding at centimetre to decimetre scale caused by higher concentrations of biotite (Fig. 3); this gneiss has field characteristics that are distinct from many other Bornholm gneisses that petrographically and geochemically resemble more-deformed equivalents of the granitoids (e.g. Johansson *et al.* 2016). The locality was described in detail by Platou (1970) who noted that over a distance of *c.* 200 m the gneiss includes weakly foliated grey biotite gneisses with plagioclase porphyroblasts, banded quartz-rich gneisses comprising quartz-rich and biotite-feldspar-rich bands, skarn-bearing gneisses containing cm-scale lenses of intergrown garnet and epidote, and 5-10 cm thick boudins of quartzite. Callisen (1956) also provides an in-depth description of a *c.* 10 cm calc-silicate xenolith found nearby *c.* 1 km inland of the gneiss–Svaneke Granite contact at Listed. This rock was interpreted by Callisen (1956) as an inclusion of a

Fig. 3: Field photos of gneiss close to the location of sample BH3A. Note the fine-grained and banded nature of the gneiss. Hammer head is *c.* 12 cm in length.

rock formed by interactions between granite magma and limestone (original text p. 159: "Utvivlsomt udgør hele indeslutningen et stykke af en kontaktbjergart, hornfels, mellem graniten og en kalksten" – 'the whole inclusion undoubtedly represents a piece of a contact rock (hornfels) formed between the granite and a limestone'). It comprises an outer shell of diopside, epidote, titanite, quartz and feldspar, an inner shell containing a similar mineralogy but dominated by garnet, and a core of wollastonite. The detailed descriptions of both Platou (1970) and Callisen (1956) suggest that the gneiss at Listed has a supracrustal origin and includes a sedimentary component – and therefore these rocks represent a potential opportunity to identify lithologies older than the 1.46 Ga ages so far obtained from the gneisses and granitoids.

Methods

Samples were crushed and sieved, and zircons were separated, handpicked and then mounted in 25 mm round epoxy mounts, ground, and polished to 1-micron grade. Prior to analysis, back-scattered electron (BSE) images were made of the zircons using a JEOL JXA8200 electron microprobe at the Institute for Geosciences and Natural Resource Management, University of Copenhagen. U-Pb geochronology was carried out by LA-ICP-MS at the Geological Survey of Denmark and Greenland, Copenhagen, using a double focusing Element2 sector-field single-collector ICP mass spectrometer from Thermo-Fisher Scientific, which was coupled to an UP213 or a NWR213 frequency quintupled laser ablation system from New Wave Research, ESI.

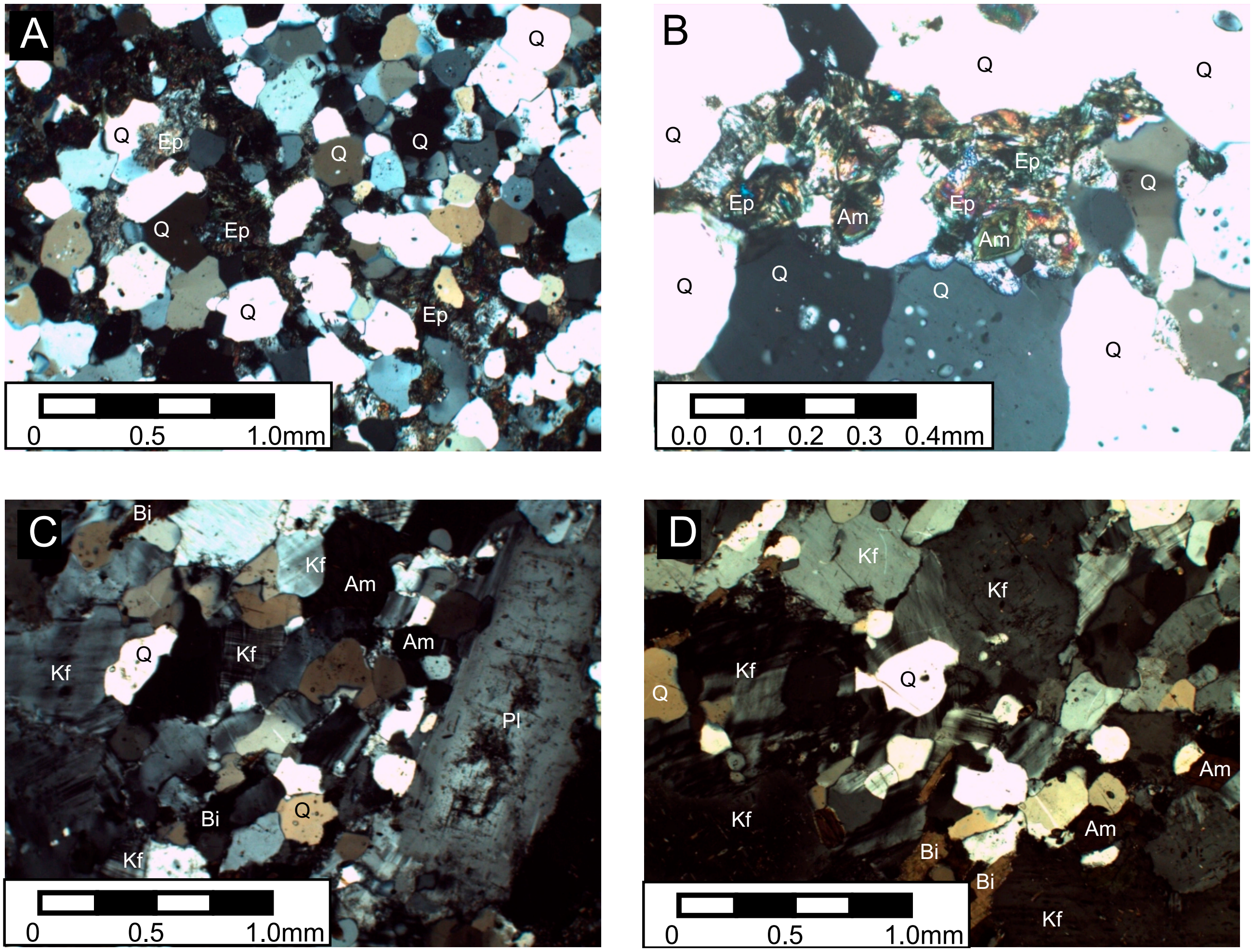

Fig. 4: Thin section images of analysed rocks viewed with crossed polars. **A, B**: BH29. **C, D**: BH3A. Q = quartz, Kf = alkali feldspar, Pl = plagioclase feldspar, Am = amphibole, Bi = biotite, Ep = epidote. Note different scale in B.

The bracketing standard zircon GJ-1 (Jackson *et al.* 2004) was used for correction of time-dependent instrumental mass bias and of U-Pb-Th isotopic down-hole fractionation. The Plešovice zircon (Slama *et al.* 2008) was used as a secondary standard for quality control of the standardization. The zircons were analyzed in sequences each including ten unknown measurements, bracketed by three or more standard measurements. Individual analyses included measurement of the isotopic background level for 30 seconds, followed by laser ablation of the zircon for 30 seconds and a wash-out period of 20 seconds. All analyses were obtained using a laser spot size of 25 μm.

For the calculation of ratios and U-Pb zircon ages, the acquired data were processed off-line through the software Iolite (Hellstrom *et al.* 2008; Paton *et al.* 2010, 2011) employing the add-in VizualAge data reduction scheme (Petrus & Kamber 2012). All analyses were carefully examined for common Pb (^{204}Pb) content and the overall stability of the signal. Samples with a significant proportion of common lead were corrected through a measured mass 204-procedure that includes correction for ^{204}Hg background. Analyses that show more than 10% discordance relative to the Concordia curve were excluded, thereby avoiding most irregularities due to, for example, Pb loss. Irregular signals caused by inclusions or cracks in the zircons were likewise excluded from the results. The ages presented here were calculated using Isoplot version 3.7.1 (Ludwig 2003). The full LA-ICP-MS data set is presented in the supplementary data file.

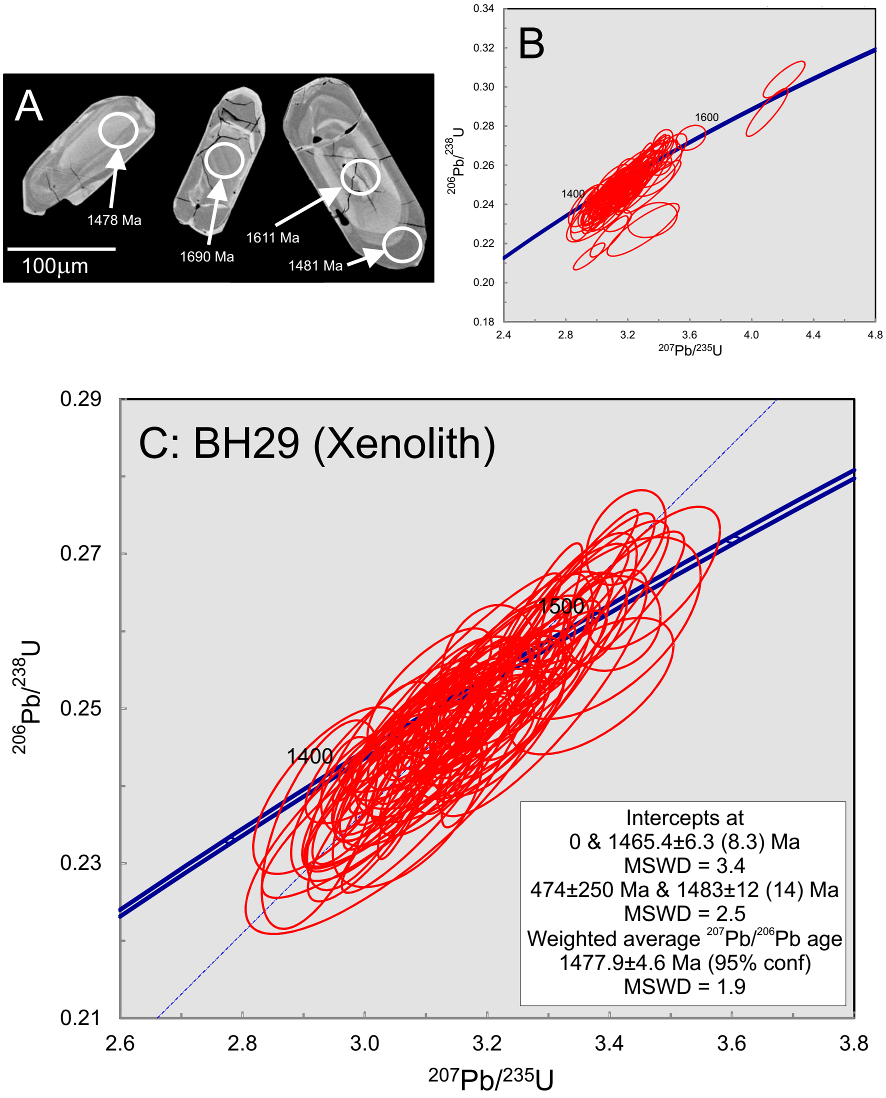

Fig. 5: **A**: Representative BSE images and spot ages from sample BH29. **B**: Concordia plot showing all concordant zircon ages. **C**: Upper intercept ages calculated using the 1400–1500 Ma zircon population, excluding presumed inherited zircons. Data point error ellipses are 2σ, error on upper intercept ages are 2σ excluding decay constant errors (error in brackets includes decay constant errors).

Results

Sample BH29 – quartz-rich xenolith included within the Svaneke Granite

The sample is fine-grained and equicrystalline, and dominated by polygonal quartz grains (*c.* 75%) *c.* 0.2 mm in diameter (Fig. 4 A,B). Other mineral phases lie interstitially between quartz crystals and comprise altered plagioclase, green pleochroic hornblende and epidote.

Zircons from sample BH29 are typically sub- to euhedral and 100–200 *µ*m in length. Complex and oscillatory zoning is evident in BSE images, as are rounded, potentially inherited cores. Representative BSE images are presented in Fig. 5A. Around 150 U-Pb analyses were made on zircons from sample BH29, of which 93 gave acceptable concordant ages. All concordant zircon analyses are plotted in Fig. 5C. The majority of concordant zircons show a tight clustering between 1.4 to 1.5 Ga, whereas three zircons show older ages at around 1.55 and 1.65 Ma and are interpreted as being inherited, and eight others that plot below the concordia are interpreted as inherited zircons that have suffered Pb loss (Fig. 5B). The concordant analyses between 1.4 and 1.5 Ga fail to define a concordia age (the assumption that all data points are equivalent is negated by an MSWD of 7.9). When anchored to a lower intercept age of 0 Ma, these zircons define an upper intercept age of 1465.4 ± 6.3 Ma (2σ, MSWD = 3.4) (Fig. 5C). The data also define an upper intercept age of 1483 ± 12 Ma (2σ, MSWD = 2.5) with a poorly defined lower intercept age of 474 ± 250 Ma. The weighted average of concordant ^{207}Pb/^{206}Pb ages is 1477.9 ± 4.6 Ma (95% confidence, MSWD = 1.9) which is slightly older than the anchored upper intercept age, but in agreement with the upper intercept age obtained with the Palaeozoic lower intercept. Due to

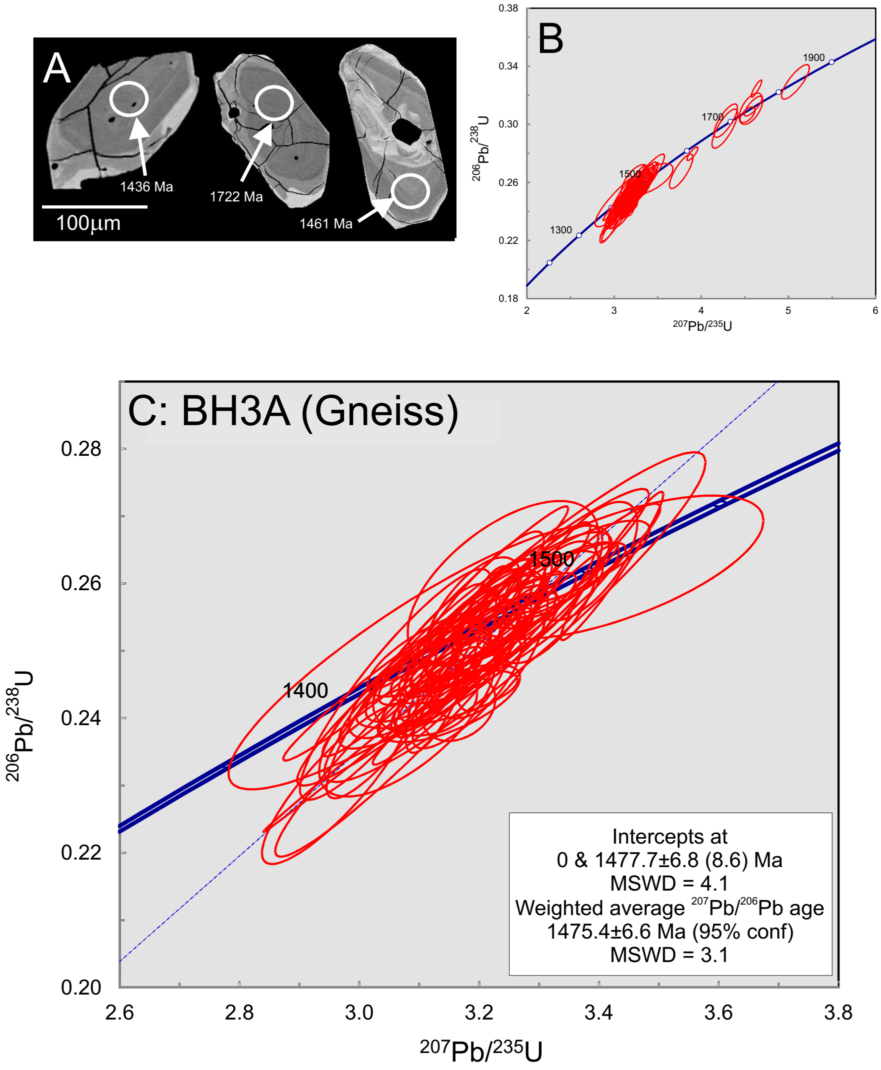

Fig. 6: **A**: Representative BSE images and spot ages from sample BH3A. **B**: Concordia plot showing all concordant zircon ages. **C**: Upper intercept ages calculated using the 1400–1500 Ma zircon population, excluding presumed inherited zircons. Data point error ellipses are 2σ, error on upper intercept age is 2σ excluding decay constant errors (error in brackets includes decay constant errors).

the agreement between the older upper intercept age and the weighted average age, we use the latter as the best estimate for the crystallization age of the zircons within the xenolith.

Sample BH3A – gneiss near contact to the Svaneke Granite

The rock is a fine- to medium-grained quartzo-feldspathic biotite gneiss. Quartz represents *c.* 25 modal % and occurs in two distinct populations of anhedral to subhedral quartz (Fig. 4 C,D). Most grains are relatively small (<1mm in size), form triple junction mosaic boundaries with each other, and display weak undulatory extinction. Some larger, millimetre-sized strained quartz grains also occur. Anhedral alkali feldspar crystals up to a few millimetres in size (*c.* 37 modal %) display cross-hatch twinning and microperthitic texture. Anhedral to subhedral plagioclases (*c.* 23 modal %) ranging up to a few millimetres in size occur, some of which are noticeably larger than the others and display clear zoning. Feldspars in the sample are typically seriticized, and some myrmekitic alteration is present bordering perthitic alkali feldspars. Mafic phases are dominated by partially chloritized anhedral dark green-yellow to brown pleochroic biotite grains <1 mm in length (*c.* 7 modal %). Small amounts of anhedral blue-green pleochroic amphibole grains (*c.* 4%) are also present and together with biotite define the foliation of the gneiss. Anhedral opaque phases are also observed (*c.* 1%), and are commonly surrounded by small anhedral titanite grains. Subhedral zircon with magmatic zoning is an accessory phase.

Zircon crystals separated from sample BH3A are typically sub- to euhedral and 100–200 μm in length with a width-to-length ratio of *c.* 1:3. The zircons show clear complex and oscillatory zoning in BSE images, and several grains show round, potentially inherited cores. Representative BSE images are presented in Fig. 6A. A total of 114 U-Pb analyses were made on zircons from the BH3A sample, of which 67 were deemed usable. All concordant zircon analyses are plotted in Fig. 6B. Most concordant zircons show a tight clustering between 1.4 and 1.5 Ga, whereas a small subset (n = 9) of zircons show older ages at around 1.6 to 1.85 Ga and are interpreted as inherited crystals. Concordant zircons between 1.4 and 1.5 Ga fail to define a concordia age (i.e. the assumption that all data points are equivalent is negated by an MSWD of 7.2). When anchored to a lower intercept age of 0 Ma, these zircons define an upper intercept age of 1477.7 ± 6.8 Ma (2σ, MSWD = 4.1) and a weighted average age of concordant ^{207}Pb/^{206}Pb ages of 1475.4 ± 6.6 Ma (95% confidence, MSWD = 3.1) (Fig. 6C). We use the latter as the best estimate for the crystallization age of zircons within this rock.

Sample BH6 – host Svaneke Granite

To ensure that the new U-Pb zircon data presented here is fully comparable to previous work we reprocessed the original data for host Svaneke Granite

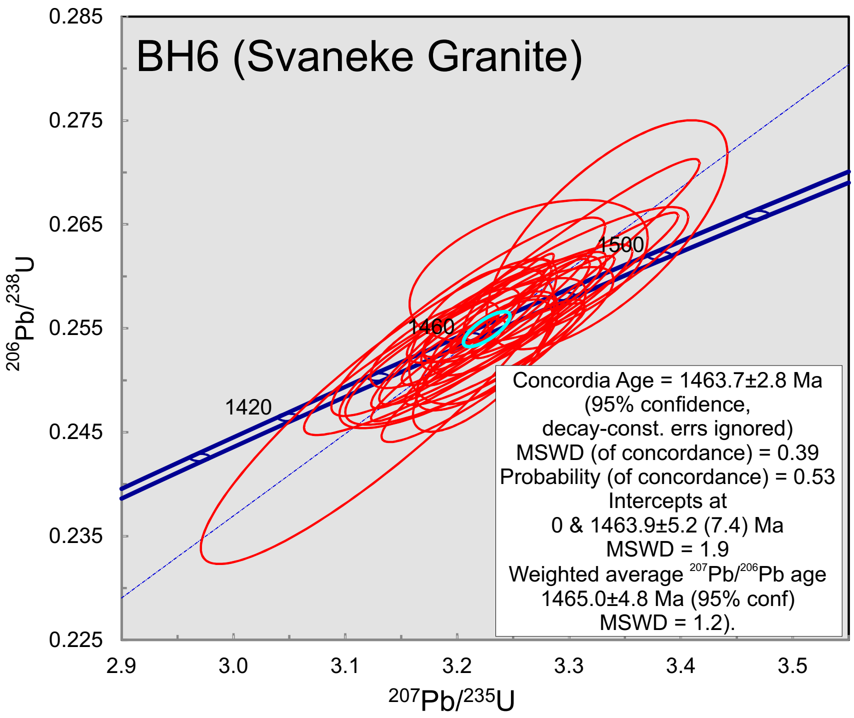

Fig. 7: Combined concordia (blue oval), upper intercept, and weighted average ^{207}Pb/^{206}Pb age for Svaneke Granite sample BH6. The upper intercept age assumes a lower intercept of 0 Ma. Data point error ellipses are 2σ, error on upper intercept age is 2σ excluding decay constant errors (error in brackets includes decay constant errors).

sample BH6 (collected from outcrops north of the town of Svaneke (55.1394°N 15.1456°E), see Johansson *et al.* (2016) for further details) presented in Waight *et al.* (2012) using the same protocols as used for samples BH3A and BH29. The data yield a concordia age of 1463.7 ± 2.8 Ma (MSWD of concordance = 0.39) in full agreement with the originally published age of 1460 ± 6 Ma. The difference is due to a larger number of zircons (n=26) fulfilling the requirements of degrees of concordance (100 ± 3%) in the re-processed data set compared with the original study (n=20). When anchored to a lower intercept age of 0 Ma, the BH6 zircons define an upper intercept age of 1463.9 ± 5.2 Ma (2σ, MSWD = 1.9) (Fig. 7), and the weighted average of concordant ^{207}Pb/^{206}Pb ages is 1465.0 ± 4.8 Ma (95% confidence, MSWD = 1.2). All three ages are identical within error.

Discussion

The results of this study, together with previously determined ages for the Svaneke Granite and the range of ages for other Bornholm basement samples by Zariņš & Johansson (2009) and Waight *et al.* (2012), are summarized in Fig. 8. In order to consistently relate the ages of the Svaneke Granite, xenolith and gneiss, we only compare the weighted average ^{207}Pb/^{206}Pb ages calculated using concordant zircons. It is evident from Fig. 8 that the gneiss sample (BH3a) shows a small but nevertheless statistically significant overlap with that of the intruding granite (BH6), whereas the xenolith sample (BH29) is older than its host Svaneke Granite. Both samples represent the oldest ages yet determined for in situ rocks on Bornholm, although we note that they overlap within error with the range of ages for other basement samples from Bornholm. It is important to note that the ages for Bornholm basement rocks presented in Waight *et al.* (2012) were produced using the same instrumentation and similar analytical protocols as this study. The main difference between the studies is the method of processing the data – however it is clear from the 1.47 to 1.48 Ga ages determined for the new samples and shown on Figs 5–7 that the different data processing does not cause significant variations of the results. Gneissic basement encountered at the base of drillholes on the Ringkøbing–Fyn high have zircon ages from 1.44 to 1.55 Ga (Olivarius *et al.* 2015) and appear to be somewhat older than the samples studied here (although crystallization ages are not presented) and thus hold the current record for the oldest rocks in Denmark.

Inherited zircons

Given the similarity between the new ages presented here and the Svaneke Granite, it is important to consider if the original U-Pb systematics of the zircons in the gneiss and especially in the relatively small xenolith sample were preserved during emplacement of the Svaneke Granite, or if the similarity in ages represents disturbance and/or complete resetting of the U-Pb systematics. Previous studies have demonstrated that U-Pb ages in zircons from metasedimentary xenoliths in granites are preserved and can be used to provide important information on the nature of the protolith (e.g. Maas *et al.* 2001; Zeck & Williams 2002). We consider disturbance of U-Pb systematics in the samples investigated here unlikely for the following reasons. Firstly, disturbance would need to have resulted in near complete resetting of the isotope systematics in order to produce such a large number of concordant zircons yielding ages similar to or identical with the

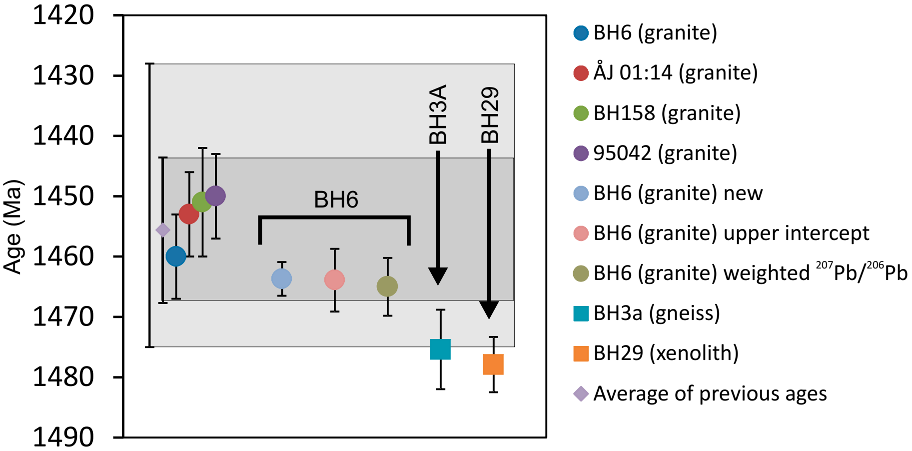

Fig. 8: Summary of new and published ages for felsic basement rocks from Bornholm. Samples BH6, ÅJ 01:14, BH158 and 95042 are previously published ages for the Svaneke Granite (Zariņš & Johansson 2009; Waight *et al.* 2012); all errors are 2σ. Ages for remaining samples are from this study. The light grey box represents the full range of all previously published ages for felsic basement rocks from Bornholm (included errors) and the darker grey box represents the average and 2 SD for the same data set (1456 ± 12 Ma).

age of the host granite. Secondly, the closure temperature for the U-Pb system in zircon is around 900° C (Lee *et al.* 1997) which is considerably higher than estimated final crystallization temperatures for Bornholm granites of around 750° C (Waight *et al.* 2012), although initial magma temperatures may have been higher. Thirdly, the zircons in BH3A and BH29 preserve oscillatory zoning and have Th/U ratios generally greater than 0.3 which is typical for granites (Kirkland *et al.* 2015) and higher than for typical metamorphic zircons (Rubatto 2002). The final and most persuasive argument against wholesale resetting of U-Pb systematics in zircon is the preservation of older concordant zircons with ages similar to inherited zircons in the Bornholm granites (i.e. 1.7–1.9 Ga, Waight *et al.* 2012) and in particular zircons which preserve older cores with sharp compositional boundaries to pristine rims yielding ages of 1.46 Ga (e.g. Figs 5–6).

Protoliths for xenolith and gneiss

The precise nature of the protolith to the xenolith (BH29) and the Listed leucocratic gneiss (BH3A) remains unclear. The fine-grained, equicrystalline and quartz-rich nature of the xenolith immediately suggests a quartz sandstone progenitor, and the presence of sediments in the region is also consistent with the identification of skarn-like inclusions within gneiss in the same area (Platou 1979). However, such an interpretation is complicated by the similarity in age to the host granite, and by the low abundance of inherited zircons. Detrital zircon populations in sediments typically have several peaks in ages that reflect the geology of the surrounding basement rocks eroding during sediment deposition. If the protolith to BH29 was originally a quartz sandstone then the catchment area must have been relatively homogeneous and dominated by rocks only slightly older than the Svaneke Granite. Examples of sediments with restricted detrital zircon populations are known from the literature, for example sediments from the Ripogenus and Rangeley Formations in Central Maine are overwhelmingly dominated by zircons that have ages that overlap with or are only 20 million years older than the biostratigraphic age of the sediment, and indicate a source region dominated by a single homogeneous igneous source (Bradley & O'Sullivan 2016). As an alternative to a sandstone, the protolith may have been a fine-grained felsic volcanic or shallow intrusive rock related to an earlier phase of Bornholm magmatism, similar to that inferred for the gneiss sample BH3A below. The protolith may potentially also have been affected by hydrothermal alteration resulting in an increase in silica content. The generally unrounded, sub-euhedral nature of the zircons in the xenolith is consistent with a volcanic protolith for the rock, but could also indicate a sedimentary progenitor where the zircons have not been transported far from their source.

Interpretation of the protolith of the gneiss is also unclear. Mineralogically, the gneiss resembles other leucocratic granitoids and gneisses on Bornholm, although texturally it is distinguished by being relatively fine-grained and banded. Geochemically, it is also indistinguishable from other rocks on Bornholm (SiO_2 = 73 wt%, within-plate/A-type granite trace element systematics, $\varepsilon Nd_{(i)} = 0$; data from Johansson *et al.* 2016) with a chemical composition similar to evolved granites such as the Hammer Granite. The presence of relatively large and zoned plagioclase crystals in the gneiss could represent original plagioclase phenocrysts in a volcanic felsic lithology such as a rhyolite, as also suggested by Graversen (1996). Alternatively, it could represent a hypabyssal felsic intrusion and therefore be an evolved equivalent to the more intermediate Mægård Granite (Waight *et al.* 2012), which also shows a strongly porphyritic texture suggestive of intrusion at relatively shallow depths. The presence of skarn inclusions and quartz boudins within the gneiss (Platou 1970) may represent original inclusions of older sedimentary material within this felsic protolith.

Metasediments in southern Skåne intruded by age equivalents to the Bornholm granites are described by Bogdanova *et al.* (2014). The Nöteboda metasedimentary migmatites have a distinct mineralogy (containing garnet, biotite, cordierite and sillimanite) consistent with a metasedimentary protolith different to the protoliths of the samples investigated here. The zircon population in the Nöteboda metasediments is also distinct and is characterized by a complex population of zircons with features consistent with detrital and metamorphic zircons overgrown by relatively thin, low Th/U rims interpreted to have grown during migmatization caused by the intrusion of the adjacent Tåghusa Granite at 1.44 Ga. The zircon cores which dominate the population preserve ages between 2.1 and 1.5 Ga, with 80% of the cores forming age peaks at 1.7, 1.67 and 1.65 Ga, suggesting an origin as detrital zircons derived from erosion of Gothian-aged granites (Bogdanova *et al.* 2014). The Bornholm samples also contain inherited zircons with similar ages to those observed in the Nöteboda migmatite, but in much lower proportions. The xenolith sample BH29 has only three older zircons which likely are inherited (1.55, 1.65, 1.68Ga) and the gneiss sample BH3A contains 9 older zircons with ages at *c.* 1.6, 1.7, 1.75, and 1.8 Ga. Notably, these older zircons have ages that overlap with the inherited zircons earlier identified in the Bornholm granites (Zariņš & Johansson

2009; Waight *et al*. 2012). Inherited zircons in Bornholm granitoids are relatively rare and have ages consistent with derivation from the Transscandinavian Igneous Belt (Johansson *et al*. 2016), either incorporated from the country rocks, or as residual phases following crustal melting.

Tectonic environment

The similarity in age between the xenolith, gneiss and Svaneke Granite is consistent with an origin for the two samples investigated here as early volcanic or sub-volcanic phases of the Bornholm magmatism, or as sediments derived from erosion of such lithologies. The lack of several distinct populations of zircons also suggests that significantly older lithologies were not exposed locally and therefore the upper crust was dominated by rocks similar in age and composition to the mid-crustal lithologies now exposed on Bornholm. This suggests a scenario where the crustal section is dominated by broadly time equivalent and chemically similar volcanics and plutonics. Such a scenario is not unrealistic as granitic magmas intruding their own consanguineous volcanic pile are known from elsewhere in the geological record, for example in the Red Sea (Chazot & Bertrand 1995) and South America (Myers 1975). Similarly, plutonic and buried volcanic rocks that are a maximum of only a few million years older than chemically equivalent modern volcanic rocks are known to exist in the mid-crust beneath the Taupo Volcanic Zone in New Zealand, and are inferred to act as potential crustal sources during magmatism (Price *et al*. 2005; Charlier *et al*. 2008).

If the xenolith and gneiss were derived from originally supracrustal protoliths then their similarity in age with the Svaneke Granite raises some interesting questions about the geodynamic setting during Mesoproterozoic magmatism and metamorphism in southern Scandinavia. The Svaneke Granite–gneiss contact at Listed is relatively sharp but with no evidence for chilling or baking at the contact, suggesting that intrusion occurred at mid-crustal depths, as is also consistent with Al-in-hornblende geobarometery from the Svaneke Granite (*c*. 15 km, T. Waight, unpublished data). Therefore, the originally supracrustal or upper crustal protoliths to samples BH3A and BH29 need to have been buried to mid-crustal depths prior to inclusion within (BH29) or intrusion by (BH3A) the Svaneke Granite on a timescale that is of a similar order of magnitude to the errors on U-Pb zircon ages (i.e. 10–12 Ma). Similarly, Bogdanova *et al.* (2014) argue that burial, metamorphism and melting of sediments in southern Skåne also took place over a relatively short timeframe between 1.46–1.44 Ga during the Danopolonian Orogeny. This suggests a dynamic tectonic environment, although given the uncertainties in the timescales involved, burial rates only need to be on the order of *c*. 1 km/Ma to bury supracrustal materials to mid-crustal depths. Such subsidence rates are realistic and within the range of estimated burial rates of *c*. 0.2 – 1.3 km/Ma at convergent margins in the Proterozoic (Nicoli *et al*. 2016), and of *c*. 2 km/Ma in modern transtensional basins (e.g. Dorsey 2010).

While the exact nature of the tectonic setting in southern Scandinavia around 1.46 Ga and during the Danopolonian Orogeny is unclear, the simultaneous granitic magmatism and deformation are consistent with a dynamic and syntectonic environment, possibly a large scale shear-zone associated with NE–SW oriented compression and/or rifting (e.g. Čečys & Benn 2007; Bogdanova *et al*. 2008; Zariņš & Johansson 2009; Waight *et al*. 2012; Johansson *et al*. 2016). Waight *et al.* (2012) identified significant differences in ages obtained using several different geochronological systems with variable closure temperatures on minerals from a single sample of Rønne Granite. The results were used as evidence for initially rapid cooling, as evident by the discrepancies between an U-Pb zircon age of 1456 ± 5 Ma (closure temperature of ~ 900°C) and a ^{39}Ar-^{40}Ar age on amphibole of 1446 ± 2 Ma (closure temperature of ~ 600°C) followed by a period of slow cooling and exhumation as recorded in considerably younger ages for the Rb-Sr and Ar-Ar systems in biotite. These ages suggest that following emplacement of the Rønne Granite there was a change to a more stable and passive environment with slow cooling, which contrasts with the more dynamic environment implied by the inclusion of supracrustal lithologies in the mid-crustal Svaneke Granite. The U-Pb zircon ages for the Rønne and Svaneke Granite are indistinguishable within error, and no cross-cutting relationships are exposed to indicate relative age. The Svaneke Granite shows foliation in some places, in particular near its contact with gneiss at Listed, which is consistent with co-magmatic tectonism. In contrast, the Rønne Granite shows a general lack of deformation and foliation which could tentatively suggest that it represents one of the younger intrusions on Bornholm emplaced following the cessation of active tectonism.

Conclusions

Two new LA-ICP-MS U-Pb zircon ages are presented for rocks included in and adjacent to the Svaneke Granite on Bornholm.

A xenolith included within the Svaneke Granite was derived from a quartz-rich sediment or hydrothermally-altered quartz-rich volcanic rock and yields an upper intercept age of 1483 ± 12 Ma (lower intercept age of 474 ± 250 Ma) and a weighted average of concordant $^{207}Pb/^{206}Pb$ ages of 1477.9 ± 4.6 Ma. These latter ages are statistically older than newly calculated concordia, upper intercept and weighted average of concordant $^{207}Pb/^{206}Pb$ ages for its host granite which are 1463.7 ± 2.8 Ma, 1463.9 ± 5.2 Ma and 1465.0 ± 4.8 Ma respectively.

A sample of the fine-grained felsic gneiss adjacent to the contact with the Svaneke Granite yields an upper intercept age of 1477.7 ± 6.8 Ma and a weighted average age for concordant $^{207}Pb/^{206}Pb$ ages of 1475.4 ± 6.6 Ma which statistically overlaps with the Svaneke Granite. The protolith to this gneiss remains unclear but textural features suggest it may represent a felsic volcanic rock or a hypabyssal felsic intrusion.

These are the oldest ages determined for a rock on Bornholm to date.

Both samples contain a limited number of inherited zircons with ages similar to inherited populations in other felsic basement rocks on Bornholm.

The morphology of the zircons, preservation of oscillatory zoning, and preservation of inherited cores indicate that the ages represent crystallization ages of the protolith volcanics or erosive sources to the protolith sediments rather than resetting during interactions with the Svaneke Granite.

The low number of inherited zircons and the similarity in ages between these rocks and other felsic basement rocks on Bornholm suggest that the upper crust during and prior to granitic magmatism was dominated by rocks only slightly older and similar in composition to the mid-crustal level lithologies now exposed on Bornholm. Evidence for older (e.g. 1.8 Ga) lithologies is absent.

The protoliths to the two investigated samples must have been buried to mid-crustal depths prior to intrusion of the Svaneke Granite, suggesting a dynamic tectonic environment and consistent with other indicators suggesting that magmatism, deformation and metamorphism occurred broadly simultaneously in the region during the Danopolonian Orogeny.

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