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THE ROLE OF COOLING RATE ON THE Al–Si ORDER OF K-FELDSPAR IN THE HERCYNIAN TÁBUA GRANITE, CENTRAL PORTUGAL

LUIS J.P.F. NEVES[§], ALCIDES J.S.C. PEREIRA AND MANUEL M. GODINHO

Departamento de Ciências da Terra, Universidade de Coimbra, 3049 Coimbra Codex, Portugal

Abstract

An assessment of the influence of the cooling rate in the Al–Si order of K-feldspar of the Hercynian Tábua porphyritic biotite granite, in central Portugal, is presented, taking into account the results of a numerical cooling model. As estimated from cell-parameter data, *ca*. 92% Al is located in T1 sites of the K-feldspar throughout the whole pluton, except in a 1.5-km-wide margin, where this occupancy rapidly decreases to *ca.* 79% close to the contact. Although below *ca*. 500°C, cooling rate was fairly uniform over the entire pluton, in the range 650–500°C it was, on average, 2°C/ka in the margin and 0.6°C/ka in the interior. Cooling rate of the pluton and degree of order of K-feldspar are highly correlated. In our opinion, cooling rate was the determining factor in establishing the Al–Si order of K-feldspar over most of the pluton. However, some observations point to reversal of the effect of cooling rate near the contact, in areas of pegmatite-bearing granite, where a fluid phase presumably had a major role.

Keywords: K-feldspar, structural state, cooling rate, Tábua granite, Portugal.

Sommaire

Nous évaluons l'influence du taux de refroidissement sur le degré d'ordre Al–Si du feldspath potassique du granite porphyrique à biotite de Tábua, au Portugal central, d'âge hercynien. Nous considérons aussi les résultats d'un modèle numérique du refroidissement du pluton. Le degré d'ordre, évalué à partir de données sur les paramètres réticulaires, indique environ 92% de l'aluminium dans le site T1 du feldspath potassique partout dans le pluton, sauf le long de sa bordure, dans un liseré de 1.5 km, où cette proportion diminue à environ 79% près du contact. Quoique le taux de refroidissement a été uniforme en dessous de 500°C, il a été, en moyenne, 2°C/ka près de la bordure et 0.6°C/ka dans l'intérieur sur l'intervalle 650–500°C. Le taux de refroidissement du pluton et le degré d'ordre du feldspath potassique montrent une étroite corrélation. A notre avis, le taux de refroidissement était le facteur déterminant dans l'établissement du degré d'ordre Al–Si du felspath potassique à peu près partout dans le pluton. Toutefois, il y a des exceptions, par exemple près du contact, là où il y a des venues pegmatitiques, cas dans lesquels nous préconisons une activité accrue d'une phase fluide aqueuse.

(Traduit par la Rédaction)

Mots-clés: feldspath potassique, degré d'ordre, taux de refroidissement, granite de Tábua, Portugal.

Introduction

The structural state of K-feldspar depends on several chemical and physical factors, the most important being temperature, availability of a fluid phase, thermal history and degree of deformation, as has been earlier recognized (*e.g.* Martin 1974, Smith 1974, Parsons 1977); feldspar composition, grain size, composition of the magma and of the fluid also are expected to have some effect. The ordering process of K-feldspar is not continuous, being retarded in orthoclase by the development of a tweed microtexture composed of ordered and antiordered domains. These domains, which occur on the scale of a few unit cells, need to be reversed and coarsened to allow ordering to proceed (Eggleton & Buseck 1980, Brown & Parsons 1989). The extent of feldspar–fluid interaction is widely accepted as the most effective factor in promoting the monoclinic–triclinic transformation; some insights concerning the mechanisms by which fluids act have been provided through experimental and microtextural studies (*e.g.,* Yund & Tullis 1980, Waldron & Parsons 1992, Waldron *et al*. 1993, Lee *et al*. 1995, 1997).

Structural state has been used in the geological literature for petrogenetic purposes. However, some limitations result from the fact that the final Al–Si configuration of the K-feldspar is determined by the influence of several of those factors, simultaneously or at different stages of the rock history, and the quantitative effect produced by each one is not exactly known.

§ *E-mail address*: lneves@ci.uc.pt

Thus, structural state can only be understood in relatively simple geological settings, where a significant amount of complementary geological, petrographic and geochemical information is available, and some of the factors can be shown to be of secondary importance. Previous studies on granitic rocks suggest that in some plutons, the availability of a fluid phase was the most influential factor (*e.g.*, Godinho 1980), yet in others the cooling rate was prominent in controlling the degree of Al–Si order attained in K-feldspar (Neves & Godinho 1990, Neves 1991a, 1996, Neves *et al.* 1996).

The Tábua granite has been the object of several geological, petrographic and geochemical studies (Pereira 1991, Pereira & Ponte 1992, Neves 1991b, 1995, 1997), and its thermal history has been numerically modeled (Pereira & Hurford 1994, Pereira *et al.* 1996). Geological and geochemical lines of evidence point to the relative scarcity of a magmatic fluid phase and suggest that fluid–rock interaction was only locally important. Thus, this granite appears to provide a suitable example with which to quantify the effect of cooling rate on the degree of Al–Si order of K-feldspar, which also occurs in the metamorphic aureole.

Geological and Petrographic Information

The Tábua granite is the external, coarse-grained porphyritic facies of a large post-tectonic composite Hercynian pluton in central Portugal. It outcrops over *ca.* 300 km^2; the country rocks are metasedimentary, mostly schists and graywackes of pre-Ordovician age. The coarse-grained facies passes to a medium-grained porphyritic biotite–muscovite granite in the innermost portion of the pluton (Fig. 1). Feldspar megacrysts attain several centimeters in size. Small pod-like bodies of pegmatite (most of them a few decimeters in size) occur discontinuously in a narrow fringe along the exocontact (<200 meters) of the granite; the pegmatite bodies are concentrated and best exposed near the village of Ázere (AZ), where the host granite is also slightly coarser than normal.

The Tábua granite is probably the result of partial melting of a heterogeneous portion of the lower crust, as inferred from oxygen isotopes (Neves 1991b). Its age has been estimated as *ca.* 282 Ma by K–Ar and Rb–Sr methods (Neves & Godinho 1992, Pereira & Hurford 1994). Its composition is moderately evolved, with average contents of SiO_2, Li, Rb, and Sn of 70%, 90 ppm, 275 ppm and 12 ppm, respectively. Biotite accounts for *ca.* 11% of the rock´s volume; where present, muscovite is a secondary mineral, generally below 0.2%. The plagioclase is sodic (*ca.* An_{22}), and limited normal zoning can be observed ($An_{15–30}$). Cordierite (up to 5 cm), intensely transformed to chlorite, occurs in the granite along the exocontact. Both quartz and K-feldspar are late minerals relative to biotite and plagioclase.

The K-feldspar is poikilitic and visibly perthitic in most of the grains, with albite lamellae normally not

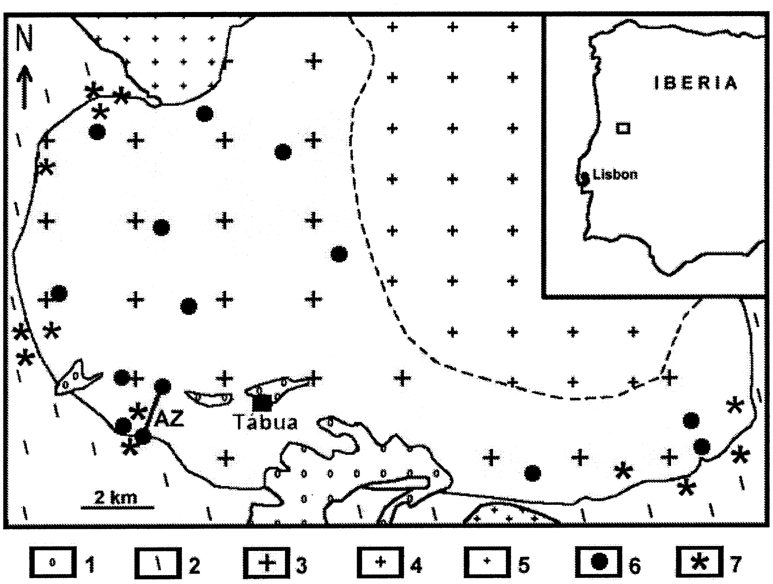

FIG. 1. Simplified geological map of the Tábua granite. Symbols: 1 Tertiary sediments, 2 Pre-Ordovician metasedimentary units (schists and graywackes), 3 coarse-grained porphyritic biotite granite, 4 medium-grained porphyritic biotite–muscovite granite, 5 other Hercynian granites, 6 samples of K-feldspar in granite, 7 samples of K-feldspar from hornfelses. AZ is the Ázere sampling traverse, with nine samples of granite.

exceeding 5 μm. Grid twinning was observed in some grains, more commonly toward the interior of the pluton; moreover, the petrographic features of the K-feldspar are remarkably uniform throughout the pluton. Accessory minerals are apatite, zircon, monazite, tourmaline and ilmenite.

The contact-metamorphic aureole in the metasedimentary country-rocks extends to *ca*. 2 km, and four petrographically different zones were identified (Pereira & Ponte 1992); beyond the aureole, the country rock is characterized by a low-grade metamorphic assemblage, which includes quartz, albite, chlorite and poorly developed white mica. The innermost zone rarely exceeds 150 meters in width and is characterized by the occurrence of hornfels with the assemblage cordierite (or sekaninaite) + K-feldspar + sillimanite, which points to a minimum temperature of 600°C. On the basis of the Fe:Mg ratio of the cordierite-group mineral and the assemblage of metamorphic minerals, and assuming that the ratio of fluid pressure to total pressure at the granite solidus was not lower than 0.8, Pereira (1991) estimated a depth of emplacement of 7 km for the presently exposed level of the granite.

Within the pluton, and usually up to a maximum distance of 1000 meters from the contact, metasedimentary enclaves can be recognized. They may attain a few hundred square meters, and their mineral assemblage is identical to that observed in the contact hornfelses.

Methods

Twelve samples of granite were collected; they are spatially distributed within a large area at various distances from the exocontact. In addition, a sampling traverse was carried out in the Ázere region, where pegmatite bodies occur locally; three samples were collected in the first 200 meters next to the contact, corresponding to an area of pegmatite-bearing granite, and six up to 1.6 km in the pegmatite-free granite (see Fig. 1 for sample locations). Thirteen samples of K-feldspar from hornfelses also were studied, seven from the contact-metamorphic aureole and six from metasedimentary enclaves in the granite.

K-feldspar concentrates were obtained from unweathered samples weighing 1–2 kg (hornfelses) or 5–6 kg (granites). Samples were crushed to a grain size no larger than 150 μm, and the K-feldspar concentrates were obtained through the combination of magnetic and heavy-liquid procedures. The purity of the concentrates was checked by optical observation after staining with a saturated sodium cobalt nitrite solution; the proportion of K-feldspar grains in the final concentrates was at least 96%.

Structural state and composition were determined by X-ray powder-diffraction methods using Philips equipment with Cu$K\alpha$ radiation. Annealed potassium bromate was added to each sample as an internal standard, and its (101) and (202) peaks used for correction of K-feldspar reflections. The diffractograms were obtained in the range 20–52° 2θ at a speed of 0.5° min.$^{-1}$, and their peaks read at a distance from the background between 0.6 to 0.9 of the total peak height; the diffractograms were manually interpreted, and final 2θ angles considered for each sample are the average of at least three scans.

Unit-cell parameters were determined with the microcomputer version of the Appleman–Evans program developed by Benoit (1987). A minimum of ten well-defined diffraction peaks for monoclinic and twelve for triclinic feldspars were used in the calculations. The Al–Si distribution in the tetrahedral positions of unstrained feldspars was subsequently determined as recommended by Kroll & Ribbe (1987), and composition was inferred by the method of Kroll *et al*. (1986).

A qualitative assessment of the variability in structural state was also carried out by a comparison of the X-ray pattern obtained in the 2θ region 29–31° (where 131 and $1\bar{3}1$ peaks occur), with a scale of nine standard patterns, in which a term is symbolized by a letter from A to I (Neves & Godinho 1999). A convenient index of degree of order (Δ_{SM}) based on the angular difference $\Delta 2\theta = 2\theta(\bar{2}04) - 2\theta(060)$ was also determined (Neves & Godinho 1999); this relation is used in order to estimate the Al content of the T1 sites of the K-feldspar for which no dominant symmetry was observed (two samples), which precludes determination of cell parameters with the methods used in this study.

The strain index (SI), which measures the coherency strain of the feldspar due to the presence of coherent exsolution, was determined using the approach of Kroll & Ribbe (1987).

The Cooling Model

The cooling of the pluton was modeled in a rectangular cross-section which approximately parallels the profile AZ (see Fig. 1). The assumption was made that the pluton was emplaced in a geological setting that was initially in equilibrium and had a constant geothermal flux and sources of radioactive heat; moreover, taking oxygen isotope evidence into consideration (Neves 1991b), we assumed that conduction was the dominant mechanism of heat transfer.

On the basis of geological, petrological and geochemical data, parameter values were estimated and assigned to: emplacement level of the pluton (7 km), temperature of the granitic material and the country rock at the time of emplacement (800 and 300°C, respectively), production of radiogenic heat (2.0 μWm^{-3} in the metasediments and 4.0 μWm^{-3} in the granite), and rate of denudation of the regional crust (0.04 mm *per annum*). The density of the granite (2680 kg.m^{-3}) and the country rock (2730 kg.m^{-3}) was measured, and thermal properties and crystallization heat of both the granite and the contact metamorphic hornfelses and mica schists were collected from the geological literature. Assigned

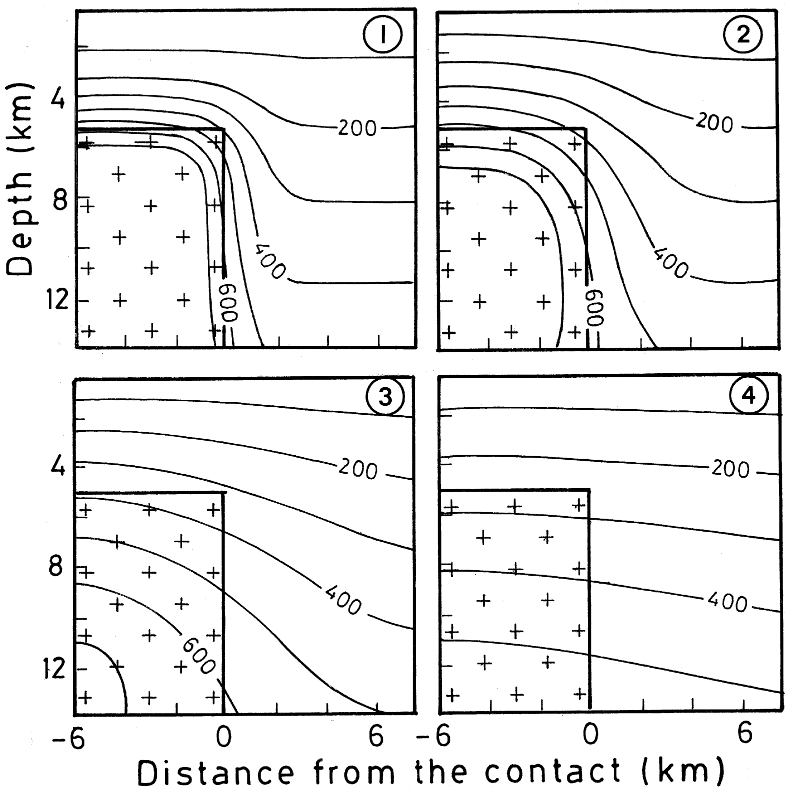

FIG. 2. Profiles of the thermal field 10 (1), 50 (2), 100 (3) and 500 (4) ka after emplacement of the Tábua granite. Isotherms were calculated from the conduction-induced cooling model and are represented as curves with figures in °C. The regional temperature expected at the level of emplacement (7 km) is *ca.* 300°C. The granite is represented with crosses.

values of the parameters are described in Pereira *et al.* (1996).

The model was calculated through the equation of heat transfer in a 2D system. This equation was numerically solved using an explicit finite-difference method with a time step of 500 years. Relevant results of the model are graphically summarized in Figure 2; see Pereira *et al.* (1996) for a full description. Simulations with several sets of parameter values lead to the conclusion that the uncertainty in some values does not affect significantly the reliability of the model.

Mineralogical information on the metamorphic reactions developed in the aureole, as well as the chemical composition of some of the newly formed minerals, permit an estimate of the temperatures at different distances from the contact with the granite. Rb–Sr, K–Ar and fission-track methods applied to whole-rock and mineral samples constrain the rates of cooling and crustal denudation (Pereira & Hurford 1994). Information from these sources provided an independent test of the quality of the model, and led to a good correlation between predicted and observed cooling-curves.

Data on Structural State

Unit-cell parameters, the index of Al–Si order and composition of the K-feldspar samples studied are presented in Tables 1 and 2. Most of the granitic samples contain a dominantly monoclinic K-feldspar; in two cases, the K-feldspar is dominantly triclinic, and two others show no dominant symmetry. The proportion of triclinic domains is significant in every case, as shown by the D_t indicator. In contrast, the K-feldspar from the hornfelses is almost invariably monoclinic, with D_t showing sparse evidence of the presence of triclinic domains.

A comparison of the degree of order of the K-feldspar from contact hornfelses and hornfelsic enclaves by parametric methods is precluded, owing to the small number of samples available (6 and 7, respectively).

TABLE 1. CELL PARAMETERS DETERMINED BY XRD ON K-FELDSPAR CONCENTRATES OF THE TÁBUA GRANITE AND RELATED CONTACT METAMORPHIC HORNFELSES

sample	*a* (Å)	*b* (Å)	*c* (Å)	β	V (Å³)
Hornfelses from metasedimentary enclaves					
AZ14	8.559 (4)	12.980 (4)	7.200 (2)	116° 03.2′ (2.5′)	718.6 (0.4)
OH75	8.579 (4)	12.985 (3)	7.200 (2)	116° 01.9′ (2.8′)	720.7 (0.5)
OH85A	8.569 (5)	12.962 (5)	7.198 (2)	115° 59.4′ (3.4′)	718.5 (0.5)
TD91	8.577 (8)	12.979 (5)	7.199 (3)	115° 59.1′ (4.5′)	720.3 (0.7)
TD97	8.573 (3)	12.956 (2)	7.193 (1)	115° 57.5′ (1.4′)	718.4 (0.3)
TD108	8.556 (5)	12.964 (4)	7.196 (2)	116° 05.1′ (2.9′)	717.0 (0.6)
Hornfelses from the contact metamorphic aureole					
AZ4A	8.573 (4)	12.977 (4)	7.203 (2)	116° 02.0′ (2.5′)	720.0 (0.4)
OH8G	8.579 (3)	12.975 (2)	7.196 (1)	116° 05.7′ (2.1′)	719.3 (0.3)
OH9G	8.583 (3)	12.984 (3)	7.196 (1)	116° 06.0′ (1.8′)	720.2 (0.3)
SCD31	8.553 (5)	12.978 (4)	7.194 (2)	115° 59.6′ (3.1′)	717.8 (0.4)
SCD49	8.561 (8)	12.988 (5)	7.193 (2)	115° 58.4′ (3.7′)	719.0 (0.6)
TD56	8.567 (3)	12.979 (3)	7.195 (1)	116° 04.8′ (2.6′)	718.6 (0.4)
TD82A	8.563 (2)	12.970 (2)	7.198 (1)	116° 02.4′ (1.5′)	718.3 (0.3)
Granite					
AZ1	8.576 (9)	12.963 (6)	7.205 (3)	115° 53.8′ (4.3′)	720.6 (0.8)
AZ2	8.562 (6)	12.964 (5)	7.199 (2)	116° 01.8′ (3.4′)	718.0 (0.7)
AZ3	8.581 (9)	12.971 (6)	7.199 (3)	116° 01.1′ (4.2′)	720.1 (0.8)
AZ4	8.570 (8)	12.965 (5)	7.202 (2)	116° 05.6′ (4.0′)	718.7 (0.8)
AZ5	8.561 (6)	12.957 (4)	7.196 (2)	116° 02.8′ (3.1′)	717.1 (0.6)
AZ6	8.575 (12)	12.959 (7)	7.202 (4)	115° 55.1′ (5.3′)	719.8 (1.1)
AZ10	8.578 (9)	12.951 (6)	7.195 (3)	116° 01.1′ (3.9′)	718.3 (0.9)
OH79	8.564 (8)	12.959 (5)	7.203 (2)	115° 54.6′ (3.8′)	719.1 (0.7)
OH88	8.567 (10)	12.961 (6)	7.203 (3)	115° 49.2′ (4.4′)	719.9 (0.9)
OH99 (1)	8.566 (10)	12.957 (9)	7.210 (4)	116° 03.6′ (5.0′)	718.4 (0.9)
SCD1	8.557 (3)	12.970 (3)	7.197 (1)	116° 10.6′ (2.0′)	716.8 (0.3)
SCD48	8.560 (4)	12.963 (3)	7.199 (1)	115° 56.8′ (2.1′)	718.3 (0.4)
SCD54	8.568 (9)	12.949 (6)	7.199 (3)	115° 54.1′ (3.9′)	718.4 (0.8)
SCD63	8.560 (6)	12.956 (4)	7.204 (2)	115° 56.0′ (3.3′)	718.5 (0.6)
SCD71 (2)	8.580 (7)	12.954 (6)	7.203 (3)	115° 58.5′ (3.2′)	719.2 (0.6)
SCD82	8.566 (9)	12.962 (6)	7.202 (3)	115° 49.4′ (5.2′)	719.8 (0.9)
TD101	8.583 (11)	12.949 (5)	7.203 (2)	116° 03.3′ (3.4′)	719.2 (0.9)
TD111	8.583 (5)	12.956 (3)	7.201 (2)	115° 56.7′ (2.1′)	720.1 (0.5)
TD113	8.578 (5)	12.957 (4)	7.202 (2)	115° 59.5′ (2.5′)	719.5 (0.5)

(1) α = 90°43.5′(6.9′); γ = 87°54.4′(7.3′). (2) α = 90°53.9′(6.8′); γ = 87°50.8′(6.1′). Errors refer to one standard deviation and were estimated through the equation of the propagation of error (Agterberg 1974).

TABLE 2. INDICES OF DEGREE OF ORDER (D_t AND Δ_{SM}), STRAIN INDEX (S_I), COMPOSITION (%Or), AND TOTAL Al CONTENT OF THE T1 SITES IN THE K-FELDSPAR OF THE TÁBUA GRANITE AND ASSOCIATED HORNFELSES

Sample	D_t	Δ_{SM}	S_I	%Or	%Al_{T1}
Hornfelses from metasedimentary enclaves					
AZ14	A	0.57	0.1	88.2	80.2 (1.8)
OH75	A	0.55	0.0	93.8	79.0 (1.6)
OH85A	A	0.66	7.4	88.0	86.4 (2.3)
TD91	B	0.57	2.2	92.7	81.6 (2.5)
TD97	B	0.62	12.3	87.5	87.6 (0.8)
TD108	A	0.59	7.0	84.0	83.0 (1.8)
Hornfelses from the contact metamorphic aureole					
AZ4A	A	0.65	0.3	92.0	83.0 (1.8)
OH8G	A	0.51	5.2	90.1	78.8 (1.2)
OH9G	A	0.48	2.7	92.5	76.0 (1.4)
SCD31	A	0.50	3.7	86.1	80.0 (1.8)
SCD49	A	0.44	1.7	89.3	76.8 (2.4)
TD56	A	0.51	3.7	88.2	77.8 (1.7)
TD82A	A	0.60	4.6	87.7	82.8 (1.0)
Granite					
AZ1	C	0.75	3.7	93.5	91.2 (2.6)
SCD1	B	0.56	4.7	83.7	79.0 (1.4)
AZ10	B	0.71	13.1	87.5	88.2 (2.5)
AZ2	B/C	0.65	5.8	86.7	85.2 (2.3)
AZ3	B	0.60	4.9	92.1	83.4 (2.7)
AZ4	C	0.67	4.4	88.5	84.8 (2.5)
AZ5	B/C	0.67	9.4	84.5	86.2 (2.0)
AZ6	D	0.73	6.5	91.3	90.8 (3.0)
SCD48	B	0.69	6.0	87.5	87.8 (1.3)
AZ7 (1)	E	0.79	--	--	88.9 (5.8)
TD111	C	0.74	8.6	92.2	90.8 (1.3)
TD113	D	0.73	7.4	90.6	89.8 (1.6)
OH79	B	0.72	5.2	89.4	91.2 (2.3)
OH99 (2)	H	0.96	2.1	88.3	93.0 (4.2)
AZ8 (1)	E/F	0.85	--	--	92.0 (5.8)
SCD54	C	0.72	10.8	87.6	93.2 (2.4)
OH88	C	0.77	4.8	91.7	92.8 (2.5)
TD101	D	0.81	9.6	89.7	91.2 (2.2)
SCD71 (3)	H	0.79	7.9	90.4	92.6 (2.7)
SCD63	C	0.81	5.3	87.9	92.4 (1.8)
SCD82	B	0.74	5.0	92.2	92.2 (2.8)

(1) %Al_{T1} estimated with the indicator Δ_{SM}. (2) T1(o) = 91.4%. (3) T1(o) = 92.5%. Errors in %Al_{T1} refer to one standard deviation and were estimated by the propagation of errors (Agterberg 1974). Granite samples are ordered according to increasing distance to the contact.

Applying the Mann–Whitney nonparametric statistical test (Swan & Sandilands 1995) to Δ_{SM} and %Al_{T1}, we infer, at the 0.90 confidence level, that distinct degrees of order were attained in the K-feldspar of the two groups; the same conclusion can be drawn when comparing K-feldspar of the granite with K-feldspar of both types of hornfelses. Indeed, K-feldspar of the contact hornfelses is, on average, the most disordered (Δ_{SM} = 0.53, %Al_{T1} = 79.3), followed by K-feldspar of the hornfelsic enclaves (Δ_{SM} = 0.59, %Al_{T1} = 83.0) and granite (Δ_{SM} = 0.74, %Al_{T1} = 89.4). In contrast, the composition of the K-feldspar in contact hornfelses, hornfelsic enclaves, and granite does not show significant differences (mean values are 89.4, 89.0 and 89.2% Or, respectively). Data on the SI parameter indicate that K-feldspar is not significantly strained, in spite of its obvious perthitic nature.

Spatial Variation of Structural State

In Figure 3, where only samples of K-feldspar from granitic rocks are considered, a regular increase in %Al_{T1} is evident from the exocontact to 1.5 km into the interior of the pluton (*ca.* 79 up to *ca.* 92% in the T1 site). From this point on, the K-feldspar shows an almost constant value of Al in the T1 sites (92%). The subordinate triclinic component of the samples also decreases in volume toward the contact, as revealed by data on D_t (Table 2).

Figure 4 is a plot of K-feldspar samples from the Ázere traverse, which includes three pegmatite-bearing samples that occur near the contact (<200 meters) and, for purposes of comparison, the six samples of pegma-

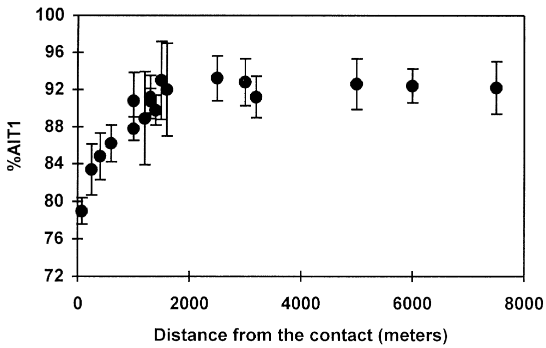

FIG. 3. Al content in T1 sites of the K-feldspar of granite samples, plotted against distance from the contact with country rock. The three samples of pegmatite-bearing granite of the Ázere traverse are not represented.

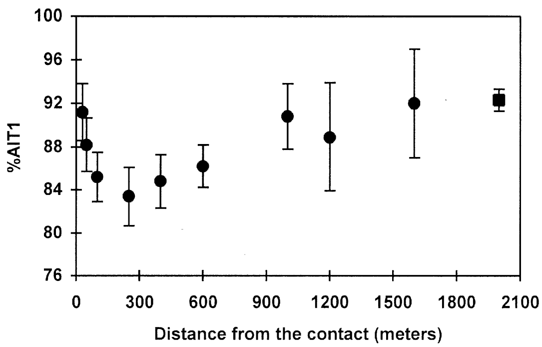

FIG. 4. Al content in T1 sites of the K-feldspar in granite samples of the Ázere traverse, plotted against distance from the exocontact. The square refers to the Al_{T1} average value of all samples of the Tábua granite situated 2 km or more from the exocontact. The three circles closest to the contact refer to the pegmatite-bearing granite, and the others, to the pegmatite-free granite.

tite-free granite already plotted in Figure 3. It is obvious that the three samples from pegmatites have a higher degree of order than expected. Thus, in the 200 meters closest to the contact in this traverse, the observed general trend of a decrease in Al–Si order closer to the contact apparently does not apply.

Discussion

The generally observed trends of Al–Si order in the K-feldspar can be related to conditions of cooling. The cooling model previously described demonstrates that two different stages can be identified in the cooling process, the first corresponding to the temperature range 650–500°C, and the second to the interval 500–350°C. In fact, for the former range, estimated rates of cooling

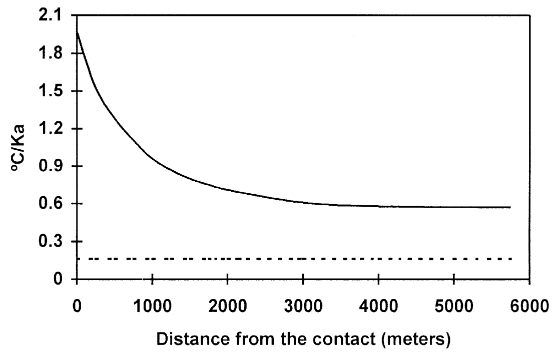

FIG. 5. Plot of the average cooling rate of the Tábua granite between 650 and 500°C (solid line) and between 500 and 350°C (dashed line) as a function of distance from the exocontact. Cooling rates were estimated with the cooling model described in the text.

within the pluton (at the level corresponding to the actual topographic surface) show a pattern remarkably similar to the one observed for K-feldspar order (Fig. 5). The upper temperature of 650°C is the one that roughly corresponds to the minimum granitic solidus at the estimated level of emplacement.

Over the 650–500°C interval, the predicted average rates of cooling range from a maximum of *ca.* 2°C per 1000 years (ka) near the contact to *ca.* 0.6°C/ka for the granite´s interior; a striking decrease is observed from the exocontact up to 1.5 km to the interior (Fig. 5), thus correlating well, in a negative way, with the variations detected in the Al–Si order of the K-feldspar. Considering the information available for the 2 km closest to the contact, a curvilinear regression equation between the cooling rate and Al–Si order is

$$\%Al_{T1} = 104.6 - 19.5c_r + 3.0c_r^2,$$

where c_r is the cooling rate in the range 650–500°C expressed as °C/ka; this equation is significant at a confidence level of 0.99.

In contrast, over the temperature range 500°–350°C, predicted cooling rates are relatively uniform throughout the whole pluton, ranging, on average, from *ca.* 0.15°C/ka near the exocontact to *ca.* 0.18°C/ka several km away from it (Fig. 5). On the basis of Na partition, the average temperature of equilibration of the perthite assemblages was estimated by Neves (1995) as 430°C (the range of variation is 350–470°C), which is in good agreement with the above interval. This fact, as well as the petrographic evidence of uniformity of perthitic texture and abundance in the granite, suggest that the involvement of a fluid phase was also uniform; thus, fluid phase alone cannot explain the different degrees of order achieved by the K-feldspar of the interior and the margins of the pluton.

After thermal equilibrium between the pluton and the nearby country-rock was attained, cooling proceeded slowly to lower temperatures, mainly as a consequence of crustal denudation. Consequently, for temperatures lower than 300–350°C, isotherms in the entire crustal region modeled can be considered horizontal. Thus it appears that the spatial variation observed in the degree of Al–Si order was basically established in the temperature range 650–500°C; this does not preclude ordering to proceed down to *ca*. 300–350°C.

Al_{T1} data for the hornfelses are in good agreement with the hypothesis that degree of order depends essentially on the cooling rate. In fact, from the model it can be inferred that the K-feldspar generated in the metasediments at the contact aureole (at a maximum distance of 200 meters from the exocontact) was subjected to a cooling rate quite similar to that of the nearby granite. Indeed, the estimated average degree of Al–Si order of the K-feldspar of the hornfelses from the contact aureole is identical to the one observed in the granite sample closest to the contact (*ca*. 79% of Al in the T1 sites). On the other hand, the slightly higher degree of order of K-feldspar from the hornfelses of the metasedimentary enclaves in the interior of the granite (*ca.* 83% of Al in the T1 sites) seems to be in part a consequence of the spatial position of the samples, located at different distances (up to a maximum of 1 km) from the exocontact. Once again, the observed average degree of order closely matches the one determined for the K-feldspar from granite in the same spatial position. At this point, the conclusion can be drawn that the cooling rate was a determining factor in establishing the Al–Si order of K-feldspar where rocks are pegmatite-free. In principle, an alternative explanation could be provided by an ordering mechanism involving solution and redeposition of the K-feldspar at a microscopic scale, resulting from interaction with low-temperature deuteric fluids (*e.g.,* Waldron *et al*. 1993); however, the margins of the pluton are the most favorable area for this mechanism to operate and induce the orthoclase–microcline transformation, as a consequence of higher stress and fracturing of the granite; this is not the pattern observed. Oxygen isotope studies also discarded the possibility of interaction with meteoric fluids (Neves 1991b).

The three samples of pegmatite-bearing granite that show a reversal in the general trend of variation observed are located in an area where geological evidence indicates the presence of substantial amounts of magmatic fluids. Though restricted to the margin of the granite, the role of the fluids appears to have been locally important in promoting ordering, allowing K-feldspar to achieve the same degree of order as in the interior of the granite, in spite of a difference in cooling rate of *ca*. 1.4°C/ka. Both this fact and the spatial association with pegmatites suggest that fluids of magmatic origin were locally important in promoting ordering. Further work, namely of a microtextural nature, is necessary for a better characterization of this local reversal in the general pattern of ordering.

Concluding Remarks

Cooling rate was the most influential factor in controlling the degree of order attained in K-feldspar almost throughout the entire Tábua pluton, although fluids of magmatic origin could have played an effective role locally. We estimate that an increase of 1°C/ka in the cooling rate produces a decrease of *ca*. 12% in the amount of Al occupying the T1 sites of the K-feldspar.

Previous work combined with the present results suggest that plutons that cooled essentially by conduction, without significant fluid–rock interaction, should show a decrease in the degree of Al–Si order near the contact with their country rocks. This hallmark can be easily detected if proper spatial sampling is undertaken. Indeed, two other cases are already known: the Avô pluton, a small Hercynian two-mica granite that occurs in central Portugal (Neves 1996), and the Sintra pluton, an Alpine composite body that outcrops near Lisbon (Neves & Godinho 1990). In both cases, the degree of Al–Si order of K-feldspar decreases near the contact, but, owing to the smaller size of the plutons (*ca.* 20 and 50 km^2, respectively), these variations are confined to a few hundred meters from the contact. Where convection was an important mechanism of heat transfer, the structural state of K-feldspar is expected to be (almost) invariant throughout the whole igneous body.

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