

Pb isotope geochemistry of a massif-type anorthositic-charnockitic body: the Hydra Massif (Rogaland, S.W. Norway).

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Abstract—The Hydra Massif (Rogaland complex, S.W. Norway) is a massif-type anorthositic-charnockitic body. It consists of undeformed anorthosites and leuconorites, grading into fine-grained jotunites at the contact with the granulite facies gneisses of the metamorphic envelope. A stockwork of charnockitic dykes cross-cuts the massif. The Pb isotopic compositions of the anorthosites and leuconorites are comparable or slightly less radiogenic than those of the jotunites ($^{206}\text{Pb}/^{204}\text{Pb}$ from 18.079 to 19.307, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.568 to 15.657 and $^{208}\text{Pb}/^{204}\text{Pb}$ from 37.617 to 38.493). These values are compatible with an upper mantle origin for the parental magma of jotunitic composition and for the plagioclasic cumulates, but show the incorporation of lower crustal material (U-depleted and thus less radiogenic). The charnockitic dykes have significantly less radiogenic Pb isotopic compositions ($^{206}\text{Pb}/^{204}\text{Pb}$ from 17.472 to 19.171, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.489 to 15.620 and $^{208}\text{Pb}/^{204}\text{Pb}$ from 36.991 to 40.922) which can be explained by a larger proportion of lower crustal contamination material. The contaminant could be the granulite facies gneisses of the metamorphic envelope. This interpretation is compatible with the K-Rb relationships of these rocks and with the O and Sr isotopic geochemistry.

The proportion of contaminating lead in the charnockitic dykes can be estimated at $55 \pm 15\%$ considering the border facies jotunite as the uncontaminated parental magma and the least radiogenic gneiss of the metamorphic envelope as the contaminant.

INTRODUCTION

Pb ISOTOPE geochemistry has been shown to be very useful in deciphering petrogenetic problems as varied as:

—the origin of ore deposit lead (STACEY and KRAMERS, 1975);

—the source of granitic magma (DOE, 1967);

—the source-region and age of Archaean calc-alkaline gneisses (TAYLOR *et al.*, 1980);

—the origin and development of continental crust with special attention to the problem of its genesis by recycling or by input of juvenile mantle-derived material (ARMSTRONG, 1968, 1981; MOORBATH, 1977; MOORBATH and TAYLOR, 1981);

—the structure, heterogeneity and geodynamics of the mantle through the study of the isotopic compositions of oceanic basalts (TATSUMOTO, 1978; SUN, 1980; ALLÈGRE, 1982).

In that respect, we think that Pb isotope geochemistry might help to clarify the much debated problem of anorthosite petrogenesis (CARMICHAEL *et al.*, 1974); more specifically, the two main questions are:

—what is the nature of the parental magma of the massif anorthosite and where does it come from?

—charnockites are commonly associated with anorthosites in the field. Are these rocks comagmatic?

Two main ways of thinking emerge from the literature:

i) the charnockites and anorthosites belong to two different magmatic series and the parental magma of the anorthosites should have a gabbroic anorthosite composition (BUDDINGTON, 1939, 1972; SIMMONS and HANSON, 1978; WIEBE, 1980); this does not exclude these rocks from intruding more or less simultaneously, the acidic rocks resulting from the anatexis of enclosing rocks at the contact with the anorthositic intrusion;

ii) the charnockites represent the residual liquid of the anorthosite differentiation sequence (BOWEN, 1917; MICHOT, 1965; PHILPOTTS, 1969; DE WAARD *et al.*, 1974).

More recent geochemical and isotopic studies mainly in the South Rogaland anorthositic-charnockitic complex of southwestern Norway (MICHOT and MICHOT, 1969) have led many people to take up an intermediate position: the acidic charnockitic rocks correspond to the residual liquid of the anorthosite differentiation process but with contamination at various stages by crustal material (PASTEELS *et al.*, 1970; MARTIGNOLE, 1974; DUCHESNE and DEMAIFFE, 1978; DEMAIFFE *et al.*, 1979).

This paper deals with the Pb isotope geochemistry of the Hydra Massif, a small anorthositic-charnockitic body in the eastern part of the South Rogaland complex, which together with other geochemical data (O isotope geochemistry, DEMAIFFE and JAVOY, 1980; REE geochemistry and Sr isotopic composition, DEMAIFFE and HERTOGEN, 1981), should give information about the petrogenesis of this massif.

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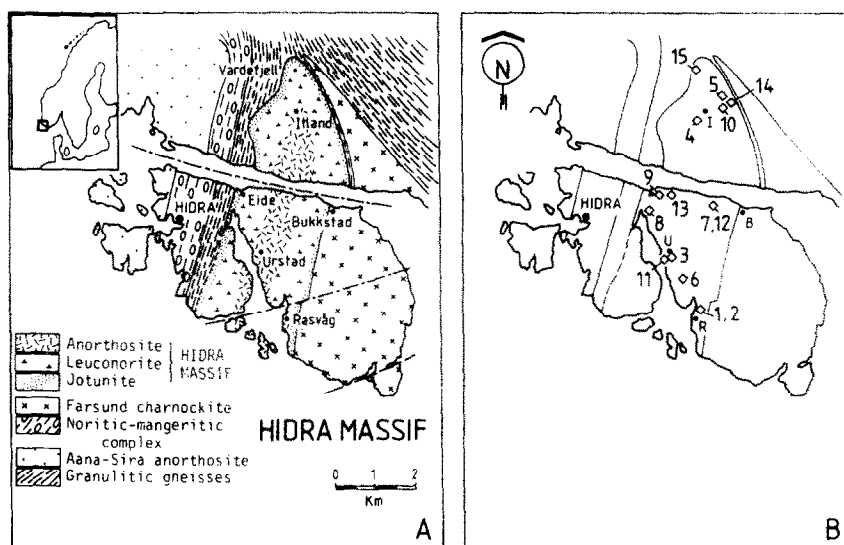


FIG. 1. A—Geological sketch map of the Hidra massif (Rogaland—S.W. Norway). From DEMAIFFE and HERTOGEN (1981) The charnockitic dykes are too thin to be mapped. B—Sample location (see Table 1).

GEOLOGICAL SETTING

The Hidra Massif (Fig. 1) is a part of the South Rogaland igneous complex. It is made up mainly of plagioclasic cumulates—coarse grained orthocumulate anorthosite and adcumulate leuconorite (= gabbroic anorthosite)—which grade progressively to a fine grained, locally porphyritic, jotunite (= hypersthene monzodiorite) following STRECKEISEN'S (1974) nomenclature. Numerous charnockitic dykes (up to 1 m thick) and lenses of granitic pegmatite cross-cut the anorthosites and the leuconorites. Detailed field relationships with the surrounding granulite facies gneisses and petrographical descriptions of its different units have been discussed by DEMAIFFE *et al.* (1973) and DEMAIFFE (1977a). Their main features together with trace element (REE) and Sr isotopic geochemistry are summarized by DEMAIFFE and HERTOGEN (1981).

From a geochronological viewpoint, two charnockitic dykes and one jotunite give U/Pb zircon data which define a discordia giving 931 ± 10 m.y.¹ (PASTEELS *et al.*, 1979). A whole-rock Rb-Sr isochron on six samples of charnockitic dykes gives 892 ± 25 m.y. with a $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of 0.7085. The initial Sr isotopic composition of the anorthosites, leuconorites and jotunites is 0.7055 ± 0.0004 (mean of 9 values; DEMAIFFE and HERTOGEN, 1981).

ANALYTICAL PROCEDURE

Samples were crushed to finer than 200 mesh in an agate mortar. About 100 mg of powder were taken for chemical processing. Four samples were usually treated simultaneously. Samples were weighed into teflon bombs (previously cleaned by four overnight washings with a 3:1 HF-HNO₃ mixture) and digested in an oven (~200°C) during a week with a 1:1 HF-HClO₄ or HF-HNO₃ mixture (this method was inspired by NUNES *et al.* (1973) and MANHES *et al.* (1978); see WEIS, 1981).

¹ All data have been calculated or recalculated with the decay constants recommended by the IGCP-IUGS subcommittee of geochronology (STEIGER and JÄGER, 1977); the 892 ± 25 m.y. age is the 909 m.y. age of DEMAIFFE and HERTOGEN (1981) recalculated with $\lambda^{87}\text{Rb} = 1.42 \cdot 10^{-11}$ yr⁻¹.

The samples were dried then dissolved in 1 N HBr-0.1 N HCl. The solutions were split into two fractions (2:1) and the smaller one was spiked with $2 \mu\text{g } ^{206}\text{Pb}$ plus $5 \mu\text{g } ^{235}\text{U}$ spike.

All samples were processed through an MP5080 100–200 mesh macroporous anion exchange column. The column was washed with 4 column volumes of 6 N HCl, 2 column volumes of concentrated suprapure HF and 4 column volumes of H₂O. The column was conditioned with 2 column volumes of 1 N HBr-0.1 N HCl; after sample loading, the column was rinsed with 2 column volumes of 1 HBr-0.1 HCl and Pb was eluted by 2 column volumes of 6 N HCl.

The sample was then dried and the operation was repeated twice on a smaller column (1 ml) before loading on a zone-refined Re filament by the silica gel-phosphoric acid method (CAMERON *et al.*, 1969). For the spiked fraction, the procedure was exactly the same but the 1 N HBr-0.1 N HCl solution of the Pb column was collected, dried and dissolved in 7 N HNO₃. This solution was passed through a Dowex 1 × 8 200–400 mesh anion exchange column which was washed with 4 column volumes of 7 N HNO₃ and then 4 column volumes of H₂O. The column was conditioned with 2 column volumes of 7 N HNO₃. After sample loading, the column was rinsed with 2 column volumes of 7 N HNO₃. U was eluted by 2 column volumes of H₂O. The sample was then dried and the operation was repeated twice. The final elution was collected in the same beaker as the Pb spiked fraction.

All operations except weighing were carried out in an ultraclean laboratory with overpressure (>3 mm Hg) and in laminar flow clean air workstations. All the reagents were subboiled (MATTINSON, 1971). Blank values were always less than 3 ng Pb for the whole experimental procedure and during the entire period of analysis; they were negligible in view of the Pb content of the samples (0.25 to ~2.5 μg) and no correction for the contamination was applied. U blanks were 0.5–1 ng. Pb isotopic compositions were determined on single Re filaments with a MAT 260 Varian mass spectrometer (sensitivity better than 100 ng, within-run precision better than 0.05%) of the "Centre Belge de Géochronologie." The Pb standard NBS 981 was measured during the work and the average of 25 analyses gave a mass fractionation of $-1.24 \pm 0.44\%$ per atomic mass unit difference in a temperature range of 1090 to 1200°C. Pb isotope ratios were thus corrected for this value of mass fractionation and

the analyses were always taken within this temperature range. Within-run precision for Pb isotopic analyses was better than 0.05% (2σ), and between-run precision better than 0.1% for the $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios, and better than 0.15% for the $^{208}\text{Pb}/^{204}\text{Pb}$ ratios.

Pb and U concentrations were measured on the same single Re filaments with a TH5 Varian mass spectrometer (sensitivity $\sim 1\ \mu\text{g}$, precision better than 0.1%), except for gneiss sample PA66/L where Pb was measured by X-ray fluorescence spectrometry. Th and U concentrations of some samples were determined by neutron activation analyses (HERTOGEN, pers. commun.).

The samples analysed for Pb isotopic composition are the same as those already used for REE and Sr isotopic analyses (DEMAIFFE and HERTOGEN, 1981) (see sample location in Fig. 1b).

RESULTS

Pb isotopic compositions have been determined for six charnockitic dykes, two pegmatites, three orthocumulate anorthosites, two leuconorites and two jotunitites of the border facies; the Pb and U concentrations of these rocks have also been obtained. All these data are reported in Table 1. Twelve granulitic gneiss samples have also been analysed for their Pb isotopic compositions (WEIS and DEMAIFFE, 1983) to constrain the isotopic character of the metamorphic envelope. The $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of the magmatic rocks vary from 17.472 to 19.307, the $^{207}\text{Pb}/^{204}\text{Pb}$ ratios from 15.489 to 15.657 and the $^{208}\text{Pb}/^{204}\text{Pb}$ ratios from 36.991 to 40.922.

In the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (Fig. 2), all the rocks of the Hidra Massif define a good linear correlation (MSWD of 1.61) whose slope corresponds to an age of 1277 ± 170 m.y. (2σ). On

the other hand, in the $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (Fig. 2), the data points are widely scattered, particularly those of the charnockitic dykes.

The U-Pb isochron diagrams (not shown) also give a rather large scatter of the data points which means that uranium has been quite mobile in this system.

In the modified concordia diagram (ULRYCH, 1967)—correction of the measured Pb ratios by the Pb isotopic composition of Canyon Diablo troilite (TATSUMOTO *et al.*, 1973)—the data points defining a linear array are all situated above Concordia which indicates that all the samples are U-depleted, especially the charnockites, which lie very far above Concordia. This depletion seems to be a primary feature of the source-magma of these rocks rather than the result of a later depletion episode. Indeed, the measured U (and Pb) concentrations account grossly for the Pb isotopic ratios of these rocks.

DISCUSSION

1) What is the meaning of the Pb-Pb age?

It appears difficult to reconcile the age deduced from the slope of the linear correlation in the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram with both field and other isotopic data. Indeed, the rocks of the Hidra Massif still show well preserved original magmatic structures (orthocumulate anorthosites) with no evidence of deformation and/or metamorphism after the magmatic crystallization. In addition, leuconoritic dykes coming from the massif cross-cut the granulitic gneisses of the metamorphic envelope. All

Table 1: LEAD ISOTOPIC COMPOSITION, Pb AND U CONCENTRATIONS OF ROCKS FROM THE HIDRA MASSIF

(1) Samples (2)	$^{206}\text{Pb}/^{204}\text{Pb} \pm 2\sigma_M$	$^{207}\text{Pb}/^{204}\text{Pb} \pm 2\sigma_M$	$^{208}\text{Pb}/^{204}\text{Pb} \pm 2\sigma_M$	Pbppm	Uppm (3) ID INAA	Thppm INAA	$^{238}\text{U}/^{206}\text{Pb}$
1. P0501-1	17.540 0.013	15.523 0.013	37.202 0.032	41.9 0.26			0.38
2. P0501-2	18.784 0.089	15.653 0.087	38.648 0.216	18.5 2.67			9.09
3. D0443-4/1	19.171 0.011	15.617 0.012	38.520 0.033	18.6 3.18	3.01	9.81	10.81
4. D0283-2/2	17.476 0.007 17.472 0.014	15.494 0.007 15.476 0.014	36.991 0.021 36.942 0.047	26.8 1.00	0.63	2.17	2.25
5. D0377-2/1	17.472 0.006	15.489 0.006	38.643 0.016	26.8 0.61			1.41
6. D0309-2/1 ::	18.131 0.009 18.144	15.562 0.010 15.581	39.875 0.029 39.837	21.2 1.48			4.43
7. D0299-2/1	18.855 0.068 18.857 0.005	15.614 0.063 15.620 0.006	37.999 0.232 37.983 0.013	2.9 0.32			6.90
8. D0511-2/1	18.439 0.020	15.580 0.026	40.922 0.079	21.6 2.50			7.48
9. L0334-1/1	18.664 0.056 18.752 0.016	15.549 0.051 15.598 0.015	37.840 0.127 37.950 0.037	2.6 1.10		0.82	26.30
10. L249-1/1 ::	18.336 0.066 18.368	15.589 0.061 15.606	37.755 0.144 37.806	2.3 2.00		0.44	53.77
11. A0058-1/1 ::	18.947 0.006 19.062	15.621 0.007 15.635	37.311 0.018 37.826	8.0 1.29		1.30	10.04
12. A0299-1/1	18.341 0.014	15.573 0.015	37.645 0.046	9.5 0.72	0.56	1.90	4.68
13. A0335-1/1	18.079 0.007	15.566 0.007	37.617 0.017	2.6 0.12			2.84
14. J0259-1/1	19.307 0.023	15.657 0.025	38.493 0.062	8.6 1.42	1.30	3.8	10.46
15. J0200-2/2	18.362 0.081	15.609 0.089	37.949 0.224	9.9 0.96		1.20	6.02

(1) This simple number identification has been used in the figures.

(2) P = pegmatite, D = charnockitic dyke, L = leuconorite, A = anorthosite, J = jotunitite

(3) ID = isotopic dilution - INAA = instrumental neutron activation analysis

:: samples reanalysed at the isotope laboratory of the Oxford University (S. MOORBATH). Samples prepared by the electrochemical deposition method (ARDEN & GALE, 1974) and analysed on a Micromass 54E mass spectrometer; within-run precision for Pb isotopic analyses averaged 0.03% (2σ) and between run accuracy is estimated as 0.02, 0.01 and 0.04 (absolute 2σ error) for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ respectively (see DICKIN & EXLEY, 1981).

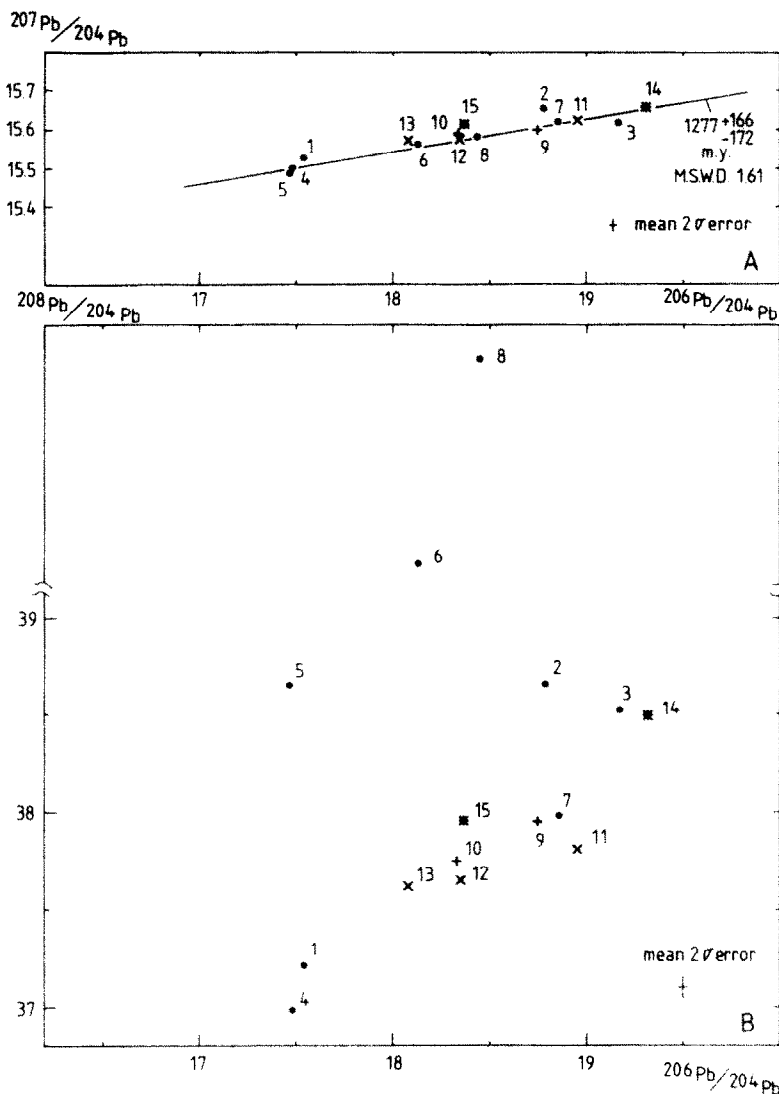


FIG. 2. Lead isotopic composition of the Hidra rocks: A— $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram; B— $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram. Symbols: ●, charnockitic dykes; +, leuconorites; ■, border facies jotunites; ×, anorthosites.

these observations indicate that the Hidra body intruded late—or post—tectonically (DEMAIFFE, 1977a). The climax of the deformation and the metamorphism has been dated at 975 m.y. (PASTEELS and MICHOT, 1975). The intrusion age of the Hidra Massif should thus be younger than 975 m.y. which is confirmed by the U/Pb data on zircons of jotunites (937 ± 4 m.y.) and of charnockitic dykes (chord to 935 m.y.) and also by the whole-rock Rb-Sr isochron on these dykes (892 ± 25 m.y., PASTEELS *et al.*, 1979). The leuconoritic dykes coming from the Hidra Massif cross-cut the Farsund charnockite dated by U/Pb on zircons between 940 and 920 m.y.

Moreover, the jotunites (samples 200-2/2 and 259-1/1) representing the undifferentiated parental magma of the Hidra Massif (DEMAIFFE and HERTOGEN, 1981) have higher $^{207}\text{Pb}/^{204}\text{Pb}$ ratios for a given $^{206}\text{Pb}/^{204}\text{Pb}$ ratio than the charnockites which are the most differentiated rocks of the massif, while the anor-

thosites and leuconorites have isotopic ratios quite comparable to those of the jotunites or even slightly lower (Table 1 and Fig. 2).

This implies that the linear correlation observed in the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram has no chronological significance, and that this line could correspond to a mixing line whose end-members have to be defined.

2) Contamination hypothesis

A comparison between the actual Pb isotopic compositions of the surrounding granulite facies gneisses (WEIS and DEMAIFFE, 1983) and those of the Hidra rocks is shown in Fig. 3a in a $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram.

Two straight lines whose slope corresponds to 892 m.y. (or to 935 m.y. which makes no difference to the petrogenetical interpretation) have been drawn,

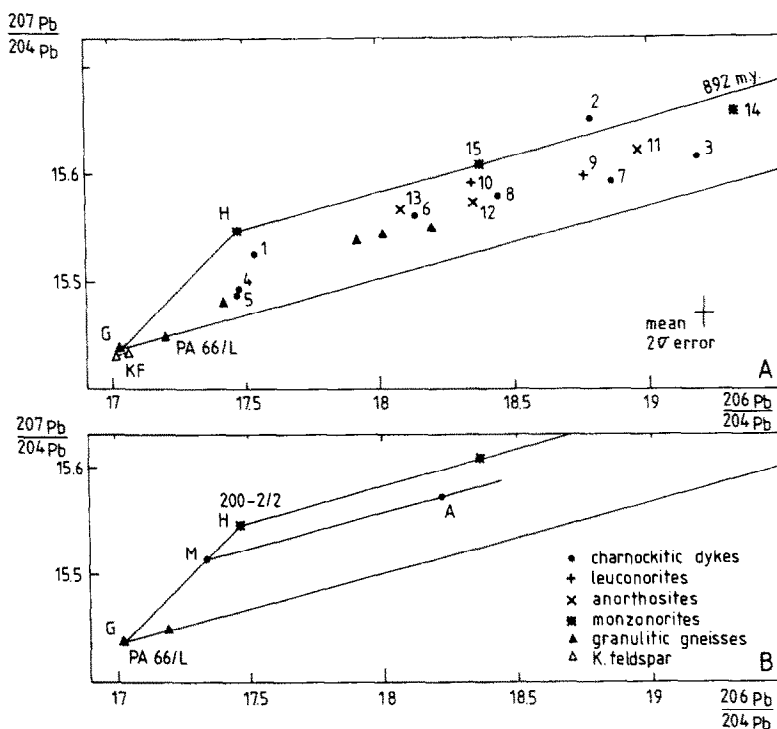


FIG. 3. A— $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram comparing the actual Pb isotopic compositions of samples from the Hidra Massif and of gneisses from the metamorphic envelope. See text for explanations. B— $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram illustrating the theoretical case (TAYLOR *et al.*, 1980) of the Hidra parental magma contaminated by Pb derived from the surrounding gneisses. See text for explanations and for significance of the symbols.

one through the Pb isotopic ratios of the jotunite 200-2/2 which has the highest $^{207}\text{Pb}/^{204}\text{Pb}$ ratio of the Hidra Massif (except one pegmatite, 0501-2 which is not considered) and the other through the Pb ratios of the granulitic augengneiss, PA66/L, which has the least radiogenic composition. If all the Hidra rocks had crystallized with the same initial Pb isotopic composition 892 m.y. ago, they should lie on the straight line (thus an isochron) passing through the jotunite 200-2/2. In fact, Fig. 3a shows that all the Hidra rocks have Pb isotopic compositions plotting between the two straight lines as defined above; each data point could be interpreted as the result of a mixing of two Pb in varied proportions: one is the Pb of the parental magma represented by the border facies jotunites, slightly or not at all contaminated and the other is the Pb of the gneissic rocks of the metamorphic envelope (granulitic lower crust), characterized by less radiogenic isotopic ratios because of their impoverishment in uranium during the granulite facies metamorphism (WEIS and DEMAIFFE, 1983).

The anorthosites and leuconorites have isotopic compositions slightly less radiogenic than the jotunites, almost within the analytical error while the charnockitic dykes have significantly lower $^{207}\text{Pb}/^{204}\text{Pb}$ ratios and are thus the most contaminated rocks of the massif. This interpretation is corroborated by the initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratios of these rocks: 0.7055 ± 0.0004 for the jotunites and the plagioclastic cumulates and 0.7085 ± 0.0006 for the charnockitic

dykes (DUCHESNE and DEMAIFFE, 1978; DEMAIFFE and HERTOGEN, 1981).

To try to estimate the proportion of contaminating material in the Hidra rocks, we have used a method similar to that used by TAYLOR *et al.* (1980) for the late Archaean gneisses of West Greenland. The theoretical case of the Hidra parental magma contaminated by Pb derived from the gneisses is shown in Fig. 3b. In the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, the line HG represents the mixing line, at the formation time of the Hidra Massif, 892 m.y. ago, between the Pb of the Hidra parental magma (point H) and the Pb derived from the gneisses (point G). The initial composition of the contaminated Hidra magma must lie necessarily on the mixing line HG. It is possible to draw a straight line through the actual Pb isotopic composition of the sample A whose slope corresponds to the age of the massif which is given by the Rb-Sr whole-rock isochron (892 m.y.) or the U/Pb zircon data (935 m.y., PASTEELS *et al.*, 1979); the intersection of this straight line with the initial mixing line HG gives the point M from which it is possible to estimate the degree of contamination. The greater the contamination, the closer the initial Pb isotopic composition of the contaminated sample will be to that of the contaminant Pb (point G).

To quantify the contamination process, it is necessary to know the following parameters:

—the Pb isotopic composition of the contaminant

material at the time of the massif's intrusion, *i.e.* 892 m.y. ago, corresponding to the point G;

—the initial Pb isotopic composition of the parental magma supposed to be uncontaminated *i.e.* point H;

—the Pb and U concentrations in the magma and the contaminant;

—the Pb isotopic composition of the different samples of the Hidra Massif at their formation time corresponding to the point M.

The Pb isotopic composition of the contaminant material was calculated by correcting the actual (measured) isotopic composition of the gneiss PA66/L for *in situ* decay of uranium² since 892 m.y. ($^{206}\text{Pb}/^{204}\text{Pb} = 17.017$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.426$).

To check this hypothesis, one K-feldspar separated from an augengneiss of the same geological unit has been analysed for Pb isotopic compositions and U-Pb concentrations after adequate leaching (hot 6 N HCl-HBr 5%-HF 5%). It gives $^{206}\text{Pb}/^{204}\text{Pb} = 17.012$ and $^{207}\text{Pb}/^{204}\text{Pb} = 15.432$ at 892 m.y.), values which are indistinguishable within error limits from those of sample PA66/L.

The initial Pb isotopic composition of the Hidra parental magma was calculated in the same way from the measured isotopic composition and U and Pb concentrations (isotopic dilution) in the jotunite 200-2/2 (*n*^o 15) ($^{206}\text{Pb}/^{204}\text{Pb} = 17.455$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.545$).

In the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (Fig. 3a), a straight line passing through these two points has been drawn (line HG). The actual isotopic compositions of all the Hidra samples have been taken back to this line HG by "subparallel isochrons" with a 892 m.y. slope. By graphical method, the proportion *X* of the contaminant Pb to the total Pb of the sample is given by:

$$X = \frac{(^{206}\text{Pb}/^{204}\text{Pb})_{\text{H}} - (^{206}\text{Pb}/^{204}\text{Pb})_{\text{M}}}{(^{206}\text{Pb}/^{204}\text{Pb})_{\text{H}} - (^{206}\text{Pb}/^{204}\text{Pb})_{\text{G}}}$$

where $(^{206}\text{Pb}/^{204}\text{Pb})_{\text{H}}$ = initial Pb ratio of the Hidra parental magma, $(^{206}\text{Pb}/^{204}\text{Pb})_{\text{G}}$ = ratio of the contaminant Pb 892 m.y. ago, and $(^{206}\text{Pb}/^{204}\text{Pb})_{\text{M}}$ = initial ratio (graphically obtained) of the samples. This calculation was done for all the Hidra samples (Table 2). It gives a mean value of $55 \pm 15\%$ for the charnockitic dykes and of $34 \pm 10\%$ for the anorthosites.

The actual age-corrected Pb isotopic data (for 892 m.y. *in situ* U decay) can also be useful to estimate the mixing ratio. Indeed, the data define a rather good linear array if one excludes the two leuconorites (for a still unknown reason, those two samples have

Table 2

Calculations of the proportion *X* of the contaminant Pb to the total lead of the Hidra Massif samples.

Charnockitic dykes	<i>X</i> ₁	<i>X</i> ₂
0501-1	1	0.34
0443-4/1	3	0.60
0283-2/2	4	0.69
0377-2/1	5	0.74
0309-2/1	6	0.46
0299-2/1	7	0.61
0511-2/1	8	0.44
Anorthosites		
0058-1/1	11	0.34
0299-1/1	12	0.43
0335-1/1	13	0.24
Jotunites		
0259-1/1	14	0.70
0200-2/2	15	0.22

*X*₁ = calculations based on the graphical method

*X*₂ = calculations based on the 892 m.y. corrected ratios

(see text for explanations)

anomalously high U/Pb ratios). Considering the gneiss sample PA66/L as the contaminant and the jotunite 259-1/1 (*n*^o 14) as the parental magma, the amount of contaminating lead in the charnockites has been estimated at $50 \pm 20\%$ and at about 20% for the anorthosites, in agreement with the graphical method. It is obvious that these values can only be considered as rough estimates. Indeed, the jotunitic parental magma can already have been slightly contaminated: the initial strontium isotopic composition of these rocks varies from 0.7052 to 0.7055 (recalculated from the data of DEMAIFFE (1977b) and DEMAIFFE and HERTOGEN (1981) with $\lambda^{87}\text{Rb} = 1.42 \cdot 10^{-11} \text{ yr}^{-1}$) which is slightly too high for a direct mantle origin. Moreover, other gneisses of different nature and/or of different Pb isotopic composition could have participated in the contamination process. It is possible that the hypothesized contaminant had a less radiogenic Pb composition than PA66/L (even if this composition has been checked by K-feldspar analysis), if, for instance, the contamination took place at a deeper level in the crust where the U-depletion associated with granulite facies metamorphism could have been more pronounced.

The geological situation of the South Rogaland area does not enable us to give a more detailed and quantitative picture of the contamination processes since the age difference between the rocks of the anorthositic suite and the surrounding gneisses are not great enough to generate significant differences in the Pb isotopic compositions of these rocks.

The μ values calculated from the Pb isotopic compositions in the Hidra rocks vary from 8.057 to 8.158. Mean upper mantle value for this time (around 900 m.y.) is near 8.9 following the "Plumbotectonics" program (ZARTMAN and DOE, 1981); for the lower continental crust, the corresponding value is 6 and for the upper crust, it is 12. These μ values for the Hidra rocks are compatible with an upper mantle origin but with some contamination by less radiogenic lower crustal material. This contamination in-

² Pb concentration in this sample was determined by X-ray spectrofluorescence (for conditions, see DICKIN, 1981) and U concentration by neutron activation analysis. It gives 0.6 ppm U (HERTOGEN, pers. commun.) for the sample PA66/L which is in the range of values given by HEIER (1973) for granulite facies gneisses (with a mean value of 0.7 ppm).

creased during the magmatic differentiation process because the charnockites representing the residual liquid are the most contaminated Hidra rocks as shown by their least radiogenic Pb ratios.

This contamination process can also be shown by the other isotopic data. Indeed, there is a rather good correlation between the initial $^{207}\text{Pb}/^{204}\text{Pb}$ ratios and either initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (DEMAIFFE and HERTOGEN, 1981) or $\delta^{18}\text{O}$ values (DEMAIFFE and JAVOY, 1980) (Fig. 4). The least contaminated rocks, *i.e.*, the anorthosite and the jotunite have the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ (0.705–0.707) and $\delta^{18}\text{O}$ values (between 5 and 6‰) and the highest $^{207}\text{Pb}/^{204}\text{Pb}$ (>15.52) while the charnockite shows the opposite.

Moreover, the Th-Pb system appear very disturbed in these latter rocks; the $^{208}\text{Pb}/^{204}\text{Pb}$ ratios are much more scattered than the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (Fig. 2b). This may also be due to the contamination process since the Th content of the granulite facies gneisses is very variable (from 0.4 to 80 ppm; HERTOGEN, pers. commun.). Some geochemical data which can not alone be unequivocally interpreted in terms of such a process can also substantiate this contamination mechanism. For instance, in the bilogarithmic K-Rb diagram, the anorthosites, norites and jotunitites display a linear array which has been explained by a fractional crystallization process (Fig. 7 of DUCHESNE and DEMAIFFE, 1978). In the same diagram, the charnockites plot on another straight line with a much lower slope. This change of slope is probably due to the crystallization of K-feldspar in the charnockites; however, the contamination of this late stage liquid by the gneisses might give the same result since the granitic gneisses of the metamorphic envelope also plot on this second line.

The REE distribution patterns in the charnockites are quite variable (DEMAIFFE and HERTOGEN, 1981); the most differentiated samples (283-2/2 and 298-2/

1) have lower REE (especially heavy REE), Hf, Ta and U contents than the least differentiated charnockite (443-4/1). This can be explained either by the crystallization of zircon, which is known to be enriched in heavy REE (NAGASAWA, 1970; WATSON, 1980) or by the assimilation by the charnockite of acidic gneisses which usually have a low REE content and are variably depleted in heavy REE (see granitic gneiss sample 134/72 in DEMAIFFE *et al.*, 1979; HERTOGEN, unpub. results).

CONCLUSIONS

In the anorthositic-charnockitic Hidra Massif, the jotunite of the border facies and the leuconorite and anorthosite have similar Pb isotopic compositions within analytical error: the measured Pb isotopic ratios are compatible with an upper mantle origin for the parental magma of these rocks; nevertheless, these ratios indicate the incorporation of lower crustal material (U-depleted) in low proportion. For the charnockitic dykes representing the residual liquid of the magmatic differentiation which gave rise to the anorthositic suite, the $^{207}\text{Pb}/^{204}\text{Pb}$ ratios are significantly lower for a given value of the $^{206}\text{Pb}/^{204}\text{Pb}$ ratio, which reflects a more important contamination by lower crustal material; the surrounding granulite facies gneisses could be this contaminant in view of their Pb isotopic ratios. Considering the border facies jotunite as the uncontaminated parental magma and the least radiogenic gneiss (or K-feldspar separated from an augengneiss) of the metamorphic envelope as the contaminant, the relative proportion of the contaminant Pb in the charnockite can be estimated at 55% while it is around 30% in the anorthosite. This interpretation is in agreement with the oxygen and strontium isotopic data—higher $(^{87}\text{Sr}/^{86}\text{Sr})_0$ and $\delta^{18}\text{O}$ ratios in the charnockitic dykes than in the an-

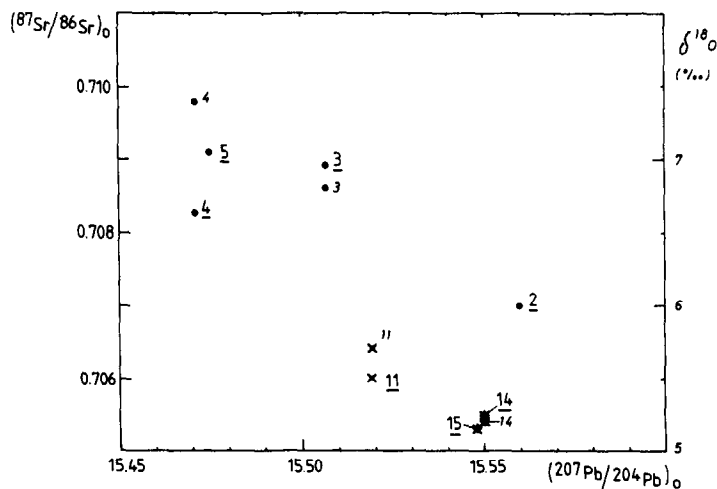


FIG. 4. $(^{87}\text{Sr}/^{86}\text{Sr})_0$ and $\delta^{18}\text{O}$ (‰) versus $(^{207}\text{Pb}/^{204}\text{Pb})_0$ diagram for some Hidra samples, illustrating the progressive contamination of the magma by granulite facies (U depleted) material. The points corresponding to $(^{87}\text{Sr}/^{86}\text{Sr})_0$ are underlined.

orthosite and jotunite—and with trace elements data (REE, K/Rb relationships, LILE, . . .).

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