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SPECIAL

Understanding K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ data: reconciling models, methods and microtextures

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Several descriptions of argon diffusion in K-feldspar have been developed, including the quantitative multiple-diffusion-domain (MDD) and multipath models and the qualitative ‘recrystallization’ model. These models remain contentious and the natural range in behaviour remains poorly understood. Feldspars from the Klokken syenite intrusion show a systematic relationship between $^{40}\text{Ar}/^{39}\text{Ar}$ age and microtexture suggesting that the loss of argon from different feldspars operates via different mechanisms such that the existing models represent only end-member scenarios. The MDD model can yield reliable thermal history information only for feldspars with pristine microtexture, with this model best viewed as a cipher for the real (but unknown) domain structure in such samples.

K-feldspars are widely used chronometers as they appear to retain radiogenic argon quantitatively in a variety of situations. However, the use of K-feldspars for geo- and thermochronology is the subject of continuing controversy. A key feature of previous work in this field has been the perceived need to develop a single description of argon loss in all natural feldspars.

The multiple-diffusion-domain (MDD) model developed by Lovera *et al.* (1989) is based on the assumption that the retention of argon during cooling in nature and the loss of argon during step-heating in the laboratory are controlled only by thermally activated volume diffusion. The model attests that the $^{40}\text{Ar}/^{39}\text{Ar}$ age gradients in K-feldspars are the result of variable argon retention by different-sized diffusion ‘domains’, which give a range in closure temperature (as much as 350–150 °C) that can be inverted to yield continuous cooling histories (Richter *et al.* 1991). Thus, the method is potentially a powerful tool for problems in tectonics and structural geology (e.g. Dunlap & Fossen 1998). However, Lee (1995) questioned the assumption that volume diffusion is the only mechanism of argon loss, and Parsons *et al.* (1999) questioned the presence of a discrete domain microstructure, suggesting that the age variations recorded by terrestrial K-feldspars are the product of the redistribution of argon during recrystallization at a variety of temperatures, including near-surface conditions. Here, recrystallization is any

process that involves dissolution or neo-formation of K-feldspar in conjunction with grain boundary migration. These views suggest that K-feldspars will contain a variety of microstructural sub-regions with mixed ages that cannot be used to infer cooling histories or other geologically significant age information.

The quantitative MDD model of Lovera *et al.* (1989) and the empirical ‘recrystallization model’ (so-named here) of Parsons *et al.* (1999) represent the polarization of previous work in this field. However, neither model has received widespread support. The MDD model (1) assumes that volume diffusion is the only mechanism controlling argon loss, (2) does not consider the possibility of the redistribution of argon during recrystallization or textural modification, and (3) provides an *a posteriori* method for evaluating the likelihood of successful application based on the relationship between the age spectra and calculated domain distribution (Lovera *et al.* 2002) but does not provide a reason for the relatively high number of K-feldspars for which the method does not give good results, nor any method for evaluating the suitability of samples prior to $^{40}\text{Ar}/^{39}\text{Ar}$ analysis. On the other hand, the recrystallization model (1) takes the calculation of a domain size distribution literally and dismisses the MDD model on the basis of a mismatch between calculated diffusion domain sizes and physical microtexture (e.g. Fitz Gerald & Harrison 1993) and (2) attests that the MDD model cannot work on any feldspar, given that it does not work on a certain proportion of feldspars (Parsons *et al.* 1999).

K-feldspars, however, commonly exhibit extraordinarily complex microtextural and chemical variability, and it would seem unlikely that a single description could account for argon loss in all natural K-feldspars, unless it could somehow reflect this complexity. Rather than developing a single model, or advocating any one existing model, we suggest that understanding the range in natural behaviour is more important. We suggest that it is possible to identify when the MDD model is likely to be successful, and thus when $^{40}\text{Ar}/^{39}\text{Ar}$ data can be used to infer the cooling history, on the basis of the appearance of the feldspar and the shape of the age spectrum.

Klokken feldspars. The Klokken layered syenite is a late Mesoproterozoic intrusion (age 1166 ± 2 Ma; Parsons *et al.* 1988) within the Gardar alkaline province in southern Greenland. The intrusion has been described by Parsons & Becker (1987), and the microtexture of the alkali-feldspars has been studied in detail by Parsons *et al.* (1988) and Worden *et al.* (1990). Parsons *et al.* (1988) and Burgess *et al.* (1992) suggested that following intrusion the complex remained essentially undisturbed tectonically and thermally.

Of the feldspar samples reanalysed here, Parsons *et al.* (1988) described samples 140182, 140115 and 140175 as ‘pristine’ non-turbid ‘strain-controlled’ cryptoperthites. In contrast, samples 140025 and 43738 are coarse ‘turbid micropertthites’ with patchy intergrowth textures. At the grain scale the ‘pristine’ group appear remarkably homogeneous, with perthitic exsolution only just discernible under high magnification (Fig. 1). In contrast, ‘turbid’ braid perthites show complex textural relationships and disrupted microstructure of dissolution pits, fractures, micropores and coarse remnant perthitic exsolution. Sample 43738 also shows evidence for a core of remnant pristine cryptoperthite (Fig. 1).

$^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology. A subset of feldspars from the laminated and granular syenites, originally subjected to step-heating $^{40}\text{Ar}/^{39}\text{Ar}$ experiments by Parsons *et al.* (1988), have been reanalysed. Here, an aliquot of each feldspar grain separate

Fig. 1. Representative back-scattered-electron (atomic number contrast) images of feldspars from the Klokken syenite: (a) 140182; (b) 140175; (c) 140115; (d) 43738; (e) 140025. In (d) and (e) lighter colour is K-feldspar, darker colour is plagioclase. Accelerating voltage 20 kV; working distance 20 mm.

(c. 0.8–1.8 mg) was subjected to a detailed step-heating experiment, involving 43 heating steps between 437 and 1450 °C. Supplementary data tables are available online at <http://www.geolsoc.org.uk/SUP18277>. A hard copy can be obtained from the Society Library.

The $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra record a remarkable range of style and apparent age (Fig. 2a). The overall shape of the spectra and the total gas ages are very similar to those obtained in the conventional 10–15 step-heating experiments of Parsons *et al.* (1988); however, our experiments show significantly more detail and also allow the diffusion properties of the samples to be determined. Samples 140115 and 140175 exhibit striking, almost flat, age spectra with age gradients only for the first 5–15% of the gas release. Sample 140182 exhibits a well-developed monotonic increase in ages with gas release ranging from c. 800–900 Ma to c. 1200 Ma. Maximum ages recorded by all three pristine samples are in the range 1100–1200 Ma, close to the intrusion age.

In contrast, samples 43738 and 140025 show less well-behaved $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra that feature ‘hump-shaped’ intermediate age maxima characteristic of K-feldspars that have experienced hydrothermal alteration and/or recrystallization (Warnock & van

der Kamp 1999). Both turbid feldspars also show evidence for excess argon contamination, particularly in the early released gas, as indicated by the large differences in age of isothermal duplicate steps (Fig. 2a). Sample 43738 records a maximum age of 1080 ± 23 Ma (1σ) with the youngest ages in the range 300–600 Ma. Sample 140025 records a maximum age of 701 ± 6 Ma (1σ), significantly younger than the intrusion age.

MDD modelling. MDD modelling was performed using the latest automated software available from <http://sims.ess.ucla.edu/argonlab/programs.html>. The software calculates (1) the diffusion parameters, here assuming an infinite-slab geometry, (2) the domain size distribution, and (3) the cooling history that gives the best fit to the laboratory age spectrum. As the MDD model assumes that thermally activated volume diffusion is the only mechanism of argon loss, an Arrhenius relationship is used. Each domain involves the same $\log(D_0)$ and activation energy, E . Calculated Arrhenius relationships for K-feldspars are commonly convex upward, showing a significant deviation from linearity, as seen in Figure 2b, consistent with diffusion occurring over a range of length scales (Lovera *et al.* 1989). For each Arrhenius plot, the slope of the linear array of points corresponding to the

Fig. 2. (a) Laboratory $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for Klokken feldspars (1σ errors shown). (b) Calculated Arrhenius relationships for the Klokken feldspars. Arrow labelled x indicates the deviation from linearity that is consistent with diffusion occurring over a range of length scales. (c) Calculated $\log(r/r_0)$ plot.

first released ^{39}Ar is used to give the activation energy, E , and the intercept the frequency factor, $\log(D_0/r_0^2)$ (Lovera *et al.* 1989). The factor r_0 is the reference length scale defined from the initial gas release to which all domains contribute. All the Klokken samples have calculated activation energies in the range 40–52 kcal mol $^{-1}$, around the global average value for K-feldspars of 46 ± 6 kcal mol $^{-1}$ reported by Lovera *et al.* (1997).

A representation of the domain size distribution is given by the $\log(r/r_0)$ plot, in which the departure of the data from the linear array in the Arrhenius plot is plotted against the volume fraction of ^{39}Ar released (Lovera *et al.* 1991). The y -axis represents the size of the domains contributing ^{39}Ar at each stage in the experiment, relative to the reference length scale, r_0 . On a $\log(r/r_0)$ plot (Fig. 2c) samples 140175, 140115 and 140182 show similar concave patterns with a limited range of $\log(r/r_0)$, indicating the presence of only a small range of diffusion domain sizes. In contrast, samples 140025 and 43738 show convex patterns with a greater range in diffusion length scale. For simplicity, we discuss only samples 140182 and 43738 as representative examples of the ‘pristine’ and ‘turbid recrystallized’ groups, respectively, as results from the remaining samples in each group are similar.

The laboratory argon loss characteristics represented in the $\log(r/r_0)$ plot can be inverted to give the calculated domain size distribution, but only in normalized form given that $\log(D_0)$ and the diffusion length scales cannot be known independently. Domain sizes are given in Table 1, in combination with $\log(D_0)$, or normalized relative to the largest domain. For comparison we have used eight domains in each case, but note that the model remains unaffected when domains 2–3 (for sample 140182) or domains 4–6 (for sample 43738) are combined. As suggested by

the $\log(r/r_0)$ plot, the domain sizes in pristine feldspar from sample 140182 vary by a factor of only about 50, whereas the domain sizes in turbid feldspar from sample 43738 vary by a factor >1000 .

Finally, the domain distribution is inverted and model age spectra corresponding to different possible thermal histories are calculated. The model and laboratory age spectra are compared by trial and error to give the best-fit thermal history. Although the feldspars in this study should have experienced the same thermal history, the modelled cooling histories contrast markedly. The pristine Klokken feldspars yield a modelled thermal history consistent with very rapid cooling following intrusion (Fig. 3c). This history gives an excellent fit to the laboratory age spectrum (Fig. 3a) and is almost identical to the regional thermal history reported by Burgess *et al.* (1992). In contrast, model results for the recrystallized turbid feldspars give thermal histories suggesting that the samples have experienced a temperature ‘spike’ >300 °C between 600 Ma and 300 Ma (Fig. 3c). These histories are meaningless in terms of the known geological history and, not surprisingly, give a very poor fit to the laboratory age spectra (Fig. 3b).

Discussion. The Klokken results for feldspars of apparently simple gross microtexture are consistent with MDD-type volume diffusion. The success of the model in predicting the known geological history for these samples provides *a posteriori* support for this assumption. Most commonly, such ‘pristine’ feldspars will be relatively homogeneous in composition, containing only high-temperature perthitic exsolution features, and without a high volume of extended defects. They should not have been subsequently modified during later recrystallization and/or fluid–

Table 1. Domain distributions from MDD models

Sample 140182				Sample 43738			
Domain	$\log(D_0/r_1^2)$ (s $^{-1}$)	Volume fraction (%)	Relative domain size (r_i/r_8)	Domain	$\log(D_0/r_1^2)$ (s $^{-1}$)	Volume fraction (%)	Relative domain size (r_i/r_8)
1	4.0145	19.97	0.02632	1	7.9602	3.34	0.00113
2	3.1576	10.23	0.07059	2	6.6815	4.24	0.00491
3	3.1518	11.81	0.07106	3	5.7210	4.68	0.01485
4	2.5963	9.38	0.13470	4	3.3860	9.68	0.21838
5	2.2388	8.34	0.20330	5	3.3844	35.53	0.21877
6	1.7000	14.77	0.37802	6	3.3833	18.29	0.21906
7	1.1625	2.77	0.70188	7	2.3810	13.73	0.69454
8	0.8551	22.7	1.00000	8	2.0644	10.41	1.00000

Fig. 3. Measured and modelled age spectra for samples (a) 140182 and (b) 43738. (c) Preferred thermal histories for samples 140182 (curves a) and 43738 (curves b).

mineral interaction, and the samples must also be characterized by 'well-behaved' monotonically increasing age spectra. Results suggest that the MDD model remains a useful tool in these cases.

In contrast, microtextural features including (1) extensive turbidity, (2) gross 'patchy' compositional variation, (3) microcrystalline defects and/or significant porosity as a result of dissolution–reprecipitation reactions and/or (4) the presence of alteration products including adularia or mica, may disrupt existing diffusion domains, prohibit large coherent diffusion domains from developing or act as fast pathways that allow argon leakage. Samples characterized by a high proportion of such features are often associated with 'hump-shaped' age spectra. Lovera *et al.* (2002) showed that such age spectra can result from recrystallization of large domains that had already closed with respect to argon diffusion, and that in such samples the age and diffusion properties are poorly correlated. We agree with Lovera *et al.* (2002) that such feldspars are invariably unsuitable for modelling using the MDD method. The failure of the MDD model for such samples, established *a posteriori*, reflects the operation of processes other than volume diffusion in the control of argon loss.

A particular criticism of the MDD model, that the calculated domain size distribution does not correspond to observable microstructures, can be addressed in part with reference to Lovera *et al.* (1991). They showed, in the context of their calculation of a discrete domain size distribution, that the calculated thermal history is independent of the domain distribution (i.e. the number or shape of domains), provided that the domain distribution can adequately describe the laboratory argon loss characteristics. This conclusion can be generalized, by analogy with Dodson (1976), to say that any volume-diffusion-based model (e.g. involving continuous domain sizes, interacting domains, etc.) that fits the data will predict equivalent thermal histories. Therefore the current MDD model can be thought of simply as a cipher for the actual (but unknown) model and domain structure. Thus, the domain distribution is not assumed to have any direct relationship to physical microtexture.

Microtextural observations provide the most useful information on the nature and quality of thermochronological information available from any given sample. Recrystallization and/or textural modification can be recognized from optical and electron microscopy, and an assessment of the potential application of $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology made. These are rapid techniques readily available to those wishing to use $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology in the solution of tectonic or structural problems. Even if the microstructures look pristine, if the shape of the $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum shows any evidence for recrystallization, then proceeding to inference on the precise form of the cooling history is not recommended.

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References

- BURGESS, R., KELLEY, S.P., PARSONS, I., WALKER, F.D.L. & WORDEN, R.H. 1992. $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of perthite microtextures and fluid inclusions in alkali feldspars from the Klokken Syenite, South Greenland. *Earth and Planetary Science Letters*, **109**, 147–167.
- DODSON, M.H. 1976. Kinetic processes and thermal history of slowly cooling solids. *Nature*, **259**, 551–553.
- DUNLAP, W.J. & FOSSEN, H. 1998. Early Palaeozoic orogenic collapse, tectonic stability and Late Palaeozoic continental rifting revealed through thermochronology of K-feldspars, Southern Norway. *Tectonics*, **17**, 604–620.
- FITZ GERALD, J.D. & HARRISON, T.M. 1993. Argon diffusion domains in K-feldspar I: microstructures in MH-10. *Contributions to Mineralogy and Petrology*, **113**, 367–380.
- LEE, J.K.W. 1995. Multipath diffusion in geochronology. *Contributions to Mineralogy and Petrology*, **120**, 60–82.
- LOVERA, O.M., RICHTER, F.M. & HARRISON, T.M. 1989. The $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronometry for slowly cooled samples having a distribution of diffusion domain sizes. *Journal of Geophysical Research*, **94**, 17917–17935.
- LOVERA, O.M., RICHTER, F.M. & HARRISON, T.M. 1991. Diffusion domains determined from ^{39}Ar released during step-heating. *Journal of Geophysical Research*, **96**, 2057–2069.
- LOVERA, O.M., GROVE, M., HARRISON, T.M. & MAHON, K.I. 1997. Systematic analysis of K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ step heating results: I. Significance of activation energy determinations. *Geochimica et Cosmochimica Acta*, **61**, 3171–3192.
- LOVERA, O.M., GROVE, M. & HARRISON, T.M. 2002. Systematic analysis of K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating results: II, Relevance of laboratory argon diffusion properties to nature. *Geochimica et Cosmochimica Acta*, **66**, 1237–1255.
- PARSONS, I. & BECKER, S.M. 1987. Layering, compaction and post-magmatic processes in the Klokken intrusion. In: PARSONS, I. (ed.) *Origins of Igneous Layering*. Reidel, Dordrecht, 29–92.
- PARSONS, I., REX, D.C., GUISE, P. & HALLIDAY, A.N. 1988. Argon-loss by alkali feldspars. *Geochimica et Cosmochimica Acta*, **53**, 1097–1112.
- PARSONS, I., BROWN, W.L. & SMITH, J.V. 1999. $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology using alkali feldspars: real thermal history or mathematical mirage of microtexture? *Contributions to Mineralogy and Petrology*, **136**, 92–110.
- RICHTER, F.M., LOVERA, O.M., HARRISON, T.M. & COPELAND, P. 1991. Tibetan tectonics from $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of a single K-feldspar sample. *Earth and Planetary Science Letters*, **105**, 266–278.
- WARNOCK, A.C. & VAN DER KAMP, P.C. 1999. Hump-shaped $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra in K-feldspar and evidence for Cretaceous authigenesis in the Fountain Formation near Eldorado Springs, Colorado. *Earth and Planetary Science Letters*, **174**, 99–111.
- WORDEN, R.H., WALKER, F.D.L., PARSONS, I. & BROWN, W.L. 1990. Development of microporosity, diffusion channels and deuteric coarsening in perthitic alkali feldspars. *Contributions to Mineralogy and Petrology*, **104**, 507–515.

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