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Direct dating of mylonite evolution: a multi-disciplinary geochronological study from the Moine Thrust Zone, NW Scotland

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Abstract: Rb–Sr dating of sub-closure temperature, syn-deformationly crystallized white micas from the Moine mylonites (Knockan and Dundonnell), has yielded ages which vary from 437 Ma to 408 Ma. Morphological and major element analyses of the micas indicate that all the micas within the analysed samples were (re)crystallized during the Moine Thrust shearing. The ages yielded are therefore interpreted as marking the end of crystal plastic deformation associated with shearing on the Moine Thrust. The variation in ages between samples is significantly greater than the individual analytical errors and may be a product of strain localization within the shear zone. Alternatively it may indicate flow of strontium-rich fluids derived from outside the shear zone implying that feldspars may act as potentially unreliable initial isotopic reservoirs even in very high strain samples within the greenschist-facies shear zones. However, the Rb–Sr age are internally consistent and compatible broadly with existing geological and geochronological data for the region suggesting that even if the feldspars have not acted as perfect initial isotopic reservoirs the resulting errors were minimal. The general cessation of ductile deformation at *c*. 430 Ma probably dates the general initiation of imbrication within footwall to the Moine Thrust. The age of 430 Ma is therefore likely to be a time of significant brittle displacement on the underlying Ben More Thrust.

K–Ar dating of the (re)crystallized Moine mylonite micas yielded anomalously old ages in comparison to Rb–Sr values as a result of incorporation of excess Ar during shearing. The degree of incorporated excess Ar decreases away from the base of the shear zone into the hanging wall, becoming indiscernible at *c*. 1.5 km structurally above the base of the shear zone. The distance (*c*. 1.5 km) may represent the distance that fluid can have flowed out of the shear zone during deformation.

Keywords: Moine Thrust Zone, Caledonides, absolute age, mylonites, shear zones.

The Moine Thrust Belt represents the Caledonian Front in NW Scotland (e.g. Coward 1983; Fig. 1). The Moine Thrust, which forms the roof of the eponymous thrust belt (Elliott & Johnson 1980), is structurally the lowest of a series of thrust-sense shear zones within the Moine (e.g. Butler 1986; Barr *et al*. 1986). Collectively, all these structures, above and below the Moine Thrust, are characterized by a classic inverted metamorphic succession with high-grade units carried on high-grade shear zones in the hinterland, with successively lower grade units being carried on lower grade shear zones out towards the foreland (e.g. Soper & Barber 1982; Kelley & Powell 1985). Within the Moine Thrust Belt these lower grade shear zones are carried on cataclastic fault systems (Butler 1982). Collectively these structures, especially the Moine mylonites, accomodated displacement which is estimated to be potentially in excess of a hundred kilometres (Elliott & Johnson 1980; Butler & Coward 1984; Butler 1986).

Although the general kinematic and metamorphic conditions for Caledonian deformation are well-established, the timing of structures is less certain. To date the timing of deformation has relied on using igneous bodies, particularly the alkaline intrusions of the Assynt district (Fig. 1), which are tied to the sequence of thrust evolution (Elliott & Johnson 1980). However, recent studies have raised doubts on the interpretation of critical field relationships between the intrusions and thrusts in southern Assynt (e.g. Butler 1997). Furthermore, the suitable intrusions are found only locally within the thrust belt and so igneous geochronology can only provide sporadic dating of deformation. Consequently, the aim of this contribution is to report on direct dating of deformation within thrust related mylonites with a view to understand better the timing of displacements within the Moine thrust belt. We combine structural, chemical and isotopic information to directly date the cessation of crystal–plastic deformation within the Moine mylonites using the Rb–Sr system applied to synkinematic white mica. Limitations of this system and the use of K–Ar methods are also discussed along with the effects of dynamic fluid flow within deforming mylonite zones.

Previous work: dating in the Moine Thrust Belt

Within the Caledonides of Scotland in general, and particularly to the northwest of the Great Glen (Fig. 1), the timing of orogenic events is critically reliant upon age-dating of plutonic rocks. The Ross of Mull granite cross-cuts and metamorphoses mylonitic Moine metasediments together with Lewisian rocks which are assumed to be part of the foreland, cropping out on the island of Iona. A crystallization age of the granite has been obtained using the Rb–Sr method (Halliday *et al*. 1979) of 414 ± 4 Ma, a date which is generally inferred to bracket the end of Caledonian thrusting on the Scottish mainland. However, the status of the Lewisian rocks on Iona as being part of the foreland is uncertain: the Moine thrust sheet also contains Lewisian basement.

The Assynt district of NW Scotland hosts the only sizeable Palaeozoic intrusions beneath the Moine Thrust and these have long been used to provide a timescale for thrusting (e.g. Elliott & Johnson 1980). The early part of the Borrolan complex has yielded a crystallization age of 430 ± 4 Ma (U–Pb zircon age, van Breeman *et al*. 1979). More recently, the Loch Ailsh syenite has yielded a crystallization age of 439 ± 4 Ma

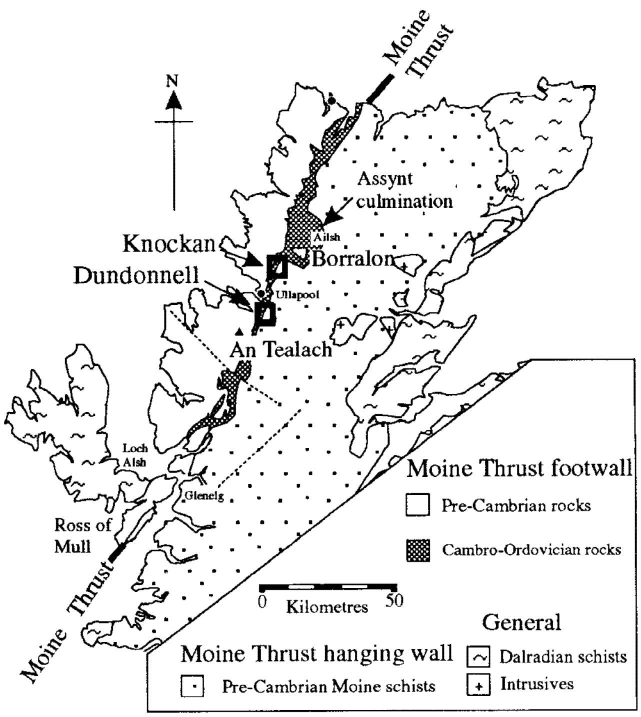


Fig. 1. Simplified geological map of N Scotland after Brown *et al.* (1965). Map shows places mentioned within the text.

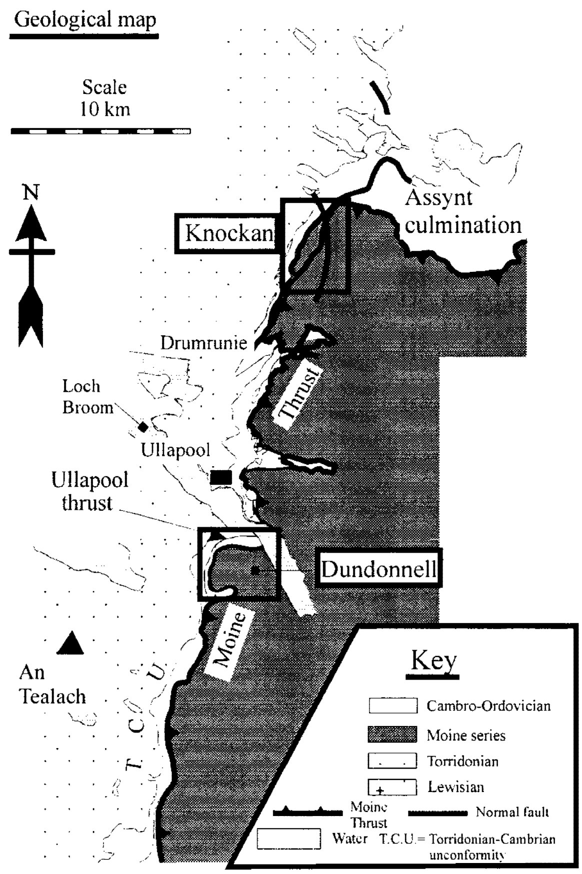


Fig. 2. Simplified geological map of the Moine Thrust Zone in the Ullapool–Assynt area, adapted from the BGS survey sheets. The map shows places mentioned within the text.

(^{207}Pb–^{206}Pb zircon, Halliday *et al.* 1987). The Loch Ailsh body has been interpreted as cutting Caledonian structures in the footwall while being decapitated by the Moine Thrust (Milne 1978) and thus being broadly coeval with thrusting. However, Halliday *et al.* (1987) and Butler (1997) show that the intrusion entirely predates those structures which are unambiguously Caledonian and thus it places only an upper age bracket on the timing of deformation.

In contrast, the Borrolan intrusion appears to cut the Ben More Thrust (Parsons & McKirdy 1983) and thus was emplaced during thrusting. However, structural correlations in the poorly exposed ground of southern Assynt are equivocal (e.g. Coward 1985). What is clear is that part of the deformation within the imbricates, which underly the Moine Thrust and which truncate the Borrolan complex, must have occurred after *c.* 430 Ma.

Cooling ages from metamorphic rocks, particularly from the hanging wall of the Moine Thrust, have been used to bracket deformation. K–Ar dates from micas may be linked to closure temperatures of muscovite and biotite (*c.* 350°C and 300°C respectively; Purdy & Jäger 1976; Hames & Bowring 1996). Brown *et al.* (1965) and Kelley (1988) applied this technique to parts of the Moine thrust sheet. Unfortunately the presence of excess radiogenic Ar lends substantial uncertainties to these K–Ar studies (Brown *et al.* 1965; Kelley 1988). However, both studies point to a cooling of the hanging wall of the Moine Thrust to below *c.* 300°C by *c.* 425 Ma.

The transition from crystal plastic to cataclastic deformation in quartz-rich fault rocks is generally considered to occur at about 300°C (Passchier & Trouw 1996), assuming conventional strain rates. Thus the cooling age of 425 Ma from the Moine mylonites may record the termination of significant crystal–plastic deformation. This interpretation is reinforced by Johnson *et al.* (1985) who have interpreted K–Ar biotite data obtained from metasediments in the hanging wall to the Moine Thrust as indicating that emplacement of the Moine Thrust Zone in the Dundonnell area (Fig. 2) occurred at *c.* 425 Ma. However, these researches have not yielded direct ages of deformation: the geochronological data are not tied to specific deformation structures and microstructures. Thus it is unclear whether they date shearing or post orogenic erosion. It is possible that deformation continued for a significant time after 425 Ma, or alternatively that it ceased several million years prior to this time.

Geochronology of deforming rocks

A variety of geochronological tools are available for the direct dating of deformation fabrics within shear zones. However, of all the potential isotopic and mineral systems, only a few are applicable. Most critically, in order to date synkinematic crystallization, the closure temperature (in the sense of Dodson 1973) for a particular isotopic system within a specific mineral phase must be higher than the synkinematic temperature (Getty & Gromet 1992). This occurs when minerals crystallize substantially below the closure temperature of the particular isotopic system.

There are two main requirements for the dating system which is used: it must yield reproducible ages, and the system must be directly related to the deformation fabric. At present, the system which best fills these criteria for greenschist-facies rocks is the Rb–Sr system applied to white mica bearing assemblages. Elsewhere, we have applied Rb–Sr white mica dating to calc-schist tectonites collected from Neogene-age shear zones in the western Alps (Freeman *et al.* 1997, 1998). The requirement for Rb–Sr deformation dating is that white mica either crystallized or recrystallized during ductile deformation, in isotopic equilibrium with the grain boundary fluid. The isotopic composition of the fluid must also be determined and this is achieved using either a mineral which acts as a proxy for the isotopic composition of the initial grain boundary fluid or a mineral which dominated the strontium composition of the grain boundary fluid. In our previous studies using the Rb–Sr system on calc-mylonites, the major reservoir of strontium in the bulk rock is calcite. In high-strain samples, mica and calcite can be shown to have grown in textural, and presumably isotopic, equilibrium. Provided the calcite–white mica system remains unaffected by post-kinematic fluxes of externally derived strontium, the calcite should act as a reliable proxy for the strontium isotopic composition of the mica at the time of crystallization. Enrichment of radiogenic strontium within the mica can thus be used to quantify the time since crystallization and thus date deformation. The challenge of the study reported here is to apply the same methodology to Palaeozoic-age shear zones with quartzo-feldspathic protoliths.

Within quartzo-feldspathic lithologies, the bulk of the Sr is contained within feldspars. However, unlike calcite, under mid-crustal conditions these minerals may not be actively involved with the deformation. The feldspars may act as porphyroclasts (e.g. Passchier & Trouw 1996). If no external Sr enters the shear zone it is likely that the limited recrystallization and local grain boundary exchange of Sr out of the feldspars will control the grain boundary Sr composition (Freeman *et al.* 1997). In such circumstances, the feldspars will act as reliable proxies for the grain boundary Sr composition. Unfortunately, when external Sr bearing fluids enter a mid-crustal shear zone, minerals which are not actively recrystallizing are unlikely to re-equilibrate with the grain boundary fluid (McCaig *et al.* 1995). If these unequilibrated phases are used in part to define the initial isotopic composition of the micas, the resultant ages may be unreliable. The characterization of such processes is obviously important if precise ages for ductile deformation are sought within quartzo-feldspathic mylonites. Here we combine structural, textural, chemical and radiogenic isotope studies in an attempt to relate the relative degrees of equilibration of these systems. Before we present our results from the quartzo-feldspathic mylonites of the Moine Thrust zone, we examine the uses and limitations of the widely used K–Ar system in the determination of metamorphic cooling ages.

The K–Ar system has been extensively used in attempts to determine the timing of deformation through the interpretation of cooling histories. One of the fundamental assumptions behind the K–Ar technique is that no 'excess' radiogenic argon is present within the crystal when it closes and loses isotopic communication with the rest of the rock (Faure 1986). There is a simple test of the validity of this assumption. In the K–Ar system the biotite closure temperature is less than that of muscovite. Therefore biotites are expected to yield younger cooling ages than co-existing muscovites. If the minerals crystallized at or below their closure temperature, then muscovites and biotites should yield the same age. In many natural shear zones, biotite yields older ages than co-existing muscovite (e.g. Roddick *et al.* 1980). In such zones, argon in the grain boundary network is preferentially incorporated into biotite, rather than muscovite mineral lattices (e.g. Dahl 1995). If the isotopic composition of this additional argon is enriched in the radiogenic isotope then biotites yield older apparent ages than co-existing muscovites. The extra radiogenic component is termed 'excess argon'. Paired K–Ar ages for co-existing biotite and muscovite can be used to assess the role of 'excess argon' in the system (e.g. Roddick *et al.* 1980).

The temperature of deformation within low-mid-greenschist facies mylonites is either close to, or above the argon closure temperature in micas (Purdy & Jäger 1976). The Rb–Sr closure temperature of muscovite is *c.* 550°C (Cliff 1985). It is assumed that the closure temperature of phengite is close to that of muscovite. Therefore at *c.* 300–400°C, the approximate temperature that deformation changes from being crystal–plastic to cataclastic within quartzo-feldspathic rocks at usual strain rates, strontium is *c.* 200°C below its closure temperature. Therefore diffusion into, and out of the grain is effectively zero over geological time and the Rb–Sr system dates the recrystallization event. A second advantage of the Rb–Sr system over the K–Ar system is that when implementing the Rb–Sr technique the intial isotopic composition of the rock is measured, albeit via a proxy, not assumed.

The Moine mylonites

Thrust systems are generally thought to migrate towards the foreland with time, a feature common to interpretations of the Moine Thrust Belt (Elliott & Johnson 1980; Butler & Coward 1984). However, more recent studies have suggested more complex patterns of thrusting (Butler 1987). If the mica (re)crystallization event is the target for dating it is important to establish whether any reworking of the mylonite occurred significantly after the cessation of the main shearing event. Breaching of the Moine mylonites, which form the Moine Thrust, by footwall structures is known to have occurred in a number of areas (Butler 1982, 1987). In such areas, reworking of the Moine mylonite by its footwall will generate a variation in the age of recrystallization that does not relate directly to the age of the main movement on the Moine Thrust. The areas studied here were chosen to minimise these effects. The Dundonnell area (Fig. 1) is characterized by piggy-back thrusting (Elliott & Johnson 1980) while the Knockan area preserves Moine mylonites which truncate and overstep footwall structures (Coward 1985; Butler 1987). Therefore any variation in the age of the cessation of recrystallization within these sections represent heterogeneous shearing during the main phase of thrust emplacement of the Moine sheet.

The regional direction of thrusting may be determined by mineral lineations defined by quartz and feldspar aggregates, showing a consistent WNW–ESE movement direction along the length of the Moine Thrust. All shear criteria (in the sense of Hanmer & Passchier 1991) show an overshear towards the WNW in all the localities. This is also seen consistently throughout the Moine Thrust Belt (Elliott & Johnson 1980; Coward 1983, 1985; Butler & Coward 1984).

The longitudinal transect from An Tealach to Southern Assynt (Fig. 1) displays a significant change in structural complexity. Late, localized detachments occur at the base of the Moine sheet giving rise to overstep geometries and the truncation of footwall structures (Coward 1983; Butler 1987) in southern Assynt. Similar geometries may be recognized to the south as far as Loch Broom (Fig. 2). On the South side of Loch Broom and continuing to An Tealach, the base of the Moine sheet shows no evidence of the overstep geometries, yet all areas record late, limited, diffuse cataclasis. At Knockan it is a late brittle fault that carries the Moine mylonites.

If the mylonites are deforming as one wide pervasive zone of shear, the ages from each section through the mylonites should be the same. The two sites (Knockan and Dundonnell, Fig. 2) are along tectonic strike from each other, which should mean that similar ages should be yielded from the two sections, but due to the complexity of the later deformation this cannot be demonstrated from field relationships.

Moine mineral chemistry

The principal reason for our analysis of mica chemistry was to identify the mica population related to the ductile deformation along the Moine Thrust. It is important to assess if the bulk population is a mixture of synkinematic and inherited grains. A mixture of significant proportions of mica grown at different times will not yield deformation ages (Dempster 1992). A secondary purpose was to find how the composition of the white micas had evolved through time. This can help constrain the ambient pressure and temperature conditions at the time of crystallization. The University of Leeds Camscan series 4 scanning electron microscope was used for the electron-optic investigation of samples and the Cameca SX 50 microprobe for the chemical analyses. For a full description of running conditions see Freeman *et al.* (1997). Table 1 shows microprobe phengite analyses from seven samples from Knockan and Dundonnell. The data show that the phengite chemistry is remarkably constant within individual samples, within areas close to each other, and between Knockan and Dundonnell. Figure 3 is a graphical compilation of the phengite data. The analyses shown had good stoichiometries and total percentages between 99 and 101% when H_2O was considered.

Massone & Schreyer (1987) show that, within a buffered, fixed assemblage, like the Moine mylonites, the composition of white mica is controlled both by pressure and temperature during crystallization. The graphs in Fig. 3 show that the phengites have a remarkably consistent composition within each individual sample, and throughout all the samples from all the localities. The similarity in composition of the phengites indicates that the P–T conditions varied only minimally during the crystallization history. The single composition indicates that any geochronological study of the white micas should not be contaminated by mica crystallization events that occurred at substantially different P–T conditions. Furthermore, the tight chemical groupings (Fig. 3) indicate that the micas approached elemental equilibrium during crystallization. It is highly likely that isotopic equilibration was also achieved (Freeman *et al.* 1997).

The Moine mylonites are predominantly composed of quartzo-feldspathic lithologies. Limited carbonate was observed within the samples studied, whereas feldspars were prolific in the majority of specimens. The overwhelming Sr reservoir within these rocks therefore lies within the feldspars. Electron microprobe analyses were conducted to assess the likely degree of chemical exchange during the deformation. Prior to mylonite formation, the Moine rocks underwent a higher grade metamorphic event (Kelley & Powell 1985). If the feldspars can be shown to be in chemical equilibrium for those lower temperatures and pressures during mylonitization then isotopic exchange is likely to have occurred during the deformation.

Both K-feldspar and albite are present in the analysed samples; microprobe analyses are shown in Table 2. The feldspars show pronounced crystallization during the mylonitic deformation. They have very obvious tails which are formed from significantly more Ca-rich oligoclase (Fig. 4). The composition of the plagioclase changes from *c.* 3 wt% Ca in the cores, to *c.* 11 wt% Ca in the tails. This relationship has been seen previously in low grade metapelites by Crawford (1966). Figure 4 shows a series of backscattered atomic number contrast images of samples from both Dundonnell and Knockan. In these images, the Ca-rich portions of feldspar are lighter. We interpret the concentric rings in the tails as charting the synkinematic growth of feldspars.

Figure 5 shows feldspar compositions for several samples. At temperatures in the region of the deformation in the Moine mylonites (*c.* 350°C), the feldspars would be evolving around the peristerite solvus for feldspar compositions of 2–15 wt% Ca content. With decreasing temperature, plagioclase with initial Ca contents of 3–15 wt% would create two phases of feldspar with a composition defined by tie lines joining across the peristerite solvus (Smith 1983). The Ca content of the oligoclase feldspars formed would increase to a maximum of *c.* 15 wt%. While the coexisting albite would be reduced to *c.* 1–2 wt%. In the Moine samples the main overgrowths seen around the early albites are Ca rich oligoclase, no obvious lower Ca albites exist in conjunction with this oligoclase. The phase diagrams of Smith (1983) suggest that the base of this solvus is at *c.* 400°C. Our morphological and microchemical data show that the feldspar tails were recrystallizing and chemically exchanging during deformation within the Moine mylonites.

Variations in the calcium content of plagioclase formed within mylonites from the Moine Thrust zone have previously been described by Winsch & Knipe (1983). They proposed that these variations in calcium content were a response to syntectonic variations in the composition of grain boundary fluid. With fluid composition evolving as phases recrystallize, a corollary is that large volumes of Sr, derived from feldspars, dominated the synkinematic isotopic compositon of the grain boundary fluid. We infer that the original feldspar grains, now represented by the cores of grains, together with the synkinematic overgrowths, had essentially the same $^{87}Sr/^{86}Sr$ ratio. Thus a single isotopic composition for the feldspar reservoir is our assumed initial value for the synkinematic mica.

The morphology and the chemistry of the feldspars suggests that the central cores of the grains probably remained as porphyroclasts during the main mylonitic deformation. Conversely, the calcium-rich overgrowths display synkinematic textures. However, the timing of this feldspar growth relative to the mica is uncertain. It is possible that overgrowth formation was relatively early within the deformation history in comparison to the mica crystallization. If true, the grain boundary-fluid Sr composition may have evolved significantly between feldspar precipitation and mica precipitation. However, to alter significantly the Sr composition of the grain boundary fluid from the feldspar composition would require a large influx of fluid with a significantly different Sr composition. There is no evidence for such processes having acted.

Syn-kinematic conditions of pressure and temperature

The Rb–Sr white mica method of dating deformation fabrics relies upon a confirmation that the temperature of deformation was considerably lower than the closure temperature of

Table 1. *Moine mylonite phengite major element analyses from samples used for geochronological investigations*

Sample	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	Ca	Na_2O	K_2O	H_2O	F	Cl	O = F	Total	Si	Ti	Al	Fe^2	Mn	Mg	Ca	Na	K	OH	F	Cl	Total	Fe#
Kn2-1	48.03	0.29	28.97	4.51	0.02	2.35	0	0.09	10.78	4.32	0.2	0	0.08	99.4	6.52	0.03	4.6	0.51	0.003	0.475	0.00	0.024	1.8	3.91	0.0	0	18.07	52
Kn2-2	48.1	0.35	29.19	3.73	0.18	2.24	0	0.18	10.78	4.36	0.1	0.0	0.04	99.1	6.53	0.036	4.6	0.42	0.021	0.454	0	0.047	1.8	3.95	0.0	0.0	18.05	49.5
Kn3-1	48.16	0.3	29.68	4.62	0	2.05	0	0.13	10.93	4.37	0.16	0	0.07	100.0	6.48	0.03	4.7	0.52	0	0.412	0	0.034	1.8	3.93	0.0	0.0	18.08	55.8
Kn3-2	49.36	0.25	28.99	4	0	2.11	0	0.07	10.94	4.47	0	0	0	100.0	6.62	0.026	4.5	0.44	0	0.422	0	0.019	1.8	4	0	0	18.00	51.5
Kn5-1	51.66	0.36	29.17	4.4	0	2.38	0.0	0.06	7.7	4.49	0.16	0	0	100.0	6.77	0.035	4.5	0.48	0	0.466	0.00	0.017	1.2	3.93	0.0	0	17.5	—
Kn5-2	50.82	0.3	30.5	3.98	0.05	2.01	0	0.11	8.2	4.57	0	0.0	0	100.0	6.66	0.029	4.7	0.43	0.005	0.393	0	0.028	1.3	3.99	0	0	17.6	—
D1-1	49.45	0.48	31.39	3.74	0	1.76	0.0	0.07	8.61	4.49	0.1	0.0	0.04	100.0	6.53	0.048	4.8	0.41	0	0.347	0.00	0.017	1.4	3.95	0.0	0.0	17.70	54.4
D1-2	49.33	0.37	31.15	3.7	0	1.73	0.0	0.09	8.8	4.51	0	0.0	0	99.7	6.55	0.037	4.8	0.41	0	0.343	0.00	0.024	1.4	3.99	0	0.0	17.73	54.5
D4-2	48.67	0.36	27.55	6.26	0.1	1.8	0	0.12	10.89	4.37	0.08	0	0.03	100.0	6.62	0.037	4.4	0.71	0.011	0.365	0	0.031	1.8	3.96	0.0	0.0	18.09	66.5
D4-2	48.61	0.57	28.32	4.24	0	2.04	0	0.18	10.91	4.41	0	0.0	0	99.3	6.60	0.059	4.5	0.48	0	0.412	0	0.047	1.8	3.99	0	0.0	18.03	53.9
D8-1	48.32	0.37	30.79	3.66	0.12	1.69	0.0	0.11	10.79	4.36	0.26	0.0	0.11	100.0	6.46	0.038	4.8	0.41	0.014	0.338	0.00	0.028	1.8	3.88	0.1	0.0	18.0	55.6
D8-2	49.57	0.13	29.22	4.15	0.04	1.6	0.0	0.19	10.43	4.46	0	0.0	0	99.8	6.66	0.013	4.6	0.46	0.005	0.321	0.00	0.049	1.7	3.99	0	0.0	17.93	59.5
D9-1	48.49	0.49	30.35	3.63	0	1.79	0.0	0.14	10.7	4.38	0.18	0.0	0.07	100.0	6.50	0.05	4.7	0.40	0	0.358	0.00	0.035	1.8	3.92	0.0	0.0	17.98	53.2
D9-2	49.25	0.29	30.75	3.62	0.12	1.81	0	0.08	10.49	4.52	0	0.0	0	100.0	6.53	0.029	4.8	0.40	0.014	0.358	0	0.021	1.7	3.99	0	0.0	17.93	53.7

Samples are from both Knockan (Kn) and Dundonnell (D). Note the very consistent major cation values for samples in the same area and between Knockan and Dundonnell. Dundonnell phengites contain slightly lower Si contents than the Knockan samples.

strontium in white mica (*c.* 550°C; Cliff 1985). For our study, samples were analysed from the local Moine hanging-wall in the areas of intense shearing to assess the ambient *P–T* conditions. The mylonites contain mineral assemblages of quartz + plagioclase + K-feldspar + white mica + biotite ± chlorite ± garnet ± calcite ± epidote ± titanite. However, garnet is generally not in textural equilibrium and forms inherited porphyroclasts. For an iron-rich pelite, the assemblage of Ksp + Bio + Chl suggests temperatures of *c.* 400°C (Spear & Cheney 1989). This temperature estimate is substantially below that for closure of strontium diffusion in white mica. Therefore the thermal requirements of the Rb–Sr fabric geochronological technique to date mylonitic deformation on the Moine Thrust are met.

The pressure during mylonitization can be estimated from the Si content of phengite using the calibration of Massone & Schreyer (1987). The Si contents for all the samples is in the range of 3.25–3.35 per formula unit (pfu, Fig. 3). This equates to pressures of 5–7.5 kbar at 400°C. The samples from Dundonnell have an average Si content which is less than 3.3 pfu, whereas the samples from Knockan have an average Si content greater than 3.3 pfu. There is no apparent difference in bulk rock chemistries between the two areas, therefore the difference in Si content in the phengites is likely to reflect variations in pressure and temperature. This implies that the Knockan area was at higher pressures or lower temperatures. The difference in the phengite compositions indicates a possible pressure difference of *c.* 1 kbar or a temperature difference of *c.* 100°C. The ductile Moine Thrust was therefore probably active at temperatures of 400 ± 50°C at approximate pressure conditions of 5–7.5 kbar.

Geochronology

A complete description of the Rb–Sr technique is provided elsewhere (Freeman *et al.* 1997). We calculate Rb–Sr ages using a two-point isochron of white mica and feldspar. Samples were only analysed where the rock's Sr budget was overwhelmingly dominated by the mineral taken as the initial $^{87}Sr/^{86}Sr$ phase. Errors were assessed by replicate analyses of natural samples, which gave reproducibilities of $^{87}Rb/^{86}Sr = 1.2\%$, $^{87}Sr/^{86}Sr = 0.0046\%$ (2σ). It follows from these analytical errors and typical mica compositions that the error in the age is dominated by the Rb–Sr uncertainty. These errors were propagated through age calculations using Isoplot (Ludwig 1990).

Bulk feldspar separates were used to obtain the initial $^{87}Sr/^{86}Sr$ ratio of bulk mylonite samples and therefore of the white mica. In the preceding discussion we suggested that a better option would have been to use only the synkinematic feldspar represented by the overgrowths. However, existing microsampling techniques have a spatial resolution of *c.* 100 μm (e.g. Meffan-Main & Cliff 1997). This is substantially larger than that required for the extraction of the feldspar overgrowths. This meant that the bulk feldspars were the only option. All the samples were crushed, sieved and washed prior to mineral separation. The feldspar separates were taken from the 180–125 μm size fraction, while the white micas were extracted from the 125–100 μm size fraction. However, minor inclusions of quartz and K-feldspar increase the amount of Sr

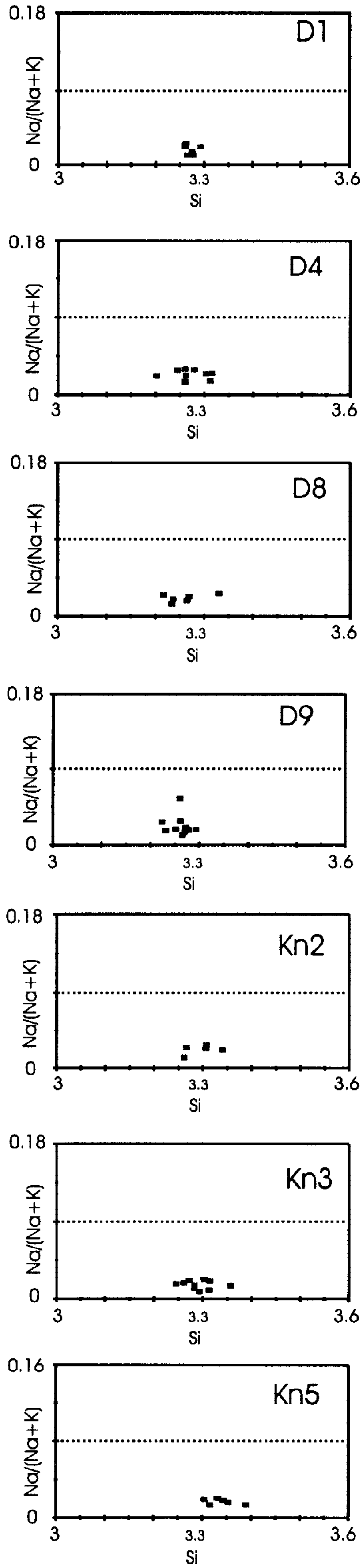
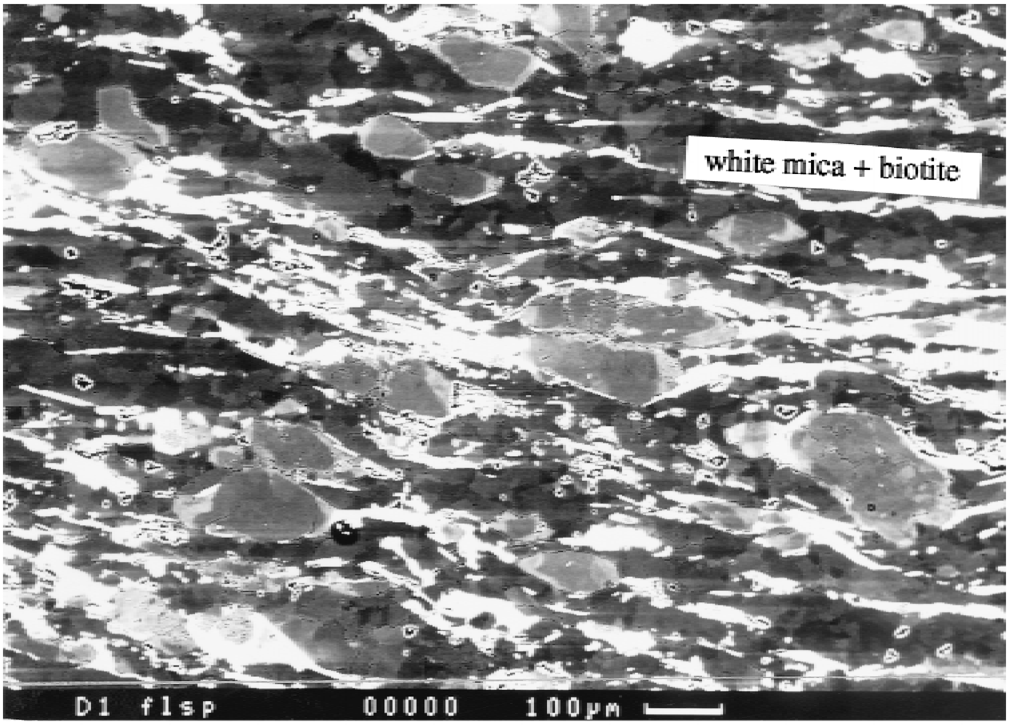


Fig. 3. Alkali versus Si plots for samples from both Knockan (Kn) and Dundonnell (D).

Table 2. *Moine mylonite feldspar major element analyses from Knockan (Kn) and Dundonnell (D). Albite tails/rims consistently record elevated Ca contents than cores*

Sample	Mineral	SiO_2	Al_2O_3	Fe_2O_3	Mn	Mg	Ca	Na_2O	K_2O	Total	Si	Al	Fe^3	Mn	M	Ca	Na	K	Total	Ca	Na	K+B
Kn2	ksp	65.09	18.38	0	0.02	0	0	0.69	15.51	99.69	3.00	1	0	0	0	0	0.062	0.914	4.982	0	6.3	93.7
	alb	69.32	19.77	0.09	0	0.02	0.27	12.2	0.09	101.76	2.98	1.003	0.003	0	0.0	0.013	1.018	0.005	5.025	1.2	98.3	0.5
Kn3	ksp	64.55	18.61	0.14	0	0	0.03	0.43	15.64	99.4	2.99	1.016	0.005	0	0	0.001	0.039	0.925	4.979	0.1	4	95.8
	alb	69.52	19.89	0	0.02	0	0.16	11.91	0.1	101.6	2.99	1.008	0	0	0	0.008	0.993	0.005	5.005	0.8	98.7	0.5
	alb	67.44	20.92	0.09	0.11	0	1.58	11.14	0.1	101.38	2.92	1.068	0.003	0.00	0	0.073	0.936	0.006	5.013	7.2	92.2	0.6
Kn5	alb1	68.58	19.21	0	0.14	0	0.28	11.56	0.11	99.88	3.00	0.991	0	0.00	0	0.013	0.981	0.006	4.997	1.3	98.1	0.6
	alb2	65.52	21.09	0.008	0.02	0	2.51	10.19	0.18	99.6	2.89	1.098	0.003	0	0	0.119	0.873	0.01	4.997	11.8	87.2	1
	alb3	66.93	20.3	0.08	0	0	1.49	10.89	0.13	99.81	2.94	1.051	0.003	0	0	0.07	0.928	0.007	5	7	92.3	0.7
	ksp1	64.16	18.13	0.12	0.04	0.02	0	0.29	15.64	98.39	3.00	1	0.004	0.00	0.0	0	0.027	0.934	4.973	0	2.8	97.2
	ksp2	64.19	18.05	0.09	0	0.01	0	0.31	15.78	98.43	3.00	0.997	0.003	0	0	0	0.028	0.943	4.979	0	2.9	97.1
D1	alb	66.11	21.33	0.09	0	0	2.38	10.73	0.11	100.75	2.88	1.098	0.003	0	0	0.111	0.909	0.006	5.017	10.8	88.5	0.6
	alb	68.39	19.54	0	0	0	0.38	11.61	0.1	100.02	2.98	1.007	0	0	0	0.018	0.984	0.006	5.003	1.7	97.7	0.6
	ksp	64.4	18.26	0.13	0	0	0	0.36	15.89	99.05	3	1.003	0.004	0	0	0	0.032	0.945	4.985	0	3.3	96.7
D4	alb	65.68	19.83	0.18	0	0	1.22	11.06	0.14	98.1	2.94	1.046	0.006	0	0	0.059	0.959	0.008	5.018	5.7	93.5	0.8
D9	alb	67.86	20.32	0.04	0.06	0	0.94	11.49	0.09	100.81	2.95	1.041	0.001	0.00	0	0.044	0.969	0.005	5.014	4.3	95.2	0.5
	alb	68.49	19.63	0.08	0	0	0.18	12	0.12	100.49	2.98	1.008	0.003	0	0	0.008	1.013	0.007	5.022	0.8	98.5	0.7



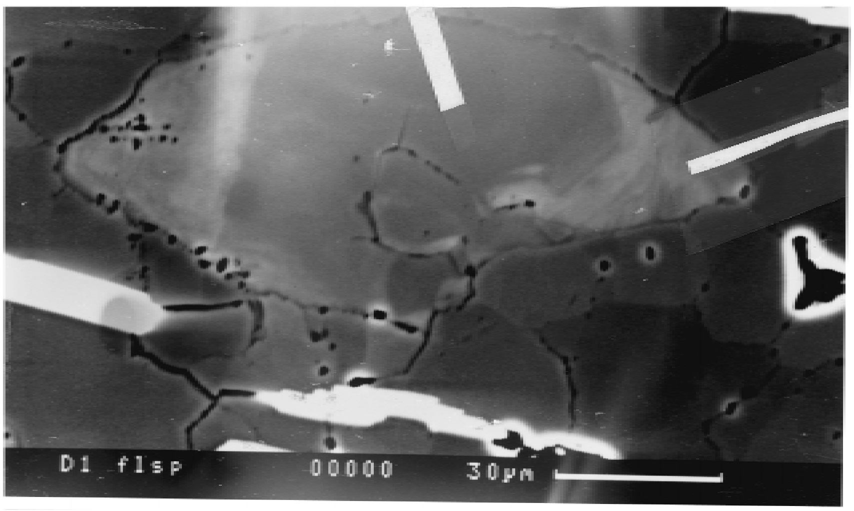


Fig. 4. SEM backscattered atomic number contrast images of feldspars in quartzite lithologies within the Moine Thrust shear zone. (**a**) General view of mylonitic fabric. Quartz is dark grey to black, feldspar is light grey with bright rims, micas and K-feldspars are white. (**b**) View of plagioclase in quartz matrix. Light feldspar rims are Ca rich.

and Rb respectively in comparison to pure plagioclase. The mica separates were very pure (>99%). Minor contamination by chlorite was unavoidable due to the fine grained nature of the micas although this has little effect on the analyses.

Our results are shown on Table 3 and summarized on Fig. 6. The Knockan samples record Rb–Sr ages 437–425 Ma, all of which are similar within error and are within the range of results expected from previous studies. At Dundonell, the age dispersion may represent the original Sr disequilibrium between the micas and feldspars. The youngest age (D1) 408 Ma, has the highest initial ratio of all the samples but this does not explain the low age. If this young age is a product of some external Sr fluid this fluid must have been less radiogenic than the host feldspars. It seems unlikely that any external Sr source could produce a significant alteration of the grain boundary $^{87}Sr/^{86}Sr$. The high feldspar content of the Moine mylonites would dominate the grain boundary fluid within these rocks. The high percentage of Sr within plagioclase means that if the grain boundary fluid interacted with only the Sr in the outer few microns of the feldspar, this is likely to have dominated over any other inputs. To create a significant change in the $^{87}Sr/^{86}Sr$ of the grain boundary fluid would have required a very large volume of Sr rich fluid to have passed through the rock. The distribution of ages within the known constraints therefore suggest that the feldspar Ca rich rims, which are ubiquitous through all the samples, do not represent fluid precipitates from a radiogenic poor Sr source.

The feldspar bulk separates are believed to have acted as reliable initial ratios. If this is the case then the age of *c*. 430 Ma is interpreted as the age when ductile deformation

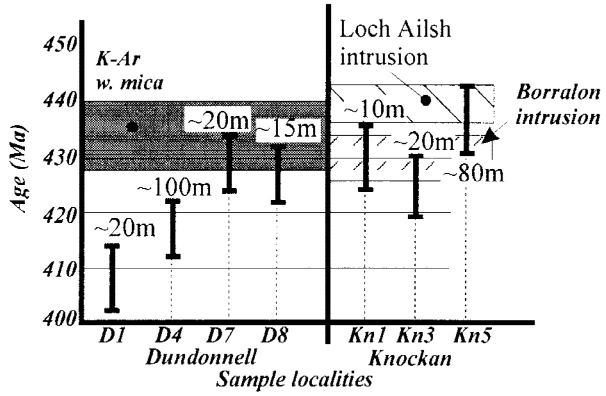


Fig. 6. Rb–Sr white mica fabric geochronological data (black bars) versus K–Ar white mica, and U–Pb zircon crystallization data (stippled). Data from this study; Van Breemen *et al.* (1979) (Borralon), Kelley (1988) (white mica K–Ar), and Halliday *et al.* (1987) (Loch Ailsh).

ceased to crystallize or recrystallize white micas in the Moine mylonites at Knockan. The Dundonnell samples record a variation in ages from 429 to 408 Ma and since ages may reflect a mixing of mica ages within individual samples, they therefore only approach the maximum and minimum values. The clustering of ages at 430 Ma suggests that a significantly older Moine Thrust related mica population ($\geqslant$450 Ma) is not present within the samples. The age of 408 Ma can only represent an upper estimate for the end of ductile deformation at Dundonnell.

The Rb–Sr data is interpreted as showing a progressive end to ductile deformation at Dundonnell from 430 Ma until at least 410 Ma. These results show that in the Dundonnell to Knockan section of the Moine mylonites, there was a general cessation of ductile deformation in the mylonites at *c.* 430 Ma, although deformation continued in a less pervasive manner until at least 408 Ma.

K–Ar ages

K–Ar analyses were carried out to assess the coherency of the Rb–Sr data. Rex (1994) provides a review of this isotopic system as a geochronological tool.

We expect that, for individual samples, the K–Ar ages should be younger than their respective Rb–Sr ages. Two K–Ar analyses were undertaken on the same samples used for the Rb–Sr analyses of samples D4 phengite and Kn1 phengite. Table 4 shows the results of these analyses in comparison with the Rb–Sr results from these samples. The K–Ar analyses produce older ages than their respective Rb–Sr analyses. The sample Kn1 yielded a K–Ar age which was significantly older (11 Ma) but this is within error of the Rb–Sr analysis. The K–Ar age of D4 is 32 Ma older than the Rb–Sr age. This is in excess of the error envelope of both the Rb–Sr and K–Ar analyses. We consider this discrepancy between the Rb–Sr and K–Ar ages to be caused by an excess Ar component within the

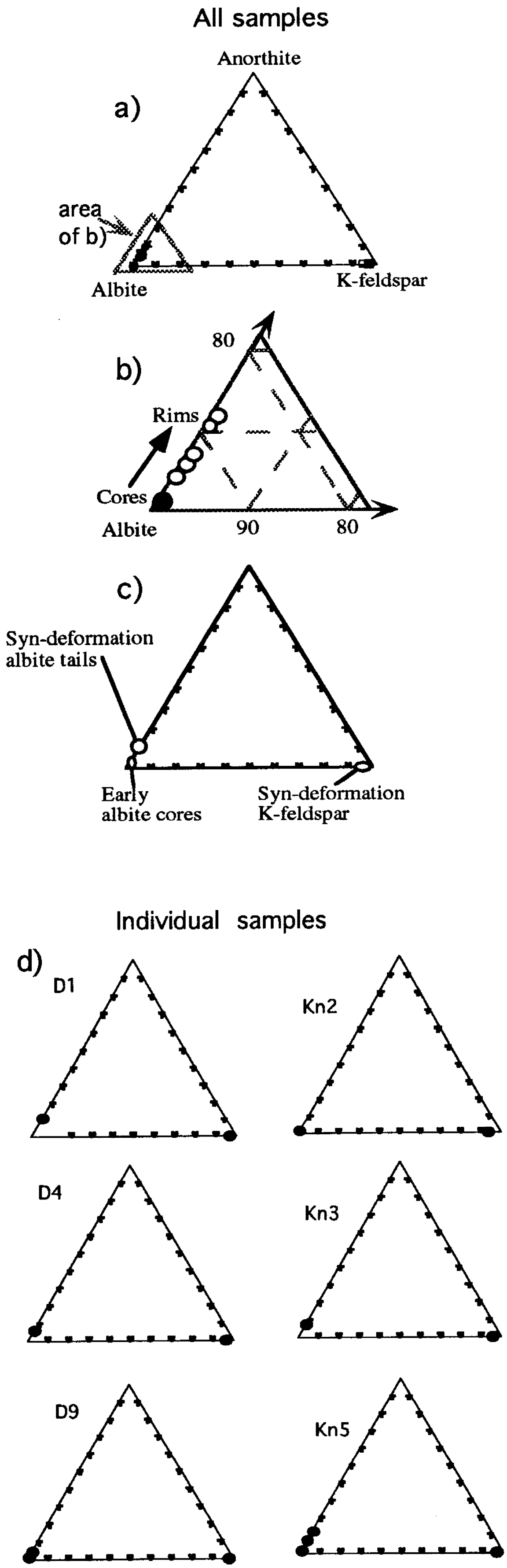


Fig. 5. Tertiary compositional plots for feldspars within the Moine Thrust shear zone. The plots are for Albite, Anorthite, K-feldspar end member compositions. (**a**) Compilation of all data; (**b**) blown up view of plagioclase compositions for all samples; (**c**) simplified compositions for all samples; (**d**) individual sample data (Kn, Knockan; D, Dundonnell).

Table 3. *Rb–Sr Moine mylonite phengite-feldspar analyses from Knockan and Dundonnell*

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr ppm ratio	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	Initial ratios	Age (na) ± 2σ
d1 mica	247.3	55.87	4.4259	0.80937	12.9		408 ± 5.9
d1 flsp	84.74	111.6	0.7592	0.74698	2.21	0.734	
d4 mica	259.6	55.21	4.7016	0.80432	13.7		417 ± 5.2
d4 flsp	43.09	170.0	0.2535	0.72712	0.74	0.723	
d7 mica	290.1	56.48	5.1356	0.8207	15.0		429 ± 5.7
d7 flsp	86.24	156.7	0.5505	0.7387	1.60	0.729	
d8 mica	249.2	63.55	3.9209	0.79927	11.5		428 ± 5.7
d8 flsp	67.54	148.0	0.4564	0.73751	1.32	0.729	
kn1 mica	280.7	68.72	4.0852	0.80539	11.9		430 ± 5.9
kn1 flsp	87.89	153.1	0.5741	0.74246	1.67	0.732	
kn3 mica	293.1	51.35	5.7090	0.83136	16.7		425 ± 5.5
kn3 flsp	77.85	145.2	0.5360	0.73967	1.56	0.730	
kn5 mica	289.5	74.71	3.8745	0.79937	11.3		437 ± 5.8
kn5 flsp	80.96	194.4	0.4164	0.73650	1.21	0.729	

Table 4. *K–Ar analyses from samples Knockan (Kn1) and Dundonnell (D4)*

Sample	Mineral	%K	^{40}Ar (cc gm^{-1})	$^{40}Ar^{*}/^{40}Ar$	Age (Ma ± 2σ)
Dundonnell					
D4	Mica	7.316	14.5048*10-5	0.993	449 ± 13.5
Rb–Sr	Mica–feldspar isochron				417 ± 5.2
Ar excess age					32 ± 18
Knockan					
Kn1	Mica	7.446	14.4599*10-5	0.981	441 ± 13
Rb–Sr	Mica–feldspar isochron				430 ± 5.9
Ar excess age					11 ± 18

The difference between the Rb–Sr age and the K–AR age is shown. K–Ar analyses yield older ages than Rb–Sr analyses.

micas, creating an apparently older K–Ar age. Our results and interpretation are in accord with those of Kelley (1988) who also found excessively old biotite ages. Kelley interpreted these as representing the incorporation of an excess Ar component within samples from Dundonnell.

Discussion

Tectonics and deformation ages

The mica chemistry indicates that the *P–T* conditions present during crystallization were approximately constant. Unfortunately the variation in *T* and *P* visible due to changing Si content of phengites is limited. The Moine Thrust Zone must therefore have remained at similar depths and/or temperatures between 430 and 408 Ma. This implies that either little exhumation via hanging wall denudation can have occurred during this period (437–408 Ma), or that exhumation was having little effect on the temperature in the deforming areas. The closure of the Ar system in mica indicates that exhumation and cooling were occurring within the hanging wall. Therefore either the shear zone was being kept at an elevated temperature compared to the hanging wall or more likely the variation in temperature and pressure caused minimal effect to the phengite chemistry.

In the Dundonnell area the phengite chemistry in all the samples is indistinguishable, although the Rb–Sr geochronological data suggest that the micas formed several million years apart. This spread of ages is believed to be a real effect of later recrystallization in some samples compared to others. Suggesting that sections of the mylonite ceased to deform at *c.* 430 Ma, whereas other sections, at a similar structural height, continued to deform down until *c.* 410 Ma. This shows that the shear zone ceased to deform at different times in different places, and therefore strain localization was occurring (Fig. 7).

The timing of deformation indicated by the Rb–Sr data agrees with the previous K–Ar ages from the hanging wall. The Ar closure temperature is likely to be similar to the temperature at which the mylonites ceased to deform in a crystal–plastic manner. Thus, as the hanging wall cooled via exhumation, deformation localized, and micas closed to Ar diffusion.

Three possibilities exist to explain the older ages yielded from Knockan in comparison to Dundonnell. These are; firstly, ductile deformation shut off earlier within the Knockan mylonites than those at Dundonnell. Secondly, a hanging-wall ramp exists in the mylonites which places older structures at the base of the nappe (Fig. 7f). Thirdly, the late Moine Thrust cuts out hanging-wall stratigraphy, thereby removing the youngest sections of the mylonite and has placed older structures at the base of the nappe (Fig. 7e).

It is plausible that thrust displacements transferred onto the base of the Moine mylonites at Knockan before this happened in the Dundonnell area. The southern Assynt district records >50 km of shortening in the footwall to the Moine Thrust

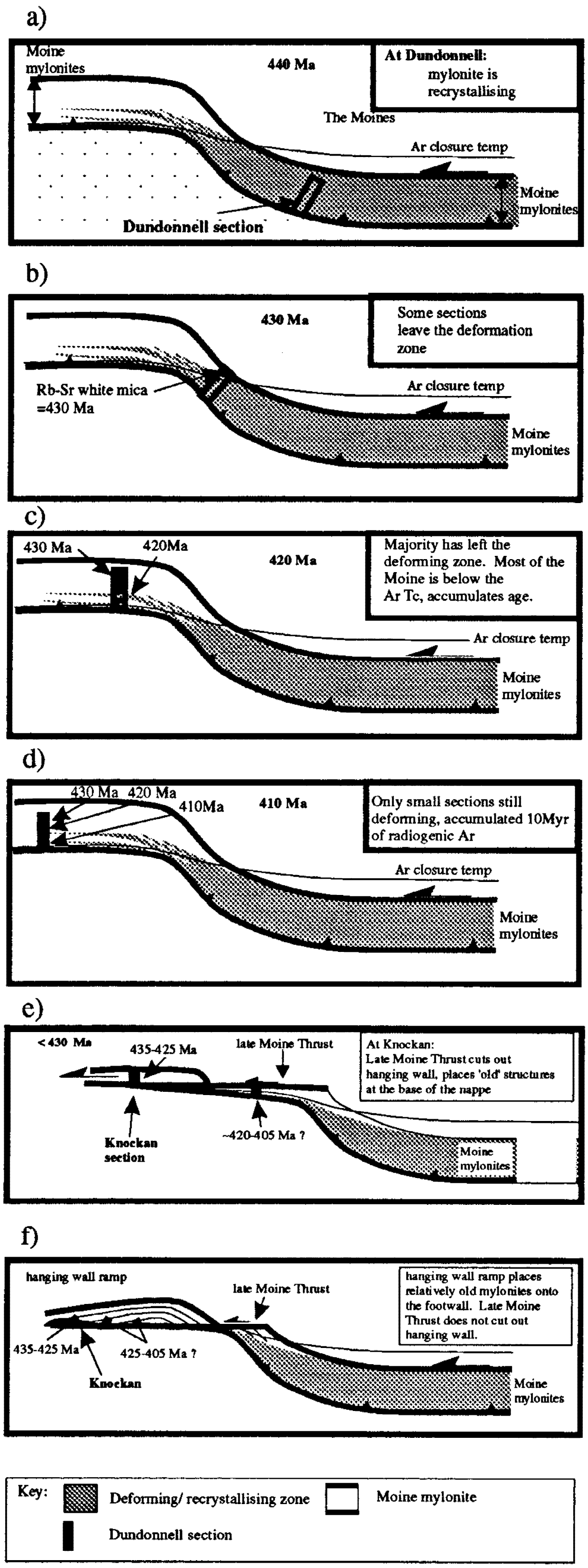


Fig. 7. Schematic evolution of the Moine mylonite, showing when the mylonite left the recrystallizing zone. (**a–d**) Evolution of the Dundonnell section through time. (**e–f**) Evolution of the Knoackan section through time. Black zones indicate the position of the Dundonnell and Knockan mylonites through time.

(Coward 1985). In the areas adjacent to Dundonnell there are no imbricates in the Moine thrust footwall. Presumably imbricate displacements were transferred via lateral ramps onto the Moine Thrust at Knockan.

The second or third options, excision of hanging-wall tectonic stratigraphy, are thought to be the most likely cause of age variation. The older ages are therefore a result of sampling higher within the mylonite. This implies that the full section of greenschist-facies Moine mylonites may record ages from at least 437 Ma down to *c.* 408 Ma. These ages therefore appear in general to decrease towards the base, but are complicated by local reworking.

Periods of rapid strain localization are likely to correspond with movement of the hanging wall up a footwall ramp, accompanied by increased rates of surface erosion. In the case of the Moines a significant freezing of structures appears to have occurred at 430 Ma within the mylonites. This may correspond with the movement of the mylonites up across a major footwall ramp onto a flat and may correspond to translation onto the Cambro-Ordovician shelf. These conclusions are in general agreement with the restored pre-deformation template of Butler (1986).

The cessation of deformation at *c.* 430 Ma within the Moine mylonites is synchronous with the intrusion of the Borrolan complex (van Breemen *et al.* 1979). As deformation shut off on the Moine Thrust it is most likely to have been accommodated on the immediately underlying Ben More Thrust. The age of 430 Ma therefore dates the transfer of shortening from the Moine Thrust onto this structure. The previous estimates for the age of activity on the Ben More Thrust were pre-Borrolan intrusion (e.g. Parsons & McKirdy 1983) which dated at 430 ± 4 Ma (van Breemen *et al.* 1979). Thus displacement transfer from the Moine Thrust onto its footwall broadly coincides with emplacement of the Borroloan complex. Although it is tempting to suggest a causal relationship between intrusion and the migration of deformation (cf. Elliott & Johnson 1980) such correlations are tenuous. The same age for the cessation of mylonitic shearing is recorded at Knockan and Dundonnell (15–20 km along strike of the Borrolan body).

The ages may be combined with existing estimates of displacements across the Moine mylonites and underlying imbricates to estimate displacement rates. The mylonites themselves are thought to represent a minimum of 100 km WNW thrusting (Elliott & Johnson 1980). Even when underlain by substantial numbers of imbricates and thrust sheets (e.g. Butler 1982) the mylonites are in excess of 100 m thick, as at Knockan and Dundonnell. These mylonites were active at least from 437 to 430 Ma. Thus the time-averaged displacement rate cannot have exceeded $100/7 = 14$ mm a^{-1}. Our data do not provide an age for the onset of penetrative mylonitization so these figures have high uncertainties. Using the above figures, an average shear strain rate estimated for the Moine mylonites is 5×10^{-12} s^{-1}. However, the local strain rate will have been greater than this if strain localized onto discrete parts of the shear zone. Nevertheless, the value is at the fast end of the range estimated using microstructural data from the mylonites (Knipe 1991).

Rather better constrained is the time-averaged displacement rate for the Moine Thrust Belt. Imbrication began at 430 Ma, our estimated time of widespread deformation localization within the mylonites, and ended at 408 Ma (the youngest age at Dundonnell), a duration of 22 Ma. Displacements in the footwall to the Moine Thrust are estimated at about 50 km (Butler & Coward 1984; Coward 1985), giving a time-averaged rate of 2.3 mm a^{-1}.

Fluid migration and K–Ar data

The assertion that the plagioclases apparently provide good measures of the initial Sr isotopic ratio implies that the limited exchange possible across the grain boundaries and during minor dissolution was sufficient to control the grain boundary fluid. This suggests that even though numerous sources could have supplied Sr into the shear zone they were insufficient to cause significant alteration of the grain boundary fluid $^{87}Sr/^{86}Sr$ value.

Argon may become liberated into fluids within shear zones during the breakdown of K-bearing phases during deformation. Once argon is within a shear zone, isotopic equilibration should occur on a large scale due to the elevated transportation distances (McCaig *et al.* 1995) and new minerals recrystallizing in the shear zone will incorporate this Ar. The degree of incorporation will depend on the concentration of Ar in contact with the crystallizing phase and the partition coefficient of the mineral. This means that the concentration of excess Ar in the mineral is a function of the concentration of Ar in the fluid, and the diffusion rates into the mineral.

The initial (excess) argon incorporated within minerals during crystallization may yield information about the transport of fluids along shear zones and minerals that have incorporated excess Ar during fluid flow in a shear zone will yield excessively old K–Ar ages. The excess age will reflect an integration of the time/excess argon concentration which is related to the Ar flux if the minerals used have similar Ar solubilities. However, in order to measure this phenomenon the true age of crystallization must be found. This has been achieved in the present case by using the Rb–Sr mineral dating technique.

The temperature of cessation of plastic deformation is in the order of *c.* 350°C following a retrograde *P–T* path. The temperature of (re)crystallization is likely to be close to the closure temperature of phengite in the K–Ar system, and is likely to be in excess of the closure temperature of biotite. The age of crystallization has been established from the Rb–Sr method to be 410–430 Ma within the Moine mylonites at Dundonnell and represents an absolute upper age limit for the K–Ar ages of the micas in the shear zone. Higher within the Moine hanging wall the huge set of Ar data suggests the age of cooling through *c.* 350°C is *c.* 425 Ma. The K–Ar data close to the Moine Thrust will now be compared against these limits.

The biotite ages from Kelley (1988) are consistently older than the muscovite ages in the increased muscovite age zone (within 6 km horizontally from the shear zone). This is indicative of significant volumes of excess Ar within the biotites. The biotite age pattern is therefore very strongly controlled by the degree of excess Ar near the shear zone. The white mica age pattern shows a similar but less marked rise in ages when compared to the Rb–Sr ages. This suggests that the white mica pattern is also a product of incorporated excess Ar. There is a clear increase in apparent ages as the footwall is approached at the base of the Moine mylonites. The degree of measured excess age reaches a maximum of *c.* 30 Ma in both the phengites and the biotites. The biotite sample closest to the base of the Moine was still a significant distance from the footwall. The predicted excess age at the contact with the footwall is therefore significantly greater than this last sample and extrapolation of this pattern to the thrust implies the excess age would be in the order of 40–50 Ma, whereas the phengite is *c.* 30 Ma.

The data show that a similar age pattern exists for both biotite and white mica, although the biotite exhibits the incorporation of the excess argon more strongly. The main zone of deformation within the mylonites of the non-faulted Dundonnell section is *c.* 300 m, this is apparently less than the zone greatly effected by the high levels of excess Ar, and suggests that the excess Ar pattern reflects a spatial distribution rather than a temporal distribution. The two scenarios (spatial and temporal) are also end-members, with the true case probably being a combination. However, the favoured model at present is that the excess Ar pattern is dominantly recording a spatial distribution of decreasing fluid flow from the footwall into the hanging wall.

The presence of Ar flow up to 1.5 km up through the shear zone probably represents an upper limit on the advection for most other elements/species. Unfortunately the relative compatibility of Ar to other elements/species is unknown and Ar studies can thus only yield information about the upper limits of fluid transfer.

In summary, the K–Ar system shows consistently older ages than the Rb–Sr system (Fig. 6). This is due to the incorporation of excess Ar at or immediately following the time of crystallization. Argon is commonly incorporated into micas at relatively low concentrations in fluids. Furthermore, it is likely to be present if the fluid has had any input from the breakdown of potassium-rich phases during the mica crystallization period. Since potassium is a very common constituent of crustal rocks, radiogenic argon is likely to be present in the majority of crustal shear zones. Modern studies from high-pressure metamorphic terrains confirm this view (von Blanckenburg & Villa 1988; Scaillet 1996; Reddy *et al.* 1996). This is obviously a hindrance when using the K–Ar system to obtain accurate geochronological data, but the incorporation of Ar at the time of crystallization may prove useful in the analysis of fluids in shear zones.

Conclusions

Rb–Sr dating of synkinematically crystallized white micas with co-existing feldspars has constrained the end of ductile Moine Thrust movement to have been between 437–408 Ma. The data suggest that the main cessation of deformation occurred at *c.* 430 Ma. The variation in ages yielded, could represent strain localization. The time between 437–408 Ma may represent the minimum period that strain localization was occurring within the greenschist facies Moine mylonites. The main cessation of crystal–plastic deformation is likely to have been controlled by the waning temperature of the Moine sheet, presumably related to surface erosion across the evolving orogen. Erosional denudation is likely to accelerate during and immediately following periods of accelerated uplift and in thrust belts this will largely be controlled by rapid climb up footwall ramps. Our age dates suggest that within the Moine mylonites the transition from penetrative shearing to localized deformation happened at *c.* 430 Ma. We suggest that the present Dundonnell–Knockan mylonite sections climbed up a major footwall ramp, which presumably included the Cambro-Ordovician sequence, at *c.* 440–430 Ma. Continued movement occurred along a footwall flat between 425–408 Ma. In the Assynt area this later period was presumably the time of substantial imbrication beneath the Moine and Ben More Thrusts. Using these data to estimate displacement rates derives values of about 2 mm a^{-1} on the imbricates of the Moine Thrust Belt.

A comparison between the Rb–Sr system and the K–Ar system has shown the presence of significant volumes of excess radiogenic Ar. The degree of excess Ar incorporation into micas increases as the base of the Moine sheet is approached. At the base of the Moine mylonites, incorporated radiogenic argon increases the apparent K–Ar ages of phengite by *c.* 30–40 Ma, and of biotite by *c.* 40–50 Ma in respect to Rb–Sr ages. The incorporation of excess Ar becomes undetectable approximately 1.5 km structurally above the thrust contact. Due to the highly incompatible nature of Ar, the distance (*c.* 1.5 km) that radiogenic Ar was incorporated may indicate the maximum distance that fluid can have travelled out of the main shear zone. We tentatively suggest that the principal sources of excess Ar within the Moine mylonites were footwall units, presumably the Lewisian gneiss buried beneath the thrust pile.

Our results show that Rb–Sr dating of greenschist-facies quartzo-feldspathic mylonites yields ages which are compatible with existing geological information and tectonic understanding of the Moine Thrust Belt. This is not the case with Ar analyses. This work shows the potential for accurate deformation ages to be linked with microstructural analyses to attain strain histories. The methods are likely to be most useful in studies of Mesozoic–Cenozoic orogens where the analytical errors are less restrictive than has been the case for our studies in the Moine. Better dating of strain fabrics should aid unravelling of multi-phase deformations. We believe that where the age of shearing is known, much more robust tectonic analyses are feasible.

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