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Discussion

AGE RELATIONSHIPS IN THE PROTEROZOIC HIGH-GRADE GNEISS REGIONS OF SOUTHERN NORWAY: DISCUSSION AND COMMENT

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Field and Råheim (1979a, b, 1980, 1981) provided interesting data on the possibility of resetting Rb—Sr whole-rock isochrons by a very low- to low-grade thermal event subsequent to a first high-grade metamorphism. In some cases, isochrons, which appear very good from a statistical point of view, nevertheless yield meaningless apparent ages, intermediate between the ages of the two metamorphisms.

The data of Field and Raheim (1981) for the Arendal charnockitic gneisses of southern Norway are quite convincing from both petrographical and geochronological viewpoints: a granulite facies metamorphism dated at 1500 Ma (by Rb—Sr whole-rock isochron) has been disturbed by a subsequent low-grade event at ca. 1000 Ma. Field and Råheim (1981) extrapolate their interpretation of the Arendal data to most of the other geochronological data of southern Norway. They claim that:

> ". . . the main high-grade gneiss-forming event may have been pre-Grenvillian (that is pre-Sveconorwegian) in all sectors (of southern Norway) and there may have been no regional high-grade reworking during the period 1.2—0.9 Ga ago."

With regard to the Rogaland and Vest—Agder provinces, it is obvious from the numerous geochronological data obtained in different laboratories that the granulite-facies metamorphic event is of Sveconorwegian (Grenvillian) age, that is between 1200 and 900 Ma.

The situation is as follows:

(1) all the U—Pb data on zircons (more than 30 fractions) from augen gneisses and granitic gneisses define discordia chords whose upper intercepts with Concordia give ages at ~ 1050—1000 Ma (Versteeve, 1975; Pasteels and Michot, 1975; Wielens et al., 1981);

(2) large massifs of anorthosites, mangerites and charnockites syn- or late-tectonically intruded into the surrounding gneisses (Michot, 1960; Michot and Michot, 1969; De Waard et al., 1974) yield Rb—Sr and U—Pb emplacement ages between 980 and 900 Ma. The magmatic structures (i.e.,

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ophitic structures, igneous layering, orthocumulate textures, . . .) are well preserved for most of the magmatic rocks and it is evident that the measured ages really represent the crystallization age (Pedersen et al., 1978; Pasteels et al., 1979).

(3) Rb—Sr and K—Ar ages measured on primary brown biotites belonging to the granulite facies mineral assemblages are close to 870 Ma (Verschure et al., 1980), interpreted as cooling ages after the last phase of the Sveconorwegian metamorphism.

The only visible secondary alteration in the metamorphic cover sequence is the incipient development of very low-grade mineral assemblages (prehnite + pumpellyite) in the Flekkefjord—Tonstad area. To the north-east, nearer the Caledonian front, greenschist-facies assemblages are observed, representing replacement of brown biotites by green biotite and titanite. These assemblages are the result of a low-grade metamorphic event which can be related, in view of the field relations, to the effects of Caledonian orogenesis on the Sveconorwegian rocks. This is confirmed by a Caledonian age of ca. 400 Ma on the green biotites (Verschure et al., 1980). In general agreement, the lower intercepts of some discordia chords give ages between 410 and 310 Ma (Wielens et al., 1981) which might be interpreted as the result of episodic lead loss from Sveconorwegian zircons during the Caledonian event.

In conclusion, in the Rogaland province, it appears that high-grade metamorphism is really of Sveconorwegian age (ca. 1000 Ma) and the incipient superimposed low-grade event is of Caledonian age (ca. 400 Ma).

WHAT ABOUT THE POSSIBILITY OF A PRE-SVECONORWEGIAN HIGH-GRADE METAMORPHISM?

For the hypothesis of a pre-Sveconorwegian (1500 Ma?) high-grade event, as postulated by Field and Råheim (1981), it is highly improbable that different zircon fractions would define linear arrays giving the observed ~ 1000 Ma in the concordia diagram if they had suffered two lower-grade thermal events and two accompanying lead losses, one of Sveconorwegian age (ca. 1000 Ma) and one of Caledonian age (ca. 400 Ma). Indeed, in that case, the zircon data points would plot in a triangle defined by the three ages ~ 1500 Ma (?) to ~ 1000 Ma to ~ 400 Ma, but not on straight lines.

Nevertheless, very few zircons, particularly those from metasedimentary rocks (garnet gneisses, quartzites, . . .), yield $^{207}Pb/^{206}Pb$ ages significantly older than ~ 1200 Ma (Pasteels and Michot, 1975). In the Rb—Sr diagram, the garnetiferous migmatite data points scatter between two reference lines corresponding to ~ 1500 Ma and ~ 1000 Ma (Wielens et al., 1981). These ages, slightly higher than the Sveconorwegian ages, could result from a pre-Sveconorwegian metamorphic event or from an incomplete resetting and/or isotopic rehomogenization of the Rb—Sr and U—Pb systems during the Sveconorwegian granulite-facies metamorphism. In such rocks, it is indeed obvious that at least a fraction of the zircon population is of detrital origin and could have retained a part of the previously accumulated radiogenic lead even after a high-grade metamorphism. In our view, these data do not constitute convincing evidence for the existence of a well-defined high-grade metamorphic event significantly older (i.e., ~ 1500 Ma) than the Sveconorwegian orogenesis in the Rogaland province.

Pb—Pb isochron age studies of whole-rock gneisses may date a high-grade event. Indeed, it is well known (Lambert and Heier, 1968; Moorbath et al., 1969; Sighinolfi, 1971; Heier, 1973) that granulite-facies metamorphism induces regional U depletion resulting in low U/Pb ratios. If these rocks behaved as closed systems to U and Pb since metamorphism, the Pb isotopic composition of whole rocks could give the age of the U depletion and, thus, the age of the high-grade metamorphism (Moorbath et al., 1969; Gray and Oversby, 1972; Beckinsale et al., 1980). In general, lower grade metamorphic events, post-dating the main granulite facies phase do not significantly disturb the Pb—Pb systematics of whole rocks.

Eleven granulite-facies gneisses of different lithologies from the Rogaland complex have been analysed for their Pb isotopic compositions. The results, together with Th, U and Pb concentrations are reported in Table I. Except the two granitic gneisses which have normal U concentrations (5—7 ppm, samples JCD 73-48 and JCD 72-111), most of the samples appear variably depleted in U although not so severely depleted as the granulite-facies Lewisian gneisses (mean U content, 0.24 ppm; Moorbath et al., 1969). The U content is quite variable; consequently there is a wide scatter in the $^{238}U/^{204}Pb$ values, from 0.8 to 4.7.

In the $^{207}Pb/^{204}Pb$ v. $^{206}Pb/^{204}Pb$ diagram (Fig. 1a), the data points define a very good straight line (MSWD = 0.55) which, if interpreted as a secondary isochron, yields an age of 1359 ± 120 Ma (2σ). In the classical interpretation of the Pb—Pb isotope data, this age corresponds to a regional U depletion occurring during a granulite-facies metamorphism. This age may be correlated with the first metamorphic phase of the Sveconorwegian orogenesis (the Ml phase of Maijer et al., 1981), as also may the age of the poorly defined U—Pb zircon ages slightly exceeding 1200 Ma discussed above and in Pasteels and Michot (1975). In the $^{208}Pb/^{204}Pb$ v. $^{206}Pb/^{204}Pb$ diagram (Fig. 1b), the scatter of the data points indicates that under granulite-facies conditions the behavior of Th is quite different from that of U, as pointed out by Moorbath et al. (1969) and Gray and Oversby (1972). The high-grade metamorphic event at 1000 Ma has not disturbed the Pb—Pb systematics in whole rocks since, in such a short time interval (300 Ma) and in a relatively U-depleted environment, there was nearly no radiogenic lead accumulation.

The possibility that the isochron represents a "transposed palaeo-isochron" (Griffin et al., 1978) has also been examined. Following this model, the rocks should have been formed at ~ 1200 Ma and became U-depleted at ~ 900 Ma. The main characteristics of the Pb isotopic data in such a situation are (Moorbath and Taylor, 1981):

TABLE I

Lead isotopic composition and U, Th and Pb concentrations of granulite-facies gneisses of South Rogaland

Sample[c]	Lithology	$^{206}Pb/^{204}Pb \pm 1\sigma$	$^{207}Pb/^{204}Pb \pm 1\sigma$	$^{208}Pb/^{204}Pb \pm 1\sigma$	Pb[a] (ppm)	U[b] (ppm)	Th[b] (ppm)	$^{238}U/^{204}Pb$
DD 354-1/1	Fine noritic gneiss	18.453 ± 0.013	15.587 ± 0.015	37.593 ± 0.039	7.9	0.6	2.1	4.7
DD 622-1/1	Opx granitic augen gneiss	17.417 ± 0.012	15.481 ± 0.013	36.765 ± 0.034	22.7	<0.3	0.35	0.8
DD 390-1/1	Granitic gneiss	19.701 ± 0.026	15.681 ± 0.026	39.963 ± 0.074	42.3	—	—	—
DD 212-1/3	Garnet—cordierite gneiss	18.016 ± 0.019	15.548 ± 0.024	37.260 ± 0.065	19.4	0.5	1.4	1.6
PA 66/L	Augen gneiss	17.192 ± 0.030	15.450 ± 0.031	37.086 ± 0.089	40.3	0.6	6.6	0.9
		17.189 ± 0.018	15.448 ± 0.020	37.088 ± 0.057				
PA 70/B	Augen gneiss	18.195 ± 0.016	15.550 ± 0.018	37.813 ± 0.047	25.7	0.5	5.9	1.2
JCD 78-34	Leucogranitic gneiss	18.553 ± 0.015	15.604 ± 0.016	37.704 ± 0.045	—	1.7	4.1	—
JCD 72-158	Granulitic gneiss	19.618 ± 0.016	15.670 ± 0.018	40.202 ± 0.052	—	2.6	2.6	—
JCD 73-48	Biotite granitic gneiss	17.938 ± 0.018	15.544 ± 0.019	36.816 ± 0.036	—	6.9	52	—
JCD 80-30	Leucogranitic gneiss	17.920 ± 0.011	15.538 ± 0.014	37.704 ± 0.037	—	1.1	4.5	—
JCD 72-111	Porphyritic granitic gneiss	19.832 ± 0.016	15.694 ± 0.015	39.760 ± 0.042	—	7.4	56	—

[a] Concentrations determined by X-ray fluorescence spectrometry.
[b] Concentrations determined by neutron activation analysis (J. Hertogen, K.U.L.).
[c] All samples were analysed in the Oxford Isotope Laboratory. Lead was separated by an electrodeposition method (Arden and Gale, 1974) and analysed on a Micromass 54E mass spectrometer. Analyses were corrected for mass fractionation. Decay constants used in the calculations: $\lambda_{^{238}U} = 1.55125 \times 10^{-10} y^{-1}$; $\lambda_{^{235}U} = 9.8485 \times 10^{-10} y^{-1}$ (Jaffey et al., 1971).

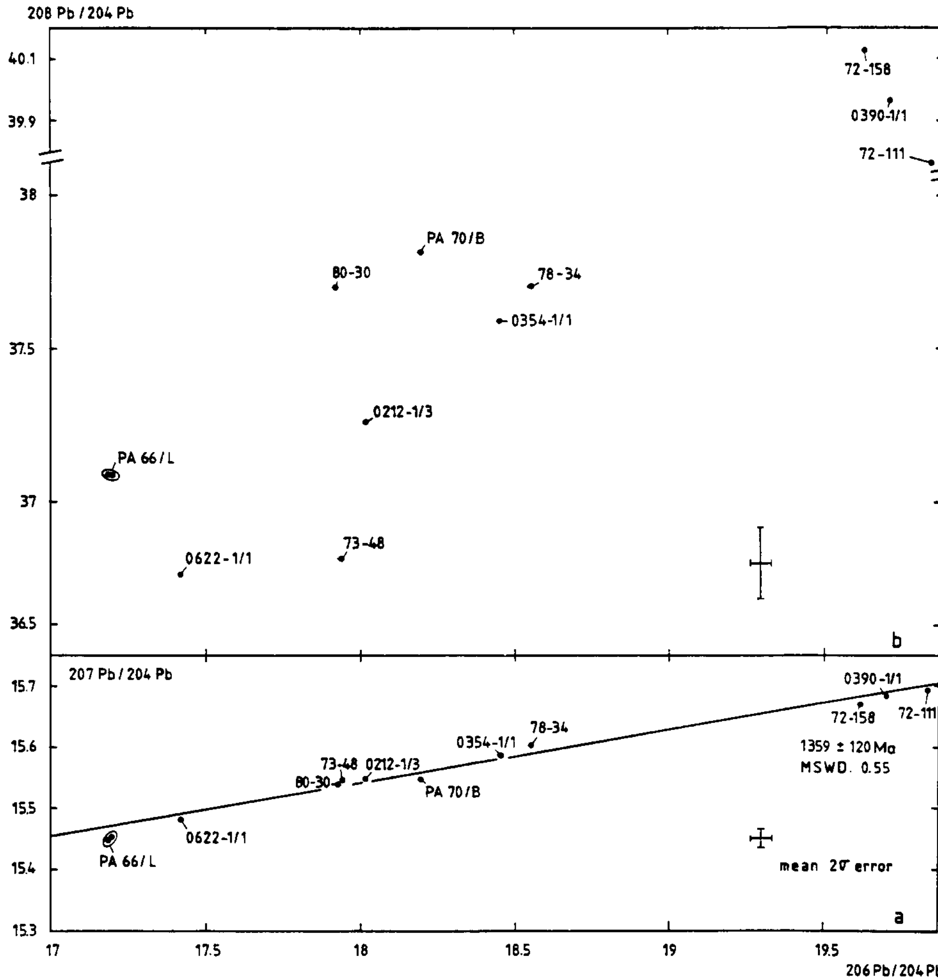

Fig. 1. (a) $^{207}Pb/^{204}Pb$ v. $^{206}Pb/^{204}Pb$ diagram for the granulite-facies gneisses of the Rogaland province. (b) $^{208}Pb/^{204}Pb$ v. $^{206}Pb/^{204}Pb$ diagram.

(1) high μ_1 value for the source-region of these rocks on the basis of a single-stage evolution model;

(2) radiogenic and variable Pb isotopic compositions.

This "palaeo-isochron" model does not seem to be appropriate to the Rogaland gneisses Pb data, because:

(i) these gneisses are not all orthogneisses, they can thus not be comagmatic;

(ii) the μ_1 calculated value is 8.07 which is not especially high compared with the mantle value at this time (~ 8.9, Zartman and Doe, 1981);

(iii) the range of Pb isotopic compositions is large, but not very large (the highest $^{206}Pb/^{204}Pb$ ratio is 19.83).

As far as the Rogaland province is concerned, the main conclusions are:

(a) the Sveconorwegian orogenic event produced high-grade (granulite facies) metamorphism closely defined at ~ 1000 Ma from U-Pb zircon data. An earlier metamorphic phase occurred at 1300—1200 Ma as indicated by whole-rock Pb—Pb dating.

(b) there is no obvious pre-Sveconorwegian high-grade event comparable to the ~ 1500 Ma age reported for the Arendal area.

(c) the very low- to low-grade retrogression of the granulite facies rocks is due to Caledonian (ca. 400 Ma) orogenesis.

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