

Strontium-isotope study of the Kleivan granite, southern Norway

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A whole rock Rb-Sr isotope study of the Kleivan granite, Farsund area in south Norway, has determined an age of 930 ± 7 m.y., and an initial strontium ratio of $.7052 \pm 2$. This result is in accord with recent estimates of the major plutonic episode of the Rogaland Province, southwestern Norway.

The age and initial Sr-ratio is markedly different from that of the Farsund charnockite, which from other geological and geochemical evidence seems strongly related. Possible explanations for the difference in initial Sr-isotope ratios are discussed. These suggest a two-step generation which involves isotope-disequilibrium melting and/or a selective ^{87}Sr -extraction, accompanying the generation of melt from a common, lower crustal source rock.

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The Kleivan granite has previously been considered as part of a complex batholith occupying more than 400 km² along the coast of southern Norway, and called the 'farsundite' (Barth 1960, Middlemost 1968). However, it has recently been demonstrated that the 'farsundite' is in fact composite and consists of several spatially separated intrusions: The Farsund charnockite, the Lyngdal granite, and the Kleivan granite (Fig. 1). Evidence for this separation is based on detailed geological mapping, supported by petrographic, geochemical, and isotopic investigations (Falkum et al. 1972, Falkum & Petersen 1974, Pedersen & Falkum 1975).

Because of the lack of field evidence concerning the time relationship between the Kleivan granite and the other plutons of the batholith, Rb-Sr whole-rock isochron studies have been carried out.

Geological setting

The Kleivan granite is an elongated body of about 20 km², occupying roughly the axial plane of a late synform. The granite can be termed postkinematic and classified as mesozonal (Budington 1959).

The pluton is surrounded by granitic gneisses, augen gneisses, and a series of banded gneisses which are regionally metamorphosed under conditions of upper amphibolite and granulite facies (Petersen 1977).

The boundaries are always sharp against country rock gneisses and are observed to be both highly discordant and locally conformable. No obvious contact effects are present in the country rocks apart from locally developed cleavage parallel to the contact.

Petrographic and geochemical investigations of the Kleivan granite have revealed a compositional variation from charnockite in the north-western part through hornblende-granite in the central part to biotite-granite in the southern part of the pluton. The transition between the different types is gradational and is illustrated by a marked and continuous variation in chemistry.

The strong differentiation restricts quantitative geochemical comparison with the remaining intrusions of the Farsund plutonic complex. However, petrographic and geochemical characteristics show strong similarities between the Kleivan granite and the Farsund charnockite. An origin comagmatic with the neighbouring Lyngdal granite is considered less probable due to the principal differences in petrography and geochemistry (Falkum & Petersen 1974).

Methods

Determinations of the concentration and the isotopic composition of Sr were carried out on ^{84}Sr -spiked samples using a Varian Mat TH-5 mass spectrometer. Rb determinations were also carried out by isotope dilution using a Varian

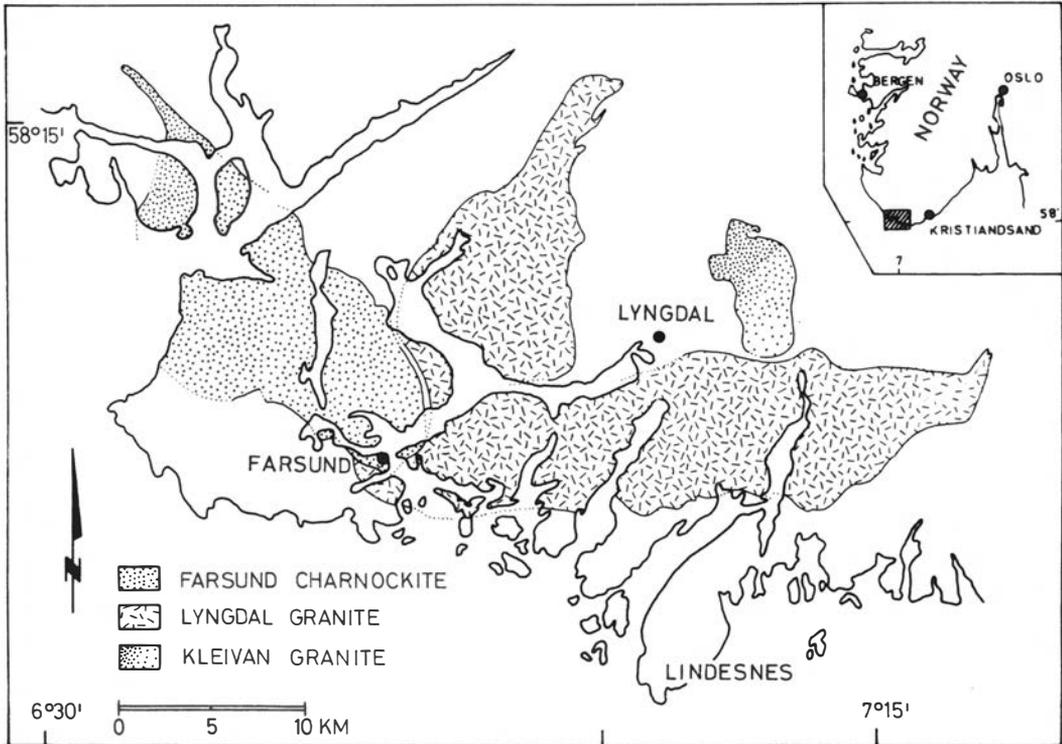


Fig. 1. Simplified geological map of the Farsund plutonic complex, south Norway, showing the spatial relations between the Kleivan granite, the Farsund charnockite, and the Lyngdal granite.

Table I. Analytical details of samples from the Kleivan granite.

Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$
89.5-51.5	89.7	374.9	.239	$.693 \pm 2\%$	$.7144 \pm 3$
90-52	84.8	344.6	.246	.713	$.7146 \pm 3$
90.5-50.5	117	267.2	.438	1.27	$.7219 \pm 6$
91-50	147	211.6	.695	2.01	$.7312 \pm 2$
91-48	220	67.0	3.28	9.63	$.8313 \pm 1$
90-47	303	84.6	3.58	10.49	$.8409 \pm 1$
91-47	294	61.9	4.75	13.95	$.8884 \pm 6$
90.5-46.5	271	46.5	5.83	17.30	$.9298 \pm 6$

Age: 930 ± 7 m.y.

λ : $1.39 \cdot 10^{-11} \text{ year}^{-1}$

Initial Sr-ratio: $.7053 \pm .0002$

MSWD: .12

Eimer & Amend SrCO_3 : $.70808 \pm .00006$

The sample numbers are referring to the UTM grid system.

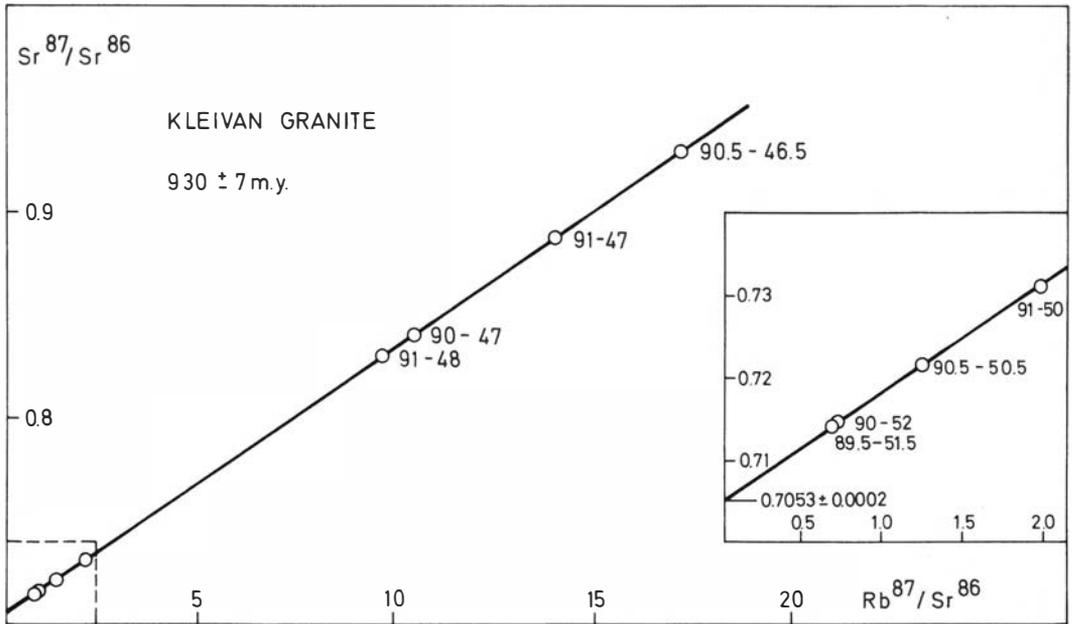


Fig. 2. Rb/Sr whole-rock isochron for the Kleivan granite.

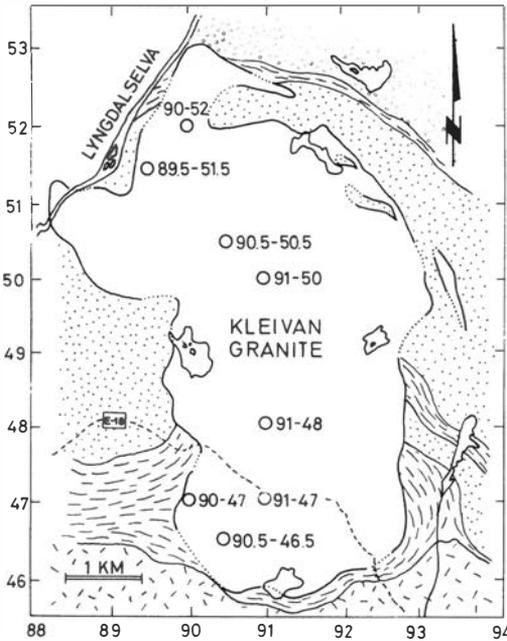


Fig. 3. Sample localities in the Kleivan granite.

CH-4 mass spectrometer. Analytical details are given in Table 1. The age and initial ratio were calculated with the aid of a computer programme by York (1966) ($\lambda = 1.39 \cdot 10^{-11} \text{year}^{-1}$). Errors are given at the 2σ -level. Isotope ratios mentioned in the text are adjusted to a $^{87}\text{Sr}/^{86}\text{Sr}$ -value for the Eimer & Amend SrCO_3 of .7080. All isotope analyses were carried out at the Belgian Centre of Geochronology in Brussels.

Results

Rb-Sr data for the Kleivan granite are presented in Fig. 2, and sample localities are shown in Fig. 3. The age of 930 ± 7 m.y. is comparable with an age of 932 ± 38 m.y. obtained for the Lyngdal granite, but is significantly different from the age of the Farsund charnockite, 852 ± 41 m.y. (Pedersen & Falkum 1975). Also the initial ratio of the Kleivan granite ($.7053 \pm 2$) is comparable with that of the Lyngdal granite ($.7054 \pm 5$), whereas the initial ratio of the Farsund charnockite is $.7128 \pm 9$ (Pedersen & Falkum 1975).

These results suggest a relationship between the Kleivan granite and the Lyngdal granite, whereas geological and geochemical investiga-

tions indicate strong coherence between the charnockitic part of Kleivan granite and the Farsund charnockite (Falkum & Petersen 1974). Chemical data show that the contents of e.g. TiO_2 , MgO , CaO , P_2O_5 , and $\text{Fe}_2\text{O}_3/\text{FeO}$ are similar in the charnockitic part of the Kleivan granite and the Farsund charnockite, and they are significantly different from those in the Lyngdal granite. The relative distribution of certain trace element ratios is particularly striking:

	Kleivan granite (northern part)	Farsund charnockite	Lyngdal granite
K/Rb	379	354	206
K/Ba	35	33	20

Petrographic data also strongly indicate a relationship between the former two granites: mineralogical and textural properties are identical, and both have mesoperthite and antiperthitic plagioclase, showing irregular grain boundaries, while quartz has interlobate and often convex borders against other minerals. Hypersthene constitutes the dominant mafic phase, followed by hornblende and clinopyroxene. Biotite is found only in subordinate amounts. Furthermore, the charnockitic Kleivan granite and the Farsund charnockite contain CO_2 -rich fluid inclusions (Madsen 1975) in contrast to the Lyngdal granite where fluid inclusions are H_2O -dominated (J. K. Madsen, pers. comm. 1976).

If one therefore accepts the obvious geochemical and petrographical similarity between the Kleivan granite and the Farsund charnockite, an explanation for the difference in their Sr-isotope ratio is needed. This includes considerations concerning the genesis of the plutons.

Discussion

A $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of .705 obtained for the Kleivan granite is consistent with estimates of both upper mantle (e.g. Faure & Powell 1972), and lower crust as represented by high-grade granulite terrains (Spooner & Fairbairn 1970) at the time of intrusion. Assuming a common homogeneous source rock for the plutons, theoretical models which result in variable increase of the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio are discussed, to attempt an explanation for the difference in isotopic composition of the Kleivan granite and the Farsund charnockite.

Isotopic behaviour during magma generation

Sr-isotope equilibrium melting (Fig. 4 A)

Crustal anatexis involving ^{87}Sr -equilibrium between melt and parental rock is rejected as an explanation here, as the possible parental rock is believed to have a mean Rb/Sr ratio too low (Hurley 1968a, 1968b, Lewis & Spooner 1973) to produce the observed increase from 7052 in the Kleivan granite to 7128 in the Farsund charnockite ($\sim 1\%$) in the course of not more than 80 m.y. (max. 130 m.y.) as suggested by a simple two-step model.

Sr-isotope disequilibrium melting (Fig. 4 B)

In a recent paper O'Nions & Pankhurst (1974) have suggested disequilibrium melting in the upper mantle in order to explain Sr-isotope variation in oceanic rock systems. Applying this model, a deep crustal source rock, essentially consisting of pyroxene, feldspar, and quartz (Spooner & Fairbairn 1970) could, as the result of partial anatexis, develop 'anomalous' Sr-isotope ratios, dependent on their relative proportions between phases entering the melt, their individual Rb/Sr ratios, and time elapsed since isotopic homogenization of the system.

In feldspar of granulite facies, such as mesoperthite and micropertthite, a Rb/Sr ratio in the range 1–2 is observed (Dahlberg 1969). Such ratios would increase the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the feldspars from 0.7–1.6% in 130 m.y., and the entrance of these K-rich minerals into the melt might therefore result in a considerable difference of initial Sr-isotope ratios, as the feldspars are the dominant Rb-bearing phases. A similar model, for deep crustal material, was proposed by Heier (1964), implying that radiogenic Sr essentially occupies Rb-sites in K-minerals, because such minerals, according to experiments are the first to break down with anatectic melting, a preferential enrichment of radiogenic ^{87}Sr would develop in the melt.

Selective ^{87}Sr -extraction (Fig. 4 C)

Under special conditions, a considerable enrichment of radiogenic Sr developed by a selective ^{87}Sr -extraction from the parental rock into the anatectic melt would be expected, possibly accompanying dehydration processes in lower crust. As radiogenic isotopes occupy lattice sites

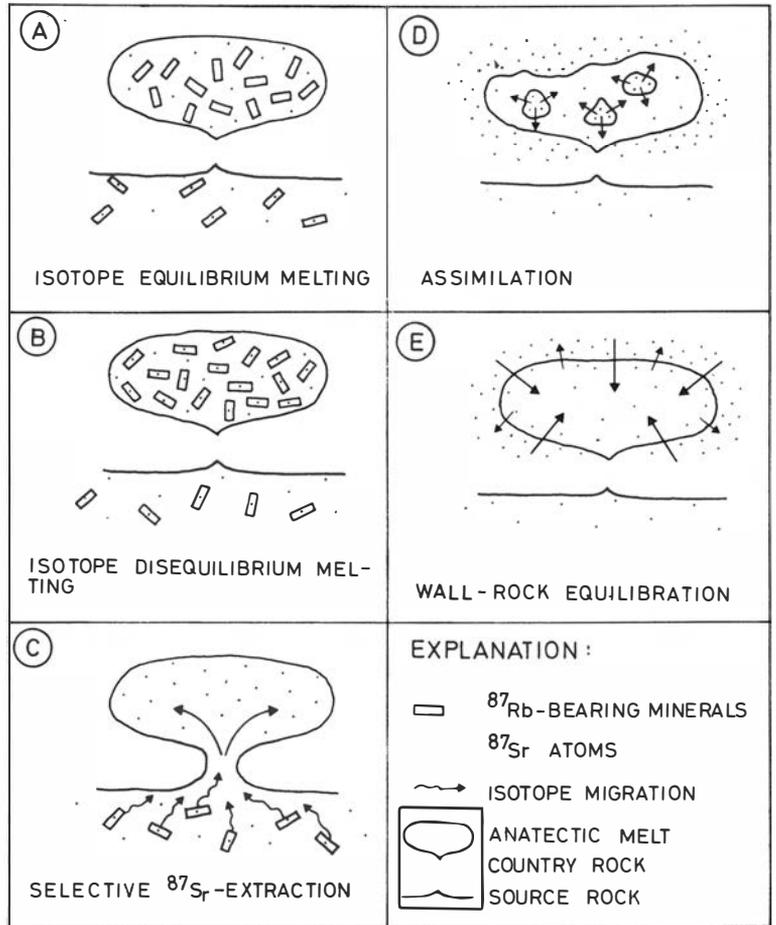


Fig. 4. Theoretical situations showing the Sr-isotope behaviour as a result of partial melting in lower crustal rocks. All lead to a variable increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ -initial ratio of the resulting intrusive.

of their parental radioelement, they can be expected to escape more readily, considering their unfavourable positions, than 'primary' isotopes which occupy more suitable lattice positions.

In view of the apparently complex data on Sr-distribution in rocks, involving crystal-liquid fractionation and solid-state reactions in feldspars (Smith 1974), the conditions of redistribution and trapping of such liberated radiogenic Sr-atoms are poorly understood and should be interpreted with caution.

The process of partial melting in the lower crust is, however, believed to provide a possible potential for trapping liberated ^{87}Sr -atoms, and thereby cause the development of anomalous $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios. This mechanism was suggested by Heier (1964), and discussed by Heier & Compston (1969).

Isotopic behaviour during emplacement

^{87}Sr wall-rock equilibration (Fig. 4 D)

Open system behaviour during ascent and emplacement of the pluton might result in contamination of radiogenic Sr-isotopes due to ^{87}Sr -equilibration between wall-rock and melt as discussed in detail by Pankhurst (1969).

Assimilation (Fig. 4 E)

The process of large scale assimilation of country-rock gneisses in order to raise the initial Sr-ratio in the Farsund charnockite is considered less important in view of the similar geochemical compositions of the two granites, including certain trace element ratios that suggest only Sr to be anomalously low in the Farsund charnockite. Country rock xenoliths are similar in character

and abundance in the farsund charnockite and the Lyngdal granite despite a low Sr-isotope ratio of .7054 for the latter, and are therefore hardly the major source for Sr-contamination in the Farsund charnockite.

Conclusion

The results obtained for the Kleivan granite suggest a time of intrusion similar to that of the Lyngdal granite. Similarities in the isotopic composition of Sr for the two granites are considered fortuitous in view of the principal differences in petrography and geochemistry, which can hardly be explained by simple differentiation or fractionation processes (Falkum & Petersen 1974). The low initial ratio, however, suggests a derivation of both plutons from strongly Rb-depleted environments.

It is suggested that the difference in initial Sr-ratios of the apparently closely related Kleivan granite and Farsund charnockite is the result of a two-step generation from a common, lower crustal source rock. A petrogenetic model involving partial melting assumes isotopic disequilibrium melting of the parental rock, but the effect of this is possibly enhanced by a selective extraction of ^{87}Sr from the source rock into the melt. Furthermore, one or another kind of ^{87}Sr -contamination during ascent and emplacement of the pluton cannot be excluded.

More detailed investigations of ^{87}Sr -distribution among co-existing mineral phases are needed to allow conclusive statements as to the development of the isotope ratios. The present investigation, however, seems to indicate that caution should be observed in using initial Sr-isotope ratios on their own as petrogenetic indicators.

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