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FELDSPAR EXSOLUTION: EVIDENCE FOR THE THERMAL EVOLUTION OF GRANULITE FACIES ROCKS

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ABSTRACT

Mesoperthites, spindle perthites and filmperthites are common exsolution textures in granulite facies rocks. When two-feldspar geothermometry is applied to such slowly (2-3 °C/ma) cooled feldspars, the problem of retrograde resetting has to be accounted for by considering the interchange and exsolution processes between alkali and plagioclase feldspars. Two-feldspar geothermometers which use these retrograde resetted compositions are obviously producing erroneous results. Using a modified version of the Fuhrman and Lindsley (1988) program, it is possible to reverse the retrograde K, Na exchange at constant An contents and derive concordant temperatures, at which the alkali feldspars and plagioclases were at equilibrium.

INTRODUCTION

The perthitic textures in alkali feldspars have been studied for many years. Due to the advantages of the TEM, fine-scale features in natural or experimental samples have been examined extensively in the recent years (Yund 1983a, b, 1984; Parsons and Brown 1984, 1991; Smith and Brown 1988; Evangelakakis et. al. 1993).

The optical microscope scale perthites received less attention. The origin of the different features have been interpreted by Yund and Ackermand 1979; Yund et. al. 1980; and Speer and Ribbe 1973. Mostly the coarse perthites have been used to determine two-feldspar temperatures (Mora and Valley 1985; Fuhrman and Lindsley 1988; Elkins and Grove 1990; Voll et. al. 1994).

The two-feldspar geothermometry uses Margules parameters that were derived from experimental data. The Margules para-meters do not include the effects of increasing Al,Si order and of the various phase transformations that occur at decreasing temperature (Kroll et. al. 1993). At the same time it is difficult to approach K-Na-Ca exchange equilibrium in experiments because of the short time scale. But the main concern is the retrograde resetting of the feldspars (Mora and Valley 1985; Brown and Parsons 1988; Fuhrman and Lindley 1988).

In following we first present the micro- and submicroscopic exsolution textures, secondly the retrograde inter- and intracrystalline exchange processes and finally suggest a correction to calculate the original equilibrium compositions so that two-feldspar geothermometry can be meaningfully applied.

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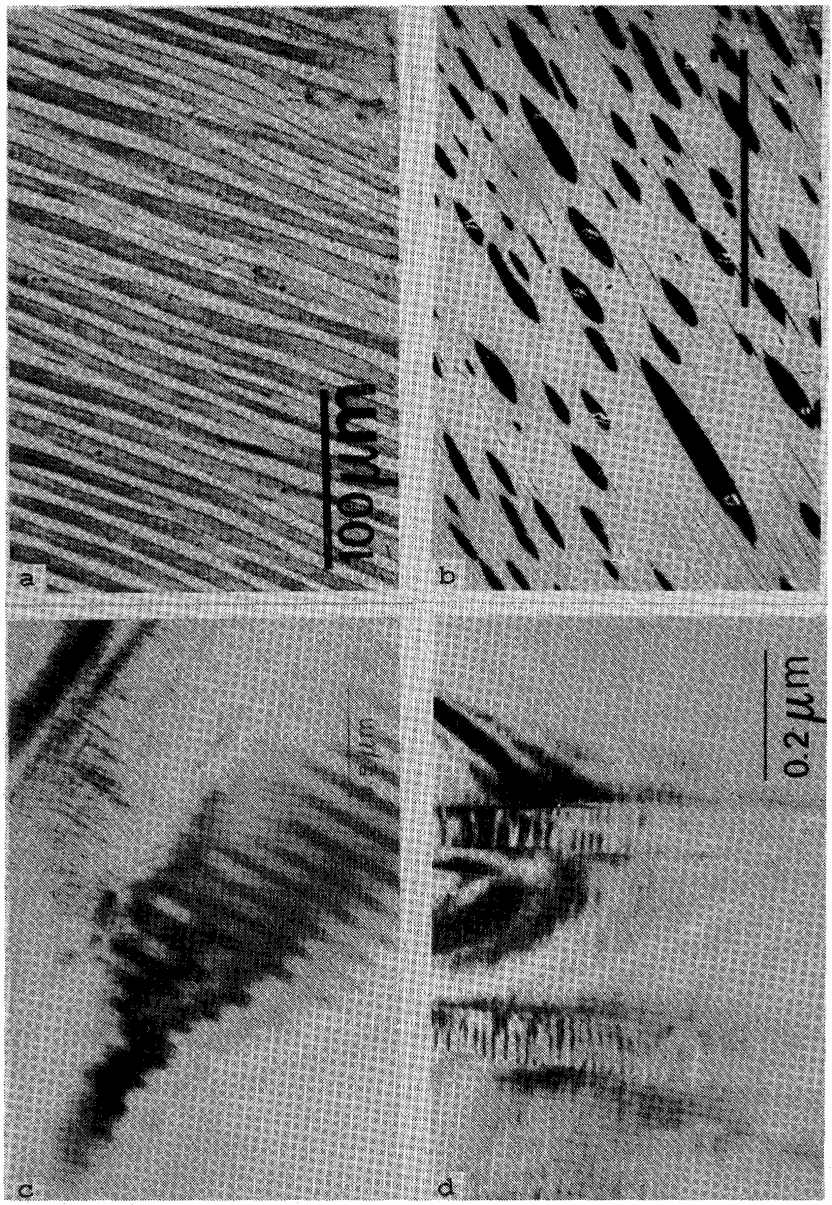

Fig. 1a-d: The textures were observed in thin sections ≈||(001). **a.**Photomicrograph: mesoperthite (VSL 523, $Or_{50.3}Ab_{44.9}An_{4.8}$) consisting of (white) Ab-rich and (black) Or-rich lamellae. Film albite lamellae are exsolved within the Or-rich lamellae. **b.** Electron microprobe backscatter photograph of a spindel perthite (VSL 522, $Or_{72.9}Ab_{23.3}An_{3.1}Cn_{0.7}$), like the mesoperthite showing the first (coarse Ab-rich lamellae: black) and the second (film albite: black) exsolution event. Scale bar =100µm. **c.** Dark-field electron micrograph of mesoperthite (VSL 523). An irregular incoherent interface separates the Or-rich lamella (tweed texture) from the Albite twinned Ab-rich lamella. **d.** Dark- field electron micrograph of albite twinned film albites within an Or-matrix (tweed texture).

EXPERIMENTAL METHODS

The optical microscope was used to examine the coarse exsolution features. Using wavelength dispersive analysis (WDA) and scanning electron microscopy (SEM) on a Cameca microprobe (CAMEBAX MB) and JEOL Superprobe (JXA-8600MX) we determined the bulk compositions of the crystals and the compositions of their exsolved phases. The submicroscopic investigations were undertaken with different TEM´s: (1) the JEM-100C, (2) the Philips 400 and the ARM-1000 at the National center for Electron Microscopy at the Berkeley Laboratory.

EXSOLUTION TEXTURES, MICROPROBE AND TEM WORK

Figure 1a shows an optical micrograph of a coarse mesoperthite (VSL523, $Or_{50.3}Ab_{44.9}An_{4.8}$) consisting of (white) Ab-rich and (black) Or-rich lamellae without a host-guest rela-tionship between the lamellae.

In more Or-rich alkali feldspars the Ab-rich lamellae appear as isolated lenses and blebs in an Or-rich matrix (VSL522, $Or_{72.9}Ab_{23.3}An_{3.1}Cn_{0.7}$, Fig. 1b). They adopt the shape of spindles and so we call them spindle perthites (Evangelakakis et. al. 1991a, b). The interface of the lamellae is oriented about parallel to (601). As film perthites are recognised alkali feldspar which straight, thin (<1-2µm) film (albite) lamellae are developed (Evangelakakis et. al. 1993). Film lamellae are present within the Or-rich matrix of the spindle perthites (Fig. 1b) as well as within the Or-rich lamellae of the mesoperthites(Fig. 1a). On a submicroscopic scale the Ab-rich lamellae of the mesoperthite are Albite twinned and the Or-rich lamellae show an orthoclase tweed texture (Fig. 1c). Both are interconnected by an irregular incoherent interface. The films are Albite (Fig. 1d) or Pericline twinned (Evangelakakis et. al. 1993) and coherently intergrown with the orthoclase matrix. They exsolve below 350°C (Evangelakakis. et. al. 1992, Evangelakakis 1992).

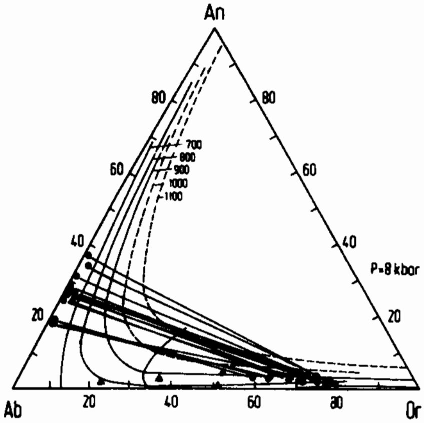

Fig. 2. Microprobe analysis of alkali feldspar-plagioclase pairs from Sri Lanka. Ternary miscibility gap calculated for P=8 kbar using Margules parameters of Elkins and Grove (1990).

RETROGRADE INTER- AND INTRACRYSTALLINE PROCESSES

The compositions of coexisting plagioclase and alkali feldspars from granulite rocks of Sri Lanka do not plot on a common isotherm. The Or content of the plagioclase is too low compared to its Or content expected from the An content of the coexisting alkali feldspar (Fig. 2). Any calculation using the measured compositions would derive erroneous two-feldspar tem-peratures. The low K content of the plagioclase is a result of the retrograde K-Na exchange (Brown and Parsons 1988).A ***fundamental correction*** is needed which takes into account the retrograde K-Na exchange. The Fuhrman and Lindsley (1988) geothermometer program allows to correct the measurement uncertainties in feldspar analysis by changing the composition within a limit of 2mol%, so that the three temperatures T_{Ab}, T_{Or}, T_{An}

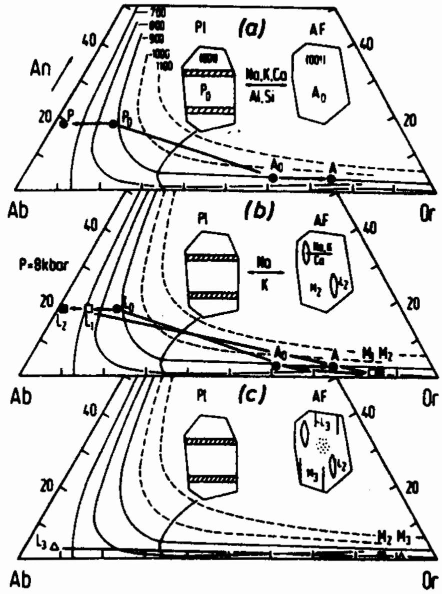

Fig. 3.a-c: Model of retrograde inter- and intracrystalline processes exchange and exsolution events of an alkali feldspar-plagioclase pair (VSL 522). **a.** The A_0 and P_0 feldspar pair which initially is at equilibrium changes its composition to A and P due to the intercrystalline K-Na exchange after the A_0-P_0 pair become a closed system with respect to Al-Si exchange. ***b.*** An exsolution of the first plagioclase lamellae (L_0) below the incoherent solvus is inevitable during further cooling. Their composition is changing through L_1 which defines the end of the intracrystalline Al-Si exchange to L_2 due to the K-Na exchange. At the same time the matrix M_0(≈A_0) shift to M_2 through the M_1. The bulk composition A_0 is sifting to A because of the intercrystalline K-Na exchange. ***c.*** A second exsolution takes places below the coherent solvus which produces L_3 and M_3 after the lamellae L_2 and matrix M_2 became a closed system with respect to the K-Na exchange.

derived from the activity equations are as close as possible (see Fuhrman and Lindsley 1988).

Before we postulate a new correction we will introduce the retrograde inter- and intracrystalline processes by examining the cooling history and exsolution sequence of a plagioclase-alkali feldspar pair at small cooling rates (2-3 °C/ma, Hölzl et.al., 1991) and dry conditions.

It is obvious that the integrated measured compositions of a feldspar pair A-P (VSL 522 , Fig. 3a, Tab. 1) do not lie on a common isotherm which should be the case if the compositions were at equilibrium. Therefore, T_{Ab}, T_{Or}, T_{An} are not identical even after applying the Fuhrman and Lindsley (1988) correction of 2mol%.(Tab. 2)

We assume that at some peak metamorphic temperature the A_0-P_0 pair is at equilibrium, so that T_{Ab}, T_{Or}, T_{An} are identical. At these conditions each crystal represents an open system with respect to K, Na, Ca as well as Al, Si exchange to maintain charge balance. The K, Ca exchange must freeze early in the cooling history, because of the low Al-Si diffusivities (Grove et. al. 1984; Yund 1986; Liu and Yund 1992). As a consequence the crystals became a closed system with respect to the Ca transfer, no Ca could be removed from the crystals. The K, Na exchange does not require an Al-Si transport. It continues to lower temperatures. Therefore the A_0 and P_0 data points shift to A and P parallel to the Ab-Or join. A and P are the measured compositions (Fig. 3a).

After the Ca transfer has been frozen, the alkali feldspar became supersaturated with respect to Ca. A plagioclase exsolution below the incoherent solvus is inevitable (Fig. 3b) (Evangelakakis el. al., 1991a). It produces the first plagioclase lamellae (L_0) within an alkali feldspar matrix M_0(≈A_0). The lamellae and the matrix represent an open system with respect to their K, Na, Ca and Al, Si exchange. During cooling the bulk composition of the alkali feldspar A_0 is changing to A, at the same time the lamellae L and the matrix M between the lamellae change their compositions from L_0 to L_2 and from M_0 ($\approx A_0$) to M_2. L_1 and M_1 are assumed compositions and defines the end of the intracrystalline Al-Si exchange. The lamellae no longer increase in volume. The shifts from L_1 and M_1 to L_2 and M_2, respectively, is caused by the intracrystalline Na-K exchange which continous to lower temperatures than the intercrystalline exchange. L_2 and M_2 defines the end of the Na-K exchange

Table 1. Bulk and phase compositions (mol%) of feldspars in sample VSL 522.

VSL 522	**Ab**	**Or**	**An**	**Cn**
Alk. feld. **A**	23.3	72.9	3.1	0.7
Plagioclase **P**	79.9	1.8	18.2	-
Lamellae **L2**	79.8	0.9	19.3	-
Matrix **M2**	13.4	84.8	0.3	1.5
Lamellae **L3**	88-90	7-8	3-4	-
Matrix **M3**	9.5	90.3	0.0	1.7

Further cooling produces a Na-supersaturated matrix (M_2). The supersaturation can be decreased by two exsolution processes: (1)Film lamellae and fine scale spindles are exsolved between the plagioclase lamellae L_2 which are coherently intergrown with their matrix (M_3) (Evangelakakis et. al. 1993).(2) Ab-rich rims develop around the plagioclase lamellae L_2.

Table 2: Different calculated temperatures (T_{Ab}, T_{Or}, T_{An}) of a granulite-facies ternary feldspar pair (Sample VSL 522)

P		**Composition (1)**			**Composition (2)**			**Composition (EG)**		
Kbar		Ab	Or	An	Ab	Or	An	Ab	Or	An
8	**PL**	79.9	1.8	18.2	77.9	3.8	18.2	67.6	14.1	18.2
	AF	23.5	73.4	3.2	25.5	73.4	1.2	37.1	59.8	3.2
	T	607	503	1522	689	620	828	884	885	885

Note: Composition (1), (2), (EG): (1) measured compositions. (2) compositions „corrected" within 2mol% analytical uncer-tainty using the original Fuhrman and Lindley (1988) program. (EG) compositions after correction (A_0, P_0) for assumed retro-grade resetting at constant An using Margules parameters of Elkins and Grove (1990). Composition (1) is normalized to Or+Ab+An=100mol% without Cn.

SUGGESTED K-Na CORRECTION

From the above interpretation of the exchange and exsolution history of the feldspar pair from a high grade metamorphic rock, two-feldspar geothermometry using uncorrected integrated feldspar compositions (e.g., A and P, Fig. 3a), inevitably produces erroneous results. It is possible, however, to get a minimum temperature at which the feldspar pair was at equilibrium by reversing the K-Na exchange. We modified the Fuhrman and Lindley (1988) routine for this purpose. The program shifts the Ab, Or contents of both alkali feldspar and plagioclase at constant An contents until the equilibrium tie-line and the common isotherm are found (e.g., A_0-P_0 in Fig. 3a). We applied the new correction on many feldspar pairs from Sri Lanka and received reasonable results fitting to the geological setting (Fig. 4.) Simultaneously, we compared the two-feldspar temperatures with

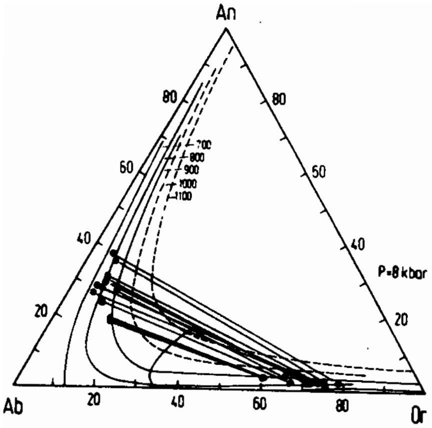

Fig. 4: Coexisting alkali feldspar-plagioclase pairs from Fig. 2 after the suggested correction (compare Or content of the plagioclases from Fig. 2).

gar-cpx and gar-opx temperatures on the same thin sections and got similar high values. Therefore, we are confidently using two-feldspar geothermometry in granulite facies rocks (Evangelakakis 1992; Kroll et.al. 1993; Voll et.al. 1994).

SUMMARY

1. Mesoperthitic textures are changing continously to spindle perthitic when the Or content of the crystals increase.

2. The coarse mesoperthic and spindle perthitic lamellae were probably exsolved below the incoherent solvus. On the other hand, the film albite lamellae are exsolved in a second exsolution event below the coherent solvus.

3. Measured feldspar compositions from granulite facies rocks deliver erroneous two-feldspar temperatures.

4. By reversing the retrograde K-Na exchange it is pos-sible to determine a minimum temperature where the alkali feldspar and the coexisting plagioclase where at equilibrium

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