Slow-cooling versus episodic fluid-injection: deciphering the Caledonian orogeny in Vestvågøy, Lofoten islands, Norway

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Short title: Caledonian Orogeny in Vestvågøy

Abstract: The determination of the thermal (temperature–time) histories of high-pressure metamorphic terranes has been commonly based on the concepts of slow cooling and closure temperatures. In this paper, we find that this approach cannot reconcile a geochronological data set obtained from the amphibolite-facies allochthonous Leknes Group of the Lofoten islands, Norway, which reveals an extremely complex thermal history. Using detailed results from several different geochronometers such as ⁴⁰Ar/³⁹Ar, Rb-Sr, and U-Pb, we show that a model invoking multiple, short-lived thermal pulses related to hot-fluid

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infiltration channelized by shear zones can reconcile this complicated data set. This model suggests that hot fluids infiltrated throughout basement shear zones and affected the overlying cold allochthon, partially resetting U/Pb titanite and rutile ages, crystallizing new zircon, and produced identical $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb/Sr ages in muscovite, biotite, and amphibole in various rocks throughout the region. This paper shows the enormous potential of coupling laser Ar-spot data with thermal modelling to identify and constrain the duration of short-lived events.

An optimal P – T – t history has been derived by modelling the age data from a previously dated large muscovite crystal (Hames & Andresen, 1996) and using Zr-in-rutile thermometry which is consistent with all geochronological data and geological constraints from the basement zones and allochthon cover. This tectonothermal model history suggests that there has been three episodic hot-fluid and ^{40}Ar -free infiltration events, resulting in the total resetting of Ar ages during the Scandian (425 Ma) for 1 Ma at 650°C, and two reheating events at 415 Ma for 400 ka at 650°C and at 365 Ma for 50 ka at 600°C, which are modelled as thermal spikes above an ambient temperature of 300°C. Independent confirmation of these parameters was provided by Pb-diffusion modelling in rutile and titanite. The model suggest that the amphibolite-facies rocks of the Leknes Group probably remained cold before being exhumed for at least 60 Ma (425–365 Ma) and successfully explains the presence of different minerals that crystallised or were totally/partially reset in the allochthon and in the basement. The migration of hot fluids for short period of times within conduits extending through the basement and allochthon rock units is likely associated with episodic seismic activity.

Key words: Caledonian orogeny; Leknes Group; Ar isotopes; muscovite thermal modelling; short-lived fluid migration.

1. INTRODUCTION

The closure-temperature concept (Dodson, 1973, 1986) has gained widespread use in understanding and interpreting the cooling histories of high-pressure (HP) metamorphic terranes (e.g. Cheng, Liu, Vervoort, & Lu, 2015; Philippot, Blichert-Toft, Perchuk, Costa, & Gerasimov, 2001). In HP-metamorphic terranes, however, the availability of fluids may be the most important factor controlling the transformation of dry rocks into eclogites (Leech, 2001). In particular, eclogites formed during the Caledonian orogeny (e.g. Roberts, 2003) in present Norway, are found in shear zones (e.g. Austrheim, 1987; Markl & Bucher, 1997). These zones acted as the main structures for the subduction and exhumation of the terrane (e.g. Fossen, 2000). The zones also served as natural pathways for hot fluids (Austrheim, 1987), where fluid-rock interactions caused recrystallization (complete or partial) and neocrystallization (e.g. Konrad-Schmolke, O'brien, & Zack, 2011; Villa & Williams, 2013). Therefore, the timing and the duration of the fluid infiltration and circulation events in these zones produce localized thermal regimes which would not be reflected accurately in thermal histories which invoke simple regional cooling.

The $^{40}\text{Ar}/^{39}\text{Ar}$ dating technique can potentially resolve complex thermal histories because Ar can serve as both a temperature-sensitive and time-sensitive marker throughout the evolution of geological processes (e.g. Lee, 2009). For example, white micas have been the focus of many $^{40}\text{Ar}/^{39}\text{Ar}$ studies in HP-metamorphic terranes due to their high potassium content, apparent lower tendency to incorporate excess argon ($^{40}\text{Ar}_\text{E}$, i.e. ^{40}Ar not associated with the *in situ* radioactive decay of ^{40}K within a crystal) compared with other K-bearing minerals (biotite or amphibole), and ubiquitous presence in many rock types (e.g. Warren, Kelley, Sherlock, & McDonald, 2012; Warren, Smye, Kelley, & Sherlock, 2011). Studies of the $^{40}\text{Ar}/^{39}\text{Ar}$ systematics of white micas such as muscovite or its HP-relative, phengite, are commonly used to provide constraints on the timing and rates of tectonic exhumation (e.g.

Sherlock, Kelley, Inger, Harris, & Okay, 1999) by determining time markers that represent cooling, decompression, or retrograde recrystallization along the metamorphic pressure–temperature (P – T) path of a terrane (e.g. Hames & Andresen, 1996; Mulch & Cosca, 2004; Warren et al., 2012). However, in instances where episodic thermal events [e.g. such as those associated with short-lived fluid infiltration, (e.g. Fournier, Lee, & Camacho, 2016)] are not recognized, the resultant temperature–time history can be misinterpreted as simple inflexions in the slope of a given cooling curve (cf. Steltenpohl, Kassos, Andresen, Rehnström, & Hames, 2011). Therefore, in such cases, integration of the geochronological data with structural and petrological studies is essential to better comprehend and model the effects of these short-lived thermal events on the terrane (cf. Camacho, Lee, Hensen, & Braun, 2005; Fournier et al., 2016).

A significant tool in thermochronological studies is solid-state diffusion theory. Volume (or lattice) diffusion, as described by the Fick's Second Law (Fick, 1855), describes the random migration of a diffusing species through a homogeneous crystal structure as a result of thermal agitation, and is the most widely studied type of diffusion in geological materials. As the “slowest” mode of solid-state diffusion, volume diffusion is often considered to be the rate-limiting diffusive process (Lee, 2009) and has been successfully applied in understanding a wide variety of geological phenomena in many metamorphic terranes (e.g. Berger & York, 1981; Camacho et al., 2005; Warren et al., 2012; Warren et al., 2011; York, 1984). The application of volume-diffusion theory in $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology has been used effectively to explain Ar mobility within fluids and minerals, and to determine the duration of burial and exhumation of an orogenic cycle in HP-metamorphic terranes (Camacho et al., 2005). Argon-diffusion modelling of the Ar distribution in a mineral can also provide significant insights about the duration of thermal events associated with the

infiltration of hot-fluid infiltration (e.g. Camacho et al., 2005; Fournier et al., 2016) due to the strong dependence of Ar mobility on temperature (Dalrymple & Lanphere, 1969).

While the notion of slow (or fast) cooling may apply to many terranes, geochronological data from the amphibolite-facies allochthonous Leknes Group of the Lofoten islands, Norway, reveals an extremely complex thermal history (Corfu, 2004b; Hames & Andresen, 1996; Klein, Steltenpohl, Hames, & Andresen, 1999; Steltenpohl, Hames, & Andresen, 2004). In this paper, we incorporate new thermal modelling results obtained from previously published age data from a large muscovite crystal from Vestvågøy (Hames & Andresen, 1996), results from Zr-in-rutile thermometry, and Pb diffusion models of titanite and rutile to constrain the thermal history of the Leknes Group rocks from Vestvågøy in the Lofoten Islands. In particular, this paper compares and contrasts the results from two thermal models: (1) a scenario involving regional slow-cooling, and (2) a punctuated series of short-lived thermal spikes throughout the terrane, leading to a new paradigm for the tectonothermal history of the region.

2. GEOLOGICAL SETTING

The Lofoten archipelago in northern Norway (68° N) is an exceptional example of a highly deformed HP-metamorphic terrane transected by shear zones that were active (documented by geochronological studies) during its subduction in the Caledonian orogeny (e.g. Froitzheim et al., 2016; Steltenpohl et al., 2011) (Figure 1). Several retrogressed eclogite-facies shear zones are situated within continental rocks of the Baltic Shield, which mainly consist of a Paleoproterozoic (*c.* 1.8–1.7 Ga) complex of anorthosite, mangerite, charnockite and granite (AMCG suite) (Corfu, 2004a, 2007; Griffin et al., 1978; Markl, Frost, & Bucher, 1998; Markl & Höhndorf, 2003; Olsen, 1978). During the Caledonian orogeny,

high-strain zones were infiltrated by Cl- and ^{40}Ar -rich fluids (documented by high concentration of ^{40}Ar in eclogitic garnet), which locally transformed the protolith rocks to eclogite (Fournier, Lee, Camacho, & Creaser, 2014; Kullerud, Flaat, & Davidsen, 2001). On Flakstadøy (Figure 1), eclogitization along shear zones is characterized by a prograde P – T path (Kullerud et al., 2001). Peak eclogite-facies metamorphic conditions at $P \approx 27$ kbar and $T \approx 650^\circ\text{C}$ were estimated in a zone from Flakstadøy (Froitzheim et al., 2016), and $P \geq 14$ kbar and $T \approx 540^\circ\text{C}$ on Austvågøy (north of Vestvågøy, Figure 1) (Markl & Bucher, 1997). The timing of peak metamorphism is still not well-constrained; two Lu/Hf whole-rock–omphacite–garnet isochron dates at 416 ± 20 Ma and 399 ± 10 Ma (2σ) [encompassed within the Scandian event of the Caledonian orogeny, Roberts (2003)] were interpreted to date peak metamorphism (Froitzheim et al., 2016) but are substantially younger than the U/Pb zircon age of 478 ± 41 Ma (Steltenpohl et al., 2011). The transition from eclogite-facies to amphibolite-facies retrogression is characterized by the formation of fine-grained symplectite composed of clinopyroxene and plagioclase after omphacite (>11 kbar and $\sim 700^\circ\text{C}$) (Markl & Bucher, 1997). This stage is also associated with the infiltration of ^{40}Ar -rich fluids at ≥ 425 Ma (documented by high concentration of ^{40}Ar in amphibole in retrogressed eclogites) (Fournier et al., 2016; Fournier et al., 2014). During the Devonian (415–413 Ma), the shear zones served as pathways for ^{40}Ar -poor hot-fluids as part of a short-lived event ($c.$ 100–50 ka) (Fournier et al., 2016; Fournier et al., 2014) also associated with the intrusion of pegmatites (Corfu, 2004b).

Overlying the continental rocks of Vestvågøy and Røst is the Leknes Group – an allochthonous metasedimentary terrane (Figure 1) (Tull, 1973, 1977). On Vestvågøy, a series of thrust faults with a general northwestern dip defines the contact between the Leknes Group and the basement rocks (Klein et al., 1999) (Figure 2). This sedimentary sequence with detrital Sveconorwegian zircons was metamorphosed at amphibolite-facies conditions ($T =$

600°C and $P = 6$ kbar) during thrusting onto the Archaean-Proterozoic basement rocks between 469–461 Ma (Corfu, 2004b; Klein et al., 1999; Waltman, 1997). In the Leknes Group, the thermal effect of the Early Devonian (415–410 Ma) event was associated with early stages of extension and enhanced fluid infiltration (Corfu, 2004b). A major extensional event during the Late Devonian (365 Ma) formed ductile greenschist-facies shear zones (Klein et al., 1999; Steltenpohl et al., 2004).

Repeated hot-fluid infiltrations through shear zones hosted in the Baltic Shield basement have been previously investigated (e.g. Fournier et al., 2016; Fournier et al., 2014), thus making the Lofoten archipelago an ideal location to study the Ar diffusion phenomena caused by these thermal events on white micas in the host and in the allochthonous rocks. Moreover, because currently published $T-t$ paths of the exhumation of the allochthonous Leknes Group (Klein et al., 1999; Løseth & Tveten, 1996) are mainly based on empirical closure temperatures rather than actual data from the rocks themselves, they are not well-constrained.

2.1 Geological Summary and Previous Geochronology of Vestvågøy

Vestvågøy contains four main groups of rocks. The oldest group is composed of a sequence of granitic Paleoproterozoic paragneisses inferred to represent continental-shelf deposits (Tull, 1977). These gneisses were intruded extensively by mangerites (second group) and by minor amounts of basic igneous rocks of the AMCG suite (third group) (Corfu, 2004a; Griffin et al., 1978). The fourth group, referred to as the Leknes Group, consists mainly of amphibolites and metasediments metamorphosed at amphibolite facies and affected by multiple deformation events (Klein et al., 1999; Tull, 1977). The tectonic contact between the Leknes Group and the basement is marked by a zone of highly foliated gneisses and amphibolites (Tull, 1977).

Furthermore, within the AMCG basement rocks of Vestvågøy, there are eclogite-facies shear zones associated with the Caledonian orogeny. One of them, the Vågje retrogressed eclogite-facies shear zone, is hosted by a massive gabbro (Fournier et al., 2014; Tveten, 1978; Wade, 1985) (Figure 2), similar to those described elsewhere in the Paleoproterozoic AMCG suite (e.g. Kullerød et al., 2001). Within one metre of the shear zone, the gabbro shows a gradual transformation from deformed gabbro to retrogressed eclogite to garnet amphibolite (dissected by muscovite pegmatite veins) and finally, amphibolite in the shear zone itself (Fournier et al., 2014).

A summary of key interpretations derived from previously published regional geochronological results in the Leknes Group (Corfu, 2004b; Hames & Andresen, 1996; Steltenpohl, Hames, Andresen, & Markl, 2003) and in the Vågje retrogressed eclogite-facies shear zone (Fournier et al., 2014) are shown in the next subsections and in Table 1.

2.1.1 The Ordovician metamorphism (470–460 Ma)

In amphibolitic and tonalitic rocks from the Leknes Group, U/Pb zircon and titanite yielded ages of 469 Ma to 461 Ma (Corfu, 2004b). These ages were interpreted as the time of amphibolite metamorphism at $T = 600^{\circ}\text{C}$ and $P = 6 \text{ kbar}$ (Klein et al., 1999; Waltman, 1997) during thrusting onto the Archaean-Proterozoic basement rocks (Corfu, 2004b).

2.1.2 The Silurian event (425 Ma)

In a $^{40}\text{Ar}/^{39}\text{Ar}$ dating study performed on muscovite crystals collected from shear zone rocks of the Leknes Group, Hames and Andresen (1996) analysed coarse-grained muscovite crystals (>2 mm of diameter) formed at peak amphibolite-facies metamorphism and often preserved in boudins within shear zones. A coarse-grained muscovite porphyroblast (their

sample 25B-93) was taken from a quartz-rich boudin of a kyanite-garnet-staurolite schist (collected ~50 m structurally above the mylonitic contact between the Leknes Group and mylonitic granite of the Lofoten basement) (Figure 2). Laser Ar-spot ages at the centre of the grain yielded *c.* 425 Ma decreasing to minimum ages of *c.* 365 Ma at the rim (results reproduced in Figure 3a). The intragrain age variation of sample 25B-93 was originally interpreted as differential argon retention during cooling (Hames & Andresen, 1996) and they proposed a *T-t* path, from 425–365 Ma, for the exhumation of the Leknes Group based on simple cooling (Klein et al., 1999). However, on the basis of U/Pb zircon and titanite Ordovician ages from the same rock units, these $^{40}\text{Ar}/^{39}\text{Ar}$ results were reinterpreted as ages reset by thermal fluid infiltration events which also partially reset U/Pb rutile ages (Corfu, 2004b). For the Lofoten eclogites and the Leknes Group simple slow-cooling models in the time span of 425–365 Ma were also proposed (Løseth & Tveten, 1996; Steltenpohl et al., 2011).

Muscovite from pegmatite veins hosted within an amphibolitic rock of the Vågje eclogite-facies shear zone (Figure 2) yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ multi-grain plateau age at 426 ± 3 Ma (Fournier et al., 2014). This age has been associated with major hydration of eclogite lenses by ^{40}Ar -rich fluids causing retrogression of the eclogites at amphibolite-facies conditions [$P = 11$ kbar; $T = 650^\circ\text{C}$, Markl and Bucher (1997)] and may represent a minimum age for this event (Fournier et al., 2014).

2.1.3 Early Devonian ages (415–410 Ma)

In Vesvågøy, a variety of geochronological techniques to different minerals from rocks of the Leknes Group and the Vågje eclogite-facies shear zone yielded Devonian ages ranging from *c.* 415–410 Ma (Corfu, 2004b; Fournier et al., 2014; Hames & Andresen, 1996; Steltenpohl et al., 2003).

In the Leknes Group, an $^{40}\text{Ar}/^{39}\text{Ar}$ single-crystal hornblende total-fusion age of 402 ± 7 Ma was interpreted as part of postcrystallization deformation (Steltenpohl et al., 2003). Ar laser-spot ages of 415–410 Ma in sample 25B-93 (Figure 3a) were also related to slow cooling of the Leknes Group (Hames & Andresen, 1996; Klein et al., 1999). However, a similar U/Pb zircon age at 412 ± 2 Ma from mica schist was interpreted as discrete recrystallization by fluid infiltration (Corfu, 2004b).

A hastingsite from an amphibolite produced a $^{40}\text{Ar}/^{39}\text{Ar}$ multi-grain plateau age of 416 ± 1 Ma, and phlogopite yielded a Rb/Sr age at 411 ± 5 Ma from the gabbro host rock of the Vågje eclogite-facies shear zone (Fournier et al., 2014). These ages were related to a second re-hydration event by ^{40}Ar -poor hot-fluid infiltration within the shear zone. Using Ar diffusion modelling based on $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating analyses, the duration and temperature of this fluid injection event was constrained to be around 100–50 ka at 500°C through relatively cold crust ($\leq 300^\circ\text{C}$) (Fournier et al., 2016).

2.1.4 The Late Devonian event (365 Ma)

Ages of *c.* 365 Ma are pervasive at Vestvågøy, as determined from $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb/Sr dating of amphiboles and micas from a variety of rock types (Fournier et al., 2014; Hames & Andresen, 1996; Steltenpohl et al., 2004; Steltenpohl et al., 2003).

In the Leknes Group, fine-grained muscovite crystals (500–250 μm in diameter) defining the mylonitic fabric and schistosity collected from shear and fault zones yielded $^{40}\text{Ar}/^{39}\text{Ar}$ single-crystal muscovite total-fusion ages of *c.* 365 Ma, which were interpreted to reflect an extensional event associated with exhumation at greenschist-facies conditions (Hames & Andresen, 1996). The Ar-spot ages of *c.* 365 Ma at the rim in sample 25B-93 (Figure 3a) were related to complete retention of radiogenic Ar ($^{40}\text{Ar}^*$) after extension and

tectonic exhumation of the Leknes Group by shear zones (Hames & Andresen, 1996; Klein et al., 1999). $^{40}\text{Ar}/^{39}\text{Ar}$ single-crystal total-fusion ages of 365 ± 5 Ma in hornblende and 372 ± 6 Ma in biotite from amphibolites and 357 ± 2 Ma in biotite from schists were interpreted as ages reflecting post-crystallization deformation from a complex thermal history (Steltenpohl et al., 2003). $^{40}\text{Ar}/^{39}\text{Ar}$ single-crystal muscovite total-fusion ages from mylonitic kyanite-bearing gneiss [collected from the same locality as sample 25B-93 of Hames and Andresen (1996)] of 385–380 Ma and $^{40}\text{Ar}/^{39}\text{Ar}$ single-crystal muscovite total-fusion ages of 370–360 Ma from schists were interpreted as ages comparable to the younger intracrystalline age variation obtained by Hames and Andresen (1996) (Steltenpohl et al., 2004).

In amphibolitic rocks from the Vågje retrogressed eclogite-facies shear zone, late-growth annite yielded a Rb/Sr age of *c.* 365 Ma and was interpreted as a late ^{40}Ar -rich fluid infiltration event (Fournier et al., 2014).

2.1.5 Permian extension and Triassic–Cretaceous brittle deformation

The development of a cordilleran-style metamorphic core complex occurred at the late Paleozoic with basement erosion during the Permian (Henstra & Rotevatn, 2014). A low-*T* constraint is given by apatite fission track (AFT) data which indicate that the rocks of the Leknes Group were at 60°C at 181 ± 42 Ma (Hendriks, Osmundsen, & Redfield, 2010) (Figure 2). During the Triassic to Cretaceous, main brittle faults, such as the Offersøya fault (Figure 2), developed the Leknes half-graben structure (Bergh et al., 2007; Bergh, Liland, Corner, Henningsen, & Lundekvam, 2018).

2.1.6 Thermal History Models of Vestvågøy

In reviewing the previous geochronological works above, it is evident that two fundamentally different models may serve to explain the geochronological data related to the Caledonian orogeny from Vestvågøy: i) simple slow-cooling (hereafter referred as M1), and ii) episodic hot-fluid infiltration events (hereafter referred as M2). For the purposes of this paper, specific thermal events throughout the chronological history of the region in model M2 have been labelled as E1–E3, and are indicated in Table 1. This paper serves to compare and contrast these two fundamental models in the context of new data from Zr-in-rutile geothermometry and new Ar modelling results.

3. METHODOLOGY

3.1 Experimental Methods

Zirconium (Zr) concentrations in rutile crystals from two retrogressed eclogite rocks [HF-08-25a and HF-08-25d, see Fournier et al. (2014) for more details] of the Vågje shear zone were obtained by electron microscope analyses to constrain the peak T of the fluids during the eclogitization using the Zr-in-rutile geothermometer. Knowledge of the peak T of the fluids is important as the thermal effect of fluid migration from the eclogite-facies shear zones to the allochthon will be examined in Ar-diffusion modelling calculations for thermal model M2 in this study.

Quantitative chemical analyses of Zr were obtained by electron microprobe in synmetamorphic rutile crystals. Using polished thick sections (thickness $\approx 40\ \mu\text{m}$) of samples HF-08-25a (12 grains) and HF-08-25d (13 grains), all analyses were obtained on an automated 4-spectrometer Cameca SX 100 electron microprobe by the wavelength-dispersive x-ray method located in the Geology Department at the University of Manitoba, Winnipeg, Canada.

Most of the spot analyses were carried out in cores and rims from individual rutile crystals. Only one spot was obtained from the core of some crystals due to the small grain sizes ($<200\text{ }\mu\text{m}$) and to avoid the presence of fine ilmenite lamellae. For each spot analysis, the Zr-L α peak was measured with a 15 kV accelerating voltage, a 200 nA beam current, and 1 μm diameter beam size. Three PET diffracting crystals were used to determine Zr-L α peaks with counting times of 510 seconds on the peak, using natural zircon as a standard. These analytical conditions resulted in detection limits of about 31 ppm.

3.1.1 Zr-in-rutile results

The Zr-in-rutile results are presented in Table 2. In sample HF-08-25a, the Zr concentration in rutile ranges from 53–122 ppm, whereas the rutile crystals from sample HF-08-25d have 44–143 ppm Zr [$\pm 52\text{ ppm}$ (2σ)]. To constrain the peak T of the fluids during the eclogitization of the Vågje shear zone, estimated metamorphic temperatures were calculated by using the equations of Watson, Wark and Thomas (2006) and the P -dependant and α -quartz field formula of Tomkins, Powell and Ellis (2007). The results range from 520°C to 650°C in sample HF-08-25a and 521°C to 660°C in sample HF-08-25d (Table 2).

3.1.2 Peak T of fluids

The Zr content in many of the rutile crystals is extremely low and approaches detection limits within analytical error [minimum value: $44 \pm 52\text{ ppm}$ (2σ)], particularly in sample HF-08-25d.

A weighted mean temperature yields 620–625 (± 15)°C using the P -dependent Tomkins calibration [P at 27 kbar (Froitzheim et al., 2016)] and around 550 (± 12)°C using the Watson calibration (Table 2). The calculated T for both samples using the P -dependent

calibration is identical within error of the T estimate in Flakstadøy of 650°C using the same geothermometers (Fournier et al., 2016) and multi-equilibrium calculations (Froitzheim et al., 2016; Markl & Bucher, 1997) for eclogite-facies metamorphism on Vestvågøy. Since the P -dependent calibration is considered more robust for eclogite-facies rocks (Meinhold, 2010), a T of 650–600°C representing the peak fluid temperature during the eclogitization of the Vågje shear zone was used in subsequent Ar-diffusion modelling calculations for thermal model M2.

3.2 Diffusion Modelling Methodology

A series of iterative, forward-modelling experiments were performed to obtain a subset of T – t histories consistent with all of the geological constraints for models M1 and M2 discussed above.

Thermochronological modelling was performed using the finite-difference programme FMPATH4 (JKW Lee, 2013, pers. comm.) – a modified version of DMPATH (Lee & Aldama, 1992) which accounts for radiogenic $^{40}\text{Ar}^*$ accumulation by ^{40}K decay through time and incorporates the ability to model time-varying boundary Ar concentrations (^{40}Ar in or out) and T conditions. Modelling was performed on Ar data from muscovite sample 25B-93 using the Ar-spot ages (Figure 3a) and from the fine-grained (500–250 μm diameter) muscovite crystals analyzed by Hames and Andresen (1996).

The total number of spatial nodes in a high-resolution finite-difference grid was fixed to 10,001 over a grain radius normalized from 0 to 1, and time steps were set to 10 ka in all the models. Due to the presence of $^{40}\text{Ar}_\text{E}$ in some of the model scenarios, an Euler Backward central-difference scheme was chosen for all models to avoid finite oscillations that may

occur in the numerical solution using the Crank-Nicolson scheme when the initial values of the concentration are non-zero (Lee & Aldama, 1992).

3.2.1 Ar diffusion parameters

The Ar diffusion parameters for muscovite were used – activation energy (E) of 63 kcal/mol and pre-exponential coefficient (D_0) of $2.3 \text{ cm}^2/\text{s}$ (Harrison, Clrier, Aikman, Hermann, & Heizler, 2009) (Table 3). Although these parameters were obtained assuming a spherical geometry, diffusion studies (e.g. Hames & Bowring, 1994) performed in muscovite have shown that Ar diffusion occurs mainly by cylindrical geometry, and this is the geometry adopted in this study. For the effective diffusion radius, the lengths (radii) for the two profiles of sample 25B-93 (3600 μm and 2980 μm) (Figure 3a) and the radii for the fine-grained muscovite crystals (250 μm and 125 μm) were used (Table 3).

Because FMPATH4 is a 1D diffusional modelling program (Ar concentration is solved as a function of distance for a slab, cylindrical or spherical diffusion geometry), Hames and Andresen’s (1996) single-crystal laser spot-dating muscovite results (their Figure 3A, reproduced in Figure 3a) were replotted along two profiles (shown by black and grey lines in Figure 3a) as a function of age versus distance from core to rim (Figure 3b,c). Each spot age (Table S1) and its uncertainty (assuming a spot size of 150 μm as stated by the authors) along the profiles was plotted over the respective lengths of the sample at 3600 μm and 2980 μm (Figure 3b,c). The selected ages are not significantly affected by newer determinations in the ^{40}K decay constants (Renne, Mundil, Balco, Min, & Ludwig, 2010) (Table S1). These core-rim Ar-age profiles define apparent “Ar-loss” patterns characterized by young ages from *c.* 365 Ma and 374 Ma at the edge of the crystal, monotonically increasing to the grain core at *c.* 425 Ma (Figure 3b,c).

3.2.2 Other Physical Parameters

To obtain the best-fit T – t paths to the geochronological data, knowledge of some additional physical parameters associated with amphibolite-facies mineralization in the host rocks is essential. These parameters are the time of amphibolite-facies crystallization (t_{xtal}), the temperature of crystallization (T_{xtal}), the pressure of crystallization (P_{xtal}), the duration of the crystallization (d_{xtal}) and the ambient temperature (T_{amb}) of the host rocks.

Pressure ($P_0 = 10$ kbar) effects were also considered in both models M1 and M2 to account for the pressure dependence of Ar diffusion in muscovite (Harrison et al., 2009). To extrapolate these data from 6 kbar (amphibolite-facies pressure of the Leknes Group) to atmospheric pressure, the coefficient D was calculated as a function of temperature and pressure using the equation $D(T,P) = D_0 \exp[-(E + V_0 (P - P_0)) / RT]$, where V_0 is the activation volume ($\sim 14 \text{ cm}^3/\text{mol}$), R is the ideal gas constant, and T is the temperature measured in K (Harrison et al., 2009). The pressure effects in the M1 and M2 models were modelled as a linear decompression from P_{xtal} at 6 kbar to the atmospheric pressure at the present, consistent with the exhumation of the Leknes Group after its emplacement (Corfu, 2004b; Klein et al., 1999).

Apatite fission track data indicate that the Leknes Group were at 60°C at 181 ± 42 Ma (Hendriks et al., 2010). A final T constraint is assumed at the present day, when all of the modelled T – t paths for the M1 and M2 models reach a mean temperature of 5°C at the surface, which is within error for the summer temperatures calculated from tree rings in northern Lofoten (Kirchhefer, 2001).

3.2.2.1 Physical parameters for Model M1

For the models using M1, the following parameters were adopted, consistent with simple cooling interpretations for the Lofoten terrane (Hames & Andresen, 1996; Klein et al., 1999; Løseth & Tveten, 1996; Steltenpohl et al., 2011). One of these interpretations (Hames & Andresen, 1996; Klein et al., 1999) suggests that retention of $^{40}\text{Ar}^*$ began at 430 Ma in the muscovite crystal sample 25B-93 for 5 Ma (d_{xtal}) (430–425 Ma), and this time (430 Ma) is taken as t_{xtal} in this paper, at amphibolite-facies conditions of $T_{\text{xtal}} = 600^\circ\text{C}$ and $P_{\text{xtal}} = 6$ kbar. To account for the other simple slow-cooling interpretations and a protracted period of residential time (425–365 Ma) at relatively high T (Løseth & Tveten, 1996; Steltenpohl et al., 2011), t_{xtal} is set to 425 Ma with a d_{xtal} of 0 Ma; and $T_{\text{xtal}} = 600^\circ\text{C}$ and $P_{\text{xtal}} = 6$ kbar (amphibolite-facies conditions).

3.2.2.2 Physical Parameters for Model M2

The U-Pb data show that the Leknes Group was metamorphosed and thrust onto the Lofoten basement between *c.* 469–461 Ma (Corfu, 2004b) (Table 1). Thus, model M2 uses the following parameters: i) time of mica crystallization $t_{\text{xtal}} = 469$ Ma, ii) duration of crystallization $d_{\text{xtal}} = 8$ Ma (from 469 to 461 Ma), iii) temperature of crystallization $T_{\text{xtal}} = 600^\circ\text{C}$ and $P_{\text{xtal}} = 6$ kbar (consistent with amphibolite-facies conditions). The following parameters were adopted, consistent with three hot-fluid events at $E1 = 425$ Ma, $E2 = 415$ Ma and $E3 = 365$ Ma, an ambient temperature after crystallization (T_{amb}), the duration d (d_{E1} , d_{E2} and d_{E3}) and temperatures T (T_{E1} , T_{E2} and T_{E3}) of each hot-fluid event, as well as the ambient temperature $T_{\text{amb(E)}}$ before and after the thermal events. These parameters are unknown for model M2 and must be modelled. Temperatures equal to 650°C and 600°C (based on the temperature of the amphibolite-facies retrogression of the eclogites within the basement and from Zr-in-rutile thermometry) were chosen to represent the range of peak temperatures at

T_{E1} , while the remaining peak temperatures (T_{E2} and T_{E3}) were varied in the models. The potential effect of fluid infiltration during each of E1, E2, and E3 containing sufficient $^{40}\text{Ar}_E$ to diffuse into the muscovite was explored in a separate set of M2 models. In these models, the amounts of $^{40}\text{Ar}_E$ for each thermal event are assumed to be equal to the following estimated amounts for the Vågje shear zone: E1 = 8.74×10^{-10} g/mol [calculated from an $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole date of 730 Ma with a K_2O content of 1.46%, (Fournier et al., 2014) and an assumed age of 425 Ma]; E2 = 0 g/mol (as this event is assumed to yield meaningful ages across the Lofoten terrane); and E3 = 1.84×10^{-9} g/mol [calculated from an $^{40}\text{Ar}/^{39}\text{Ar}$ annite date of 472 Ma with a K_2O content of 9.47%, (Fournier et al., 2014) and an assumed age of 365 Ma] (Table 3).

3.2.3 Ar Modelling assumptions

There are certain fundamental assumptions inherent in modelling Ar diffusion in the muscovite crystals, namely: i) volume diffusion is the only diffusional process, ii) the spot-fusion ages selected from the muscovite sample 25B-93 and the analyses performed in the fine-grained muscovite crystals were carried out on inclusion- and phase-free areas and free of defects (cf. Lee & Aldama, 1992), iii) there are no chemical compositional gradients along the selected transects or in the fine-grained crystals that would account for any apparent Ar-loss/gain profile (this is supported by the lack of any detectable chemical gradients from the Cl/K and Ca/K values derived from the spot analyses selected, suggesting that the mica is free of other phases or inclusions in the selected data set), iv) muscovite grains crystallized with no initial Ar in the lattice, and v) the ^{40}Ar diffusion in mica occurred in an open system (i.e. $^{40}\text{Ar}^*$ diffuses outwards from the grain into the surroundings or $^{40}\text{Ar}_E$ diffuses inwards from the circulating fluids into the crystal – situations entirely dependent on the boundary concentration of ^{40}Ar).

Numerical models solving the diffusion equation (Fick's Second Law) (Fick, 1855) in one dimension with a radioactive source term (^{40}K) were performed to constrain the $T-t$ histories of the allochthonous Leknes Group in Vestvågøy. The diffusion equation was solved numerically using finite-difference methods (e.g. central-difference scheme) following the approach described by Lee and Aldama (1992). Because of this numerical approach, complex, non-uniform $T-t$ histories can easily be modelled. Four basic assumptions were considered in solving the diffusion equation: i) the initial concentration of the diffusing species is uniform throughout the matrix, ii) the concentration of the diffusing species at any boundary is constant for all t , iii) the diffusion geometry is simple (e.g. cylinder for muscovite), and iv) the diffusion coefficient D is known or well-constrained (Lee, 2009).

3.2.4 Ar Modelling sensitivity

In order to determine the possible effects of variations in P and T , a sensitivity analysis on the modelling results was performed. For this analysis, only the $T-t$ histories obtained from the Ar-diffusion models M1 and M2 which yield model diffusion profiles that best fit the Ar data defining the diffusion profile with a length of 3600 μm of muscovite sample 25B-93 (Hames & Andresen, 1996) were considered (Figure 3b). The pressure P_{xtal} and temperature T_{xtal} associated with peak amphibolite-facies metamorphism were modelled with uncertainties of ± 0.25 kbar and $\pm 25^\circ\text{C}$, consistent with the kyanite stability field (e.g. Spear, 1993).

3.2.5 Pb Diffusion modelling

U/Pb geochronological data previously obtained from rutile and titanite (Corfu, 2004b) were used to provide an independent check on the plausibility of the $T-t$ histories obtained from the Ar-diffusion models M1 and M2 that best replicate the apparent diffusion-loss profiles of muscovite sample 25B-93 (Figure 3b,c). The following samples and their chemical analyses were chosen: i) rutile sample C-17; analysis # 7 with 5.8 ppm of U; $^{238}\text{U}/^{206}\text{Pb}$ age of *c.* 453 Ma; and ii) titanite sample C-79B; analysis # 18 with 100 ppm of U; $^{238}\text{U}/^{206}\text{Pb}$ age of *c.* 461 Ma (see Table 1 of Corfu, 2004b). The diffusion parameters for Pb in rutile (Cherniak, 2000) and titanite (Cherniak, 1993) were combined with a spherical geometry and the isotope ^{238}U as the parent isotope in all the Pb diffusion models. Grain diameters of 150 μm for the rutile (F. Corfu, 2012; pers. comm.) and 1 cm for the titanite (Corfu, 2004b) were used in these test models.

4. DIFFUSION MODELLING RESULTS

Theoretical $T-t$ histories associated with models M1 (simple slow-cooling) and M2 (episodic fluid infiltration events) were used to produce theoretical Ar distributions in the large muscovite crystal, sample 25B-93, and in the fine-grained muscovite crystals (Hames & Andresen, 1996) which could be compared to the actual Ar data from these samples. Moreover, two different scenarios involving no excess Ar and the presence of excess Ar were also examined for the M2 model.

The modelling results yield two key pieces of information: i) the model age profile within a crystal, and ii) the model integrated cooling (i.e. total fusion) age associated with that age profile. These model results were obtained for two profiles from muscovite sample 25B-93 and for the fine-grained muscovite crystals, as reported in Hames and Andresen (1996). Tables S2–S6 summarize the various Ar-diffusion model results using the $T-t$

constraints in the Leknes Group. In the case of the fine-grained muscovite crystals, only the final integrated ages resulting from the models are compared with the reported 365 Ma age by Hames and Andresen (1996) in these crystals (the fine-grained profiles can be found in Figures S1–S4).

4.1 Model M1 (Slow Cooling) Results

Several previous studies have proposed simple cooling models to explain the Ar age data and the thermal history of the Leknes Group, and we have also explored these to assess their viability. Klein et al. (1999) proposed a slow-cooling T – t path (see their Figure 9) starting with a crystallization age of 430 Ma ($=t_{\text{xtal}}$) at 600°C ($=T_{\text{xtal}}$). An alternative hypothesis indicating that the Leknes Group may have resided at relatively high T for a protracted period of time (425–365 Ma, and $t_{\text{xtal}} = 425$ Ma) was also considered (Løseth & Tveten, 1996; Steltenpohl et al., 2011). In all of these models the effect of P in diffusion was included, however, they did not account for the presence of $^{40}\text{Ar}_\text{E}$ because the age results were interpreted as meaningful ages in these studies. The modelling results are shown in Figures 4 and S1 and the parameters tabulated in Table S2.

4.1.1 Klein et al. (1999)

The parameters for the proposed T – t path for the Leknes Group from 430–365 Ma (following their Figure 9) with $t_{\text{xtal}} = 430$ Ma and $d_{\text{xtal}} = 5$ Ma are given in Table S2. Using these parameters, the Ar model profiles obtained in the large muscovite grain from sample 25B-93 yielded 7.4–7.7% of ^{40}Ar lost by volume, muscovite ages of 406–404 Ma at the grain core decreasing to 360–358 Ma at the rim, and integrated cooling ages of 406–404 Ma (Table S2) so they clearly do not fit the observed Ar-spot results (Figure 4a,b). Thermal modelling

of the fine-grained muscovite crystals yielded volumetric ^{40}Ar losses of 9.7–10.3%, muscovite ages of 395–394 Ma at the core decreasing to 324–315 Ma at the rim, and integrated cooling ages of 392–390 Ma (Table S2, Figure S1). Thus, the Klein et al. (1999) model clearly fails to replicate the Ar-data of Hames and Andresen (1996).

4.1.2 Other slow-cooling models

Other simple slow cooling paths have been suggested for the Lofoten terrane after the Scandian event at *c.* 425 Ma (Løseth & Tveten, 1996; Steltenpohl et al., 2011). Three model runs were performed at various slow-cooling rates (-5.0 , -3.25 and -2.5°C/Ma) from 425 Ma ($= t_{\text{xtal}}$) to 365 Ma as tabulated in Table S2. For the large muscovite crystal of sample 25B-93, the model results at -5.0°C/Ma yielded Ar-loss profiles with 3.6–4.0% of ^{40}Ar lost by volume, muscovite ages of 418–416 Ma at the grain core decreasing to 360–358 Ma at the rim, and integrated cooling ages of 411–410 Ma (Table S2, Figure 4a,b). At a cooling rate of -3.25°C/Ma , the resultant Ar-loss profiles yielded 6.3–6.9% ^{40}Ar lost, muscovite ages of 411–409 Ma at the grain core decreasing to 309–307 Ma at the rim, integrated cooling ages of 401–398 Ma and replicating the Ar-spot ages (Table S2, Figure 4a,b). With a cooling rate of -2.5°C/Ma , the resultant Ar-loss profiles showed 8.8–9.8% ^{40}Ar lost, muscovite ages of 405–401 Ma at the grain core decreasing to 295–293 Ma at the rim, and integrated cooling ages of 391–388 Ma (Table S2, Figure 4a,b).

At -5.0°C/Ma , the modelled fine-grained crystals yielded volumetric ^{40}Ar loss of 8.6–9.7%, muscovite ages of 397–393 Ma at the core decreasing to 325–316 Ma at the rim, and integrated cooling ages of 392–388 Ma (Table S2, Figure S1). At -3.25°C/Ma these modelled crystals yielded a volumetric ^{40}Ar loss of 14.4–16.6%, muscovite ages of 380–372 Ma at the core decreasing to 282–275 Ma, and integrated cooling ages of 370–361 Ma in agreement with the results of Hames and Andresen (1996) (Table S2, Figure S1). The

modelled fine-grained crystals at $-2.5^{\circ}\text{C}/\text{Ma}$ yielded 19.1–21.6% ^{40}Ar lost, muscovite ages of 363–353 Ma at the core decreasing to 270–264 Ma at the rim, and integrated cooling ages of 351–341 Ma (Table S2, Figure S1).

4.2 Model M2 (Short-lived fluid injection) Results

The model M2 used the following parameters: i) time of mica crystallization $t_{\text{xtal}} = 469$ Ma, ii) duration of crystallization $d_{\text{xtal}} = 8$ Ma, iii) temperature of crystallization $T_{\text{xtal}} = 600^{\circ}\text{C}$ and $P_{\text{xtal}} = 6$ kbar. The ambient temperature after crystallization (T_{amb}), the duration d (d_{E1} , d_{E2} and d_{E3}) of each hot-fluid event (at $\text{E1} = 425$ Ma, $\text{E2} = 415$ Ma and $\text{E3} = 365$ Ma), as well as the ambient temperature $T_{\text{amb(E)}}$ before and after the thermal events, were modelled. Temperatures equal to 650°C and 600°C (Zr-in-rutile thermometry) were chosen to represent the range of peak temperatures at T_{E1} , while the remaining peak temperatures (T_{E2} and T_{E3}) were varied in the models.

4.2.1 $^{40}\text{Ar}_{\text{E}}$ -free environment

In this scenario of model M2, the presence of $^{40}\text{Ar}_{\text{E}}$ was not considered. The background or ambient temperature (T_{amb}) was modelled first. The T_{amb} that preserves the crystallization muscovite ages ($t_{\text{xtal}} = 469\text{--}461$ Ma) was then used as the base temperature for modelling the thermal pulses (E1–E3).

4.2.1.1 Maximum ambient temperature

Because the portion of the thermal history (T – t path) of the Leknes Group after peak metamorphism at 461 Ma and before the Scandian (425 Ma) is unknown, we modelled the ambient temperature (T_{amb}) using a broad range of T – t paths (Table S3) until 365 Ma (the

youngest age at the rim in muscovite sample 25B-93): i) simple cooling from 461–425 Ma at different cooling rates followed by a constant T_{amb} from 425–365 Ma; and ii) constant T_{amb} (600–300°C) from 461–365 Ma. These two T – t paths (i–ii) were followed by linear cooling paths constrained by the apatite fission-track age and the surface temperature as specified above.

The model results for both T – t paths (tabulated in Table S3 but not plotted) indicate that, in order to preserve a crystallization age of ≥ 461 Ma in the centre of the muscovite crystal from sample 25B-93, the T_{amb} of the mica must be $\leq 400^\circ\text{C}$ after crystallization. To preserve a crystallization age of 461 Ma in the fine-grained crystals (250–125 μm radius), T_{amb} must be $< 300^\circ\text{C}$.

4.2.1.2 Effect of fluid injection event E1

All of the muscovite Ar-spot ages of Hames and Andresen (1996) in sample 25B-93 yielded ages ≤ 425 Ma (Figure 3a). As discussed above, these ages were interpreted to result from partial resetting (Corfu, 2004b) (reflecting approximately 15% Ar loss) during three pulses of hot-fluid injection, at $E1 = 425$ Ma, $E2 = 415$ Ma and $E3 = 365$ Ma. Consequently, the duration (d_{E1}) and temperature (T_{E1}) conditions of the first thermal event associated with the fluid pulse E1 that reset the mica at 425 Ma must first be examined. As the thermal events caused by the fluid infiltration at 415 Ma and at 365 Ma are superimposed on the effects of E1, they are modelled subsequently.

4.2.1.3 Minimum temperature and duration (T_{E1} , d_{E1}) of the thermal event E1

The model results from the previous section indicate that the crystallization ages (t_{xtal} = 469–461 Ma) are preserved with minimal Ar loss when the ambient temperature (T_{amb}) of the terrane is $\leq 400^\circ\text{C}$ after crystallization. Therefore, in order to establish the minimum conditions (temperature T_{E1} and duration d_{E1}) of the thermal event E1 at 425 Ma that reset the mica, a T_{amb} range of 400–300°C immediately after crystallization (1 ka after t_{xtal} = 461 Ma and before E1 = 425 Ma) was used. At 425 Ma, the models then incorporate a temperature spike (representing hot-fluid injection) at T_{E1} = 650°C and 600°C (based on the Zr-in-rutile temperature for the amphibolite-facies retrogression of the eclogites within the Vågje shear zone). The duration of the thermal event (d_{E1}) was modelled at 0.5 Ma, 1 Ma and 5 Ma. After 425 Ma, the $T_{\text{amb}(E1)}$ continues to be 400–300°C (1 ka after E1) until 365 Ma. The model runs were conducted to fit the Ar age profiles near the grain core as the subsequent thermal events (E2 and E3) will further affect the Ar age distribution near the crystal margins. Table S4 shows all the parameters used to reset the muscovite crystals at 425 Ma.

The set of conditions from the thermal modelling which are most consistent with the Ar data is T_{E1} = 650°C and d_{E1} = 1.0–0.5 Ma or T_{E1} = 600°C and d_{E1} = 5.0 Ma with a constant ambient temperature $T_{\text{amb}(E1)}$ = 300°C (Figures 5 and 6). These conditions completely reset the mica at 425 Ma and yielded flat profiles from rim to core, while models with $T_{\text{amb}(E1)}$ = 400°C yielded diffusive-loss profiles, particularly in the fine-grained crystals (Table S4, Figure S2). These parameters are also consistent with the thermal parameters obtained in another eclogite-facies shear zone of Lofoten (Fournier et al., 2016). To avoid repetition, T_{E1} = 650°C and d_{E1} = 1.0 Ma have been further used in the subsequent sections.

4.2.1.4 Effect of fluid Injection events E2 and E3

The model-age profiles generated in the previous section (resulting from the thermal effects of E1) were then used as a basis to superimpose the effect of subsequent thermal events at 415 Ma (E2) and 365 Ma (E3) correlated with pulses of fluid infiltration and neocrystallization recorded in the Vågje shear zone (Table 1) and elsewhere in the basement of Lofoten (Fournier et al., 2016; Fournier et al., 2014). In particular, the effect of injecting medium T (i.e. 500°C) and high T (i.e. 600 and 650°C) fluids was examined on the age profiles within the muscovite. The peak temperature T and duration d used for each event are tabulated in Table S5. In the models, both thermal events were superimposed on an ambient temperature ($T_{\text{amb(E2)}} = T_{\text{amb(E3)}}$) of 300°C (effectively 1 ka before and after E2 and E3).

4.2.1.4.1 Medium- T fluid injection

In one set of model runs, a moderate fluid temperature ($T_{\text{E2}} = T_{\text{E3}}$) of 500°C was chosen because it is consistent with the temperature for two thermal spikes (at 415 Ma and 335 Ma) obtained in a similar Ar-diffusion study in minerals at the Sommartuva shear zone within the Lofoten basement of Flakstadøy (Fournier et al., 2016). This temperature was combined with either short-lived or longer durations of either $d_{\text{E2}} = 100$ ka or 2 Ma at 415 Ma and either $d_{\text{E3}} = 25$ ka or 1 Ma at 365 Ma, respectively. The short durations reflect the same durations estimated in that shear zone, whereas the longer durations reflect extended fluid infiltration periods that are at least an order of magnitude longer. The thermal effects of these two events (E2 and E3) were then superimposed on the age profiles in Figures 5b and 6b (and Figure S2b for the fine-grained crystals) generated after E1 with $T_{\text{amb}} = 300^\circ\text{C}$.

For the two profiles of the large muscovite crystal, sample 25B-93, and using the short-term durations ($d_{\text{E2}} = 100$ ka and $d_{\text{E3}} = 25$ ka), the resultant Ar-loss profiles yielded 11.1 volume % of ^{40}Ar loss (mainly due to the E1 event at 425 Ma), muscovite ages at the grain

centre of 424 Ma decreasing to 357–355 Ma at the rim, and the resultant integrated cooling ages of 423–422 Ma (Table S5, Figure 7a,b). For the fine-grained muscovite crystals, the Ar-loss profiles yielded 15.0–18.4 volume % of ^{40}Ar loss, with ages of 423–414 Ma at the grain centre decreasing to 324–315 Ma at the rim, and integrated cooling ages of 406–391 Ma (Table S5, Figure S3). This set of conditions clearly does not produce model age profiles which replicate the Ar-data of Hames and Andresen (1996).

Considering the longer durations ($d_{\text{E2}} = 2$ Ma and $d_{\text{E3}} = 1$ Ma), the model results yielded Ar-loss profiles with 12.5–12.9 volume % of ^{40}Ar loss, muscovite ages of 424 Ma at the grain core decreasing to 356–354 Ma at the rim, and integrated cooling ages of 416–415 Ma (Table S5, Figure 7a,b). The fine-grained crystals yielded Ar-loss profiles with 24.4–24.7 volume % of ^{40}Ar loss, ages of 367–364 Ma at the grain core decreasing to 323–314 Ma at the rim, and integrated cooling ages of 365–364 Ma (Table S5, Figure S3). Although the integrated ages of 365 Ma were obtained for the fine-grained crystals, this set of conditions does not produce model age profiles which replicate the Ar-spot ages in the large crystal of Hames and Andresen (1996).

4.2.1.4.2 High-T fluid injection

Fluid injection events at E2 and E3 were also modelled with higher temperatures at 650°C and 600°C at 415 Ma and 365 Ma, respectively. These temperatures (T_{E2} and T_{E3}) were chosen in order to explore the effects of high- T fluid infiltrations that crystallized the amphibolite rocks in the Vågje shear zone at E2 [see Section ‘Early Devonian ages (415–410 Ma)’] and reset the $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende ages in the schists of the Leknes Group at E3 (Steltenpohl et al., 2003) (Table 1). These temperatures (T_{E2} and T_{E3}) were combined with a range of durations ($d_{\text{E2}}, d_{\text{E3}} \leq 1$ Ma) to simulate short- and long- lived fluid infiltration events.

Using short-lived events ($d_{E2} = 400$ ka and $d_{E3} = 50$ ka) at $T_{E2} = 650^{\circ}\text{C}$ and $T_{E3} = 600^{\circ}\text{C}$, the model results in the two profiles of sample 25b-93 yielded volumetric ^{40}Ar loss of 15.9–16.6%, a muscovite age of 415 Ma at the grain core decreasing to 357–355 Ma at the rim, and integrated cooling ages of 402–400 Ma (Table S5, Figure 7a,b). The modelled fine-grained crystals yielded a volumetric ^{40}Ar loss of 24.5%, muscovite ages of 365 Ma at the core decreasing to 324–315 Ma at the rim, and integrated cooling ages of 365 Ma (Table S5, Figure S3). In this set of conditions, the model does produce age profiles which replicate the Ar-spot age profiles reported in Hames and Andresen (1996) and further predicts that the fine-grained muscovite crystals would be completely reset at 365 Ma.

For longer durations ($d_{E2} = 1$ Ma and $d_{E3} = 1$ Ma), the resultant Ar-loss profiles for the sample 25B-93 yielded volumetric ^{40}Ar loss of 22.9–23.8%, muscovite ages of 382–373 Ma at the grain centre decreasing to 356–354 Ma at the rim, and integrated cooling ages of 372–368 Ma (Table S5, Figure 7a,b). The modelled fine-grained crystals yielded a volumetric ^{40}Ar loss of 24.7%, muscovite ages of 364 Ma at the core decreasing to 323–314 Ma at the rim, and integrated cooling ages of 364 Ma (Table S5, Figure S3). Although integrated ages of 365 Ma were obtained for the fine-grained crystals, however, this set of conditions fails to produce model age profiles which replicate the Ar-spot age profiles of Hames and Andresen (1996).

4.2.2 $^{40}\text{Ar}_E$ -rich environment

Given the prevalence of $^{40}\text{Ar}_E$ documented in previous studies from Vestvågøy (e.g. Fournier et al., 2014), it is important to examine the potential effect of the fluid infiltration pulses (E1–E3) containing $^{40}\text{Ar}_E$. The amounts of $^{40}\text{Ar}_E$ for each thermal event were assumed to be equal to the estimated amounts for the Vågje shear zone (see Section ‘Physical parameters for Model M2’) ($E1 = 8.74 \times 10^{-10}$ g/mol, $E2 = 0$ g/mol, and $E3 = 1.84 \times 10^{-9}$

g/mol). The parameters T_{E1} and d_{E1} were 650°C and 1.0 Ma, respectively, and consistent with the parameters that reset the muscovite with a constant ambient temperature $T_{amb} = 300^\circ\text{C}$. The model results use the same parameters T_{E2} , T_{E3} , d_{E2} and d_{E3} stated in Section ‘Effect of fluid Injection events E2 and E3’ and are shown in Table S6. The results yielded both diffusion-gain and flat profiles, integrated cooling ages of 460–458 Ma and ages at the grain cores as young as 415 Ma (Table S6 and Figures 8 and S4). These models clearly yielded ages older than those obtained within sample 25B-93 and failed to replicate the integrated ages for the fine-grained crystals, strongly suggesting that $^{40}\text{Ar}_E$ -rich fluids were not circulating in the Leknes Group.

4.3 Summary of Ar model results

For the M1 cooling models the T – t path of Klein et al. (1999) clearly fails to reproduce the Ar-age gradients or the Ar dates of fine-grained crystals of Hames and Andresen (1996) (Figures 4 and S1). Using the inferred simple slow-cooling thermal histories, only slow cooling at $-3.25^\circ\text{C}/\text{Ma}$ results in age profiles (Figure 4) that are in agreement with the apparent Ar-loss profiles for the large muscovite crystal (sample 25B-93) and with the integrated cooling ages of 365 Ma in fine crystals obtained by Hames and Andresen (1996) (Figure S1).

M2 models show that thermal pulses of 500°C for E2 and E3 of any duration do not provide a good fit to the data obtained by Hames and Andresen (1996) (Figure 7). Similarly, higher- T thermal pulses of $T_{E2} = 650^\circ\text{C}$ and $T_{E3} = 600^\circ\text{C}$ and durations of ~ 1 Ma or greater do not generate model-age profiles which match the Ar-spot data. However, thermal pulses of $T_{E2} = 650^\circ\text{C}$ and $T_{E3} = 600^\circ\text{C}$ combined with short durations ($d_{E2} = 400$ ka and $d_{E3} = 50$ ka) and in an $^{40}\text{Ar}_E$ -free environment adequately fit the data (Figure 7).

4.3.1 Ar-diffusion modelling sensitivity results

Model sensitivity results applied to the best fit Ar-diffusion models can be found in Table S7. For M1 (simple cooling at $-3.25^{\circ}\text{C}/\text{Ma}$), varying the amphibolite-facies T_{xtal} and P_{xtal} conditions by $\pm 25^{\circ}\text{C}$ and ± 0.5 kbar, respectively, leads to uncertainties on the resulting volumetric ^{40}Ar loss of $\pm 2\%$, integrated age of ± 9 Ma and modelled ages at the core of ± 8 Ma (Table S7). For M2 (high- T fluid injection combined with short-lived durations), varying the starting T_{xtal} and P_{xtal} by $\pm 25^{\circ}\text{C}$ and ± 0.5 kbar, respectively, yielded no change in the volumetric ^{40}Ar loss, integrated cooling ages and the modelled ages at the core (Table S7).

4.4 Pb-diffusion modelling results

Pb-diffusion results in rutile (grain diameter = $150\mu\text{m}$) and titanite (grain diameter = 1cm) using the best fit Ar-diffusion M1 and M2 models are found in Table S8.

The best-fit $T-t$ history for M1 (simple cooling at $-3.25^{\circ}\text{C}/\text{Ma}$) yielded a ^{207}Pb -diffusion rutile loss profile with 2.1 volume % of diffusive ^{207}Pb loss, a U/Pb date at the centre of 469 Ma that decreases to 386 Ma at the rim and an integrated U/Pb age of 459 Ma (Figure 9a, Table S8). For the titanite, this $T-t$ history yielded a ^{207}Pb -diffusion loss profile with 0.05 volume % of ^{207}Pb loss, a date at the centre of 461 Ma that decreases to 426 Ma at the rim and an integrated age of 461 Ma (Figure 9b, Table S8).

The best-fit $T-t$ history for M2 ($E1 = 425$ Ma, $d_{E1} = 1.0$ Ma, $T_{E1} = 650^{\circ}\text{C}$, $E2 = 415$ Ma, $d_{E2} = 400$ ka, $T_{E2} = 650^{\circ}\text{C}$, $E3 = 365$ Ma, $d_{E3} = 50$ ka, $T_{E3} = 600^{\circ}\text{C}$, $T_{\text{amb}} = 300^{\circ}\text{C}$) yielded a ^{206}Pb -diffusion rutile loss profile with 5.5 volume % of diffusive ^{206}Pb loss, a U/Pb date at the centre of 469 Ma that decreases to 365 Ma at the rim and an integrated U/Pb age of 444 Ma (Figure 9a, Table S8). For the titanite crystal, the same $T-t$ history yielded a ^{207}Pb -

diffusion loss profile with 0.3 volume % of ^{206}Pb loss, a date at the centre of 461 Ma that decreases to 372 Ma at the rim and an integrated age of 460 Ma (Figure 9b, Table S8).

5. DISCUSSION

5.1 Simple cooling (M1) vs. episodic thermal events (M2)

All modelling is subject to a number of uncertainties. It has been shown that the uncertainties in E and D for muscovite (Harrison et al., 2009) lead to an uncertainty of just ± 4 Ma on the resulting integrated age (Warren et al., 2012). For M1 (simple cooling at a rate of $-3.25^\circ\text{C}/\text{Ma}$), varying the starting T_{xtal} and P_{xtal} by $\pm 25^\circ\text{C}$ and ± 0.5 kbar, respectively, yielded modelled integrated cooling ages up to ± 8 Ma (Table S7). However, these uncertainties do not significantly affect the cooling rate of $-3.25^\circ\text{C}/\text{Ma}$ yielded by model M1. The same uncertainties yielded no perceptible change in the model results for M2 (high- T fluid injection combined with short-lived durations) (Table S7). This is due to the thermal event E1 at 425 Ma that completely reset the muscovite, and consequently any uncertainties introduced at the starting conditions of $t_{\text{xtal}} = 469$ Ma have minimal effects in the final result yielded by M2.

Significantly, the two contrasting thermal M1 and M2 models highlight an important and fundamental issue with the interpretation of diffusion profiles. It is well-known that a single diffusion profile is not unique in temperature-time space, because identical profiles can be generated by rapid diffusion rates (at high T) for a short period of time or by slower diffusion rates (at lower T) for a longer period of time, i.e. there are an infinite number of T - t combinations which can yield the same diffusion profile (e.g. Lee, 2000). In effect, a diffusion profile in a mineral represents the cumulative integrated effects of all of the thermal events which a rock has experienced in its geological history; while an age profile may

appear to reflect simple cooling, there may be additional thermal effects which are not apparent in the profile because they have been superimposed on top of it. For example, the age profiles in Figure 7 resulting from the episodic fluid-infiltration modelling resemble “typical” Ar-loss profiles which could readily be modelled as having resulted from simple slow cooling. As a result, a full understanding of the rocks incorporating, for example, structural or petrological observations and independent field or age evidence, becomes essential for accurately interpreting the thermal histories of metamorphic terranes.

The range of $^{40}\text{Ar}/^{39}\text{Ar}$ spot ages from sample 25B-93 of Hames and Andresen (1996) are similar (or within error) to the range of $^{40}\text{Ar}/^{39}\text{Ar}$ ages yielded by the step-heating and Rb/Sr techniques in different minerals (425–365 Ma) from the eclogite-facies rocks of the Vågje shear zone and elsewhere in Lofoten (Fournier et al., 2016; Fournier et al., 2014) (see Figure 2; Table 1). Moreover, the geochronological and textural evidence from rocks in the Vågje shear zone and in the Leknes Group demonstrate unequivocally the existence of hot-fluid infiltration events (Corfu, 2004b; Fournier et al., 2014). Further structural evidence of fluid Caledonian pathways (ductile and brittle shear zones) in the Leknes Group were mapped out and correlated with episodes of compression and extension (Klein et al., 1999; Steltenpohl et al., 2004; Tull, 1973). Another significant structural relation is the interpretation of a major normal fault, the Offersøya fault, dipping to the southeast and located northwest from the Leknes Group (Klein & Steltenpohl, 1999; Klein et al., 1999) (Figure 2). This fault, after restoration, likely places the Vågje eclogite-facies shear zone deeper and structurally underneath the Leknes Group. Indeed, this brittle normal fault is related to the formation of the Leknes half-graben structure during the Triassic (Bergh et al., 2018), considerably younger than the thermal event E3 at 365 Ma. In addition, sample 25B-93 was collected just 50 m above the shear zone contact between the Leknes Group and the

Lofoten basement [data repository of Hames and Andresen (1996)] suggesting the presence of a main conduit for the hot-fluid circulation (Figure 2).

A uniform slow-cooling thermal regime would be expected to yield a more symmetric age pattern in the large muscovite crystal (Figure 3a). Significantly, the same thermal regime with a slow cooling rate at $-3.25^{\circ}\text{C}/\text{Ma}$ does not produce ages which are consistent with the broader geochronological data set containing similar ages from different minerals using different geochronometers (Table 1) – specifically, a common geological history yielded by the simple cooling history of model M1 and applied to the Vågje shear zone would result in temperatures too high to preserve $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite ages at 425 Ma; $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole ages at 415 Ma; Rb/Sr phlogopite ages at 415 Ma; and Rb/Sr biotite ages at 365 Ma reported from that shear zone (Fournier et al., 2014). Therefore, a common geological history yielded by the simple cooling history of M1 and applied to both the Vågje shear zone and to the Leknes Group cannot be reconciled. Furthermore, the independent Pb-diffusion models show that Pb-loss profiles in rutile and titanite would be more prominent due to episodic thermal events yielded by M2 (Figure 9a,b). This diffusive loss of Pb would explain the variation in U-Pb rutile ages in sample C-17 and the younger age at the rim of the titanite sample C-79B (Corfu, 2004b). More significantly, both of these effects, i.e. partial resetting of the rutile, and resetting of titanite ages along the grain margins are consistent with the $T-t$ history yielded by M2. Finally, with all of the geological evidence of fluid activity in the region, it is difficult to conceive of a scenario where such activity would not have significantly perturbed the thermal regime of the Leknes Group rocks over 60 Ma, from 425 Ma to 365 Ma. Therefore, we believe that the episodic fluid-infiltration model M2 best explains the Ar results.

This model can further account for the following: i) neocrystallization and total/partial resetting of relict minerals such as annite, hastingsite, rutile, zircon, titanite, muscovite, phlogopite in the allochthon and in the basement resulting in identical ages within error

across different isotopic systems ($^{40}\text{Ar}/^{39}\text{Ar}$, Rb/Sr, U/Pb) (Table 1), and ii) the migration of hot fluids for short periods of time through conduits within the basement and allochthon rock units.

5.2 Siluro–Devonian reheating events in the Leknes Group

Model results from M2 indicate that the basic geological conditions (T_{E1} and d_{E1}) related to the Scandian phase of the Caledonian orogeny which are needed to reset the mica from 469–461 Ma to 425 Ma are in the range of 650°C for 1 Ma and 600°C for 5 Ma. These conditions, and in particular 650°C for 1 Ma, are consistent with previous Ar-diffusion modelling results in the Sommartuva eclogite-facies shear zone of Flakstadøy (Fournier et al., 2016). The temperatures also agree with the amphibolite-facies retrogression of the eclogites within the basement at 425 Ma (Fournier et al., 2014; Markl & Bucher, 1997). The longer duration d_{E1} than the durations of d_{E2} and d_{E3} of 400 ka and 50 ka, respectively, suggests the relative significance of the E1 event. However, if the portion of the T – t path after peak metamorphism at 461 Ma and before the Scandian (425 Ma) involved a slow cooling process (e.g. the crystallization ages of 469–461 Ma were not preserved), then, the thermal effect of E1 at 650°C would require even less time ($d_{\text{E1}} < 1$ Ma) to reset the mica to 425 Ma. Late-stage fluid injection events E2 and E3 are consistent with high- T and short-lived pulses at 415 Ma (650°C for 400 ka) and at 365 Ma (600°C for 50 ka), followed by rapid cooling through an ambient temperature of 300°C. This temperature value (300°C) for the terrane is in agreement with previous research in the Lofoten islands (Fournier et al., 2016; Griffin et al., 1978).

One question important to address is why there is no petrographic evidence to support the predicted temperatures yielded by M2. Because thermal events E1–E3 are interpreted to be thermal spikes with short-lived durations, the terrane is not at thermal equilibrium, and

therefore, all minerals are likely metastable for these brief periods of time and would not transform. Moreover, the pressures during each of the thermal events (E1–E3) for model M2 are given in Table 3 (P_{E1} at 5.4 kbar; P_{E2} at 5.3 kbar and P_{E3} at 4.7 kbar). Considering the P – T stability conditions for muscovite in pelitic rocks (KFMASH system) (Spear, 1993), we find that the reaction: muscovite+quartz is indeed stable with these calculated pressures and the modelled temperatures for each event (T_{E1} at 650°C; T_{E2} at 650°C and T_{E3} at 600°C).

The thermal model M2 also highlights the complicated nature of ^{40}Ar -bearing fluids infiltrating along pathways within the basement to the allochthon. For example, while annite in the Lofoten basement was crystallizing from ^{40}Ar -rich hot fluids in the Vågje shear zone at 365 Ma (Fournier et al., 2014), the large muscovite porphyroblasts in the allochthonous Leknes metasediments (Hames & Andresen, 1996) were experiencing ^{40}Ar loss. The reason for this is speculative, but it may either indicate that the fluids “discharged” their ^{40}Ar concentrations at depth, biotite incorporated more $^{40}\text{Ar}_E$ relative to the coexisting muscovite due to its higher ionic porosity (Dahl, 1996), or there was a complex interplay of Ar partitioning and temperature between biotite and muscovite (e.g. Kelley, 2002; Roddick, Cliff, & Rex, 1980).

The thermal pulses E2 at 415 Ma (650°C for 400 ka) and E3 at 365 Ma (600°C for 50 ka) in the Leknes Group occur at higher temperatures and for longer durations compared to those affecting the basement in the Sommartuva shear zone in Flakstadøy [i.e. at 500°C for 100–50 ka at 413 Ma, and 500°C for 25 ka at 335 Ma – Fournier et al. (2016)]. Although, verification of these results from Ar-spot analyses would be ideal, these higher temperatures and longer durations may result from a combination of: i) the relative structural position of the Leknes Group (higher than the eclogite-facies shear zones within the basement); and ii) the greater abundance of Caledonian pathways (shear zones) observed in the Leknes Group (Klein et al., 1999; Steltenpohl et al., 2004; Tull, 1973) than in the basement (Steltenpohl et

al., 2011). In modern subduction zones, it has been shown that, after a major earthquake, considerable volumes of fluids are released which can breach permeability seals previously formed due to high compressive stresses between the overlying and subducting plates (Husen & Kissling, 2001; Koerner, Kissling, & Miller, 2004). Due to its structural position above the Lofoten basement, the Leknes Group was likely subjected to a much greater volume of hot fluids for longer periods of time.

5.3 A new T - t history for the Leknes Group

The T - t history yielded by the episodic fluid-injection model M2 incorporates thermal spikes lasting 1 Ma at 425 Ma at 650°C, 400 ka at 415 Ma at 650°C and 50 ka at 365 Ma at 600°C superimposed on an ambient temperature of 300°C, with a linear decompression from 6 kbar (at 469 Ma) to atmospheric pressure (at the present) (Figure 10). The ambient temperature of 300°C should be viewed as the maximum ambient T of the Leknes Group from 425–365 Ma, although lower ambient temperatures (i.e. $\leq 300^\circ\text{C}$) are also possible. The tectonic models for this time span coincide with the Scandian continental subduction where the allochthonous Leknes Group remained at higher crustal levels than the Lofoten eclogites within the basement (Steltenpohl et al., 2004; Steltenpohl et al., 2011) but punctuated by episodic thermal events (Figure. 10). These episodic events were presumably triggered by multiple deformation events associated with major earthquakes and their aftershocks as envisaged in modern seismogenic zones (e.g. Husen & Kissling, 2001), and documented by the presence of pseudotachylytes in Flakstadøy of the Lofoten islands (Figure 1) (Fournier et al., 2016; Steltenpohl, Kassos, & Andresen, 2006) with analogous occurrences in other parts of Norway related to the Caledonian orogeny (e.g. Austrheim & Boundy, 1994; Camacho et al., 2005). A sedimentary basin formed in an extensional regime during the Devonian (400–365 Ma) without exposing the crust and the overlying allochthon (Steltenpohl et al., 2011), in

agreement with the presence of Permian sedimentary rocks found offshore and adjacent to Lofoten (Henstra & Rotevatn, 2014).

The M2 model was based on the laser Ar-spot muscovite ages of Hames and Andresen (1996) highlighting the enormous potential of this technique over other more conventional $^{40}\text{Ar}/^{39}\text{Ar}$ analyses (e.g. step-heating technique) in which apparent diffusion profiles are more difficult to interpret (e.g. Fournier et al., 2016). The M2 model proposed in this work is consistent with the current geochronological data. Moreover, it may be worthwhile considering the effect of episodic fluid injections in modelling the thermal histories of other HP-metamorphic terranes (e.g. Camacho et al., 2005; Fournier et al., 2016).

6. CONCLUSIONS

Using the most recently published geological, geochemical and tectonic constraints, detailed $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronological modelling was performed on previously obtained muscovite data from the Leknes Group in Vestvågøy (Hames & Andresen, 1996) to further elucidate the temperature–time history of the Lofoten basement and overlying Leknes sedimentary sequence in northern Norway. The argon ages from a large muscovite porphyroblast as well as fine-grained crystals are consistent with fluid infiltration in the Vågje shear zone on the same island. From the thermal modelling, a new T – t path (469 Ma–present) for the Leknes Group has been derived, which includes at least three episodic thermal events (E1 at 425 Ma, E2 at 415 Ma, and E3 at 365 Ma) associated with the Scandian collision and subsequent tectonic extension. E1 reflects resetting of the Ordovician (469–461 Ma) mica during the Scandian phase (425 Ma) of the Caledonian orogeny for 1 Ma at 650°C. E2 is a short-lived event at 415 Ma ($T = 650^\circ\text{C}$ for 400 ka), and E3 is a final episodic event at 365 Ma ($T = 600^\circ\text{C}$ for 50 ka), where both events are associated with extension.

Incorporating all of these events into an integrated thermal model for the Lofoten archipelago yields an excellent fit with the Ar muscovite data of Hames and Andresen (1996).

The allochthonous Leknes Group terrane appears to have resided for at least 60 Ma (425–365 Ma) at shallow crustal levels during a period of relative tectonic stability only punctuated by occasional episodic injection of hot fluids. The late-stage episodic events in the Leknes Group and associated with the Vågje shear zone have longer durations and higher temperatures than those associated in other parts of the Lofoten (e.g. Sommartuva). This may be due to the ubiquitous Caledonian shear zones found throughout the Leknes Group and its relatively shallow structural position in the crustal sequence. These pathways could have facilitated not only the injection of a large volume of hot fluids but also longer exposure times to these hot fluids.

The model results are consistent with the migration of fluids at different geological times from the basement to the allochthon rock units through interconnected conduits potentially triggered by seismic activity syn- and post-orogenesis. Moreover, the hot-fluid infiltration model proposed in this paper successfully integrates and reconciles the presence of identical ages obtained from multiple isotopic systems applied to different minerals from rocks of the allochthon and the basement. Such transient thermal events may be worthwhile to consider in elucidating the thermal histories of other HP metamorphic terranes. This work highlights the immense potential of coupling laser Ar-spot analyses with diffusion theory.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Results of Ar-diffusion modelling in two fine-grained muscovite crystals (radii 250 μm and 125 μm) using previously published T – t paths. Diffusion profiles are for the inferred T – t path of the Leknes Group of Klein et al. (1999) from 430 Ma to 365 Ma and for three simple slow-cooling models at $-5.0^\circ\text{C}/\text{Ma}$, $-3.25^\circ\text{C}/\text{Ma}$ and at $-2.5^\circ\text{C}/\text{Ma}$ from 425 Ma to 365 Ma. The black arrow indicates the model parameters which best fit the data.

Figure S2. Results of Ar-diffusion modelling for two fine-grained muscovite crystals (radii 250 μm and 125 μm) incorporating the thermal effects of an episodic event E1. Ar diffusion profiles result from using an ambient temperature (T_{amb}) of 400°C (**a**) or 300°C (**b**) in which a thermal pulse (T_{E1}) of 650°C or 600°C of duration (d_{E1}) 1 Ma or 5 Ma is superimposed at 425 Ma. The pressure effects in the diffusion models were input as described in Figure 5. The large black arrow indicates the model parameters which best fit the data.

Figure S3. Results of Ar-diffusion modelling in two fine-grained muscovite crystals (radii 250 μm and 125 μm) integrating the effects of an ambient temperature (T_{amb}) of 300°C and the thermal effects of E1, E2, and E3. Diffusion profiles reflect the resultant age profile of a muscovite that crystallized at 469–461 Ma at 600°C and was thermally reset at E1 = 425 Ma (650°C for 1 Ma), and then further affected by reheating associated with two subsequent fluid-injection events (E2 and E3) at different temperatures and durations in an $^{40}\text{Ar}_{\text{E}}$ -free environment. The black arrow indicates the model parameters which best fit the data.

Figure S4. Results of Ar-diffusion modelling in two fine-grained muscovite crystals (radii 250 μm and 125 μm) for integrating the effects of E1, E2, and E3 in an $^{40}\text{Ar}_{\text{E}}$ -rich environment.

Table S1. Selected Ar-spot ages (Ma) from muscovite sample 25B-93 of Hames and Andresen (1996).

Table S2. Muscovite thermal modelling parameters: Simple slow-cooling histories.

Table S3. Muscovite thermal modelling parameters: Ambient temperature.

Table S4. Muscovite thermal modelling parameters: Reset at 425 Ma.

Table S5. Muscovite thermal modelling parameters: $^{40}\text{Ar}_\text{E}$ -free environment.

Table S6. Muscovite thermal modelling parameters: $^{40}\text{Ar}_\text{E}$ -rich environment.

Table S7. Ar-model sensitivity results yielded by the best fit Ar-diffusion models M1 and M2.

Table S8. Pb-diffusion results in rutile and titanite using the best fit Ar-diffusion models M1 and M2.

Figure 1. Location of the Lofoten archipelago in Norway (inset). Geological map of the Lofoten-Vesterålen islands showing the main lithological units. The black rectangle shows the area of study in Figure 2. Modified from Andresen and Tull (1983); Sigmond, Gustavson and Roberts (1984); and Tveten (1978).

Figure 2. Geological map of part of Vestvagøy showing the locations of the Vågje eclogite-facies shear zone and previously published geochronological data. Modified from Klein et al. (1999), Tull (1977) and Bergh et al. (2018). Cross-section profile (A–B) modified from Klein et al. (1999) and Bergh et al. (2018). Ages ($\pm 2\sigma$ uncertainty) shown here are interpreted to be geologically meaningful: amphibolite-facies metamorphism (469–461 Ma; U/Pb zircon), crystallization/resetting (425–365 Ma; $^{40}\text{Ar}/^{39}\text{Ar}$ and Rb/Sr muscovite and annite) by fluid infiltration events and a cooling age at 60°C (181 Ma; apatite fission-track). Published geochronological data are from Corfu (2004b); Fournier et al. (2014); Hames and Andresen (1996); and Hendriks et al. (2010).

Figure 3. (a) $^{40}\text{Ar}/^{39}\text{Ar}$ laser spot ages (Ma) in a large muscovite porphyroblast of the Leknes Group of Vestvågøy from Hames and Andresen (1996). The black (length: 3600 μm) and grey (length: 2980 μm) transects from rim to core correspond to the profiles shown in (b) and (c). Modified from Hames and Andresen (1996). (b–c) Re-plotted $^{40}\text{Ar}/^{39}\text{Ar}$ laser spot ages (black transect) and (grey transect) with age errors at 2σ level and an individual spot size of 150 μm [see Table S1 for the selected spots (age $\pm$ error) obtained from the data repository of Hames and Andresen (1996)].

Figure 4. Results of Ar-diffusion modelling in muscovite: (a) black transect (diffusion distance = 3600 μm) and (b) grey transect (diffusion distance = 2980 μm) using previously published T – t paths. Diffusion profiles are for the inferred T – t path of the Leknes Group of Klein et al. (1999) from 430 Ma to 365 Ma and for three simple slow-cooling models at $-5.0^\circ\text{C}/\text{Ma}$, $-3.25^\circ\text{C}/\text{Ma}$ and at $-2.5^\circ\text{C}/\text{Ma}$ from 425 Ma to 365 Ma. The black arrow indicates the model parameters which best fit the data.

Figure 5. Results of Ar-diffusion modelling for a large muscovite crystal (black transect, diffusion distance = 3600 μm) (black line in Figure 3a), incorporating the thermal effect of an episodic event E1. Ar diffusion profiles result from using an ambient temperature (T_{amb}) of 400°C (a) or 300°C (b) in which a thermal pulse (T_{E1}) of 650°C or 600°C of duration (d_{E1}) 0.5 Ma, 1 Ma or 5 Ma is superimposed at 425 Ma. The pressure effects in the diffusion models were input as a linear decompression from 6 kbar (at 469 Ma) down to atmospheric pressure (at the present). The large black arrow indicates the model parameters which best fit the data.

Figure 6. Results of Ar-diffusion modelling in a large muscovite crystal for the grey transect (diffusion distance = 2980 μm) (grey line in Figure 3a) integrating the effects of an ambient temperature (T_{amb}) of 400°C (a) or 300°C (b) in which a thermal pulse (T_{E1}) is superimposed and detailed in the caption of Figure 5.

Figure 7. Results of Ar-diffusion modelling in large muscovite crystal: **(a)** black transect (diffusion distance = 3600 μm) and **(b)** grey transect (diffusion distance = 2980 μm)

integrating the thermal effects of E1, E2, and E3. Diffusion profiles reflect the resultant age profile of a muscovite that crystallized at 469–461 Ma at 600°C and was thermally reset at E1 = 425 Ma (650°C for 1 Ma), and then further affected by reheating associated with two subsequent fluid-injection events (E2 and E3) at different temperatures and durations in an $^{40}\text{Ar}_\text{E}$ -free environment. The black arrow indicates the model parameters which best fit the data.

Figure 8. Results of Ar-diffusion modelling in a large muscovite crystal for **(a)** black transect (diffusion distance = 3600 μm) and **(b)** grey transect (diffusion distance = 2980 μm) integrating the effects of E1, E2, and E3 and detailed in the caption of Figure 7 in an $^{40}\text{Ar}_\text{E}$ -rich environment.

Figure 9. Model Pb diffusion profiles in **(a)** rutile that crystallized at 469–461 Ma at 600°C and titanite **(b)** that crystallized at 461 Ma. The grey solid curves are the Pb-diffusion profiles using the best-fit solution of model M1: a simple slow-cooling model at $-3.25^\circ\text{C}/\text{Ma}$ (calculated from 461 Ma to 365 Ma see Table S8). The grey dashed curves are the Pb diffusion profiles using the best-fit solution of model M2: three thermal events at 425 Ma (650°C for 1 Ma), at 415 Ma (650°C for 400 ka) and at 365 Ma (600°C for 50 ka) at an ambient temperature of 300°C until 365 Ma, immediately followed by simple cooling at $-1.3^\circ\text{C}/\text{Ma}$ from 365 Ma to 180 Ma and $-0.3^\circ\text{C}/\text{Ma}$ from 180 Ma to present. Because the experimental diffusion data in rutile and titanite were performed at 1 atmosphere conditions these models were run without considering the effect of pressure.

Figure 10. (Top) Theoretical Ar diffusion profile in a large muscovite porphyroblast (black transect, diffusion distance = 3600 μm) using the T – t path derived in this study (black line in the bottom). The T – t history involves thermal events at 650°C lasting 1 Ma at 425 Ma (E1)

which reset crystallization ages (469–461 Ma) preserved by an inferred rapid exhumation of the Leknes Group after its emplacement (black dashed T – t path), at 650°C lasting 400 ka at 415 Ma (E2) and at 600°C lasting 50 ka at 365 Ma (E3), superimposed on an ambient crustal temperature regime of 300°C in an $^{40}\text{Ar}_\text{E}$ -free environment. The approximate age for the initiation of the erosion (275 Ma) (Henstra & Rotevatn, 2014; Steltenpohl et al., 2004) of the Lofoten basement is also noted. The T – t path is further constrained by the apatite fission track data (AFT) (Hendriks et al., 2010), the estimated time for the development of the Leknes half-graben (Bergh et al., 2018) and is extended to the present-day mean surface temperature (5°C). The grey box delineates the range of times and temperatures for the main eclogitization event in Lofoten (*c.* 416–399 Ma, $650 \pm 50^\circ\text{C}$) (Froitzheim et al., 2016).

Table 1. Chronological summary of ages (Ma) and significant geological events in the Vågje shear zone and the Leknes Group of Vestvågøy.

Table 2. Summary of Zr-in-rutile temperatures using the Tomkins et al. (2007)^a and Watson et al. (2006)^b calibrations.

Table 3. Diffusion and physical parameters used for the muscovite thermal modelling.

Table 1. Chronological summary of ages (Ma) and significant geological events in the Vågje shear zone and the Leknes Group of Vestvågøy

Age ± 2σ (abs.)	Isotopic System	Mineral	Locality	Rock	Interpretations
181±42 ^a	AFT	Ap	Leknes Group	Schist	Cooling at 60°C ^a
357±2 ^b	⁴⁰ Ar/ ³⁹ Ar (SCTF)	Bt		Schist	Postcrystallization deformation and complex thermal history ^b . Resetting/neocrystallization by fluid-infiltration event (E3) ^c .
360±4 ^d	Rb/Sr (MP)	Bt	Vågje zone	Retrogressed eclogite	Fluid-infiltration event (E3) causing neocrystallization associated with extensional events as described in the Leknes Group ^d .
363±4 ^d				Amphibolite	
365±5 ^b	⁴⁰ Ar/ ³⁹ Ar (SCTF)	Hbl	Leknes Group	Schist	Postcrystallization deformation and complex thermal history ^b . Resetting/neocrystallization by fluid-infiltration event (E3) ^c .
365 (no error quoted) ^e				Mylonite	Extensional event and exhumation ^e . Resetting/neocrystallization by fluid-infiltration event (E3) ^c .
385–360 (no error quoted) ^f		Ms		Mylonite and schist	Comparable to the younger ages obtained by Hames & Andresen (1996) ^f . Resetting/neocrystallization by the combined effect of E1–E3 ^{g,c} .
372±6 ^b		Bt		Amphibolite	Postcrystallization deformation and complex thermal history ^b . Resetting/Neocrystallization by fluid-infiltration event (E3) ^c .
402±7 ^b		Hbl		Amphibolite	Postcrystallization deformation and complex thermal history ^b . Resetting/neocrystallization by the combined effect of E1–E3 ^c .
411±4 ^d	Rb/Sr (MP)	Phl	Vågje zone	Gabbro (host rock)	Resetting by the Devonian event (E2) ^d .
416±1 ^d	⁴⁰ Ar/ ³⁹ Ar (SH)	Hst		Amphibolite	Fluid-infiltration event (E2) causing neocrystallization ^c .
426±3 ^d				Felsic vein in Grt-amphibolite	Major fluid infiltration causing retrogression of eclogites, recrystallization and neocrystallization (E1). Minimum age for the amphibolite-facies retrogression ^d .
425 (core)–365 (rim) ^e	⁴⁰ Ar/ ³⁹ Ar (SFA)	Ms	Leknes Group	Ky-Grt-St schist (Qtz-rich boudin)	Beginning of Ar retention during 425 Ma, followed by loss of ⁴⁰ Ar* until c. 390 Ma, and isotopic closure at 390–365 Ma ^e . Partial resetting by Devonian events ^g . Total/partial reset ages by the combined effect of E1–E3 ^c .
451±3–412±2 ^g	U/Pb (TIMS)	Rt, Zrn		Ky-Grt-St schist	Partial resetting ages. Discrete recrystallization of Zrn by fluid infiltration at 412 Ma ^g .

$\geq 461 \pm 1^g$	Ttn	Amphibolite	Thrusting and imbrication at amphibolite-facies (600°C, 6 kbar) into the Lofoten basement. Ttn (1 cm diameter) rim was isotopically reset ^g .
469 ± 3^g	Zrn	Tonalite	

^aHendriks *et al.* (2010).

^bSteltenpohl *et al.* (2003).

^cEvents (E1, E2, and E3) for model M2 from this study.

^dFournier *et al.* (2014).

^eHames & Andresen (1996).

^fSteltenpohl *et al.* (2004).

^gCorfu (2004b).

Ap = apatite; Bt = biotite; Hbl = hornblende; Ms = muscovite; Phl = phlogopite; Hst = hastingsite; Ky = kyanite; Grt = garnet; St = staurolite; Qtz quartz; Rt = rutile; Zrn = zircon; Ttn = titanite. AFT: apatite fission track analyses; SCTF: single-crystal total-fusion analyses; MP: Mineral pair analyses; SH: Step-heating analyses; SFA: Spot-fusion analyses; TIMS: thermal ionization mass spectrometry analyses.

Table 2. Summary of Zr-in-rutile temperatures using the Tomkins et al. (2007)^a and Watson et al. (2006)^b calibrations

Sample	Grain	Position	Zr ppm	1 σ	$T(^{\circ}\text{C})^{\text{a}}$	1 σ	$T(^{\circ}\text{C})^{\text{b}}$	1 σ
HF-08-25a	1	Centre	53	26	592	38	520	33
	1	Rim	72	26	613	33	539	27
	2	Centre	55	26	594	38	522	32
	2	Rim	75	26	615	32	542	26
	3	Centre	80	26	620	31	546	25
	4	Centre	70	26	611	33	538	27
	5	Centre	68	26	609	34	536	28
	5	Rim	71	26	612	33	538	27
	6	Centre	65	26	606	34	533	28
	6	Rim	66	26	607	34	534	28
	7	Centre	101	26	636	29	562	22
	7	Rim	90	26	628	30	554	23
	8	Centre	84	26	623	31	549	24
	9	Centre	92	26	630	30	555	23
	9	Rim	98	26	634	29	560	22
	10	Centre	96	26	633	29	558	23
	11	Centre	78	26	618	32	544	25
	12	Centre	122	26	650	27	575	20
Weighted Mean ^c					621 $\pm$ 15		548 $\pm$ 12	
					(MSWD = 0.2)		(MSWD = 0.3)	
HF-08-25d	1	Centre	125	26	652	27	576	20
	1	Rim	120	26	649	28	573	21
	2	Centre	142	27	662	27	585	20
	2	Rim	143	27	662	27	586	20
	3	Centre	131	27	656	27	580	20
	3	Rim	117	27	647	28	572	21
	4	Centre	138	26	660	27	583	19
	4	Rim	115	27	646	28	571	21
	5	Centre	50	26	588	40	517	34
	5	Rim	45	26	581	42	510	37

	6	Centre	52	26	591	39	519	33
	6	Rim	59	26	599	36	527	30
	7	Centre	59	26	599	36	527	30
	8	Centre	62	26	602	35	530	29
	8	Rim	54	26	593	38	521	32
	9	Centre	66	26	607	34	534	28
	9	Rim	72	26	613	33	539	27
	10	Centre	44	26	580	43	509	37
	10	Rim	56	26	596	37	524	31
	11	Centre	48	26	586	41	514	35
	11	Rim	57	26	597	37	525	31
	12	Centre	54	26	593	38	521	32
	13	Centre	54	26	593	38	521	32
Weighted Mean ^c					624 ± 13	554 ± 12		
					(MSWD = 0.9)	(MSWD = 1.2)		

^aTomkins et al. (2007) *P*-dependent temperature at *P* = 27 kbar.

^bWatson et al. (2006) calibration.

^cWeighted Mean value calculated using Isoplot (Ludwig, 2010).

MSWD: Mean Square Weighted Deviation.

Table 3. Diffusion and physical parameters used for the muscovite thermal modelling.

Diffusion Parameters						
E (kcal/mol)	D_0 (cm ² /s)	Geometry	a_1 (μm) ^a	a_2 (μm) ^a	a_3 (μm) ^b	a_4 (μm) ^b
63	2.3	Cylindrical	3600	2980	250	150
Physical Parameters						
Crystallization (xtal)						
t_{xtal} (Ma)	T_{xtal} (°C)	P_{xtal} (kbar)	d_{xtal} (Ma)	T_{amb} (°C)	$^{40}\text{Ar}_{\text{E}}$ xtal (g/mol)	
469–461	600	6	8	Unk.	0	
Thermal Event 1 (E1)						
t_{E1} (Ma)	T_{E1} (°C)	P_{E1} (kbar) ^c	d_{E1} (Ma)	T_{amb} (°C)	$^{40}\text{Ar}_{\text{E}}$ E1 (g/mol) ^d	
425	650	5.4	Unk.	Unk.	8.74×10^{-10}	
Thermal Event 2 (E2)						
t_{E2} (Ma)	T_{E2} (°C)	P_{E2} (kbar) ^c	d_{E2} (Ma)	T_{amb} (°C)	$^{40}\text{Ar}_{\text{E}}$ E2 (g/mol) ^d	
415	Unk.	5.3	Unk.	Unk.	0	
Thermal Event 3 (E3)						
t_{E3} (Ma)	T_{E3} (°C)	P_{E3} (kbar) ^c	d_{E3} (Ma)	T_{amb} (°C)	$^{40}\text{Ar}_{\text{E}}$ E3 (g/mol) ^d	
365	Unk.	4.7	Unk.	Unk.	1.84×10^{-9}	

^aLengths of the profiles in Figure 3.^bRadii of the muscovite crystals dated by Hames & Andresen (1996).^cCalculated pressures following a linear decompression from 6 kbar at 469 Ma to the atmospheric pressure at the present.^dQuantity of excess Ar ($^{40}\text{Ar}_{\text{E}}$) for each thermal event (E1–E3) and applied to the $^{40}\text{Ar}_{\text{E}}$ -rich environment models of M2.

Unk.: Unknown.

Figure 3

Figure 4

Figure 5

Figure 6

Figure 8

Figure 9

Figure 10