Brecciation related argon redistribution in K-feldspars: an in naturo crushing study

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$^{40}Ar/^{39}Ar$ thermochronologic data from reactivated portions of the Nordfjord-Sogn Detachment Zone (NSDZ) and the Dalsfjord Fault (DF) in western Norway document late Palaeozoic through Mesozoic tectonothermal activity. 40Ar/39Ar white mica ages indicate maintenance of a relatively low geothermal gradient through post-Caledonian removal of >60 km of crustal overburden by the Middle Devonian. Diffusion and thermal modelling of K-feldspars sampled through the NSDZ indicate a major Early Carboniferous (360 to 340 Ma) rapid cooling event, while brittle reactivation of the NSDZ and the DF has been constrained to one episode in latest Permian time (250–260 Ma) and one in latest Jurassic time (134–150 Ma) (Eide *et al.*, 1997). One unit cut by the brittley reactivated faults is a mangerite suite; we tested for potential variations in the domain structure of deformed feldspars by sampling and cycle-step heating three K-feldspars: one from the mangerite series 2 km from the fault breccia ('unbrecciated'), a second sample from the same suite, but ca. 100 m from the brittle fault ('slightly brecciated'), and a third sample from within the fault breccia. The latter has been dated previously to be latest Permian in age (Eide *et al.*, 1997). The unbrecciated sample comprises microcline, plagioclase, quartz, oxides and accessory garnet. The quartzofeldspathic textures indicate partially-recovered strain via subgrain zone development around alkali feldspars, strained twins in plagioclase, and polygonal quartz rinds around coarse alkali feldspars. Alkali feldspar composition is $Or_{95-97}Ab_{3-5}$ with exsolved albite strings. The slightly brecciated sample is mineralogically similar but is much more deformed. Grain boundaries are generally serrated and irregular and the quartzofeldspathic minerals exhibit extensive subgrain growth. Microperthite is slightly turbid and plagioclase porphyroblasts are clouded by fine-grained white micas. Feldspar hosts (Or_{96-99}) contain <20 μm albite lamellae. The breccia sample consists of anastomosing veinlets of feldspar fragments, chlorite, epidote, titanite, magnetite and fine, layer silicates around larger feldspar clasts with sub-grains and partially annealed stair-step fractures.

Argon gradients and diffusion kinetics

$^{40}Ar/^{39}Ar$ data acquisition from the feldspars followed Arnaud and Kelley (1997); modelling used the multi-domain theory algorithm (Lovera *et al.*, 1993).The age spectrum from the unbrecciated feldspar climbs rapidly from low-age, low-temperature steps through to a voluminous, high-temperature plateau maximum of 400 Ma. The spectrum has been interpreted to reflect post-crystallization cooling (Eide *et al.*, 1998). Modelled diffusion characteristics are consistent with a five-domain distribution with constant domain activation energies ('E') of 46 kcal/mol. Most significantly, almost 90% of the gas is concentrated in the two most retentive and 'biggest' domains, characterized by a size ratio of 1.84 on the log(r/ro) plot.

The age spectrum from the slightly brecciated sample essentially shows the same release pattern: the high-temperature steps yield a semi-plateau at around 400 Ma and are preceded by a clustered group of cycled, isothermal temperature steps with ages climbing through 250–300 Ma. However, we note a distinct change in the domain structure of this sample compared to the unbrecciated feldspar: 1) the size ratio between low and high retentivity domains is slightly greater (maximum value of the log(r/ro) plot = 2.13); 2) the log(r/ro) plot exhibits shallower slopes; and 3) only 77% of the gas is released from the biggest domains in the slightly brecciated sample. We suggest that these differences indicate first, a small variation in the relative size of the domains between the unbrecciated and slightly brecciated samples, and second, that low retentivity sites (or smaller domains) played a greater role during the degassing than they did in the large-domain-dominated, unbrecciated sample. Interestingly, the E of the domains in the slightly brecciated sample remains identical (46.6 kcal/mol) to the unbrecciated sample.

The breccia feldspar release pattern follows the tendency outlined by the other samples, but has fairly dramatic departures. The age spectrum increases from almost 'zero age' to a maximum age group at 300 Ma. Apparent ages in the highest temperature portion of the spectrum decrease again to nearly zero ages. The maximum of the log(r/ro) plot is slightly higher than in the other two samples, suggesting an even greater ratio of small to large domains. The most intriguing difference is a complete 'change of residence' of gas into the low retentivity domains: up to 86% of the gas released resided in 'small' domains ! We note again E consistent (44.8 kcal/mol) to the other samples.

Discussion

The redistribution of gas in domains made progressively smaller during deformation is effective evidence for the physical existence of domain structures in feldspars. At the same, time no change in the activation energy is noticeable, suggesting that the lattice integrity was respected while the biggest domains were progressively erased. The domains are thus unlikely to be distributed, systematic lattice variations, but rather domains limited by coherent boundaries in an otherwise constant lattice structure. The variation of the size ratios (increasing log(r/ro)) together with the redistribution of argon into the low retentivity domains implies a reduction of the maximum size of the biggest domains together with the development of much smaller domains in the breccia. Age variations show that argon loss occurred only from the brecciated sample: very low ages at the beginning of the spectrum suggest a sample preparation (crushing) artefact that caused complete argon loss from highly deformed zones. This effect is attributed to rapid diffusion paths that intersect the sample surface during laboratory crushing (Arnaud and Kelley, 1997). This breccia sample must have had a higher defect density than the other two, less deformed samples that do not exhibit argon loss. The low ages at the end of the breccia experiment (high-temperatures in the age spectrum) are interpreted to result from natural argon loss from large domains during their *in situ* size-reduction in the late Permian brecciation process.

A simple model results in which propagation of fractures during natural crushing (brecciation) produced a reduction in size of the largest 'unlimited' areas in the original feldspar lattice. The sample which was only partially brecciated does not exhibit any argon loss and at the same time, shows a small redistribution of argon but no increase in the population of smaller domains. This implies that deformation was not intense enough to generate numerous small domains, and that crack propagation did not produce a significantly connected network that could lead to rapid diffusion paths to the grain surfaces. With increasing deformation, manifested within the fault breccia itself, genesis of very small domains was accompanied by argon loss from the pre-existing large domains; the latter were statistically more likely to be intersected by cracks that could behave as rapid diffusion pathways. Moreover, our analysis of the breccia whole-rock sample shows that the argon lost from the large feldspar domains was not redistributed in the bulk rock: argon loss was active on a larger scale, and probably flushed entirely from the system by fluid flow accompanying brecciation.

Conclusions.

This *in naturo* crushing experiment leads to several important conclusions. First, the diffusion domains outlined in these feldspar analyses are real, physical entities with a spatial wavelength that was altered during a natural brecciation process. Second, when brittle deformation began to increase, domain size reduction occurred by crack propagation that created smaller domains containing proportionally more argon. At this latter stage, no argon loss or diffusion-associated argon redistribution took place, thus suggesting that diffusion of argon in a general sense is not significantly enhanced in nature by simple cataclasis without accompanying temperature increase or fluid flow. Third, when the brittle deformation was at its peak within the breccia, two essential behaviours appeared: 1) size reduction of the existing small domains and/or development of yet smaller domains and 2) argon loss probably enhanced by rapid diffusion along the developed crack lattice network.

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