

Trace element studies in the Alpine type peridotite of Beni-Bouchera (Morocco)

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The content of rare earth and transition elements has been analysed in Beni-Bouchera orogenic peridotites. Results suggest that lherzolite - the predominant petrographic type - is of residual nature while pyroxenite layers represent the product of multiple melting episodes.

INTRODUCTION

The processes governing the formation of lherzolite massifs give rise to different interpretations. These massifs, which are taken as pieces of upper mantle material mechanically raised to the surface, present a characteristic structure. Lherzolite is usually the main rock type, while dispersed layers of mostly pyroxenite composition and running approximately parallel one to another form the remaining part. In order to discuss the genesis of such massifs and because the peridotite and pyroxenite layers compositions and types vary in the detail from one massif to another, we undertook specific trace element studies on these massifs. Studies with respect to the Lanzo massif in the Italian Alps have been previously presented (LOUBET and ALLEGRE, 1978) and a work on the Lherz and the Freychinède massifs (French Pyrénées) is almost completed (LOUBET and ALLEGRE, unpublished results). In this paper we present and discuss results with respect to the Beni-Bouchera massif (Morocco).

GEOLOGICAL SETTING AND SAMPLE DESCRIPTION

The petrography of the Beni-Bouchera massif has been studied by KORNPROBST (1969) and DICKEY (1970). The massif is located in the northeastern part of Morocco close to the Mediterranean shore. It outcrops in the center of an anticline of recent (alpine) age. The common peridotites which constitute the most important part of these massifs are *spinel lherzolites*, with the following approximative modal composition = olivine 60–62%, ortho-

pyroxene 19–21%, clinopyroxene 12–15%, spinel 3–5%.

The *pyroxenite layers* display a large variety of compositions which have been summarized in Fig. 1 (from KORNPROBST, 1969): These layers may be simple or complex. In the latter case, sublayers with various compositions are disposed symmetrically relative to the center of the dyke. In the most complete layers, enstatite constitutes the outer sublayers and grades to an inner garnet clinopyroxenite through an intermediate zone of websterite mineralogy. All the variety of rock compositions found in the sublayers of the complex layer can also form simple layers. The samples analyzed in this study cover the variety of compositions found.

RESULTS

The REE and Ba contents have been measured using an isotopic dilution and mass spectrometry technique. Precisions concerning the experimental procedure and blank values, can be found in previous articles (LOUBET *et al.*, 1972; LOUBET and ALLEGRE, 1978). Major elements and transition elements have been measured using the X-ray fluorescence technique by H. BOUGAULT. The details of this technique have been described by BOUGAULT *et al.* (1977).

The REE and Ba contents of the rock samples have been reported in Table 1 and plotted in Figs. 2 and 3 using the usual chondrite normalized representation. The major elements and transition elements contents are given in Table 2.

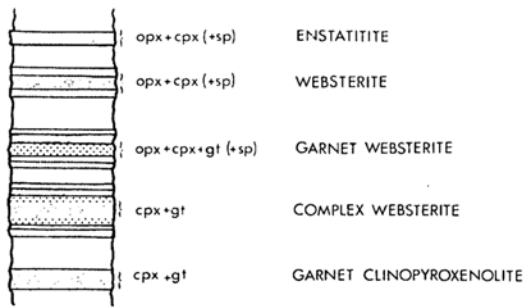


Fig. 1. Various types of pyroxenite layers found in the Beni-Bouchera massif (from KORNPROBST, 1969). Opx = orthopyroxene, Cpx = clinopyroxene, Sp = spinel, Gt = garnet.

Table 1. List of the analyzed samples

Peridotites

M5-102	Spinel Lherzolite (common)
BB5	Spinel Lherzolite
M6-128	Spinel Lherzolite

Pyroxenite layers

M6-78	Enstatite	
M6-79	Garnet Clinopyroxenite	
M5-367	Garnet Clinopyroxenite	
M5-103	Olivine websterite	
M7-58	Complex layer	
M7-701	Enstatite	
M7-702	Spinel and garnet websterite	} Sublayers of a complex layer.
M7-703	Garnet Clinopyroxenite	

DISCUSSION

Genetic models for peridotite massifs Two main models have been proposed to explain the composition of the lherzolite massifs, that we shall summarize before discussing our results:

a) One model relates the entire massif to huge crystallization process. The peridotites as well as the pyroxenite layers would result from the crystallization of the same magma (CONQUERE, 1973, 1977).

b) In an alternative model, the composition of the "common peridotites i.e. the lherzolite which makes the most important part of these massifs, would correspond to the residual part of an Upper Mantle affected by one or more partial melting processes. The pyroxenite layers are supposed to have crystallized from the melts produced during these events.

We supported this last model from the results we obtained in our previous study (LOUBET and ALLEGRE, 1978). This is also the

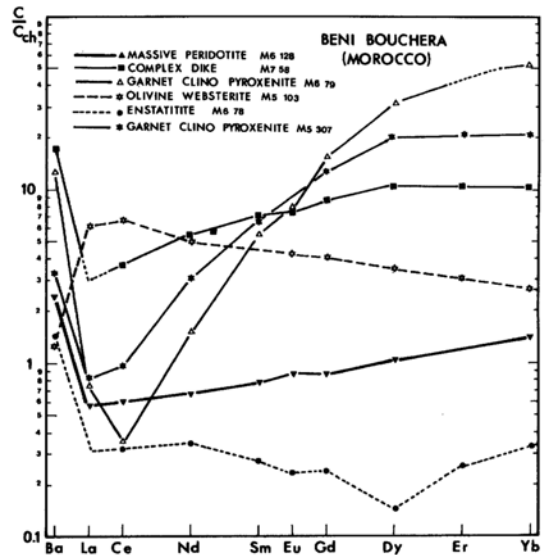


Fig. 2. REE and Ba contents of the rocks analyzed in the Beni-Bouchera massif, in the chondrite normalized representation.

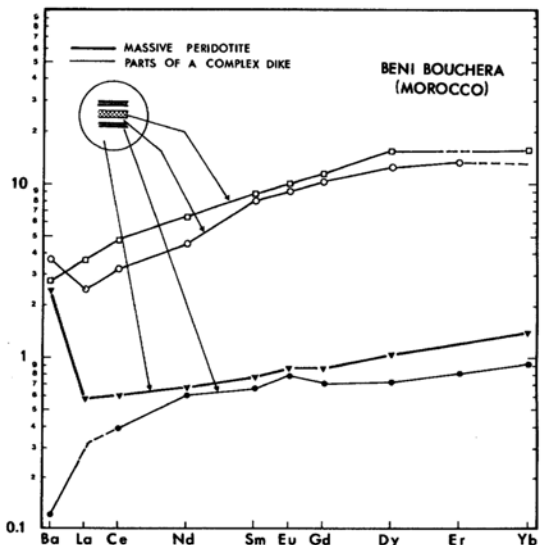


Fig. 3. REE and Ba contents in the chondrite normalized representation of the various sublayers constitutive of a complex layer.

model supported by most of the authors who studied these massifs and in the particular case of Beni-Bouchera massif, by KORNPROBST (1969) and DICKEY (1970). However, if in these studies the authors support an origin of the pyroxenite layers by a partial melting process,

Table 2. Ba and REE contents (ppm) of the analyzed samples

	Ba	La	Ce	Ne	Sm	Eu	Gd	Dy	Er	Yb	Lu
<i>Peridotites</i>											
M5-102	1.03	0.20	0.61	0.59	0.236	0.0985	0.386	0.537	0.342	0.337	
BB5	0.04	0.145	0.52	0.65	0.257	0.110	0.584	0.584	0.383	0.40	
M6-128	8.64	0.17	0.48	0.382	0.14	0.062	0.218	0.313		0.27	
<i>Pyroxenites</i>											
M6- 79	45.5	0.22	0.29	1.24	0.03	0.55	3.89	9.41		10.0	
M7- 58	63.3		2.90	3.20	1.31	0.534	2.23	3.20	1.89	1.93	
M5-367	12.1	0.24	0.75	1.78	1.26	0.641	3.35	6.09	3.78	3.99	
M5-103	4.5	1.85	5.23	3.20		0.30	1.05	1.05	0.54	0.50	0.052
M6- 78	5.2		0.52	0.20	0.050	0.016	0.061	0.43	0.45	0.60	0.12
<i>Complex layer</i>											
M7-701	1.11		0.30	0.35	0.12	0.056	0.178	0.21	0.148	0.16	0.03
M7-702	13.3	0.75	2.6	3.52	1.49	0.64	2.61	3.87	2.41		
M7-703	10.0	1.1	3.8	3.76	1.63	0.704	2.53	4.65		2.98	

they do not pay attention to the necessary residual nature of the peridotites which is a consequence of the model. Thereby, we will emphasize that peridotites and pyroxenites are requested to represent two products of the same phenomenon.

The use of trace elements will permit to quantify these models by means of some hypotheses concerning the conditions prevailing during the events. In Fig. 4 a theoretical model is presented which estimates the REE contents of various products resulting from partial melting in the upper mantle if it is originally of uniform peridotitic composition. The conditions of this model (original REE content of the Upper Mantle, mineralogical compositions...) are taken from our previous analysis of lherzolite massifs (LOUBET and ALLEGRE, 1978). Among the calculated models only those corresponding to 4% of partial melting have been represented in Fig. 4. Since the most noticeable conclusions drawn from it may be shown to be valid for different degrees of fusion, before discussing the results let us underline these conclusions.

The primary peridotitic Upper Mantle represented in Fig. 2 (curve Co) was supposed to have a flat chondrite normalized REE pattern. Two different partial melting processes giving rise to two different residual peridotite trends were modeled: 1) equilibrium partial melting (batch melting) (curve Re), 2) fractional partial melting (curve Rf). The melts Me and Mf produced by these processes are those in equilibrium with the respective residual peridotites Re and Rf. These melts are supposed to have evolved subsequently through a fractional crystallization process in which cumulates (respectively Ce and Cf) are formed that we have characterized by

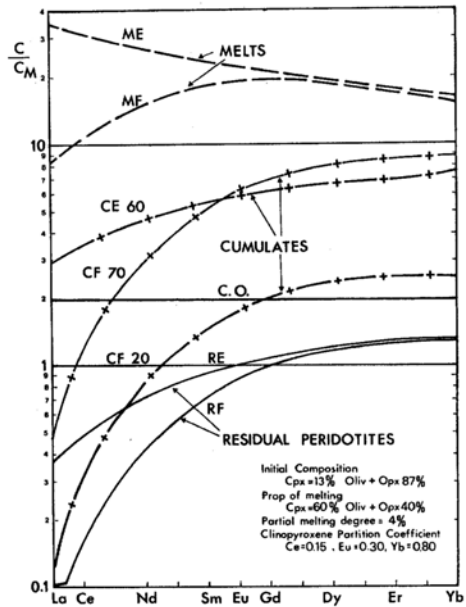


Fig. 4. Model of REE in a peridotitic Upper Mantle affected by a 4% partial melting process, The residual peridotites, the melts produced during the partial melting and the cumulates crystallized from these melts have been represented. See terminology in the text. Clinopyroxene partition coefficients are from TANAKA and NISHIZAWA (1975).

their clinopyroxene content (number in parentheses). Garnet is supposed to have been absent. As a consequence, the fractionation of the REE appears to be controlled mainly by clinopyroxene throughout the various events.

The most noticeable conclusions resulting from these models are:

– *The residual peridotites* produced by a low degree of partial melting present typical light REE depleted patterns. Large variations in light REE contents are expected (this depletion depending on the degree and the type of the partial melting process) while variations in their heavy REE contents must be much more restricted.

– *The melts* present REE patterns with variable light to heavy REE fractionation.

– *The cumulates* as well as the melts, can display REE patterns having a large variety of light REE - heavy REE fractionations. As a consequence of the major role of the clinopyroxene the cumulates crystallized from the same melts but with different mineralogical compositions should present parallel REE patterns.

These patterns should also be parallel to the one of the residual peridotite in equilibrium with the primary melt.

The products of the partial melting of a peridotitic mantle may be easily differentiated by REE patterns from cumulates of various mineralogical compositions supposed to have crystallized from the same magma according to the first model (CONQUERE, 1973, 1977). In this case, we should actually expect (all the other conditions being equivalent to those assumed in the model of Fig. 4) parallel REE

patterns, whatever rock type (pyroxenites and peridotites) is considered.

Analysis of the results

The common Beni-Bouchera peridotites present the same REE characteristics as common lherzolites from similar massifs of other areas, i.e. a large depletion of light REE relative to heavy REE, and a normalized heavy REE content between 1.4 and 2.2. Furthermore, important variations in light REE contents and correlatively a rather narrow range of heavy REE contents may be observed. These are just the characteristics we can expect from the model depicted in Fig. 4 (LOUBET *et al.*, 1975). Additional trace element data, and in particular Ni contents have given us further support to this interpretation (LOUBET, 1976; LOUBET and ALLEGRE, 1978).

The pyroxenite layers from Beni-Bouchera present highly variable REE patterns with variable fractionation of light relative to heavy REE (Figs. 2, 3). The olivine websterite M5-103 is enriched in light REE while other pyroxenite layers are significantly depleted with a variable depletion from one rock to another. The complex layer M-78 presents a REE pattern parallel to those of the common lherzolites, whereas the garnet clinopyroxenite layers are much more depleted in light REE. Finally, the enstatitic

Table 3. Major and transition elements contents (Analyses H. BOUGAULT)

	BB5	M5-102	M5-367	M6-79	M7-58
<i>Major Elements</i>					
SiO ₂	41.82	42.73	43.10	44.67	44.29
Al ₂ O ₃	3.50	3.29	14.76	112.42	10.61
Fe ₂ O ₃	9.06	9.19	17.35	13.96	10.65
MgO	37.99	38.90	11.20	13.87	17.50
MnO					0.19
CaO	3.02	3.00	10.66	11.56	11.85
Na ₂ O				1.24	0.96
K ₂ O	0.014	0.015	0.02	0.02	0.02
TiO ₂	0.14	0.14	1.01	0.50	0.55
P ₂ O ₅	0.04	0.02	0.05	0.04	0.037
P for 110°	0.20	0.09		0.11	0.20
P for 1050°	3.87	1.68		0.84	2.03
<i>Transition Elements</i>					
Ti	840	840	6060	3000	3300
V	42		381		305
Cr	1340		600		1120
Mn					1470
Fe					74490
Co	103		90		105
Ni	1940		1550		1480
Cu	41		7		506
Zn	85		129		68

layer M7-58 has particularly low REE contents. Another noticeable observation is that the heavy REE content of the pyroxenite layers appears to increase with the modal proportion of clinopyroxene plus garnet in the rock.

Various sublayers constituting the layer M7-58 have also been analyzed. They display parallel REE patterns and their absolute REE contents increase progressively with the content of clinopyroxene plus garnet (Fig. 3).

Some transition elements are interesting to consider along with REE, because they can help decide the cumulate or melt nature of these rocks. As we have previously shown (LOUBET and ALLEGRE, 1978), it is possible to get a good guess for the content of some of these elements (precisely those which enter preferentially the solid phase) in the first percents of the cumulate which one assumes to have crystallized from melts in equilibrium with the common peridotite. Results of such an estimation for Ni are given in Table 4. The observed contents are found to be higher than the calculated as we just mentioned. This supports a cumulative origin for the pyroxenite layers. Such high Ni contents may be explained by an increase in the Ni partition coefficient at the level where these layers crystallized, for example as a consequence of a variation in the composition of the melt (HART and DAVIS, 1978) while differentiation proceeds.

If we refer to the model represented in Fig. 4, results on the pyroxenite layers are also in agreement with such a cumulative origin. The large variety of light REE - heavy REE fractionations of these pyroxenite layers favors an origin of these layers from melts by partial melting of the peridotitic mantle.

As noted above, the parallelism between the REE patterns of the sublayers constituting the complex layer M7-58 is the feature we can expect for cumulates of variable mineralogical compositions crystallized from the same melt, and for which clinopyroxene separation played the major role in the REE fractionation. The parallelism between the REE patterns in this complex layer and in the common peridotites can be explained either by an equilibrium of the melt at the origin of this layer with the common peridotite (local partial melting or late equilibrium of a foreign melt), or an origin of this melt in a part of the upper mantle in which the common peridotites are also of residual nature.

Table 4. Estimation of the Ni content that should be observed in the first percents of cumulate crystallized from melts in equilibrium with the common peridotites, and comparison with the Ni content of some analyzed pyroxenite-layers. For this estimation the Ni contents of the various phases constitutive of the cumulates are taken equivalent to the corresponding phases in peridotites.

Parameters of the calculation:

Ni content of the common peridotites = 22ppm.

Mineralogical composition of the common peridotites = Ol: 60%, Opx 20%, Cpx 20%. Ratios of Ni partition coefficients in Cpx, Opx and Ol phases.

$$K_{Cpx}/K_{Ol} = 1/3 \quad K_{Opx}/K_{Ol} = 1/2$$

		Ni estimated	Ni measured
M5-367	(Cpx 100%)	1000	1550
M7-58	(Cpx 40%, Opx 60%)	1200	1480

A possible late partial melting event

If in general a good consistency is observed with the model depicted in Fig. 4, however, as in the other massifs we studied, some discrepancies may also be noticed. So is the very low light REE content of the garnet clinopyroxenite layer M5-367. In particular the Ce content of this rock is lower than the common peridotites. As a consequence of the subsolidus reactions, the present clinopyroxene content of this rock must be lower than its primary contents. Then we should expect that such a clinopyroxene rich rock (observed clinopyroxene content 60-70%) present a light REE content much higher than in residual peridotites from the mantle (according to the model developed in Fig. 4).

Three kinds of explanations can account for these low light REE contents:

a) A change in the clinopyroxene REE partition coefficient at the time when these layers crystallized (due to a change in the composition of the melt).

b) An origin of the parent melt by partial melting of a mantle very depleted in light REE.

c) This light REE depletion might be the result of a selective *late partial melting event* which affected preferentially the most differentiated layers, i.e. the garnet clinopyroxenite layers.

From several arguments, we supported this last explanation in our previous studies (LOUBET *et al.*, 1975; LOUBET, 1976; LOUBET and ALLEGRE, 1978). These arguments look still

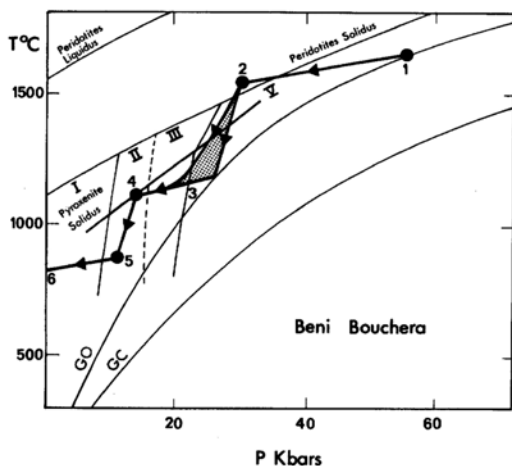


Fig. 5a

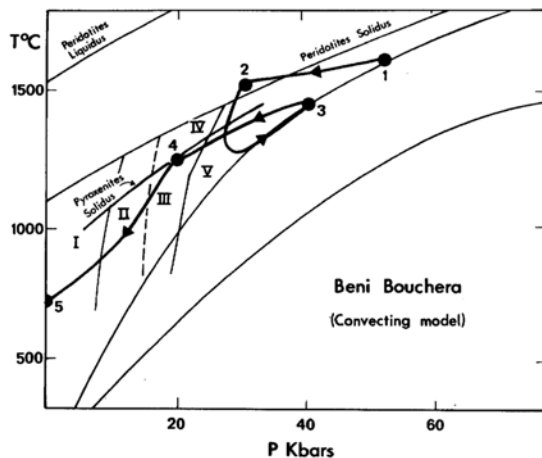


Fig. 5b

Fig. 5. Evolution model for the Beni-Bouchera massif from its situation at depth to the surface represented in a (P, T) diagram. The peridotite equilibrium fields are from GREEN and RINGWOOD (1970) as well as the oceanic (GO) and the continental (GC) geotherms.

- I Plagioclase peridotite facies
- II Spinel peridotite facies - subfacies Seiland
- III Spinel peridotite facies - subfacies Ariegite
- IV Two aluminous pyroxene peridotite facies
- V Garnet peridotite facies.

The lherzolite solidus and liquidus are indicated. The solidus of a complex pyroxenite layer, the complex layer M7-58, (from KORNPROBST, 1969) has also been plotted as well as the hypothetical solidus of a garnet pyroxenite layer (PG).

The heavy line retraces the evolution model of the (P, T) stability field of the massif from the depth to the surface:

- 1 - Situation of the massif at depth in mantle equilibrium conditions.
- 2 - Partial melting of the peridotitic body in the garnet (2) peridotite facies.
- 2 to 3 Fractional crystallization of the melts, subsequent formation of the pyroxenite layers and equilibration in the ariegite facies.
- 4 - As a consequence of a second sudden uprising of the massif, the pressure decreases rapidly and partial melting of the most differentiated pyroxenite layers.
- 5 - Equilibrium of the massif in the spinel peridotite facies.
- 6 - Uprising to the surface.

In Fig. 5b a similar scheme has been drawn except it involved an overturn into the mantle initiated by the convective processes.

valid in the case of this massif. Let us summarize them:

— The discrepancies concern specifically the garnet clinopyroxenite layers, i.e. the most differentiated ones. This is what we should effectively expect in the case of a late selective partial melting event.

— Some massifs present clearly the evidence of such a late partial melting event in the form of dikes crosscutting the peridotite-pyroxenite structure (Lherz and Lanzo massifs). Such dikes have not been found at Beni-Bouchera, but might be conceivably observable only at

some definite levels.

— Analyses of Sr isotopic composition performed on these rocks might also be interpreted by a late partial melting event (M. POLVE and C. J. ALLEGRE, unpublished data).

CONCLUSIONS

The final scheme of the evolution of Beni-Bouchera peridotites looks similar to what we deduced from studies on other areas.

We interpret the common lherzolites which constitute the most important part of these

massifs as the residues left by partial melting of the upper mantle. These likely multiple events of partial melting are of low degree (2 to 5%) and affected an original peridotitic upper mantle of rather homogeneous global composition. The pyroxenite layers represent cumulates which crystallized from the melts produced during this (these) event(s). We also conclude the occurrence of a second partial melting event of weaker intensity which later affected the massif on a selective way. In this massif the most differentiated layers, i.e. mainly the garnet pyroxenite layers, were affected by this event.

The evolution of this body from its situation at depth to the surface can be drawn in a (P, T) diagram in the way depicted in Fig. 5. During the uprising process the conditions of equilibrium are progressively modified. When the equilibrium temperature and pressure in the massif exceed those of the solidus, then partial melting of these rocks takes place. Two stages of partial melting have been represented; one affecting the entire peridotitic massif (points 2 and 3), and a later one affecting only the most differentiated layers (point 6).

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