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U-Pb zircon age dating of diamond-bearing gneiss from Fjørtoft reveals repeated burial of the Baltoscandian margin during the Caledonian Orogeny

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ABSTRACT

The first find of micro-diamond in the Nordøyane UHP domain of the Western Gneiss Region (WGR) of the Scandinavian Caledonides reshaped tectonic models for the region. Nevertheless, in spite of much progress regarding the meaning and significance of this find, the history of rock that the diamonds were found in is complex and still largely ambiguous. To investigate this, we report U-Pb zircon ages obtained from the exact crushed sample material in which metamorphic diamond was first found. The grains exhibit complicated internal zoning with distinct detrital cores overgrown by metamorphic rims. The cores yielded a range of ages from the Archean to the late Neoproterozoic/early Cambrian. This detrital zircon age spectrum is broadly similar to detrital signatures recorded by metasedimentary rocks of the Lower and Middle allochthons elsewhere within the orogen. Thus, our dating results support the previously proposed affinity of the studied gneiss to the Seve-Blåhø Nappe of the Middle Allochthon. Metamorphic rims yielded a well-defined peak at 447 ± 2 Ma and a broad population that ranges between *c.* 437 and 423 Ma. The data reveal a prolonged metamorphic history of the Fjørtoft gneiss that is far more complex then would be expected for an UHP rock that has seen a single burial and exhumation cycle. The data are consistent with a model involving multiple such cycles, which would provide renewed support for the dunk tectonics model that has been postulated for the region.

Key words: geochronology, Western Gneiss Region, ultrahigh pressure metamorphism

1. Introduction

The Scandinavian Caledonides is an archetypal collisional orogen, containing some of the world's best preserved and most spectacular examples of deeply buried continental rocks. The mountain belt formed between the late Cambrian (Furongian) to early Ordovician and the late Silurian to early Devonian (e.g. Gee *et al*. 2013 and references therein), when the Iapetus basin contracted towards closure and multiple subduction-collision events occurred between the hyper-extended margin of Baltica and the outboard terranes (island arcs and/or microcontinents). The terminus of this period was the collision between Baltica and Laurentia, with the former undergoing transient subduction deeply beneath the latter (e.g. Krogh, 1977; Andersen *et al*. 1991; Brueckner & van Roermund, 2004; Majka *et al*. 2014). The various subduction-collision processes produced a multitude of (ultra-)high pressure (UHP-HP) rock types yielding various ages of peak metamorphism. The most pronounced of the early (late Cambrian and early to mid-Ordovician) UHP-HP events are those recorded in the Middle Allochthon (*sensu* e.g. Gee *et al*. 2010), which is exposed along the entire length of the Scandinavian Caledonides. UHP rocks are currently known from several localities spanning almost the full length of the outcrop of the Middle Allochthon, a few of which contain well-established metamorphic microdiamond (e.g. Smit *et al*. 2010; Janák *et al*. 2013; Majka *et al*. 2014; Gillio *et al*. 2015; Klonowska *et al*. 2016, 2017; Bukała *et al*. 2018). While these occurrences are widely spaced and UHP metamorphism may not have been continuous or exactly contemporaneous between them, subduction of the Baltica continental margin was clearly an important and widespread process during the Caledonian orogenic cycle prior to the final Scandian collision.

Vestiges of the Middle Allochthon also occur as deep infolds or tectonic intercalations within the largest UHP-HP province in the Scandinavian Caledonides (Terry & Robinson, 2004; Robinson *et al*. 2014), the Western Gneiss Region (WGR), which is a large tectonic window in which the Baltic cratonic margin, intensively reworked, emerges in the hinterland through the pile of allochthons. This giant UHP terrane represents the deeply subducted margin of Baltica (Krogh, 1977; Cuthbert *et al*. 1983). Here, the Middle Allochthon is intimately associated with HP or UHP Baltica basement rocks (Terry & Robinson, 2004). Differences between the ages for UHP metamorphism in the Middle Allochthon in Sweden (Ordovician) and in the basement orthogneisses of the WGR (latest Silurian to early Devonian) suggest that inliers of the Middle Allochthon in the WGR could have undergone both Ordovician and Silurian-Devonian metamorphism and thus may have been subducted at least twice during the Caledonian orogenic cycle.

The possibility of dual or even multiple subduction episodes was embodied in the 'dunk tectonics' evolutionary model proposed by Brueckner & van Roermund (2004) and Brueckner (2006) and revived by Majka *et al*. (2014), in which a continental margin is repeatedly subducted into the mantle ('dunked') during successive collisions with arcs and continental fragments during ocean closure, including the climactic final continental collision. The dunk tectonics model predicts repeated UHP-HP metamorphism across laterally extensive domains of the terranes now dispersed among the thrust stack in the orogenic foreland. If this is the case, the early to mid-Ordovician subduction-related metamorphism recorded in the Seve nappes exposed in Sweden (e.g. Janák *et al*. 2013; Klonowska *et al*. 2017; Bukała *et al*. 2018) should also have affected the Blåhø Nappe

(Middle Allochthon) in the WGR, but would have been strongly overprinted by the late Silurian-Devonian 'Scandian' collision between Baltica and Laurentia and the resulting (U)HP metamorphism that is so spectacularly recorded in the WGR basement. Tracing this early subduction record into the highest-grade domains of the WGR deep within the orogenic core has, indeed, proved difficult thus far. (U)HP rocks in these domains mostly belong to the Baltic basement and record only Siluro-Devonian (Scandian; 425-400 Ma) overprinting. However, a well-known but enigmatic occurrence of high-grade pelitic gneiss outcropping in the Nordøyane area of western Norway has yielded microdiamond (Dobrzhinetskaya *et al*. 1995) and thus shows petrological similarity to some metapelitic UHP rocks in the Seve Nappe Complex near the Caledonide foreland (Klonowska *et al*. 2017). To trace the history of high-grade allochthonous rocks in the WGR and ultimately test the efficacy of the dunk tectonics model, we subjected zircon from this unusual lithology to U-Pb zircon chronology. These rocks have long been ascribed to the Seve-Blåhø Nappe of the Middle Allochthon (e.g. Krill, 1985) and thus may provide a record of earlier metamorphic cycles that are otherwise overlooked or lacking.

2. Geological setting

This study focuses on high-grade gneisses exposed within the northern part of the WGR (Fig. 1a) - a giant Baltic (U)HP terrane exposed in the high-grade core of the Scandinavian Caledonides of western Norway (e.g. Hacker *et al*. 2010, 2015). The WGR is predominantly composed of felsic-to-intermediate orthogneisses and psammitic metasediments with Mesoproterozoic and Neoproterozoic protoliths derived from the Fennoscandian craton and its pre- to syn-orogenic metasedimentary cover (the 'paraautochthon') rocks (e.g. Krill, 1980, 1985; Gaal & Gorbatschev, 1987; Tucker *et al.* 1991, 2004; Robinson *et al*. 2014; Young, 2018). Near the southeastern margin of the WGR, the terrane is dominated by rocks resembling the pristine Baltican basement rocks of the foreland. Towards the northwest and west, however, the basement rocks are intensely *Caledonized*, i.e. reworked by Caledonian tectonism and metamorphism, and show widespread evidence for (U)HP metamorphism, mainly in the form of abundant pods of eclogite, but also HP or UHP felsic rocks (Krogh, 1977; Griffin & Brueckner, 1985; Cuthbert *et al*. 2000; Hacker *et al*. 2010). In the highest-P parts of the WGR several isolated bodies of mantle-derived ultramafic rocks including dunite, garnet peridotite and garnet pyroxenites appear (e.g. Brueckner *et al*. 2010), reinforcing the evidence that the WGR rocks have been subducted into the mantle. The eclogite-facies mineral assemblages have been pervasively overprinted by amphibolite and granulite-facies parageneses associated with exhumation, decompression, partial melting and late flattening and shearing (Wilks & Cuthbert, 1994; Labrousse *et al*. 2002; Hacker *et al*. 2010). However, the overprint was not total and fresh eclogite bodies are still frequent across the WGR.

An exceptional effort in multi-method chronology during the past decades has constrained the age of (U)HP metamorphism to between 425 and 400 Ma, i.e. during the Scandian Orogeny (Hacker *et al*. 2010, and references therein). During this time, the hyper-extended Baltic margin was buried beneath the Laurentian continental lithosphere at rates of *c.* 5 mm yr^{-1} (Cutts & Smit, 2018), ultimately reaching depths of 100 km or more (Hacker *et al*. 2010 and references therein). The (U)HP stage was followed by amphibolite-facies overprinting between 400-385 Ma (Terry *et al*. 2000; Kylander-Clark *et al*. 2008; Krogh *et al*. 2011) and cooling below 400°C by *c*. 375 Ma (Hacker & Gans, 2005; Root *et al*. 2005; Walsh *et al*. 2013).

The WGR basement is bounded by the major Caledonide thrust complexes of the Middle and Upper Allochthons. The Middle Allochthon comprises discrete lithotectonic units that vary along the orogen. In southern Norway it is dominated by Proterozoic crystalline complexes with metasandstones, e.g. the Jotun Nappe Complex, Lindås and Jaeren Nappes. In central and northern Sweden and northern Norway Caledonian high-grade rocks, e.g., migmatite, granulite, metasandstone, augen gneiss, amphibolite and eclogite of the Seve and Kalak Nappe Complexes dominate (see e.g. Gee *et al*. 2013 and references therein). The Middle Allochthon is interpreted to represent the distal continental margin of Baltica and may include micro-continental fragments (Cuthbert *et al*. 1983; Emmett, 1996; Andersen *et al*. 1991; Gee *et al*. 2010, 2013). The Upper Allochthon contains a diverse assemblage of ophiolite and arc rocks that originated outboard of Baltica within the Iapetus Ocean between 490-440 Ma (Stephens & Gee, 1985, 1989; Stephens, 1988).

Both allochthons underwent reworking and final emplacement onto the Baltican continental margin during the Scandian collision. In addition, however, they show evidence of earlier tectonometamorphic episodes. In the large Seve Nappe Complex in Sweden, as well as in small slivers of allochthonous rocks in southwesternmost Norway, this is indicated by (U)HP metamorphism at *c*. 460 – 445 Ma, which has been attributed to a pre-Scandian arc-continent collision (e.g. Brueckner *et al*. 2004; Brueckner & Van Roermund, 2004, 2007; Smit *et al*. 2010; 2011; Majka *et al*. 2012, 2014; Root & Corfu, 2012; Grimmer *et al*. 2015; Klonowska *et al*. 2016, 2017; Fassmer *et al*. 2017). Yet older, *c*. 500-485 Ma, (U)HP metamorphic rocks are also recognized in the Seve Nappe Complex of northern Sweden (Mørk *et al*. 1988, Root & Corfu, 2012, Barnes *et al*. 2019).

In the foreland regions of southern Norway, and central and northern Sweden an additional nappe complex, the Lower Allochthon, underlies the Middle Allochthon and comprises thrusted repetitions of basement and sedimentary cover derived from the Fennoscandian shield (hereafter termed the Baltican basement). These rocks record the long-lived thrusting of the allochthons onto the Baltic margin during the Scandian.

Outcropping within the high-grade sections of the Baltican basement in the WGR are belts (inliers) of more diverse lithological assemblages including psammitic and pelitic metasediments, anorthosites and distinctive megacrystic augen gneisses. Such assemblages may represent basement-cover repetitions derived from the Baltica slab (i.e. Lower Allochthon), although they commonly also exhibit lithological similarities with the Middle Allochthon in the main allochthon exposures (Krill, 1980; Robinson, 1995; Robinson *et al*. 2014).

These inliers of the allochthons are conventionally regarded as being above the main mass of orthogneisses in the tectonostratigraphy and down-folded into these (Krill, 1985; Tucker *et al*. 2004; Robinson & Hollocher, 2008). The complete sequence is (from base to top above the Baltican basement) the Risberget nappe (augen orthogneisses, anorthosites, metagabbros); Saetra Nappe (quartzite with deformed dykes of metadolerite); Blåhø Nappe (high grade metapelite, calc-silicate, marble, amphibolite and mafic granulite); Støren Nappe (ophiolitic and arc rocks of greenschist to low amphibolite facies). The last of these is part of the Upper Allochthon, while the others are correlated with the Middle Allochthon. The Blåhø Nappe is correlated with the high-grade Middle Seve Nappe in the main allochthon outcrop in central and northern Sweden. Their structural evolution has been established in the north-eastern WGR in the Trollheimen-Trondheim district (Robinson *et al*. 2014), where tectonostratigraphic units of the Middle Allochthon were thrust over the Baltican basement, then this combined sequence was folded to form a basement cored nappe that was translated eastwards towards the foreland along the late, out-of-sequence, Storli Thrust. The nappe core contains eclogite dated at 425 ± 10 Ma (Beckman *et al*. 2013), but the lower basement unit below the thrust is devoid of eclogite. The same sequence can be traced to Moldefjord and the southern part of the Nordøyane, far to the west (Fig. 1; see also Robinson, 1985). A similar structural evolution was demonstrated by Young (2018) in the central WGR, where allochthonous rocks ('mixed rocks') were tectonically imbricated and infolded following emplacement onto the Baltica basement along major foreland-vergent shear zones.

The allochthons have also been mapped out eastwards into the main allochthon outcrop in the frontal zone in central Sweden (e.g. Gee *et al*. 2010). Here, the Middle Allochthon is more continuously exposed, is several km thick and bounded by major thrusts. In the WGR, however, these nappes are either extremely attenuated to a few meters in thickness or excised entirely (Robinson, 1995). In the Trondheim area and southwestwards to Moldefjord the upper boundary of the Middle Allochthon against the Upper Allochthon is a major west-vergent, late orogenic ductile detachment fault, the Agdenes Detachment (Robinson *et al*. 2014).

2a. Nordøyane ultra-high pressure domain

The sample investigated here comes from the island of Fjørtoft (Fig. 1b) in the Nordøyane archipelago, immediately west of Moldefjord, which lies within the northernmost UHP domain of the WGR (Root *et al*. 2005). The Middle Allochthon sequence established in the Trollheimen-Moldefjord area has been mapped across the Nordøyane by Terry & Robinson (2003, 2004). The lithology of interest is a pelitic garnet-kyanite gneiss in an assemblage also including biotite-garnet migmatite, calc-silicate, marble and eclogite, all correlated with the Blåhø Nappe. The structural and fabric evolution in the Nordøyane provides key constraints in the interpretation of the zircon dating set out in the following sections.

There are two major structural domains in Nordøyane (Terry & Robinson, 2013, 2014) separated by a major late-orogenic, steep sinistral discontinuity, the Åkre-Midøy shear zone. To its south the structural evolution resembles the situation in Trollheimen and Moldefjord. The northern structural domain has been brought in against the southern domain from the NE by motion along the Åkre-Midøy shear zone (Terry & Robinson, 2003, 2004). Evidence for UHP metamorphism is found in the Baltican basement, the allochthons and in mantle-derived ultramafic massifs (Dobrzhinetskaya *et al*. 1995; Terry *et al*. 2000; Carswell *et al*. 2006; Vrijmoed *et al*. 2006; Spengler *et al*. 2009; Butler *et al*. 2013). The Middle Allochthon is only represented by the Blåhø Nappe, which has been folded into the core of a large recumbent, isoclinal synform with dioritic to granitoid gneisses of the Baltican basement on either limb (Terry & Robinson, 2004). The contact is coincident with an eclogite- (or high-P granulite-) facies shear zone that extends through Blåhø and a few hundred meters into the adjacent basement, and in which mylonite lineations and rotated porphyroclasts show top-SE shear sense when the folds are restored to pre-folding geometry (Terry *et al*. 2000a; Terry & Robinson, 2004). These fabrics are associated with transformation of two metagabbro lenses to eclogite (Mørk, 1985; Terry & Robinson, 2004) dated at 410 ± 2 Ma (Krogh *et al*. 2011; see also Mørk & Mearns, 1986). Terry *et al*. (2000a) and Terry & Robinson (2004) proposed that this shear zone emplaced the UHP Blåhø Nappe over Baltican basement that had only experienced HP eclogite conditions, but Carswell *et al*. (2006) showed that nearby eclogites in the Baltican basement equilibrated under UHP conditions, in which case the shear zone operated during exhumation and the metamorphic assemblages are retrograde. It remains possible, however, that all the UHP eclogites are part of the sheared basement pediment attached to the underside Blåhø Nappe and a cryptic HP basement unit lies at a deeper structural level.

Lenses of garnet peridotite and pyroxenite derived from subcontinental mantle decorate the basement-cover contact and are scattered through the Baltica basement in a zone a few hundred meters below it, confirming the existence of a fundamentally important tectonic contact here. Late fabrics defined by UHP mineral assemblages in these garnet pyroxenites at Bardane, Fjørtoft and Flemsøy give P ≈ 6 GPa at sub-geotherm temperatures for cratonic mantle (e.g. Vrijmoed, van Roermund & Davies, 2006; Scambelluri, van Roermund & Pettke, 2010). A mineral isochron age of 429 ± 3.1 Ma for this mineral assemblage was interpreted to represent an early stage in the subduction of the outermost Baltica continental margin (Spengler *et al*. 2009).

Two kyanite eclogites from the Blåhø Nappe very close to its lower boundary record P-T conditions overlapping the diamond stability field (Terry *et al*. 2000) and one of these gives a Lu-Hf mineral age of 404.9 ± 7.9 Ma (Cutts & Smit, 2018). A distinctive feature of the Blåhø in the Nordøyane and Moldefjord area is that eclogites and other mafic rocks are a common part of the rock assemblage, while these are less common in the main outcrop of the equivalent Seve Nappe in Sweden. An eclogite from the island of Gossa, adjacent to Fjørtoft, gives a Scandian Sm-Nd mineral isochron age of 413.9 ± 3.7 Ma (Kylander-Clarke, 2009). Another two from the mainland along strike from Nordøyane have given Scandian ages for (U)HP metamorphism (418 ± 27 Ma, Tverfjell north of Molde; Griffin & Brueckner, 1985 and 415.2 ± 0.6 Ma, Averøya, near Kristiansund; Krogh *et al*. 2011).

The age of UHP metamorphism in the Baltican basement in the northern domain is constrained by a U-Pb zircon date of 405 ± 1 Ma from an eclogite at Midsund, Otrøy (Krogh *et al*. 2011) although, puzzlingly, Kylander-Clark *et al*. (2007) derived Lu–Hf garnet and Sm–Nd garnet – whole-rock ages for this eclogite of 380 ± 14 Ma and 388 ±10 Ma, respectively, which are significantly younger than any other UHP eclogite ages in the WGR; they are, however, Scandian. Zircons from the Svartberget microdiamond-bearing metasomatic veins in garnet websterite within Baltican basement orthogneiss give a robust U-Pb (LA-ICP-MS) age for a cluster of concordant points of 410.6 ± 2.6 Ma (Quas-Cohen, 2013) which is taken to date metasomatism and microdiamond formation. Samples from the same body also yielded significantly younger and perhaps less robust dates by U-Pb on zircon using ID-TIMS, which gave a discordia intercept of 397.2 ± 1.2 Ma (Vrijmoed *et al*. 2013) and Sm-Nd mineral isochrons yielded dates of 393 ± 3 Ma to 381 ± 6 Ma (Vrijmoed *et al*. 2008) interpreted to be cooling ages.

Overall, it is possible to reconstruct an evolution for this northern, UHP domain, based on the tectonic model of Terry & Robinson (2004) in Nordøyane and adjacent areas:

1) The Blåhø Nappe is emplaced on to the Baltica basement (time uncertain but before 430 Ma).

2) Baltica basement and Blåhø Nappe are subducted deep enough to capture mantle ultramafic rocks (at least 200 km) at ~430 Ma during the early stages of the Scandian continent-continent collision.

3) UHP eclogites form, or continue to equilibrate, in both units until ~410 Ma.

4) The Blåhø Nappe and a detached pediment of Baltica Basement rise as a nappe over the (still descending?) deeper basement, generating the top-southeast HP eclogite or HP granulite shear fabrics ($\leq$ 410 Ma).

The available evidence favours a common, roughly synchronous, Scandian diamond-eclogite facies metamorphism for both the Blåhø Nappe and the Baltica basement in the northern domain of Nordøyane, with a basement-cover nappe similar in geometry to the Trollheimen-Moldefjord region but operating at much deeper levels. The whole basement-cover package in both northern and southern structural domains has then been refolded about upright, folds associated with a pervasive, sinistral or top-west amphibolite-facies fabric with horizontal lineations and fold axes (Terry & Robinson, 2003) dated at 396 Ma from boudin-neck pegmatites (Krogh *et al*. 2011). (U)HP lithologies and fabrics are preserved only as rare relics where they have survived overprinting by the late-orogenic deformation. Any signature of pre-Scandian metamorphism must have survived both this and the Scandian UHP tectono-metamorphism.

3. Sample Description

The sample investigated here was collected from an old quarry at Vågholmane, just north of the ferry terminal. It is the residue of the same sample (ID: Fj-19; Fig. 2) from which Dobrzhinetskaya *et al*. (1995) extracted metamorphic diamond by a chemical dissolution process performed on a crushed block. The lithology has been described previously by Dobrzhinetskaya *et al*. (1995), Holder *et al*. (2015), Liu & Massonne (2019) and Terry *et al*. (2000b); the latter's sample (recoded by them as UHP1) was a thin section cut from the microdiamond-bearing sample, so is the same sample block from which our zircons were sourced. It is composed of garnet, kyanite, phlogopite, K-feldspar, plagioclase, quartz, graphite and additionally rutile, sulphides, monazite and zircon. Garnet is abundant, pale mauve-coloured, typically 0.5-1.0 cm in size, and locally occurs as globular megacrysts of 3-5 cm surrounded by conspicuous coronas of felsic minerals. It shows distinctive zoning with low Ca garnet cores (Terry *et al*. 2000b; Holder *et al*. 2015; Liu & Massone, 2019; authors' unpublished data) enclosing abundant, small needles of kyanite. High Ca rims contain larger inclusions of kyanite, quartz, rutile, graphite, perthitic feldspar and sulphides, along with rationally orientated needles of rutile. It has not often been recognised that the rock is a blastomylonite with streaky appearance suggesting pre-tectonic migmatization. Relics of granitic (partial) melt are preserved as embayments and inclusions in the garnet rims and are composed of perthite, quartz and phlogopite. Monazite and zircon are found in both cores and rims of garnet. The rock matrix is generally composed of fine-grained plagioclase and K-feldspar (from the breakdown of coarse perthite and garnet), quartz and large flakes of phlogopite and graphite. No microdiamond has yet been found in-situ, nor any other (U)HP phases, although muscovite inclusions in garnet associated with phlogopite may be relics after phengite. Larsen *et al*. (1998), who described the rock as a 'felsic granulite', estimated P = 16-23 kbar at 600-800 °C for the matrix assemblage assuming equilibrium with garnet rims. However, the recent detailed study by Liu & Massonne (2019) suggests that this rock underwent most probably a prolonged anticlockwise P-T path, with peak conditions around 1.35-1.45 GPa and 770-820 °C and an earlier equilibration event at *c.* 1.35-1.45 GPa and 770-820 °C.

In the field, two linear fabrics can be recognised in the Blåhø Nappe felsic gneisses (Terry *et al*. 2000; Terry & Robinson, 2004). The earlier fabric is represented by the sample UHP1 described above, and is defined by mineral-aggregate rods and common orientation of kyanite. Kinematic indicators on steep foliation surfaces including rotated kyanite and garnet porphyroclasts indicating north-side-up shear that translates to top-southeast shear when the effects of later folding are removed, as found in the eclogite-facies shear zones described above. Terry & Robinson (2004) attributed the tectonite fabrics of the basement metagabbros and dioritic orthogneisses to the same kinematic system as this early fabric in the Blåhø Nappe gneiss, suggesting that it operated at about 410 Ma, postdating an episode of partial melting, and was related to foreland directed transport of a (U)HP basement with associated Seve-Blåhø allochthon.

The later fabric is a mineral-aggregate rodding lineation defined by sillimanite replacing deformed, fish-shaped kyanite porphyroclasts or disseminated in the matrix, which displays extreme grain-size reduction. Garnet porphyroclasts are dismembered and strung out in the lineation (Terry *et al*. 2000b). Mica- and sillimanite-rich elements of the matrix display S-C fabrics. The lineations and associated fold axes are roughly horizontal and the kinematic indicators show consistent top-west or sinistral shear. This fabric overprints and re-orientates the steeper kyanite lineation. This late top-west shear fabric also dominates large parts of the allochthons and some of the adjacent basement gneisses in the westernmost WGR, indicating a top-to-the-west transport. This was related to reversal of motion on the major thrust surfaces, the development of Agdenes Detachment and Nordfjord-Sogn Detachment Zone and the late-orogenic Old Red Sandstone basins (Norton, 1987; Wilks & Cuthbert, 1994; Brueckner & Cuthbert, 2013; Robinson *et al*. 2014; Young, 2018).

Zircons in the mineral separate that we obtained from sample Fj-19 contains micro-inclusions of quartz, feldspar, mica, apatite, graphite and rutile (H.-J. Massonne, pers. comm. 2005). No HP or UHP indicator micro-inclusions such as diamond, coesite, phengitic mica or jadeitic clinopyroxene have been found. Monazite from the microdiamond-yielding sample has been analysed by electron microprobe (Th-U-total Pb) and secondary ionization mass spectrometry (U-Th-Pb), along with a sample of porphyroclastic mylonite with the younger lineation from 1km west of Vågholmane (Terry *et al*. 2000; their samples UHP1 and 929, respectively). The analyses yield a cluster of dates between 1100 and 950 Ma, a few scattered dates between 900 Ma and 500 Ma, and other clusters at *c.* 415, 408, 395 Ma and *c.* 375 Ma. The older dates of 415.0 ± 6.8 Ma (SIMS) and 408.0 ± 5.6 Ma (EPMA) were obtained from the same monazite inclusions in garnet and have been interpreted as indicating the maximum age of garnet growth. The two youngest dates were interpreted to represent different phases of exhumation from deep subduction conditions. Recently, Holder *et al.* (2015) have also performed *in-situ* monazite U-Th-Pb dating using laser ablation split stream inductively coupled plasma mass spectrometry. These authors dated two samples of the same rock and obtained the following results: a cluster of ages between 1200 and 900 Ma, Caledonian concordia ages peaking at 431.1 ± 1.7 Ma, 426.8 ± 1.7 Ma, 425.5 ± 3.0, 393 ± 3.0 Ma and 391.3 ± 2.7 Ma. Contrasting REE patterns for inclusions and matrix grains dated at *c*. 425 Ma suggest that garnet growth took place at this time, but other inclusions as young as *c*. 390 Ma may indicate either continued growth to this time or re-setting. A continued growth of monazite is also suggested by Liu & Massonne (2019), who reported Th-U-total Pb monazite dates spanning from 460 to 380 Ma and interpreted them to reflect a prolonged residence time under relatively high temperatures due to two burial events that have never reached UHP conditions. We differ by not ruling out diamond-stable P-T conditions at some time during its history, as some stages of the rock history may have been destroyed during overprinting, for example during partial melting.

To our knowledge, no zircon dates have so far been documented in the literature for this unusual and widely studied rock.

4. Methods

Uranium-lead dating was performed on zircon grains initially separated by D. A. Carswell and H.-J. Massonne for studies of inclusions; the separate was kindly provided by H.-J. Massonne, who mounted and polished the grains in an epoxy mount. The zircon grains are from the same rock volume from which micro-diamond was isolated (Dobrzhinetskaya *et al*. 1995). The grains are 100-250 µm in length and were polished to their geometric core. U-Pb dating of zircon was performed at the Swedish Museum of

Natural History, Stockholm, using a Nu Instruments Plasma II multi-collector inductively coupled plasma mass spectrometry (MC-ICPMS) instrument coupled to an ESI NWR193UC excimer laser ablation system. The m/z (mass-to-charge ratio) corresponding to masses 202, 204, 206, 207 and 208 were measured on ion counters, and those corresponding to 232, 235, and 238 were measured on Faraday collectors. The laser was fired for 35 s with a fluence of 3.5 J/cm^2, a pulse rate of 8 Hz and a spots size of 15 µm. Helium was used as a sample carrier gas (0.3 l/min) to flush the laser cell and was mixed with argon sample gas (0.9 l/min) before entering the ICP-MS. Analyses were corrected for mass bias and elemental fractionation using the protocols of Kooijman *et al*. (2012). The 91500 zircon reference material (1065 Ma; Wiedenbeck *et al*. 1995) was used for normalization and repeated analyses indicated external reproducibility of 1.0% 2RSD for the ^{207}Pb-^{206}Pb age and 1.2% 2RSD for the ^{206}Pb-^{238}U age (n = 58). Accuracy was assessed by analysing the secondary reference zircons Plešovice (337 Ma; Sláma *et al*. 2008), GJ-1 (609 Ma; Jackson *et al*. 2004) and Temora 2 (417 Ma; Black *et al*. 2004). We obtained 336 ± 11 Ma (Plešovice; n = 8), 606 ± 3 Ma (GJ-1; n = 8), and 416 ± 9 Ma (Temora 2; n = 5), all of which agree within 1% of published age estimates for these materials. Data reduction employed in-house Excel macros. Age calculations and construction of concordia diagrams were prepared using the Excel extension Isoplot 3.75 (Ludwig, 2012). All uncertainties are reported at the 2σ level. Age data are illustrated in Figure 4 and presented in Table 1.

5. Results

Separated zircon grains are spherical or slightly elongated in shape, with rounded edges. Cathodoluminescence (CL) images reveal complex internal structure and most zircons display obvious multi-stage growth features (Fig. 3). Most commonly, zircon grains display cores with well-defined concentric oscillatory zoning, typical of magmatic zircon, which is overgrown by a bright-CL rims. Such rims show no visible zoning and are likely of metamorphic origin. U-Pb isotope data obtained from the dated grains are presented in Table 1 and reveal a complex multi-component age signature. The majority of dates older than 700 Ma were obtained from zircon cores and display significant degrees of discordance (Figs. 4a, d, f). Several ^{207}Pb-^{206}Pb date clusters can be distinguished among the obtained results: (1) a Neoarchean cluster between 2.8-2.5 Ga (n = 6); (2) a small cluster in the Mesoproterozoic (1.5-1.3 Ga; n = 3); (3) late Mesoproterozoic to early Neoproterozoic dates between 1.1-0.9 Ga (n = 6); and (4) a group of Neoproterozoic dates between 0.9-0.7 Ga (n = 7). A small group of three concordant dates between 540-520 Ma (Table 1) was also obtained, one of which is from a core domain, whereas the other two were obtained from rims. A notable number of Caledonian spot dates range from 450 to 400 Ma (Fig. 4b). Two subgroups of dates can be distinguished among the concordant results (Fig. 4e). Five of the oldest Caledonian dates cluster between 450-440 Ma and give a concordia age of 446.6 ± 2.1 Ma (Fig. 4c). Another cluster of concordant dates is observed between 437-423 Ma, and yield a weighted average ^{206}Pb-^{238}U date of 428.3 ± 1.7 Ma. The three youngest dates are *c.* 415 Ma and younger.

6. Discussion

6.a. Provenance and exotic nature of the Fjørtoft diamondiferous gneiss

The oldest detrital ages (2.8-2.5 Ga) are not known from the Baltica basement rocks of the WGR. Such detrital ages are, however, observed in the Lower and Middle Allochthons in Sweden (e.g. Gee *et al*. 2014, 2015; Ladenberger *et al*. 2014), as well as in southwesternmost Norway (Smit *et al*. 2011). Two younger groups, 1.5-1.3 Ga and 1.1-0.9 Ga, correspond to the Gothian and Sveconorwegian orogenies, respectively. The older group is widespread in the WGR and marks a major episode of magmatism within the Fennoscandian basement (e.g. Corfu & Andersen, 2002; Tucker *et al*. 2004; Krogh *et al*. 2011). The younger group is also common across the WGR, both in the allochthons and in the basement; it derives from magmatism and metamorphism during the Sveconorwegian Orogeny (e.g. Tucker *et al*. 1990; Bingen & van Breemmen, 1998; Bingen *et al*. 2001; Røhr *et al*. 2004; Walsh *et al*. 2007; Des Ormeau *et al*. 2015; Corfu & Andersen, 2002). Terry *et al*. (2000) recognised a similar group of ages among monazite cores from the diamond-bearing gneiss on Fjørtoft. These age components clearly establish the Baltic provenance of this rock, indicating that its sedimentary protolith was deposited within the Baltic continental realm or its Iapetus Ocean margin.

Neoproterozoic ages between 0.9 and 0.7 Ga are less common within the Baltic basement (Bingen & Solli, 2009). They are, however, reported from detrital zircons in the Seve Nappe Complex in Sweden (Gee *et al*. 2014) and igneous bodies of similar age are also known from other parts of the Middle Allochthon. Paulsson & Andréasson (2002) reported *c.* 845 Ma U–Pb age of the Vistas granite in the Seve Nappe Complex in northern Sweden, while *c.* 840 and 710 Ma ages are typical of granitic magmatism in the Sørøy-Seiland and Havvatnet nappes of the Kalak Nappe Complex in northernmost Norway (Kirkland *et al*. 2006). Walker *et al*. (2016) have also reported a *c.* 725-700 Ma tectonothermal event recorded in the Caledonides of Shetland. Several of these possible sources derive from Neoproterozoic magmatism and tectonism (Renlandian and Knoydartian) whose products subsequently involved in the northern Iapetus-Caledonide cycle (Cawood *et al*. 2010). The exact source of zircons with 0.9-0.7 Ga ages in the Fjørtoft sample remains unresolved, but it is clear that these data represent an exotic component acquired when the sedimentary protolith was located in a palaeogeographic location distal to the Baltic craton.

A similar explanation may be proposed for the small group of 540 to 520 Ma ages, which were also obtained by Terry *et al*. (2000), but left them uninterpreted. The dates are concordant and form a distinct cluster, indicating that they have geological meaning. Components of similar age are extremely rare in the present-day Scandinavian Caledonides, and are mainly restricted to the Kalak Nappe Complex (e.g. Roberts *et al*. 2010). Interestingly, dates in the range 650-500 Ma are rare but persistently found in the mantle-derived ultramafic rocks and enclosed eclogite in Nordøyane (Jamtveit *et al*. 1991; Spengler *et al*. 2009) and in the central WGR (Medaris *et al*. 2018), suggesting magmatism or tectonism in the Iapetus realm during this interval that may have also had a crustal expression.

The spectrum of different age populations further distinguishes the Fjørtoft gneiss from the adjacent basement orthogneisses and confirms its profoundly allochthonous nature and reinforces its correlation with the Seve-Blåhø Nappe. Moreover, it suggests a previously unrecognised link between this lithotectonic unit and the terranes of the north-Norwegian and Swedish Caledonides.

6.b. Caledonian ages and evidence for double-dunking

U-Pb zircon dates from the Fjørtoft gneiss corresponding to the span of the Caledonian orogenic cycle cluster around *c.* 447 Ma and *c.* 437-423 Ma with three younger dates ≤ *c.* 415 Ma. The oldest age of these mentioned above was not identified in published monazite age studies by Terry *et al*. (2000b) or Holder *et al*. (2015). This age is significantly earlier than almost all previous higher-precision ages for (U)HP-HT metamorphism in the WGR.

This Ordovician age peak may be compared with dates in other outcrops of the allochthons in the WGR. Zircon U-Pb dates of 470-430 Ma were reported for eclogites in allochthonous units (Blåhø Nappe?) in the western and eastern-central parts of the WGR but were attributed to protolith ages (Walsh *et al*. 2007 - discordant dates; DesOrmeau *et al*. 2015). We speculate that these are lower Palaeozoic metavolcanics similar to the layered eclogites described in the Blåhø Nappe on Fjørtoft by Terry & Robinson (2004) and on the mainland north of Molde by Carswell & Harvey (1985). Walsh *et al*. (2007) also reported a protolith (detrital?) zircon age of 480 ± 12 Ma from a pelite in the Blåhø Nappe. However, our zircon ages are clearly metamorphic and do not represent growth in magmatic protoliths. In contrast, Gordon *et al*. (2016) presented U-Pb zircon age populations of *c.* 467 and *c.* 439 Ma obtained from leucosomes in metapelites of the Seve-Blåhø Nappe north of Trondheim, which they interpreted to represent (U)HP zircon growth and subsequent migmatization.

The younger of our two larger Caledonian U-Pb zircon age-peaks matches well with the timing of Ca-rich garnet rims as indicated by *in-situ* monazite ages of *c.* 425 Ma and perhaps as old as 430 Ma, (Holder *et al*. 2015) corresponding to an episode of migmatisation evidenced by granitic melt inclusions enclosed in Ca-rich garnet rims. It is also not much younger than the earliest ages attributed to Scandian subduction of the Baltica margin around 430 Ma as indicated by garnet pyroxenites in mantle-derived ultramafites in Nordøyane (Jamtveit *et al*. 1991; Spengler *et al*. 2009) and elsewhere (Medaris *et al*. 2018). These ages are all significantly older than the timing of HP-eclogite facies SE-vergent shearing involving the metagabbros in Nordøyane (Terry *et al*. 2000a; Terry & Robinson, 2004) at 410 ± 2Ma (Krogh *et al*. 2011) which has been correlated with the SE-vergent shear overprinting the migmatite fabric in the Fjørtoft gneiss. This puts a younger age bracket on the duration of migmatisation. Also, ages around 410 Ma are relatively scarce in our dataset, suggesting that during this foreland-directed shearing little new zircon was generated, and/or there was little resetting of the zircon U-Pb isotopic system.

The late Ordovician age components in our dataset (*c*. 447 Ma) are uncommon or absent in the WGR, but widely recognised within the Seve Nappe Complex of Jämtland in Sweden and in tectonic slivers of probable Middle Allochthon rocks in southwesternmost Norway (e.g. Brueckner *et al*. 2004; Brueckner & van Roermund, 2007; Smit *et al*. 2011; Majka *et al*. 2012; Root & Corfu, 2012; Ladenberger *et al*. 2014; Grimmer *et al*. 2015; Klonowska *et al*. 2017; Fassmer *et al*. 2017). These terranes record a mid- to late Ordovician episode of (U)HP metamorphism. The lithologies in the Åreskutan Nappe, Middle Seve Nappe in Jamtland, central Sweden are similar to the Fjørtoft gneiss in that they are metapelitic sillimanite or kyanite-bearing migmatites that record a pre-migmatite, diamond-stable UHP metamorphism. Granulite-facies metamorphism and migmatisation has been dated at *c*. 439 Ma during decompression and partial melting, following UHP metamorphism at *c.* 455 Ma (Majka *et al*. 2012). Emplacement of these rocks as a hot nappe above the Lower Seve Nappe Complex was dated from monazite in basal mylonites at 424 ± 6 Ma (Majka *et al*. 2012) which was within error of the age for crystallisation of post-migmatite, pre-mylonite pegmatites during nappe emplacement at *c.* 430-428 Ma (Ladenberger *et al*. 2014). The close correspondence of the age for this migmatisation with the earliest Caledonian ages from the Fjørtoft gneiss encourages the tentative proposal that migmatisation took place there, too, at that time. While this may be true, the *c.* 430-428 Ma age for pegmatite intrusion at Åreskutan during Scandian nappe emplacement corresponds closely to the evidence for growth of high-Ca garnet rims in the Fjørtoft gneiss around 430-425 Ma (Holder *et al*. 2015), which we attribute to partial melting. This suggests that partial melting of the Fjørtoft gneiss took place during the earliest phase of exhumation of the far-western, Blåhø segment of the Seve Nappe Complex. If two episodes of partial melting took place in these rocks (late Ordovician and mid-Silurian), evidence must have been obscured by the subsequent intense ductile shearing. If the Blåhø Nappe in western Norway can be directly correlated with the Seve Nappe Complex in central Sweden, the evidence that the Blåhø Nappe, and possibly a sheared pediment of Baltica basement orthogneisses, was still moving forelandwards around 410 Ma suggest deformation at the base of the Åreskutan Nappe transferred to a deeper structural level soon after *c.* 425 Ma.

The interpretations above, based on geological evidence and previous geochronological studies, suggests that partial melting may have been significant in generating the zircon U-Pb age pattern. If representative of the rock, the 447 Ma and 437-423 Ma zircon age clusters probably represent discrete stages in which new zircon formed. This may have involved complete neocrystallization and/or re-crystallisation of pre-existing zircon. The latter is common in (U)HP granulites in other collisional orogens (e.g., Bröcker *et al*. 2010), as well as in ultra-high temperature (UHT-HT) rocks (e.g., Mezger & Krogstad, 1997; Kooijman *et al*. 2010), where partial melting was an important process. In the Fjørtoft rocks there was an apparent cessation in zircon crystallisation (or neocrystallisation) during a period of *c*. 15 Ma, which also requires explanation.

Zircon crystallisation in felsic rocks can take place following an excursion beyond the solidus (Yakymchuk & Brown, 2014), either by transient decompression or heating or both. The following two options are hence proposed for the interpretation of the 447 and 437-423 Ma age clusters: (1) they postdate two distinct cycles of high-grade, possibly kyanite-stable high temperature (HT) metamorphism - one before 447 Ma and the other before 423 Ma; (2) they bracket two thermal excursions beyond, and back to, the solidus during a single protracted stage of possibly kyanite-stable HT metamorphism. Regardless of which of the two options proves true or which of these may be associated with micro-diamond growth, the history and context of the rocks, as set out in the foregoing text, requires at least one pulse of pre-Scandian metamorphism.

Previously published ages derived from the (U)HP eclogites in the Nordøyane and adjacent region in the WGR, mainly in the range 415-400 Ma, are only represented in our dataset by one concordant date of *c*. 415 Ma and a slightly discordant, similar date (Fig. 4b). The presence of Scandian UHP eclogites in the basal parts of the Blåhø Nappe in Nordøyane (404.9 ± 7.9 Ma; Cutts & Smit, 2018) suggests that the Blåhø Nappe of Fjørtoft underwent Scandian, perhaps diamond-stable, UHP metamorphism. This apparently resulted in very little new zircon growth or re-crystallisation in the sample examined here. Scandian UHP eclogite formation in the allochthons and Baltica basement evidently continued well after migmatisation of the Blåhø metapelitic gneisses such as those at Fjørtoft (there is evidence that gneisses in this area underwent partial melting during UHP metamorphism; see e.g. Vrijmoed *et al*. 2013; Quas-Cohen, 2013). The single concordant metamorphic zircon date at *c*. 396 Ma is identical within error with a cluster of U-Th-Pb ages for matrix monazites in the Fjørtoft gneiss (Terry *et al*. 2000b). This also closely corresponds to a regionally-distributed suite of titanite U-Pb ages (Tucker *et al*. 1991) interpreted to date a widespread cessation of Pb loss during exhumation of the WGR from below the major extensional Agdenes Detachment (Tucker *et al*. 2004). The late horizontal lineation and sinistral shear fabric in northern Fjørtoft may be attributed to this late-Scandian tectonism.

The zircon U-Pb dataset presented here demonstrates an early Caledonian, pre-Scandian metamorphic event in the northwestern WGR that corresponds to a mid-Ordovician to early Silurian subduction episode recorded in the main outcrop of the Seve Nappe. The evidence for coeval Scandian UHP metamorphism of the Blåhø Nappe and in the Baltica basement in Nordøyane (and probably more widely in the WGR) strongly suggests that both underwent subduction in the late Silurian and early Devonian, and thus a 'double-dunk' for the Blåhø-Seve Nappe of Fjørtoft.

The 'double-dunk' hypothesis (Brueckner & Van Roermund, 2004; Brueckner, 2006) predicts both subduction and eduction of a continental margin, so evidence is required for an episode of exhumation of the subducted slab between any two 'dunks'; if this is lacking it is difficult to refute a single, prolonged subduction episode. In the WGR, evidence for pre-Scandian tectonism and metamorphism has been effectively obliterated by Scandian deformation and overprinting. All that can be deduced is that assembly of the Middle Allochthon nappe stack and its emplacement onto the Baltica basement was the earliest discernable event (e.g. Robinson *et al*. 2014). However, petrological evidence for migmatisation during decompression in the correlative Åreskutan Nappe in the foreland Seve Nappe Complex (Majka *et al*. 2012; Klonowska *et al*. 2014) shows that the Seve Nappe did, at least partially, exhume following the Ordovician subduction event, but before the Scandian subduction and climactic collision. The distribution of concordant ages in our U-Pb zircon dataset, while showing clear clustering at specific time intervals, does indicate some continuity of Caledonian zircon generation, which may be due to incomplete eduction after the first dunk and stalling at fairly deep, hot crustal levels during the relatively brief interval before the Scandian dunk. Overall, the age pattern from our new geochronological evidence for the Middle Allochthon within the WGR is consistent with the predictions of the dunk tectonics model.

The sample from which our zircon set was separated has been iconic in UHP metamorphic studies since the discovery of microdiamonds within it by Dobrzhinetskaya *et al*. (1995), as this was the first metamorphic microdiamond find in the Caledonides and one of the first globally. Yet, this sample remains enigmatic because no microdiamond has yet been found *in*-situ within it. The demonstration of multiple metamorphic events in this rock, of which two are probably high- or ultrahigh- grade, begs the question of the genesis of the diamonds, although this is challenging because of their lack of petrographic context. The possible double-dunk scenario for the Fjørtoft gneiss set out above permits that these rocks passed through diamond-stable physical conditions twice during the Caledonian cycle. Hence, a priority for future work is to find the microdiamonds *in-situ*, although several workers have already made great efforts to do this. A possible barrier to success is the late structural-metamorphic overprint that this belt of Blåhø has suffered, so future efforts might be better focused on adjacent areas where this overprint is less complex and intense.

Finally, it is worth noting the comparison between the zircon dates presented above and previously published monazite dates (Terry *et al*. 2000b; Holder *et al*. 2015; Liu & Massonne, 2019), which reinforce the common observation that zircon and monazite age records are complementary and that both only rarely provide the same age results, and represent the same petrological process, in a single rock (Kooijman *et al.* 2017).

7. Conclusions

(1) The diamond-bearing gneiss from Fjørtoft in the Nordøyane UHP domain of the Western Gneiss Region contains detrital zircon cores that reveal Baltic provenance. This is consistent with previously proposed affinity of the studied gneiss to the Seve-Blåhø Nappe of the Middle Allochthon. A few Archean ages are, however, clearly exotic in respect to the local basement of the WGR directly underlying the studied gneiss. Thus, a more exotic source is required for these zircons both at Fjørtoft and in the other diamond-bearing gneisses of the Seve Nappe Complex.

(2) At least two distinct high-grade metamorphic events preceding the final stage of the Scandian collision are recorded by the diamond-bearing gneiss from Fjørtoft: (1) at 446.6 ± 2.1 Ma; and (2) prolonged or multiple event(s) lasting from *c.* 437 to *c.* 423 Ma. None of the above-mentioned ages can yet be unequivocally linked directly to UHP

metamorphism; they instead could represent P-T excursions related to episodes of partial melting, each most likely following an episode of UHP metamorphism.

(3) The youngest obtained metamorphic zircon dates, scattering from *c.* 415 to *c.* 397 Ma suggest a metamorphic overprint subsequent to the previous events, likely related to the exhumation following final stages of the Scandian phase of the Baltica-Laurentia collision, first of all by translation toward the foreland, then by motion on major west-vergent detachments, but both relating to exhumation of Scandian UHP rocks.

(4) Multiple zircon growth events recorded in the Fjørtoft gneiss reflect its complicated and protracted metamorphic evolution. It is inferred that such complex metamorphic zircon ages pattern resulted from several subduction-exhumation cycles, as predicted by the dunk tectonics model for the Scandinavian Caledonides.

(5) The data are consistent with predictions of the dunk tectonics model, indicating that it provides a plausible explanation for the development of a major part of the Scandinavian Caledonides.

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Declaration of Interest

None

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Figure captions

Figure 1. (Colour online) (a) Simplified geological map of the Western Gneiss Region (modified after Brueckner & Cuthbert, 2013) with (b) generalised geological map of Fjørtoft (after Carswell & van Roermund, 2005) showing the location of the diamond-bearing garnet kyanite gneiss. NSD - Nordfjord-Sogn detachment zone, MTD - Møre Trondelag detachment zone, black dashed line - early E/SE late W/NW décollements, black thin lines - W/NW vergent lineation directions.

Figure 2. (Colour online) Hand specimen of the diamond-bearing garnet-kyanite gneiss from Fjørtoft (sample ID: Fj-19).

Figure 3. (Colour online) Cathodoluminescence images of representative zircon crystals from the Fjørtoft diamond-bearing garnet kyanite gneiss. White circles mark analytical spots and given numbers indicate ^{206}Pb-^{238}U dates.

Figure 4. (Colour online) (a-d) U-Pb concordia diagram for zircon analyses; (a) all analyses for both metamorphic and detrital zircon domains, (b) concordia diagram of zircon with Caledonian ages with inset (c) showing ages for which Concordia age has been calculated. (d) Magnification of the fragment of Concordia diagram (a) showing late Precambrian dates. (e) Histogram of ^{206}Pb-^{238}U age frequency of metamorphic zircon domains. (f) Histogram of ^{207}Pb-^{206}Pb age frequency of concordant detrital zircon (10% discordance accepted).

Table 1. Summary of the U-Pb zircon analyses from the diamond-bearing garnet kyanite gneiss.

Analysis	U conc.	Ratios							Common Pb		Degree of con-cordance	Ages (Ma)						Comments
nr	(ppm)	$^{207}Pb/^{206}Pb$	±2σ	$^{207}Pb/^{235}U$	±2σ	$^{206}Pb/^{238}U$	±2σ	rho:	$^{206}Pb/^{204}Pb$	ƒ206%	(%)	$^{206}Pb/^{238}U$	±2σ	$^{207}Pb/^{235}U$	±2σ	$^{207}Pb/^{206}Pb$	±2σ	
2	236	0.0558	0.0004	0.5454	0.0048	0.0709	0.0004	0.69	146049	0.01	**99.6**	**441.7**	**2.6**	442.0	3.2	443	14	rim
6	286	0.0554	0.0004	0.5195	0.0047	0.0680	0.0004	0.71	6482	0.27	**98.8**	**424.0**	**2.6**	424.8	3.1	429	14	metamorphic (no core)
17	384	0.0560	0.0003	0.5538	0.0056	0.0717	0.0006	0.79			**98.7**	**446.5**	**3.5**	447.5	3.7	452	14	rim
22	35	0.0555	0.0006	0.5348	0.0074	0.0699	0.0006	0.58	688	2.37	**101.2**	**435.8**	**3.4**	435.0	4.9	431	25	core
23	549	0.0553	0.0002	0.5219	0.0040	0.0685	0.0004	0.81	12869	0.13	**100.6**	**426.8**	**2.6**	426.4	2.7	424	10	rim
24	387	0.0552	0.0003	0.5191	0.0043	0.0682	0.0005	0.82	7163	0.23	**101.1**	**425.3**	**2.8**	424.6	2.9	421	11	core
25	106	0.0557	0.0004	0.5339	0.0049	0.0695	0.0004	0.69	2278	0.72	**98.6**	**433.4**	**2.7**	434.4	3.3	440	15	rim
27	125	0.0553	0.0004	0.5499	0.0051	0.0721	0.0005	0.72	26178	0.06	**105.6**	**448.8**	**2.9**	445.0	3.3	425	14	rim
28	30	0.0555	0.0008	0.5517	0.0089	0.0721	0.0005	0.47	2025	0.81	**103.5**	**448.6**	**3.3**	446.1	5.8	434	32	rim
30	233	0.0550	0.0003	0.5154	0.0042	0.0679	0.0004	0.74	2733	0.60	**102.3**	**423.5**	**2.5**	422.1	2.8	414	12	rim
31	207	0.0554	0.0002	0.5473	0.0054	0.0717	0.0006	0.89	22998	0.08	**104.4**	**446.2**	**3.8**	443.2	3.6	428	10	metamorphic (no core)
36	197	0.0553	0.0002	0.5332	0.0050	0.0699	0.0006	0.88	20051	0.09	**102.8**	**435.8**	**3.4**	433.9	3.3	424	10	metamorphic (no core)
37	211	0.0552	0.0002	0.5299	0.0048	0.0696	0.0006	0.90	6968	0.25	**103.4**	**434.0**	**3.4**	431.8	3.2	420	9	fragment of zircon grain
46	87	0.0562	0.0004	0.5574	0.0051	0.0719	0.0003	0.50			**97.2**	**447.7**	**2.0**	449.8	3.3	461	17	rim
52	307	0.0544	0.0003	0.4764	0.0036	0.0635	0.0003	0.55	356385	0.00	**102.5**	**397.0**	**1.6**	395.6	2.5	387	14	metamorphic (no core)
53	863	0.0553	0.0003	0.5192	0.0038	0.0681	0.0003	0.63			**100.6**	**425.0**	**1.9**	424.6	2.6	423	13	metamorphic (no core)
54	185	0.0561	0.0005	0.5540	0.0050	0.0716	0.0003	0.44			**97.5**	**445.7**	**1.7**	447.6	3.3	457	18	rim
55	839	0.0557	0.0004	0.5257	0.0061	0.0685	0.0006	0.81			**97.1**	**427.0**	**3.9**	429.0	4.0	440	15	core
61	182	0.0553	0.0002	0.5260	0.0044	0.0689	0.0005	0.87			**100.8**	**429.7**	**3.0**	429.2	2.9	426	9	metamorphic (no core)
62	265	0.0554	0.0002	0.5265	0.0031	0.0689	0.0003	0.83	15572	0.11	**100.5**	**429.8**	**2.1**	429.5	2.1	428	7	metamorphic (no core)
63	535	0.0553	0.0003	0.5171	0.0040	0.0678	0.0003	0.65	11250	0.16	**99.4**	**422.8**	**2.1**	423.2	2.7	425	13	fragment of zircon grain
64	189	0.0553	0.0002	0.5224	0.0031	0.0685	0.0003	0.78	2626	0.59	**100.4**	**427.0**	**1.9**	426.7	2.1	425	8	rim
65	81	0.0558	0.0004	0.5398	0.0048	0.0702	0.0003	0.52	1133	1.56	**98.8**	**437.5**	**2.0**	438.3	3.2	443	17	rim
67	160	0.0545	0.0005	0.5003	0.0056	0.0666	0.0004	0.53	3638	0.49	**106.4**	**415.7**	**2.4**	411.9	3.8	391	21	rim
71	249	0.0553	0.0002	0.5201	0.0040	0.0682	0.0004	0.86	6196	0.29	**99.8**	**425.1**	**2.7**	425.2	2.6	426	9	metamorphic (no core)
74	257	0.0554	0.0003	0.5264	0.0057	0.0689	0.0007	0.91	3931	0.42	**100.1**	**429.5**	**4.1**	429.4	3.8	429	10	rim
75	319	0.0554	0.0002	0.5258	0.0039	0.0688	0.0005	0.91			**100.2**	**429.2**	**2.8**	429.0	2.6	428	7	rim
78	157	0.0557	0.0003	0.5217	0.0041	0.0679	0.0004	0.78	2216	0.80	**95.9**	**423.5**	**2.5**	426.3	2.7	441	11	metamorphic (no core)
81	142	0.0556	0.0004	0.5335	0.0052	0.0696	0.0005	0.67	2456	0.72	**99.3**	**433.7**	**2.8**	434.1	3.5	437	16	metamorphic (no core)
96	250	0.0555	0.0004	0.5270	0.0044	0.0688	0.0004	0.61			**98.9**	**429.0**	**2.1**	429.8	2.9	434	15	metamorphic (no core)
97	385	0.0555	0.0004	0.5307	0.0044	0.0693	0.0003	0.60			**99.8**	**432.2**	**2.1**	432.3	2.9	433	15	core
101	147	0.0560	0.0003	0.5355	0.0047	0.0693	0.0005	0.74	3896	0.44	**95.1**	**431.9**	**2.7**	435.4	3.1	454	13	rim
102	233	0.0554	0.0003	0.5182	0.0041	0.0679	0.0004	0.70	103170	0.02	**99.1**	**423.4**	**2.3**	423.9	2.7	427	13	core
103	62	0.0554	0.0004	0.5233	0.0043	0.0685	0.0003	0.60	3546	0.46	**99.5**	**427.0**	**2.0**	427.4	2.9	429	15	metamorphic (no core)
104	223	0.0554	0.0003	0.5235	0.0040	0.0686	0.0004	0.71	20895	0.34	**100.4**	**427.7**	**2.4**	427.5	2.7	426	11	metamorphic (no core)
105	148	0.0559	0.0004	0.5068	0.0043	0.0658	0.0003	0.60			**91.8**	**410.7**	**2.0**	416.3	2.9	448	15	rim
60	78	0.0579	0.0005	0.6710	0.0061	0.0841	0.0003	0.43			**99.2**	**520.6**	**2.0**	521.3	3.7	525	18	rim
70	1362	0.0576	0.0001	0.6715	0.0040	0.0846	0.0005	0.94			**101.8**	**523.4**	**2.9**	521.6	2.5	514	4	core
69	118	0.0584	0.0004	0.7072	0.0063	0.0878	0.0005	0.58			**99.4**	**542.5**	**2.7**	543.1	3.8	546	16	rim
1	651	0.1042	0.0052	1.3385	0.0746	0.0932	0.0024	0.45	3766030	0.00	33.8	574.3	13.9	862.6	32.4	**1700**	**92**	core
5	261	0.0899	0.0005	3.0303	0.0281	0.2444	0.0017	0.77	53281	0.03	**99.0**	1409.5	9.0	1415.3	7.1	**1424**	**11**	core
7	251	0.2927	0.0021	16.1291	0.1504	0.3997	0.0023	0.62	9214	0.13	63.2	2167.4	10.7	2884.5	8.9	**3432**	**11**	core
12	191	0.1783	0.0010	12.5367	0.1365	0.5099	0.0048	0.86	43533	0.04	**100.7**	2656.0	20.5	2645.5	10.2	**2637**	**9**	core
13	128	0.0713	0.0004	1.6293	0.0273	0.1657	0.0026	0.94	3412	0.52	**102.2**	988.1	14.4	981.6	10.5	**967**	**12**	rim
14	1128	0.0653	0.0003	0.9729	0.0089	0.1081	0.0008	0.81	49091	0.04	84.6	661.9	4.7	690.0	4.6	**783**	**11**	core

15	206	0.0713	0.0003	1.4834	0.0124	0.1509	0.0010	0.81			**93.8**	905.9	5.7	923.6	5.1	**966**	**10**	rim
16	51	0.1677	0.0012	11.2274	0.2311	0.4855	0.0093	0.93	8352	0.21	**100.6**	2551.0	40.5	2542.2	19.2	**2535**	**12**	core
506	201	0.0830	0.0015	0.9346	0.0211	0.0817	0.0011	0.58	9400	0.17	39.9	506.2	6.4	670.0	11.1	**1269**	**36**	core
19	145	0.0651	0.0006	1.0268	0.0207	0.1145	0.0020	0.89	1246	1.31	**90.0**	698.7	11.9	717.3	10.4	**776**	**19**	core
743	658	0.0847	0.0006	1.4270	0.0231	0.1222	0.0018	0.90			56.8	743.3	10.3	900.3	9.7	**1308**	**14**	core
26	726	0.0760	0.0003	1.9710	0.0202	0.1882	0.0017	0.91	34372	0.05	**101.6**	1111.6	9.5	1105.7	6.9	**1094**	**9**	core
29	129	0.0700	0.0006	1.3920	0.0154	0.1442	0.0011	0.67	4447	0.37	**93.5**	868.2	6.0	885.5	6.5	**929**	**17**	core
35	960	0.0726	0.0006	1.6851	0.0318	0.1684	0.0029	0.91	20931	0.08	**100.2**	1003.5	15.9	1002.9	12.0	**1002**	**16**	core
39	573	0.1552	0.0013	4.9275	0.0732	0.2303	0.0028	0.82	10407	0.17	55.6	1335.9	14.8	1807.0	12.5	**2404**	**14**	core
40	485	0.1580	0.0012	4.9258	0.0798	0.2261	0.0033	0.89	52300	0.03	54.0	1314.0	17.1	1806.7	13.7	**2434**	**13**	core
42	935	0.0883	0.0006	2.1687	0.0343	0.1781	0.0025	0.89	19352	0.09	76.0	1056.3	13.8	1171.1	11.0	**1390**	**14**	core
43	442	0.0677	0.0005	1.3162	0.0186	0.1409	0.0017	0.84	15083	0.10	**98.7**	849.8	9.4	852.9	8.1	**861**	**16**	rim
45	605	0.0912	0.0006	3.1539	0.0372	0.2507	0.0024	0.82	27975	0.06	**99.3**	1442.1	12.5	1446.0	9.1	**1452**	**13**	core
48	371	0.0652	0.0009	1.2208	0.0202	0.1357	0.0012	0.52	7296	0.24	**104.9**	820.4	6.6	810.1	9.2	**782**	**30**	core
50	507	0.1488	0.0015	4.5197	0.0673	0.2204	0.0024	0.74	4529	0.31	55.1	1283.7	12.9	1734.6	12.4	**2332**	**17**	core
57	330	0.2115	0.0017	17.3921	0.2252	0.5963	0.0061	0.78			**103.3**	3014.9	24.5	2956.7	12.4	**2917**	**13**	core
59	435	0.1326	0.0033	5.8086	0.1765	0.3178	0.0056	0.58	14261	0.10	83.4	1778.8	27.2	1947.7	26.3	**2132**	**43**	core
66	279	0.1064	0.0003	2.9824	0.0428	0.2032	0.0029	0.98	18269	0.09	68.6	1192.5	15.3	1403.2	10.9	**1739**	**5**	core
68	965	0.0725	0.0003	1.6708	0.0146	0.1672	0.0013	0.91	29862	0.06	**99.7**	996.7	7.3	997.5	5.6	**999**	**8**	core
73	663	0.1576	0.0018	5.2052	0.1127	0.2395	0.0044	0.85	9696	0.18	56.9	1384.0	22.8	1853.5	18.4	**2431**	**20**	core
76	191	0.1777	0.0009	10.4769	0.1101	0.4275	0.0039	0.86	9230	0.19	87.2	2294.5	17.5	2477.9	9.7	**2632**	**9**	core
77	512	0.0666	0.0003	1.2174	0.0115	0.1326	0.0011	0.84			**97.2**	802.5	6.0	808.6	5.3	**825**	**11**	rim
80	655	0.1319	0.0009	3.1985	0.0376	0.1758	0.0017	0.82	253587	0.01	49.2	1044.2	9.2	1456.8	9.1	**2124**	**12**	rim
84	1089	0.1395	0.0012	4.2227	0.0793	0.2195	0.0037	0.89	30084	0.06	57.6	1279.2	19.4	1678.4	15.4	**2221**	**15**	core
86	269	0.1755	0.0011	11.2620	0.0972	0.4654	0.0028	0.70			**94.3**	2463.2	12.4	2545.1	8.0	**2611**	**10**	rim
87	153	0.1847	0.0011	12.4118	0.1241	0.4874	0.0038	0.78	9232	0.19	**94.9**	2559.3	16.6	2636.1	9.4	**2696**	**10**	core
88	151	0.1921	0.0012	14.0338	0.1553	0.5298	0.0049	0.84	19746	0.09	**99.3**	2740.4	20.7	2752.0	10.5	**2761**	**10**	core
91	33	0.1452	0.0015	3.2180	0.0506	0.1607	0.0019	0.74			41.9	960.6	10.4	1461.5	12.2	**2291**	**18**	core
92	25	0.1828	0.0014	8.2464	0.1310	0.3272	0.0046	0.88			68.1	1824.9	22.2	2258.4	14.4	**2678**	**13**	core
94	223	0.1197	0.0022	5.7115	0.1074	0.3462	0.0014	0.21			**98.2**	1916.4	6.6	1933.1	16.2	**1951**	**33**	core
95	37	0.0844	0.0006	2.5112	0.0225	0.2157	0.0012	0.64			**96.7**	1259.3	6.6	1275.3	6.5	**1302**	**13**	fragment of zircon grain
98	39	0.0637	0.0005	1.0104	0.0122	0.1150	0.0010	0.72	5605	0.31	**95.8**	701.7	5.8	709.1	6.1	**733**	**18**	rim
99	113	0.0689	0.0005	1.2650	0.0124	0.1333	0.0009	0.71			**90.2**	806.4	5.3	830.2	5.6	**894**	**14**	core
100	166	0.0658	0.0008	1.1848	0.0166	0.1306	0.0008	0.46	3066	0.56	**98.8**	791.0	4.8	793.5	7.7	**801**	**26**	rim
108	54	0.1390	0.0020	2.6482	0.0522	0.1381	0.0019	0.69	6571	0.26	37.7	834.1	10.6	1314.2	14.5	**2215**	**25**	core
110	194	0.1678	0.0017	8.0060	0.0934	0.3460	0.0021	0.53	4178964	0.00	75.5	1915.5	10.2	2231.7	10.5	**2536**	**17**	core

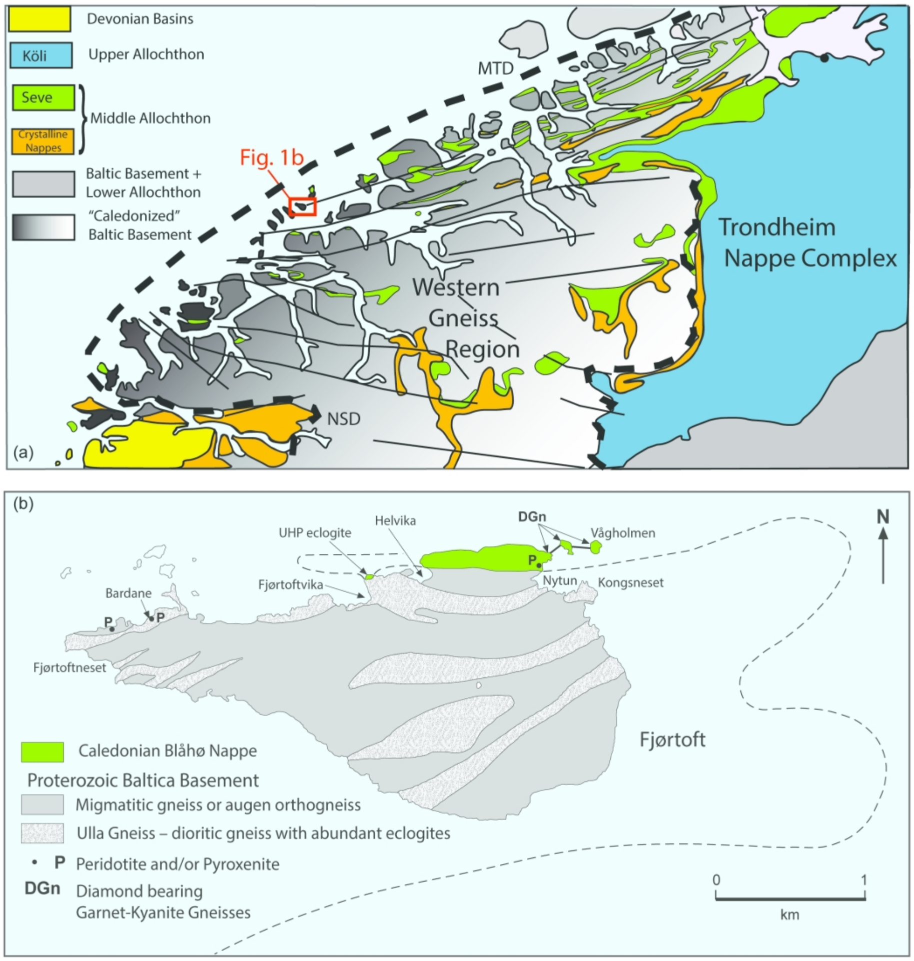

Figure 1. (Colour online) (a) Simplified geological map of the Western Gneiss Region (modified after Brueckner & Cuthbert, 2013) with (b) generalised geological map of Fjørtoft (after Carswell & van Roermund, 2005) showing the location of the diamond-bearing garnet kyanite gneiss. NSD - Nordfjord-Sogn detachment zone, MTD - Møre Trondelag detachment zone, black dashed line - early E/SE late W/NW décollements, black thin lines - W/NW vergent lineation directions.

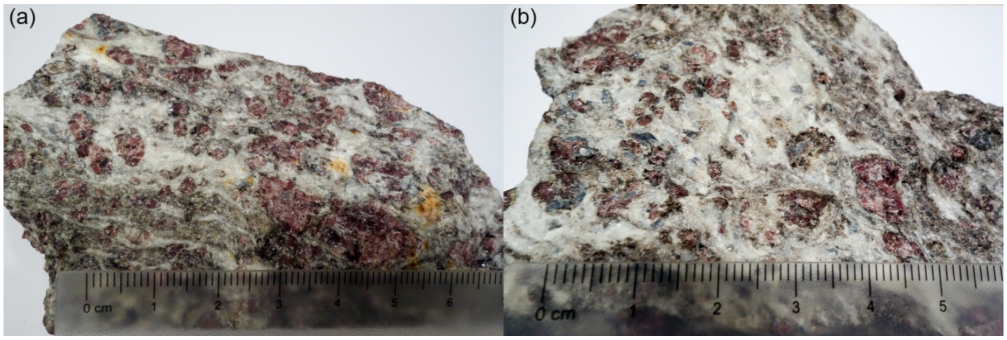

Figure 2. (Colour online) Hand specimen of the diamond-bearing garnet-kyanite gneiss from Fjørtoft (sample ID: Fj-19).

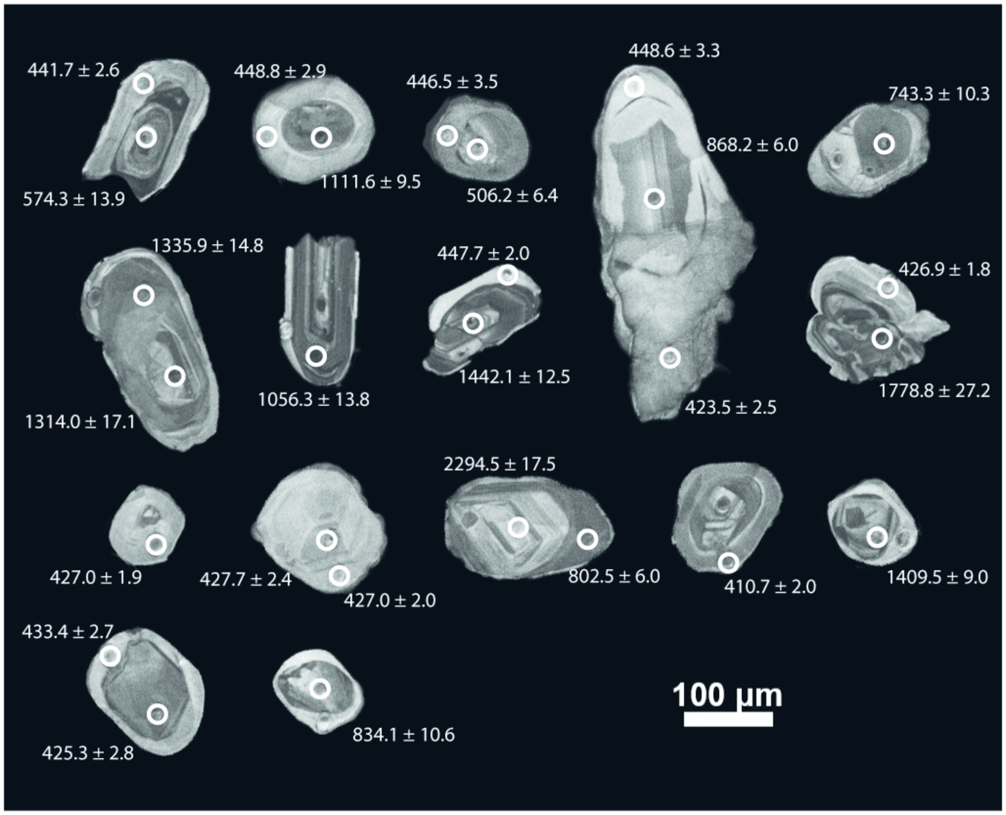

Figure 3. (Colour online) Cathodoluminescence images of representative zircon crystals from the Fjørtoft diamond-bearing garnet kyanite gneiss. White circles mark analytical spots and given numbers indicate 206Pb-238U dates.

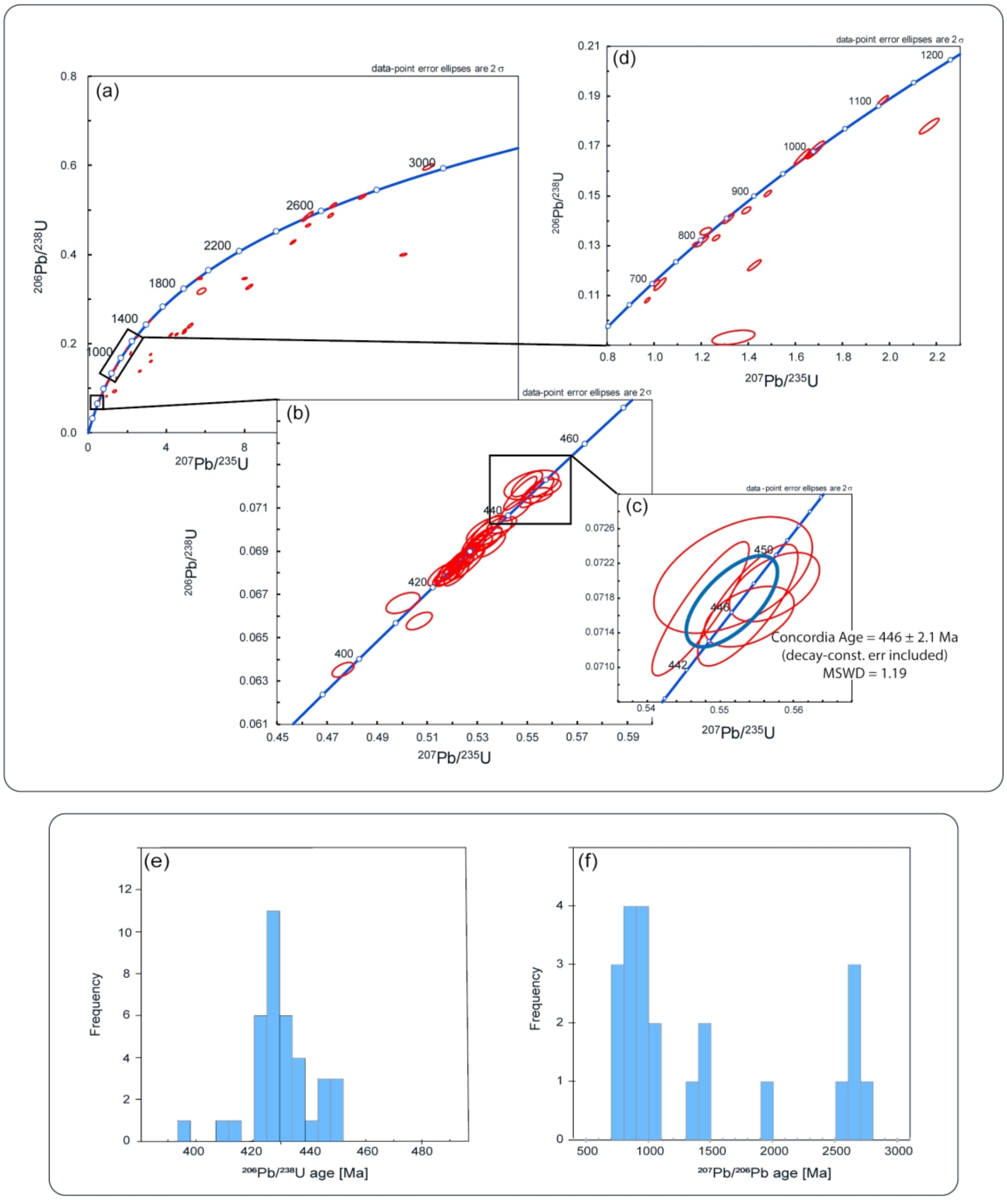

Figure 4. (Colour online) (a-d) U-Pb concordia diagram for zircon analyses; (a) all analyses for both metamorphic and detrital zircon domains, (b) concordia diagram of zircon with Caledonian ages with inset (c) showing ages for which Concordia age has been calculated. (d) Magnification of the fragment of Concordia diagram (a) showing late Precambrian dates. (e) Histogram of 206Pb-238U age frequency of metamorphic zircon domains. (f) Histogram of 207Pb-206Pb age frequency of concordant detrital zircon (10% discordance accepted).