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## Sr Isotopes and the Structural State of Feldspars as Indicators of Post-Magmatic Hydrothermal Activity in Continental Dolerites

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**Abstract.** Late-crystallised interstitial alkali feldspars and a single epidote from selected Proterozoic dolerites in Sweden have higher initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, (e.g., 0.709) than the early-crystallised minerals of the same rocks ( $\sim 0.704$ ); anomalies in Rb and Sr concentrations are also noted. This radiogenically-enriched Sr must originate in the older host rocks of the intrusions. As the contaminated phases often occupy  $< 1\%$  of the dolerite, only an aqueous fluid would have been capable of transporting the contamination through the 99% solid intrusions. Textural association of late feldspars with hydrous alteration products supports this interpretation. Feldspar structural data suggest that most dolerites have been affected by subsolidus aqueous fluids, causing extensive structural re-equilibration in interstitial K-feldspars, as well as occasional metasomatic effects. Anomalies in  $^{87}\text{Sr}$  developed only where the fluids interacted with host rocks.

and (2) important Sr isotopic differences may occur between the mineral phases of single samples. In this study, such mineral isotopic anomalies are related to feldspar structural state and composition and to alteration of mafic minerals, phenomena which reflect the influence of migrating aqueous fluids at the deuteric stage.

Petrographically the samples, all dolerites, consist of calcic plagioclase, clinopyroxene, Fe-Ti oxides and apatite. Olivine, orthopyroxene and biotite may be present, and almost all rocks contain a small proportion of interstitial alkali feldspar or granophyric intergrowth. Amphibole, chlorite and sericite commonly appear as secondary minerals, usually associated texturally with the late-crystallising alkali feldspar. The hydrous minerals may comprise up to 10% of a sample; more altered rocks occur in most intrusions, but were avoided. Sample locations and references to field maps and reports are given in the appendix.

### Introduction

The results described in this paper are based on an extensive study of undisturbed Upper Proterozoic dolerite intrusions from Sweden; these occur in a region of crust thermally unaffected since Middle Proterozoic time,  $\sim 1,650$  m.y. ago. The dolerites belong to three distinct intrusive episodes ( $\sim 1,550$ ,  $\sim 1,220$  and 1,000-850 m.y.), defined mainly by a combination of Rb-Sr mineral methods (Patchett, 1978). Whereas the majority of data yield consistent age results, some cases of discordance show that (1) whole-rock regression lines for continental dolerites commonly give anomalously old ages (compare Brooks et al., 1976),

### Analytical Methods

The crushing of dolerite samples and the separation of mafic minerals were performed by standard techniques<sup>1</sup>. The plagioclases are usually zoned at their margins, and 4 to 7 feldspar fractions were obtained by serial sinking in tetrabromoethane diluted by stages with acetone, using a size fraction of 45-84  $\mu\text{m}$ . Each separate, numbered F1 (most dense, hence most calcic) onwards, was cleaned at 1.0 amp. in a Frantz magnetic separator to remove composite grains. The fine grain-size minimises the compositional overlap between successive fractions, and the higher-numbered separates contain the later-crystallised portions of the feldspars (e.g., interstitial alkali feldspar or granophyric intergrowth).

Rb-Sr analyses were performed by the isotope dilution method as described by Patchett (1978). Mineral samples were carefully washed, but not crushed before dissolution. Overall

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<sup>1</sup> Hand-picking of clinopyroxenes (Hart and Brooks, 1974, 1977) was not performed. The separates, consisting entirely of clinopyroxene, therefore correspond to the cloudy type of Hart and Brooks, with Rb contents  $> 0.1$  ppm (compare Table 1)

Table 1. Rb—Sr data

Sample	Material <sup>a</sup>	Rb ppm	Sr ppm	<sup>87</sup> Rb/ <sup>86</sup> Sr	<sup>87</sup> Sr/ <sup>86</sup> Sr <sup>b</sup>	( <sup>87</sup> Sr/ <sup>86</sup> Sr) <sub>0</sub> <sup>c</sup>
Breven dolerite						
SÖ-3	WR	5.9	260.5	0.0656	0.70480 ± 15	0.7033 ± 2
SÖ-3	F7	150.1	651.1	0.6682	0.72379 ± 2	0.7090 ± 2
SÖ-4	WR	6.8	267.1	0.0737	0.70561 ± 6	0.7040 ± 1
SÖ-4	F1	5.3	443.7	0.0346	0.70459 ± 18	0.7038 ± 2
SÖ-4	F5	6.1	454.2	0.0388	0.70501 ± 18	0.7041 ± 2
SÖ-4	F6	19.5	470.6	0.1201	0.70730 ± 13	0.7046 ± 2
SÖ-4	F7	114.4	696.1	0.4762	0.71988 ± 10	0.7093 ± 2
SÖ-4	CPX	1.7	10.6	0.4625	0.71353 ± 36	0.7033 ± 5
Idre dolerite						
DN-21	WR	7.7	306.8	0.0725	0.70462 ± 20	0.7034 ± 2
DN-21	F1	8.4	527.4	0.0461	0.70416 ± 20	0.7034 ± 2
DN-21	F2	4.1	521.6	0.0227	0.70373 ± 8	0.7033 ± 1
DN-21	F3	3.6	504.0	0.0204	0.70376 ± 10	0.7034 ± 1
DN-21	F5	5.5	475.5	0.0337	0.70399 ± 16	0.7034 ± 2
DN-21	CPX	1.1	35.2	0.0918	0.70520 ± 20	0.7036 ± 2
DN-31	WR	19.8	356.4	0.1604	0.70766 ± 16	0.7049 ± 2
DN-31	F1	36.8	572.9	0.1857	0.70772 ± 14	0.7045 ± 2
DN-31	F3	7.7	384.9	0.0580	0.70557 ± 10	0.7046 ± 1
DN-31	F4	5.1	311.3	0.0472	0.70578 ± 6	0.7050 ± 1
DN-31	F5	5.1	317.3	0.0463	0.70583 ± 6	0.7050 ± 1
DN-31	CPX	0.8	32.0	0.0681	0.70535 ± 52	0.7042 ± 6
DN-31	CPX + 10% EP	0.8	227.9	0.0096	0.70898 ± 14	0.7088 ± 1
DN-31	CPX + 10% EP	0.7	237.9	0.0088	0.70920 ± 12	0.7090 ± 1
Bunkris dolerite						
DN-37	WR	69.7	268.0	0.7543	0.72584 ± 26	
DN-37	F1	57.1	630.5	0.2621	0.71527 ± 8	
DN-37	F2	66.9	556.2	0.3481	0.71748 ± 16	
DN-37	F3	130.5	362.3	1.0444	0.73305 ± 16	
DN-37	F4	201.1	255.8	2.2857	0.75882 ± 10	
DN-37	CPX	1.0	21.0	0.1354	0.70984 ± 28	
DN-42	WR	46.4	281.2	0.4777	0.71795 ± 12	
DN-42	F1	44.5	618.8	0.2082	0.71254 ± 16	
DN-42	F2	51.6	582.2	0.2568	0.71346 ± 10	
DN-42	F3	69.6	516.2	0.3906	0.71644 ± 12	
DN-42	F4	138.1	378.2	1.0589	0.73161 ± 12	
DN-42	CPX	2.5	21.9	0.3299	0.71138 ± 26	

<sup>a</sup> WR = whole-rock; F = feldspar; CPX = clinopyroxene; EP = epidote

<sup>b</sup> In-run errors at 2σ

<sup>c</sup> Initial <sup>87</sup>Sr/<sup>86</sup>Sr ratio calculated only where age of dolerite is known: for Bunkris dolerite the relationships are apparent from Fig. 3. Calculation of initial ratio performed using in-run errors plus a 1.4% (2σ) component on <sup>87</sup>Rb/<sup>86</sup>Sr

blanks were consistently less than 8 ng Rb and 4 ng Sr; this Rb blank can affect the <sup>87</sup>Rb/<sup>86</sup>Sr ratio of clinopyroxenes by up to 2%, but as these results are used only qualitatively, and as the isotopic composition of the blanks is unknown, no corrections were applied. Sixteen analyses of the Eimer and Amend SrCO<sub>3</sub> standard (by J. Hutchinson) over the period of study yielded a mean of 0.70804 ± 0.00012 (2σ). Ages are quoted relative to the decay constant λ<sup>87</sup>Rb = 1.42 × 10<sup>-11</sup> yr<sup>-1</sup> (Steiger and Jäger, 1977), with errors given at 2σ.

Information concerning composition and degree of Si—Al order of the feldspars in the least dense fraction is derived from cell dimensions, refined from indexed 2θ values corrected using a spinel internal standard (Guinier-Hägg camera, Cu Kα<sub>1</sub> radia-

tion, λ = 1.54056 Å; synthetic spinel a = 8.0833 Å at room temperature) using the fixed option of the cell refinement programme of Appleman and Evans (1973).

### Mineral Sr Isotopic Anomalies

For a majority of mineral isochrons, no variation in (<sup>87</sup>Sr/<sup>86</sup>Sr)<sub>0</sub> occurs amongst the separates; Rb increases and Sr decreases with decreasing density of the feldspar separate. The feldspars, together with the whole rock, clinopyroxene, etc., thus define a line

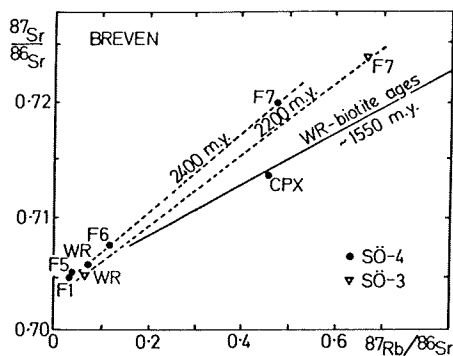


Fig. 1. Rb-Sr data for two Breven dolerite samples. WR=whole rock; F=feldspar; CPX=clinopyroxene.  $2\sigma$  errors fall within the symbols. Analyses are listed in Table 1

on an isochron diagram, representing the age of emplacement of the intrusion (Patchett, 1978). In some cases, however, isotopic anomalies are observed; the clearest examples are described below:

### 1. Breven Dolerite

The Breven dyke is 25 km long, up to 1,200 m wide and intrudes Svecofennian (1,900–1,700 m.y.) gneisses and granites (Krokström, 1932). Samples SÖ-3 and SÖ-4 come from a portion of the dyke where the entire 400 m width consists of fresh, medium to coarse-grained olivine dolerite. The two samples lie only 20 m apart across strike of the intrusion, and both consist mainly of olivine, calcic labradorite, clinopyroxene and opaque minerals. Accessories include apatite, biotite and minor alkali feldspar, quartz and hydrous alteration products (e.g., sericite, chlorite, and amphibole). Except for apatite, these accessory minerals are commonly associated in interstices between the major minerals, and clearly were the latest parts of the rocks to crystallise. Alkali feldspar and quartz are associated, but not in granophyric intergrowths. Occasionally, irregular veinlets of sericite and hydrous mafic minerals penetrate plagioclase and olivine, respectively; serpentine was not positively identified. The dolerites generally preserve a quite pristine appearance.

Olivine dolerites SÖ-3 and SÖ-4 define whole-rock/biotite ages of  $1,548 \pm 23$  and  $1,542 \pm 23$  m.y., in agreement with other results for this dyke swarm; these data are thus interpreted to indicate the time of intrusion (Patchett, 1978). However, lines joining the analyses for the lightest feldspar fractions (F7) and the whole rocks define apparent ages of 2,200 and 2,400 m.y. (Fig. 1). As the dyke cuts rocks metamorphosed or intruded during 1,900–1,700 m.y. (Magnusson, 1965), these dates are definitely spurious. For

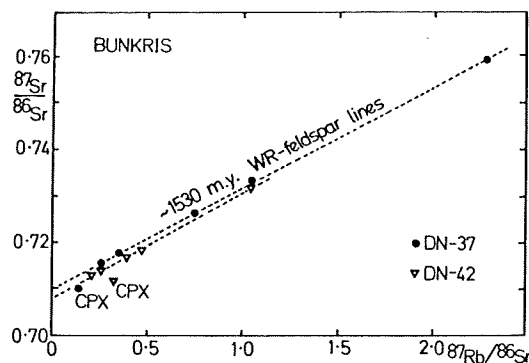


Fig. 2. Rb-Sr data for two Bunkris dolerite samples. CPX=clinopyroxene.  $2\sigma$  errors fall within the symbols. Analyses are listed in Table 1

an emplacement age of 1,550 m.y. the F7 feldspars have  $(^{87}\text{Sr}/^{86}\text{Sr})_0$  values of 0.709, in contrast to 0.704–0.705 for the main mineral constituents of the rocks (Table 1). The F7 feldspars are also anomalous in having Sr contents 200 ppm higher than the plagioclase F1 in SÖ-4 (Table 1), a relationship in opposition to the normal within-sample trend of reduction in Sr with progressive crystallisation. Interestingly, the poikilitic clinopyroxene of SÖ-4 does *not* follow the trend of the F7 feldspars, but lies close to the real age line defined by the whole-rock/biotite pair (Fig. 1).

### 2. Bunkris Dolerite

This dolerite, either a dyke or a sill, intrudes felsic volcanic rocks dated at  $1,634 \pm 34$  m.y. (Welin and Lundqvist, 1970) and possibly overlying continental sediments as well. The rock consists mainly of zoned plagioclase, clinopyroxene and Fe–Ti oxides. Interstitial granophyre and alkali feldspar are present, and there is abundant alteration of pyroxene to amphibole and plagioclase to sericite. Additionally, a recrystallisation in plagioclase seems to obliterate the normal zoning.

Analyses of feldspar separates from two least-altered specimens (Table 1, Fig. 2) define mineral lines of  $\sim 1,530$  m.y. Whether or not this represents the time of intrusion is debatable, as the lines have values of  $(^{87}\text{Sr}/^{86}\text{Sr})_0$  of 0.708 and 0.710, clearly indicative of  $^{87}\text{Sr}$  contamination. If the feldspars in the different separates were not equally contaminated, then 1,530 m.y. could not be regarded as dating the magmatic event.

The fact that the clinopyroxenes lie *below* the feldspar lines (Fig. 2), as in the Breven dyke, strengthens the inference of contamination. These pyroxenes have clearly been little affected by introduction of  $^{87}\text{Sr}$ .

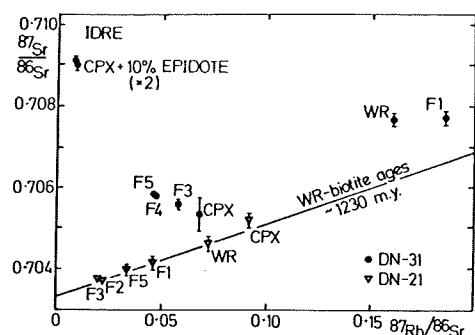


Fig. 3. Rb-Sr data for two Idre dolerite samples. *WR*=whole rock; *F*=feldspar, *CPX*=clinopyroxene.  $2\sigma$  errors fall within the symbols unless indicated. Analyses are listed in Table 1. Note that the clinopyroxene in the epidote-bearing separate differs magnetically from the pure cpx, such that co-linearity between these analyses and the inferred position of the epidote would not be expected

Unlike the clinopyroxenes from Breven, the ones from Bunkris crystallised before or with the plagioclase; these relationships imply that the feldspars became contaminated with radiogenically-enriched Sr during or after their crystallisation from outside the dolerite. The slight difference in  $(^{87}\text{Sr}/^{86}\text{Sr})_0$  between the two clinopyroxenes (Fig. 2) may be ascribed to a small component of secondary amphibole in one or both of the separates, although this is not apparent in the material. The difference could also imply that the melt was slightly inhomogeneous in its Sr isotopic composition.

### 3. Idre Dolerite

This sill, probably > 50 m thick, intrudes unmetamorphosed continental sediments (Hjelmqvist, 1966). Specimen DN-21 is from a quarry where the dolerite contains partly amphibolitised olivine, slightly sericitised labradorite, with clinopyroxene, opaque minerals and accessory apatite, biotite and quartz. Two biotites from this quarry (DN-17 and DN-21) define ages of  $1,232 \pm 18$  and  $1,228 \pm 18$  m.y., in agreement with other results from dolerites in this region (Patchett, 1978). Specimen DN-31 occurs 1 km away from DN-21, and differs in its olivine, entirely transformed to amphibole, its labradorite, more thoroughly sericitised, and in the absence of biotite. DN-31 also carries a small amount of interstitial granophyre and epidote. These two constituents, the latest to crystallise, rarely occur in contact, such that their mutual relationship cannot be established. The epidote occurs between labradorite grains but probably not as a pseudomorph after a primary mafic phase.

The minerals in the fresher sample DN-21 are concordant with the 1,230 m.y. whole-rock/biotite

lines (Fig. 3). The feldspars are however peculiar in that F1, the most calcic separate, has more Rb and a higher Rb/Sr ratio than the less dense fractions (Table 1). This feature is more clearly developed in DN-31 (Table 1; Fig. 3). The lighter feldspar fractions F3, F4, and F5, which include the interstitial granophyre and alkali feldspar, have much lower Rb content than F1, and lie at lower Rb/Sr than the whole-rock, in spite of an expected and observed reduction in Sr from F1 through F3 to F4 and F5. This apparent high Rb content of the labradorite in the Idre samples may be due to a minor amount of sericite in the separates, although reconnaissance X-ray diffraction did not detect this. The less-dense separates F4 and F5 seem to have a distinctly higher  $(^{87}\text{Sr}/^{86}\text{Sr})_0$  at 1,230 m.y. ( $0.7050 \pm 1$ ) than the F1 ( $0.7045 \pm 2$ ) and the clinopyroxene ( $0.7042 \pm 6$ ). Although the interstitial epidote could not be separated, a mixture of 90% clinopyroxene + 10% epidote, analysed in duplicate, gives a much higher value of  $^{87}\text{Sr}/^{86}\text{Sr}$  than pure clinopyroxene. The epidote thus probably contains approximately 2,000 ppm Sr (Table 1) and apparently had  $(^{87}\text{Sr}/^{86}\text{Sr})_0 \sim 0.75$  1,230 m.y. ago.

### Other Approaches and the Origin of the Anomalies

An origin for the isotopic anomalies in later thermal disturbance is considered unlikely because the Breven and Idre dolerites give biotite ages which agree with abundant other data interpreted to represent the time of intrusion. This would not allow any post-intrusive reheating exceeding  $\sim 300^\circ\text{C}$  (Jäger, 1973). Additionally, the raised  $(^{87}\text{Sr}/^{86}\text{Sr})_0$  values are commonly observed in relatively high-Rb/Sr mineral phases, whose  $^{87}\text{Sr}/^{86}\text{Sr}$  would be expected to be reduced by any later disturbance. The observed isotopic effects are inferred to date from the time of intrusion and cooling of the dolerites.

Mineral separates that account for > 99% of the Breven and Idre dolerites have low  $(^{87}\text{Sr}/^{86}\text{Sr})_0$  ratios near 0.704, and only the last fraction to crystallise, in interstices, is contaminated with  $^{87}\text{Sr}$ . There seems no doubt that this radiogenic Sr must originate in the nearby host rocks. Contamination by diffusion of  $^{87}\text{Sr}$  through a siliceous residual melt could not be an effective process, even under optimum circumstances (Hofmann, 1975), and certainly not plausible if the 1% melt remains as films and disconnected interstitial pools. It seems necessary to appeal to a more mobile medium to transport  $^{87}\text{Sr}$ , and in this context the textural association of the latest-crystallising parts of the dolerite with secondary hydrous alteration is probably significant. An aqueous fluid, necessary for this hydrous alteration, seems to be the only

medium capable of transporting the  $^{87}\text{Sr}$ -enriched Sr into a 99% solid rock. The late epidote from Idre, itself a hydrous mineral, contains highly anomalous Sr, consistent with a raised  $^{87}\text{Sr}/^{86}\text{Sr}$  in the fluid phase.

At this point the high resistance of clinopyroxene to this hydrothermal isotopic effect should be noted, even at Bunkris where all the feldspars have been contaminated, and the clinopyroxene is itself partly altered to amphibole. Previous observations to this effect are in Vallance (1974); Compston and McElhinny (1975); and Hart and Brooks (1977).

Microprobe analysis of feldspars in dolerites clarified to some extent the relationship between plagioclases and interstitial Na–K feldspars. Normally, crystallisation of the last residue of the dolerite magma in cavities has led to an intense zoning effect from the edges of plagioclase grains through andesine and oligoclase compositions into the interstitial Na–K feldspars (it should be noted that full equilibrium between plagioclase and alkali feldspars in the conventional sense is not allowed to occur because of this sequence of crystallisation). In the Breven and Idre samples however, any intermediates between labradorite and Na–K feldspar are absent, and the alkali feldspars have very sharp grain boundaries against unzoned labradorite. When coupled with the isotopic contrast between the two types of feldspar, and compared to the normal dolerites, the relationship probably implies that at Breven and Idre, the plagioclases and the medium from which the alkali feldspars derived their geochemistry did not interact at all in the terminal stages of solidification.

An X-ray diffraction study of the structural state and composition of feldspars in the least-dense separated fraction from several dolerites was undertaken to investigate their structural/thermal history. The cell dimensions of sodic and potassic feldspars, especially where these form a non-coherent intergrowth, can readily be used to calculate composition and degree of Si–Al order. In Table 3, two values of  $N_{\text{Or}}$  (in mol %) are given, one based on  $a$  cell edge corrected for degree of Si–Al order (Martin, 1974a), the other on cell volume (Stewart and Wright, 1974). Also tabulated are values of  $t_{10}$ , the proportion of Al statistically present in the  $T_{10}$  site: these have been calculated using the approach of Blasi (1978). In a magmatic alkali feldspar, expected to be disordered,  $t_{10}=0.25$  whereas for a fully-ordered microcline,  $t_{10}=1.00$ . Table 3 also contains information on the plagioclase in the least-dense fraction; clearly, this material could be either a Na-rich composition exsolved from alkali feldspar, or be part of the magmatic plagioclase (possibly the outer zones) allowed through by imperfections in the separation. Unfortu-

nately, cell parameters of plagioclases do not provide unambiguous indicators of composition and structural state, because adding Ca and disordering the tetrahedrally-coordinated cations have essentially equivalent effects on cell dimensions.

For the plagioclase results (Table 3), a plot of  $\beta^*$  vs  $\gamma^*$  (Smith, 1974, Figs. 7–44) and a calculated value of  $\psi$  ( $2\theta_{131}-2\theta_{1\bar{3}1}$  (see Bambauer et al., 1967; or Smith, 1974, Figs. 7–47b) suggest that in most cases the plagioclase in the least-dense separate is either a well-ordered andesine/oligoclase or a slightly more disordered albite. An andesine/oligoclase could represent the outer zones of labradorite grains whereas albite could correspond to the exsolved Na-feldspars, commonly observed with the microprobe in the interstitial areas.

Structural and compositional data for alkali feldspars (Tables 2 and 3) are given for three dolerites which define concordant mineral isochrons (Forserum, Västra Nornäs and Karlshamn; Patchett, 1978), and for the three anomalous dolerites Breven, Bunkris and Idre. The Forserum and Västra Nornäs samples contain orthoclases >95% pure. This indicates that exsolution continued down to low temperatures; however, the orthoclases are not particularly well-ordered ( $t_{10}=0.35$  and  $0.39$  respectively). The Karlshamn sample contains intermediate microcline with 92%  $\text{KAlSi}_3\text{O}_8$ , which thus achieved better order than the Forserum and Västra Nornäs feldspars, but did not equilibrate compositionally to such low temperatures.

A better ordered microcline of similar composition to Karlshamn is present in the Breven sample SÖ-4 (Table 3). The rather altered and recrystallised sample DN-37 from Bunkris contains two potassic feldspars, on the basis of careful observation of diffraction peaks; orthoclase, well-ordered for a monoclinic feldspar, apparently predominates over an intermediate microcline. Both K-feldspars are relatively pure, the orthoclase being slightly more potassic than the microcline, in opposition to the expected equilibrium relationship. Some of the orthoclase may result from low-temperature K-metasomatism of plagioclase, which would explain the turbid patches, found to obliterate the normal zoning in thin section.

The lightest separate F5 of the relatively fresh Idre dolerite DN-21 contains only a plagioclase of composition  $\text{An}_{60}$  if the "low" curve applies. This is consistent with the lack of an interstitial feldspar in thin sections of this rock. The more altered DN-31 on the other hand, does contain turbid granophyric patches. The feldspar in these areas is structurally intermediate pure albite, a composition confirmed by microprobe. In this sample, most of the K may reside in sericite, phengitic according to the probe, produced by alteration of plagioclase.

Table 2. Cell dimensions<sup>a</sup> of K- and Na-feldspars in Swedish dolerites

	<i>a</i> (Å)	<i>b</i> (Å)	<i>c</i> (Å)	$\alpha$ (°)	$\beta$ (°)	$\gamma$ (°)	<i>V</i> (Å <sup>3</sup> )	$\Delta 2\theta$ (°)	<sup>b</sup>
Forserum	8.5977	13.0069	7.1923	90	116.027	90	722.74	0.017	23
AL-6 F6	0.0020	0.0024	0.0016		0.017		0.20		
	8.1613	12.8689	7.1184	93.587	116.294	89.821	668.71	0.009	13
	0.0021	0.0017	0.0007	0.015	0.021	0.021	0.26		
V. Nornäs	8.5978	12.9675	7.1911	90	115.891	90	721.28	0.017	30
D75-26 F8	0.0013	0.0018	0.0017		0.018		0.18		
	8.1695	12.7937	7.1422	93.944	116.504	88.603	666.44	0.008	24
	0.0007	0.0008	0.0006	0.010	0.009	0.007	0.08		
Karlshamn	8.5738	12.9654	7.2171	90.468	116.089	88.455	720.26	0.009	18
BL-3 F5	0.0011	0.0017	0.0008	0.013	0.012	0.013	0.11		
	8.1516	12.7913	7.1333	94.048	116.518	88.337	663.87	0.010	17
	0.0017	0.0021	0.0014	0.015	0.009	0.014	0.13		
Bunkris	8.5870	12.9841	7.2079	90	115.967	90	722.51	0.016	25
DN-37 F4	0.0013	0.0022	0.0013		0.015		0.17		
	8.5762	12.9554	7.2136	90.518	115.932	88.276	720.46	0.010	17
	0.0013	0.0019	0.0009	0.015	0.015	0.024	0.17		
	8.1415	12.7812	7.1549	94.207	116.553	87.913	664.19	0.009	24
	0.0007	0.0014	0.0009	0.009	0.008	0.009	0.09		
Breven	8.5775	12.9445	7.2132	90.303	116.019	88.498	719.46	0.009	19
SÖ-4 F7	0.0012	0.0024	0.0009	0.015	0.008	0.015	0.13		
	8.1659	12.8518	7.1166	93.707	116.392	89.530	667.44	0.008	22
	0.0009	0.0014	0.0006	0.011	0.008	0.014	0.08		
Idre	8.1775	12.8654	7.1058	93.522	116.144	90.155	669.45	0.009	36
DN-21 F5	0.0006	0.0010	0.0005	0.007	0.007	0.008	0.06		
Idre	8.1423	12.7935	7.1482	94.167	116.595	88.182	664.08	0.011	28
DN-31 F5	0.0008	0.0017	0.0010	0.014	0.009	0.011	0.10		

<sup>a</sup> Refinement of indexed diffraction lines using program of Appleman and Evans (1973). Number of lines in each case indicated by <sup>b</sup>. Plagioclases were refined assuming a  $c=7$  Å unit cell

It is widely accepted that both feldspar exsolution and ordering are strongly promoted by the presence of an aqueous fluid phase, irrespective of whether transformations are achieved by solution-redeposition (O'Neil and Taylor, 1967; Martin, 1974b), or by other mechanisms (see Parsons, 1978 for discussion). Si-Al ordering in fact probably *requires* the presence of a fluid phase. The uncontaminated samples from Forserum and Västra Nornäs contain orthoclases which are still relatively disordered. In the uncontaminated Karlshamn sample, and in the dolerites showing Sr anomalies, feldspar structure shows stronger evidence for aqueous fluid activity. Intermediate microcline is present where K-feldspars occur, implying that fluids were available below its upper stability limit of  $\sim 500^\circ$  C. At Bunkris, there is evidence of metasomatic K-feldspar growth, and at Idre <sup>87</sup>Sr contamination occurs only in the sample that contains an alkali feldspar, implying a related origin for both alkali feldspar and contamination.

Inasmuch as the K-feldspars from all the dolerites are more ordered than the forms stable near solidus temperatures (e.g., Martin, 1974b), we suggest

that postmagmatic fluids have been active in most or all dolerite intrusions, but that detectable contamination effects only appear where the isotopic chemistry of the fluids became modified by interaction with country rocks (see also Fratta and Shaw, 1974; Dostal and Fratta, 1977). Almost all country rocks, including the arkosic sandstone at Idre, could have supplied the necessary <sup>87</sup>Sr. Unradiogenic lithologies, such as amphibolite and quartzite, are rare as host rocks of dolerites in Sweden.

Two scenarios are possible for the history of the contaminated alkali feldspars. They could have crystallised as interstitial primary magmatic minerals, and then have become affected by diffusion, metasomatism and Si-Al ordering in response to subsolidus fluid circulation. On this view, the alkali feldspars were most affected by the fluids simply because they were the least resistant phases. Alternatively, some of the alkali feldspars may have crystallised in the subsolidus directly from fluids enriched in radiogenic Sr; metasomatism resulting in disequilibrium between coexisting alkali feldspars is in fact evident in the Bunkris dolerite. It is not possible to assess these

Table 3. Composition<sup>a</sup> and structural state<sup>b</sup> of interstitial feldspars

	K–Na feldspars					Plagioclases				
	$N_{Or} (a)$	$N_{Or} (V)$	$t_{10}+t_{1m}$	$t_{10}-t_{1m}$	$t_{10}$	$\Delta$	$\alpha^*(^\circ)$	$\beta^*(^\circ)$	$\gamma^*(^\circ)$	$\psi (^\circ)$
Forserum AL-6 F6	0.957	0.995	0.690 0.012		0.345		86.087 0.018	63.663 0.022	88.425 0.024	1.810
V. Nornäs D75-26 F8	0.959	0.951	0.780 0.012		0.390		86.290 0.011	63.527 0.009	89.595 0.008	1.394
Karlshamn BL-3 F5	0.912	0.922	0.962 0.007	0.667 0.008	0.814	0.62	86.305 0.015	63.530 0.009	89.840 0.014	1.316
Bunkris DN-37 F4	0.938	0.988	0.854 0.010		0.427		86.339 0.010	63.522 0.008	90.233 0.009	1.185
	0.918	0.928	0.962 0.008	0.745 0.013	0.853	0.69				
Breven SÖ-4 F7	0.921	0.900	0.985 0.008	0.646 0.007	0.815	0.70	86.094 0.008	63.581 0.008	88.683 0.011	1.733
Idre DN-21 F5							85.999 0.007	63.792 0.007	88.095 0.008	1.940
Idre DN-31 F5	0.001	-0.019	0.901 0.007	0.800 0.006	0.850		86.250 0.015	63.463 0.009	89.948 0.012	1.301

<sup>a</sup> Composition of the K–Na feldspar is calculated using the  $\alpha$  cell edge corrected for degree of Si–Al order (Martin, 1974); a second value is based on unit cell volume  $V$  (Stewart and Wright, 1974)

<sup>b</sup> Degree of Si–Al order is derived from  $b$ ,  $c$ ,  $\alpha^*$  and  $\gamma^*$  of K- and Na-feldspars using the approach of Blasi (1978). Also listed are calculated values of  $\Delta$  (obliquity) and  $\psi$  (the angular separation  $2\theta_{131} - 2\theta_{1\bar{3}1}$ )

two alternatives at this stage, but the influence of aqueous fluids at subsolidus temperatures is in any case proved by the presence of hydrous minerals; in the one example analysed, interstitial epidote is shown to be heavily contaminated with  $^{87}\text{Sr}$ . Data for the upper stability limits of epidote (Liou, 1973) and muscovite (taken to be approximately equivalent to the phengitic “sericites” of this study) (Chatterjee and Johannes, 1974) show that, as long as  $P_{\text{H}_2\text{O}}$  did not grossly exceed lithostatic pressure, then hydrothermal alteration must have taken place below 600°C, and probably at lower temperatures. The presence of microcline in some intrusions also suggests temperatures below its upper stability limit, taken to be ~500°C.

The conduction-based cooling models of Jaeger (1957, 1964) show that the centre of a 400 m dolerite will remain above 500°C for >5,000 years, whereas the diffusion measurements of Misra and Venkatsubramanian (1977) show that this time would allow ~2 mm of Sr diffusion in alkali feldspars. Even allowing for the unknown Sr diffusion rate in plagioclase, these data may imply that to preserve isotopic and other discordances between feldspars in medium-grained rocks under hydrothermal conditions, it is necessary for the circulating fluids to have accelerated the cooling of the dolerite. This would also explain the non-attainment of the stable low microcline state in any of the dolerites.

Finally, it should be noted that the hydrothermal effects described document introduction of radiogenic Sr into cooling igneous rocks which may later appear quite pristine, as at Breven. Progressively more severe effects may result in most of the minerals in a rock being contaminated, as at Bunkris, in which case the  $(^{87}\text{Sr}/^{86}\text{Sr})_0$  is significantly raised on a whole-rock scale. The situation is geochemically analogous to that for oceanic basalts (e.g., Chapman and Spooner, 1977; O’Nions et al., 1978; Hawkesworth and Elderfield, 1978).

## Conclusions

1. Certain Proterozoic dolerite intrusions from Sweden show large discordances in  $(^{87}\text{Sr}/^{86}\text{Sr})_0$  between mineral phases, documenting contamination during or soon after crystallisation. The minerals affected may comprise from a very small up to a very large proportion of the dolerite.

2. The Sr-contaminated phases, chiefly late-crystallising interstitial alkali feldspars, are texturally associated with secondary hydrous minerals formed from olivine, pyroxene and plagioclase. A single late epidote analysed is very strongly contaminated.

3. Since the phases affected by the contamination account in some cases for <1% of the samples, then the 87-enriched Sr must have been transported

through dolerite which was at least 99% solid. Only mobile aqueous fluids would have been capable of this.

4. Structural data for alkali feldspars suggest that aqueous fluids were active in most cooling dolerites, leading to formation of orthoclases and intermediate microclines from the original high-temperature forms.  $^{87}\text{Sr}$  contamination only occurred where the fluid interacted with country rocks.

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## Appendix

### Sample Locations

- DN-21: Idre dolerite, central Sweden. Thickness of sill unknown, probably >50 m. Sample from small road-side quarry in interior of dolerite on North side of lake Idresjön, 81 Idre 13402/68607. Geological map Sver. Geol. Unders. ser. Ca No. 40 (Hjelmqvist, 1966).
- DN-31: Idre dolerite, central Sweden. Sample from natural cliff in interior of dolerite on South side of lake Idresjön, 81 Idre 13377/68607.
- DN-37: Bunkris dolerite, central Sweden. Sample at least 15 m from contact of dolerite, collected from roadcut at Bunkris village, 107 Älvdalsåsen 13749/68152. Geological map as for Idre.
- DN-42: Bunkris dolerite, central Sweden. 30 m North of DN-37, and probably 5 m closer to contact.
- D75-26: Västra Nornäs dolerite, central Sweden. Thickness of dolerite dyke unknown. Sample kindly provided by Zoltan Solyom of Lund University, Sweden, and collected a short distance North of road Sörsjön-Västra Nornäs, 107 Älvdalsåsen 13611/68144. Geological map as for Idre.
- SÖ-3: Breven dolerite, central Sweden. Sample from roadcut in centre of dyke where ~400 m in width consisting of fresh olivine dolerite, 9F Finspång NV 14686/65397. Geological map Krokström (1932).
- SÖ-4: Breven dolerite, central Sweden. 20 m across strike from SÖ-3.
- AL-6: Forserum dolerite, southern Sweden. Sample from interior of sill (>30 m thickness) in a quarry, 6E Nässjö NV 14221/63994. Geological map Sver. Geol. Unders. ser. Aa No. 123.
- BL-3: Karlshamn dolerite, southern Sweden. Sample from centre of ~250 m dyke in quarry, 3E Karlshamn NO 14408/62251. Geological map Norin (1936).

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