ARTICLES

Short-lived orogenic cycles and the eclogitization of cold crust by spasmodic hot fluids

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Collision tectonics and the associated transformation of continental crust to high-pressure rocks (eclogites) are generally well-understood processes, but important contradictions remain between tectonothermal models and petrological–isotopic data obtained from such rocks. Here we use ^{40}Ar–^{39}Ar data coupled with a thermal model to constrain the time-integrated duration of an orogenic cycle (the burial and exhumation of a particular segment of the crust) to be less than 13 Myr. We also determine the total duration of associated metamorphic events to be ~20 kyr, and of individual heat pulses experienced by the rocks to be as short as 10 years. Such short timescales are indicative of rapid tectonic processes associated with catastrophic deformation events (earthquakes). Such events triggered transient heat advection by hot fluid along deformation (shear) zones, which cut relatively cool and dry subducted crust. In contrast to current thermal models that assume thermal equilibrium and invoke high ambient temperatures in the thickened crust, our non-steady-state cold-crust model satisfactorily explains several otherwise contradictory geological observations.

Transformation of crustal rocks to eclogite takes place during burial by the effect of deformation and/or fluid infiltration[1–4]. However, many exposed high-pressure terranes are only partly transformed to eclogite, suggesting that buoyancy may be a controlling factor in their rate of exhumation[1,5–8]. The Southern Caledonides of Norway, including the Lindås nappe in the Bergen arcs, are one of the best-documented examples of a continental-collision zone containing high- and ultrahigh-pressure rocks. Eclogites, confined to Caledonian (~425 Myr ago)[9] shear zones within Proterozoic unreacted dry granulites and anorthosites, formed at temperatures of ~700 °C and depths of ~60 km (refs 1, 10–12). Phlogopite in undeformed ultramafic lenses surrounded by Caledonian eclogite, however, preserves Proterozoic Rb–Sr ages (~850 Myr)[13]. Because the temperature of eclogite formation was assumed to reflect the ambient thermal regime[13,14] in the subducted crust at 60 km depth, this unexpected result was inferred to indicate a Rb–Sr phlogopite closure temperature of ~700 °C under dry, static conditions[13]. Using the ^{40}Ar–^{39}Ar dating technique, we explore the alternative possibility that the country rocks did not reach the high temperatures recorded by the eclogites, and investigate the resulting geological implications.

The ^{40}Ar–^{39}Ar method is especially well-suited to thermochronological studies of the Earth's crust, and allows us to uniquely constrain the thermal history of the untransformed, granulite-facies country rocks in the Bergen arcs. Various minerals (see Supplementary Tables 1–6 for all analyses) were separated from two ultramafic lenses surrounded by eclogitic shear zones on Holsnøy island (Fig. 1); these were the same lenses examined in the Rb–Sr study[13]. The Alvfjellet lens (samples Alv6 and Alv7) is a 25 × 30 m outcrop, whereas the Hundskjeften lens (sample Hunds14) is 10 × 20 m. Phlogopite in these lenses is in textural equilibrium with other minerals and is compositionally uniform from core to rim, suggesting negligible compositional re-equilibration after granulite-facies metamorphism at ~930 Myr ago[13,15]. Amphiboles from Alv6 are also pristine, uniform in composition, and do not contain either fluid or mineral inclusions, as demonstrated by optical microscopy, backscattered electron imaging, X-ray mapping and electron microprobe analyses (Supplementary Table 1). The Hundskjeften lens also preserves its original magmatic assemblage, but locally is partially overprinted by Caledonian garnet and clinopyroxene forming a rind a few centimetres thick along the margins.

Argon dating and isotope systematics

^{40}Ar–^{39}Ar laser step-heating experiments on two amphibole aliquots of different grain size from sample Alv6 yielded age spectra (Fig. 2) partially affected by argon (^{40}Ar) that did not form from radioactive decay of ^{40}K within the crystal (here termed 'excess'[16] $^{40}Ar_E$). Ca/K and Cl/K ratios for 99.99% of the ^{39}Ar released are concordant, indicating that argon is derived exclusively from amphibole with uniform chemical and isotopic composition. The larger grain (~350 μm diameter) is less affected by $^{40}Ar_E$ than the smaller grain (~100 μm diameter), consistent with the uptake of excess argon as predicted by diffusion theory. The plateau segments (representing >70% of ^{39}Ar released) for both aliquots yield identical ages of ~885 Myr, which are slightly younger than the U–Pb zircon age of ~930 Myr for regional granulite-facies metamorphism[15]. Total-fusion ^{40}Ar–^{39}Ar ages of eight amphibole crystals range from ~885 to 915 Myr, also reflecting varying degrees of $^{40}Ar_E$. Phlogopite from the two lenses also yielded ^{40}Ar–^{39}Ar age spectra partially affected by $^{40}Ar_E$ (Fig. 3); dates monotonically decrease from ~975 to 900 Myr ago in the lower-temperature steps to plateau-like segments in each age spectrum. Together, the plateau-like segments from all three samples span a range of ages from ~820 to 895 Myr, similar to the Rb–Sr phlogopite ages of ~840–860 Myr (ref. 13). In addition, the integrated ^{40}Ar–^{39}Ar ages from 18 phlogopite crystals (1,600–200 μm

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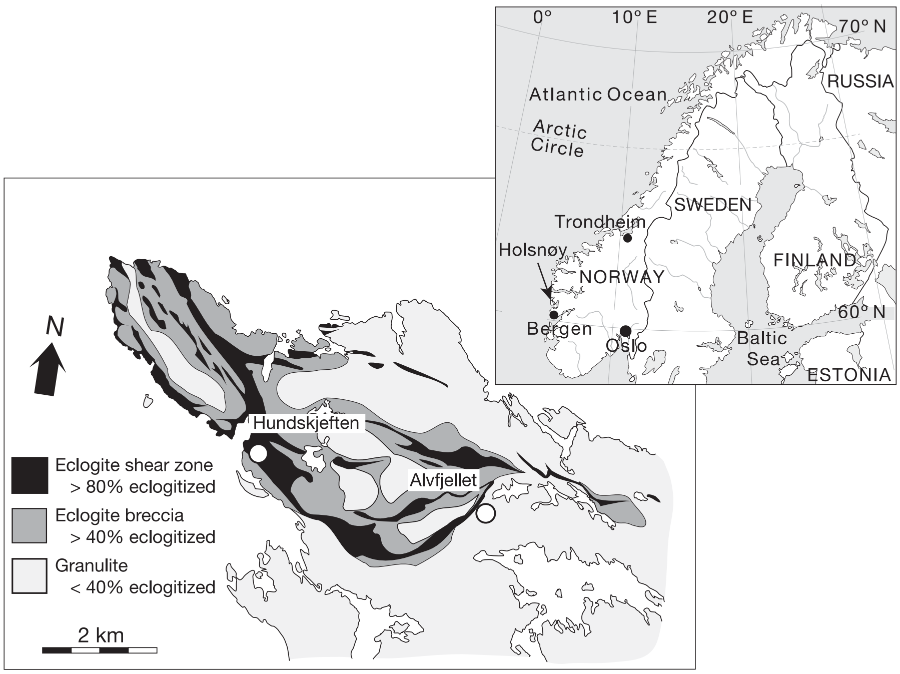

Figure 1 | Geological map of Holsnøy island, northwest of Bergen, western Norway. This shows the distribution of the Caledonian (~425 Myr ago) eclogite-facies overprint and the Alvfjellet and Hundskjeften localities within the eclogite-facies rocks. After refs 40 and 41.

diameter) show that the ages of the larger grains are less affected by $^{40}Ar_E$ than those of the smaller grains (Fig. 4), also consistent with the uptake of excess argon by diffusion. As well as the step-heating experiments, narrow trenches (~30 μm wide) parallel to the grain margin were ablated in three phlogopite grains, using an ultraviolet laser[17]. The age profiles from the three grains (Fig. 5) show that the ages decrease inwards away from the grain boundary, confirming the intragrain age distributions inferred from the step-heating experiments. Our data clearly demonstrate that amphibole and phlogopite are affected by $^{40}Ar_E$ and must have been open to argon diffusion since the Proterozoic.

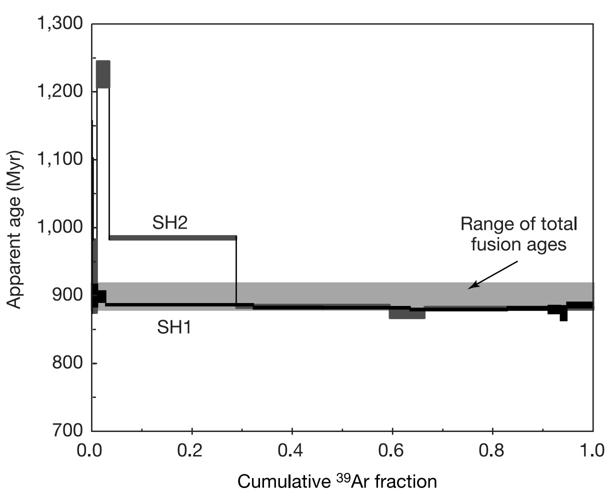

Figure 2 | ^{40}Ar–^{39}Ar release spectra for two step-heated amphibole aliquots of different grain size from the Alvfjellet lens (sample Alv6) on Holsnøy island. Both age spectra are affected by excess argon ($^{40}Ar_E$) in the lower-temperature steps to varying degrees. Aliquot SH1 (~350 μm diameter) and SH2 (~100 μm diameter) yield identical plateau ages of 885 ± 2 Myr (2σ; mean square of the weighted deviates MSWD = 1.3; 97.2% of ^{39}Ar) and 882 ± 3 Myr (2σ; MSWD = 0.7; 71.3% of ^{39}Ar), respectively, and constrain the cooling age for granulite-facies metamorphism. The shaded band represents the range of ^{40}Ar–^{39}Ar total-fusion ages (885–915 Myr) of eight amphibole crystals from the same sample. Box heights are ±1σ.

Because Caledonian metamorphism is the only other recorded thermal event since the Proterozoic[13], we investigated whether the incorporation of $^{40}Ar_E$ in the phlogopites could be linked to that event by analysing the argon concentrations of other minerals in the host rocks (Supplementary Table 6). Caledonian garnet and clinopyroxene along the margin of the Hundskjeften lens contain $^{40}Ar_E$ concentrations that are 1–2 orders of magnitude higher than those in the Proterozoic magmatic assemblage in the ultramafic lenses. Thus, we can directly attribute the source of $^{40}Ar_E$ to the fluids associated with the Caledonian event, in agreement with previous studies[18,19]. However, as the untransformed lenses have not been hydrated during the eclogitization event[13], this suggests that an argon-rich, but water-poor fluid infiltrated along the grain boundaries of the ultramafic

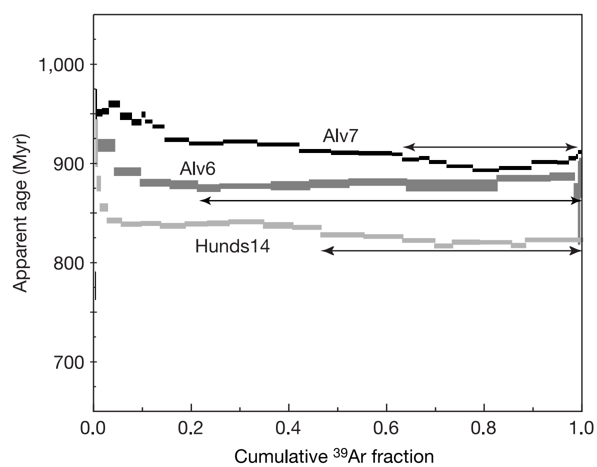

Figure 3 | ^{40}Ar–^{39}Ar release spectra for step-heated phlogopite from the Alvfjellet (Alv6; Alv7) and Hundskjeften (Hunds14) lenses on Holsnøy island. All three age spectra exhibit excess argon ($^{40}Ar_E$) in the lower-temperature steps. Alv6 yields a plateau age (spanned by arrow) of 880 ± 4 Myr (2σ; MSWD = 1.3; 78.71% of ^{39}Ar). Alv7 and Hunds14 do not yield plateaus, but plateau-like segments as indicated by arrows; Alv7 = 897 ± 3 Myr (2σ; MSWD = 5.6; 37.77% of ^{39}Ar) and Hunds14 = 821 ± 3 Myr (2σ; MSWD = 2.9; 52.44% of ^{39}Ar). Box heights are ±1σ.

rocks, in contrast with the water-rich fluid in the shear zones. This is, to our knowledge, the first evidence for an open system in the untransformed protolith well beyond the eclogitization front (compare ref. 18).

Modelling uptake of excess ^{40}Ar

The presence of $^{40}Ar_E$ in rocks is generally considered to be detrimental to the interpretation of ^{40}Ar–^{39}Ar age data, but we can take advantage of its presence by examining the distribution of $^{40}Ar_E$ in various K-bearing minerals. By considering the effect that $^{40}Ar_E$ would have on the ages of coexisting phlogopite and amphibole (such as in Alv6), we can constrain, in a novel way, the temperature and duration of heating of the country rocks during the eclogitization event. The partitioning of argon between different coexisting K-bearing minerals is commonly assumed to be 1. This supposition, however, is questionable when biotite is involved, given its known high argon solubility relative to most other K-bearing minerals[20]. Although there are no experimental data on the distribution of argon between amphibole and phlogopite, we derived an approximate partition coefficient ($K_d \approx 0.6$), consistent with the above observation, from argon isotopic concentrations of coexisting amphibole and biotite in rocks from central Australia[21]. Raising the age of a phlogopite with 8.1 wt% K from 875 Myr (youngest age peak from the Alvfjellet lens, Fig. 4) to 1,100 Myr (laser trench at grain margin of Alv6; Fig. 5) requires 5.47×10^{-9} mol g^{-1} of $^{40}Ar_E$. Complete equilibration of the $^{40}Ar_E$ into the coexisting amphibole with 1.5 wt% K, using the estimated partition coefficient, increases its apparent age from 885 to 1,521 Myr—much older than any of our measured ^{40}Ar–^{39}Ar amphibole ages (885–915 Myr). This apparent age discrepancy can be reconciled by considering the partial uptake of $^{40}Ar_E$ controlled by diffusion, as discussed below.

The range of experimentally determined amphibole ages (885–915 Myr) in amphibole crystals with a diameter of ~300 μm can be produced by the uptake of up to 3.97% of the total $^{40}Ar_E$ concentration. Assuming that only the outermost region of an amphibole grain, equivalent to 3.97% of its volume, is affected (which is further supported by the amphibole step-heating spectrum SH1 in Fig. 2), this translates into a mean radial diffusion distance ($\bar{x}$) for $^{40}Ar_E$ diffusion of 2.01 μm for a ~300 μm grain (assuming a spherical diffusion geometry). In the largest phlogopite grains, only the first 20% of the age spectra is affected by $^{40}Ar_E$ (Fig. 3), which volumetrically corresponds to $\bar{x} = 79.2$ μm (cylindrical geometry) for a 1,500 μm diameter grain. The $\bar{x}$ of Ar (for either phlogopite or amphibole) can be used in conjunction with the appropriate diffusion parameters (see legends to Figs 5 and 6) to generate a temperature (T) versus time (t) curve composed of an infinite number of (T–t) pairs corresponding to this $\bar{x}$. By plotting the T–t curves for both minerals, we obtain the conditions under which both isotopic data sets are internally consistent at the intersection of the two curves, where $t = 18$ kyr and $T = 526$ °C (Fig. 6). This intersection represents an integrated thermal spike experienced by the interiors of the ultramafic lenses due to heat conducted from the hot fluids in the surrounding eclogitized shear zones.

The temperature spike is consistent with the preservation of the

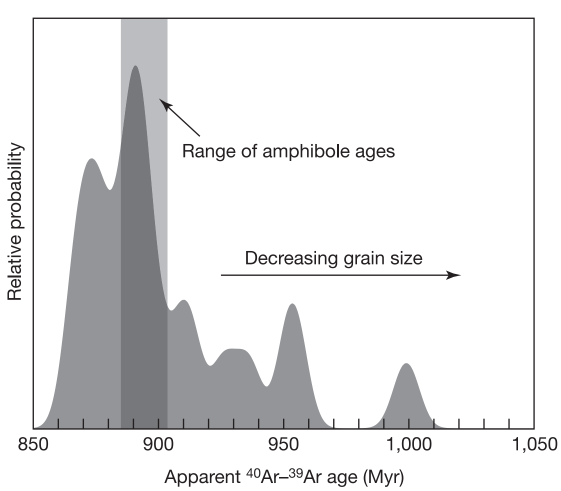

Figure 4 | Cumulative probability diagram of integrated ^{40}Ar–^{39}Ar ages for phlogopite from the Alvfjellet lens. The figure shows the correlation between older ages and decreasing grain size. Grains range from 1,600 to 200 μm in diameter ($n = 18$). The shaded band represents the same range of amphibole ages as shown in Fig. 2.

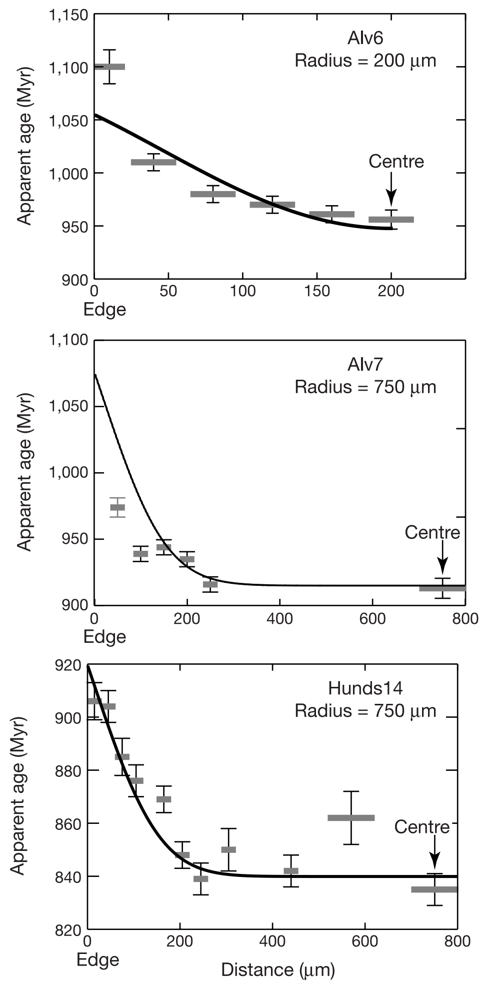

Figure 5 | Apparent ^{40}Ar–^{39}Ar age versus distance profiles across phlogopite from Alv6, Alv7 and Hunds14. On the horizontal axis, the length of the symbol represents the width of the trench analysed; the error on the age is $\pm 2\sigma$. Superimposed on these profiles are the theoretically derived apparent-age curves for volume diffusion of $^{40}Ar_E$ into different-sized phlogopites from the grain boundary due to a thermal spike of 526 °C lasting 18 kyr. Observed maximum diffusion distances of 200 μm are entirely consistent with the mean (integrated) diffusion distances of 79 μm discussed in the text. $^{40}Ar_E$ concentrations in the grain-boundary network are: Hunds14, 1.00×10^{-8} mol g^{-1}; Alv6, 1.37×10^{-8} mol g^{-1}; Alv7, 1.25×10^{-8} mol g^{-1}. These concentrations are remarkably similar to each other, suggesting that the fluids served as a common argon reservoir. Argon diffusion parameters for phlogopite[42] were used (activation energy $E = 242.3$ kJ mol^{-1} and pre-exponential coefficient $D_o = 7.5 \times 10^{-5}$ m^2 s^{-1}), together with a cylindrical diffusion geometry. Note that some of the ages within the profile are anomalously high relative to their position in the grain, and probably reflect the introduction of $^{40}Ar_E$ along structural defects[29].

diffusion profiles in phlogopite (Fig. 5). To preserve these age profiles, the ambient temperature of the rocks must have been well below 700 °C, because at that temperature the profiles would homogenize within 30–50 yr. Our new temperature estimate, however, indicates that the high temperature (~700 °C) determined for eclogite minerals within the shear zones cannot apply to the country rocks, and therefore, the common assumption that the temperature derived from metamorphic assemblages in shear zones reflects the ambient thermal regime may not be correct. Our calculated integrated heating time of only 18 kyr is much shorter than previous estimates for the life of the shear zones based on diffusion profiles in garnet (1–2 Myr)[12,22], although this difference may not be significant, given the uncertainties. However, the calculated duration of heating is consistent with the ~1 kyr period inferred from models of fracture-controlled eclogitization[4]. Our results not only are compatible with current experimental data for argon diffusion in phlogopite and amphibole, but also provide compelling evidence for diffusion-controlled argon gain under dry, static conditions (as the lenses are competent units within zones of deformation). Hence, it is not necessary to invoke anomalously high closure temperatures or the inhibition of intragranular diffusion under dry conditions[13] to explain the preservation of protolith ages.

Tectonic constraints

To constrain the duration of the complete orogenic cycle (subduction and exhumation of a particular segment of the crust), we combine a thermal model of subduction and exhumation with the diffusion modelling of the argon isotopes. Before discussing the modelling in detail, we first briefly review the tectonic regime during the late Caledonian.

Closure of the Iapetus Ocean during oblique collision between Baltica and Laurentia in Mid Silurian to Early Devonian times (the Scandian event of the Caledonian orogeny) led to the high-pressure subduction of the Baltic margin[23,24]. Before this collision, crustal movement is considered to be predominantly subhorizontal; tectonic events that transported crust to depth were confined to the continent–ocean transition zone of the Baltoscandian margin (Late Cambrian) and to the eastern margin of Laurentia (Mid to Late Ordovician)[24,25]. In the Bergen arcs, the Lindås nappe is considered to have a probable Baltica ancestry, and burial from depths of <30 km to ~60 km has therefore been linked with the onset of the Scandian collision[9]. The Scandinavian margin of Baltica subducted at rates of 6–10 cm yr^{-1} beneath Laurentia at ~430 Myr ago[25,26], with some estimates considering the entire Scandian event to have been of relatively short duration, ~40 Myr (ref. 27).

Modelling the crustal thermal regime

For the thermal model we used a modified version of the program Pecube[28] to estimate the pressure–temperature–time (*P–T–t*) path of a particle that is subducted and then exhumed during the collision/subduction event. This is done by solving the transient heat transport (by conduction and advection) equation in three dimensions. Figure 7 shows the *P–T–t* path (lasting 13 Myr) predicted by Pecube for the above tectonic regime of a particle that (1) was initially positioned at mid-crustal levels (20 km) of the subducting plate, (2) was subducted to a depth of 60 km in 1 Myr, (3) resided at that depth for 2 Myr after 'detaching' from the subducting plate (the choice of the duration of this interval is discussed below), and (4) was finally exhumed by moving back up the subduction channel to the

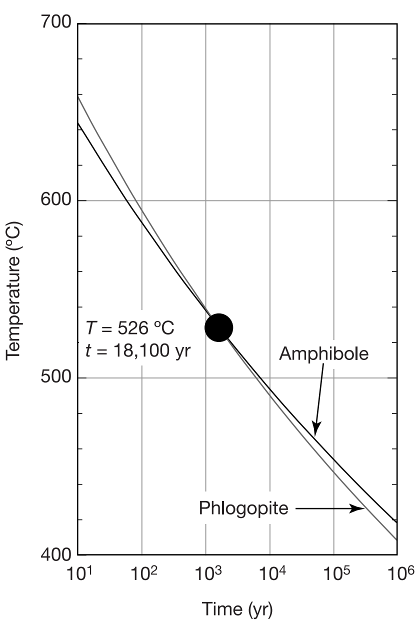

Figure 6 | Relationship between time and temperature required for a 300-μm-diameter amphibole grain and a 1,500-μm-diameter phlogopite grain to incorporate 3.97 vol.% and 20 vol.% $^{40}Ar_E$, respectively. The calculated curves incorporate a K_d of 0.6 and represent the corresponding conditions that yield respective mean diffusion distances of 2.01 μm (amphibole) and 79 μm (phlogopite). The two data sets are internally consistent only at the intersection of the two curves (time $t = 18$ kyr and temperature $T = 526$ °C). Argon diffusion parameters for phlogopite (as stated in Fig. 5) and amphibole[43] ($E = 268.3$ kJ mol^{-1} and $D_o = 2.4 \times 10^{-6}$ m^2 s^{-1}) were used.

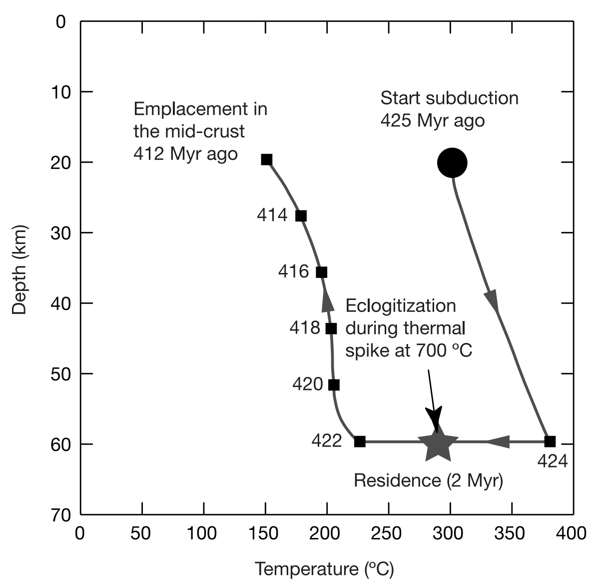

Figure 7 | Modelled pressure–temperature–time path for the Lindås nappe, Bergen arcs. Time markers (square symbols) are at 2 Myr intervals. The following geological constraints were used as input parameters. (1) The granulites of Holsnøy were at depths of 20 km before collision; (2) collision between Baltica and Laurentia commenced 430 Myr ago[23,44]; (3) subduction 425 Myr ago of the Lindås nappe beneath Laurentia occurred at a rate of 6 cm yr^{-1} (refs 25, 26); (4) eclogitization during a thermal spike at 700 °C at depths of 60 km (ref. 12) took place 423 Myr ago[9]; (4) exhumation to mid-crustal levels 413 Myr ago is constrained by Rb–Sr mineral isochron ages for amphibolite-facies overprint[30]. The modelled domain is a 300 km by 100 km cross-section through the upper lithosphere centred on the subduction zone with an angle of 45°. Radiogenic heat production is not considered, and a geothermal gradient of 15 °C km^{-1} is assumed. The thermal model has three phases: first, subduction for 1 Myr to bury the particle from 20 km to 60 km depth; second, the particle detaches from the subducting plate and resides at 60 km for 2 Myr; third, exhumation to the surface along the subduction zone to the mid-crust in 10 Myr. The residence and exhumation phases of the particle history are related to the formation of a thin channel 5 km wide (the width of Holsnøy island) that forms along the surface of the subducting slab.

mid-crust (20 km) in 10 Myr. Over the entire orogeny, subduction is continuous. The results show that during burial the particle experiences heating to a temperature of 385 °C, followed by substantial cooling after detachment at maximum depth (Fig. 7) because the cold adjacent slab continues to subduct, thus retarding steady-state thermal equilibrium. During exhumation, the particle heats up monotonically, with temperature never exceeding the value reached during burial. Significantly, the thermal modelling shows that with the imposed geological constraints (Fig. 7 legend) the particle never attains temperatures >400 °C.

The integrated thermal spike (total duration of 18 kyr at 526 °C) with concomitant uptake of $^{40}Ar_E$ during the period of residence at depth can now be superimposed on the thermal history from Fig. 7, and used in a modified finite-difference numerical model[29] of argon mobility in phlogopite. Volume-diffusion modelling using this *T–t* history yields remarkably good correlations between the calculated diffusion profiles and the age data from the phlogopites (Fig. 5). Although the durations of both subduction (1 Myr) and exhumation (10 Myr) are relatively well-constrained[4,9,30], the residence time of the rocks at maximum depth is not well-known. Because of the high sensitivity of the argon systematics to different thermal regimes, however, we can now place narrow limits on the residence time of the subducted crust at maximum depth. Coupling the argon diffusion and thermal models provides an iterative feedback mechanism for the refined fitting of the diffusion profiles (Fig. 5); the results show that residence times longer than 2 Myr result in poor fits.

Spasmodic fluid injection

Finally, by using thermal diffusivity data[31], we can reconcile the heating of an ultramafic lens with our integrated thermal spike. Assuming an ambient (initial) *T* of 385 °C (Pecube results) and fluids (passing through the shear zones) acting as a constant heat source (at 700 °C)[32], heat-conduction calculations show that the core of a lens 30 m in diameter will attain a temperature of 526 °C in ~10 yr, substantially shorter than our total heating duration estimate of 18 kyr, and at first sight, geologically implausible. However, this apparently contradictory result can be reconciled with our data if the shear zones were repeatedly injected by hot fluid for very short periods (~10 yr), with each injection event only affecting the integrated thermal budget such that the mean temperature of the entire terrane did not exceed 400 °C. This is exactly what would be expected if fluid migration was triggered by multiple, spasmodic deformation events associated with earthquakes. Evidence for earthquakes and brittle deformation abounds in the Bergen arcs, where hydraulic fracturing[33] and the presence of pseudotachylytes[34] are closely associated with the eclogite-bearing shear zones[4]. Thus, the 18 kyr duration of the thermal spike calculated above represents the integrated time over the 2 Myr residence period of the terrane at 60 km depth in which multiple, short-lived fluid pulses were active.

A new cold-crust model

We therefore propose a new model for the behaviour of the subducting continental lithosphere, in which the rate of subduction and exhumation far outstrips the ability of the temperature of the subducting crust to equilibrate. This alternative interpretation is attractive because it elegantly explains: (1) the widely described 'metastability' of non-eclogitized domains[2,10,35–37]; (2) steep diffusion profiles in relict minerals in partially transformed eclogite[22]; and (3) brittle behaviour of the crust at high pressure[34]. In this model, the crust remains cool and is repeatedly deformed at high strain rates. Heating is transient, and is caused by either fluid advection along shear zones or frictional heating[38]. An important consequence of the model is that for transient, episodic fluid flow, the widespread practice of estimating crustal fluid volumes on a time-integrated basis[39] does not apply. This study provides a new quantitative approach for constraining the cycle of burial and exhumation of a segment of the crust during orogenesis; given that the bulk of the crust remained relatively cool (≤400 °C), thermal modelling combined with volume-diffusion argon modelling indicate that the timescale for the complete orogenic cycle of the Lindås nappe in the Bergen arcs must have been 13 Myr or less (Fig. 7). This timescale for orogenesis is considerably shorter than previous estimates of ~40 Myr (ref. 27) for the Scandian collision, and may be relevant to continental collisions in general.

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