

by comparison with the limited temperature range at a single kimberlite pipe of many deformed peridotites (group V of Gurney and Harte 1980, Table 1).

As partly shown in figure 1 the Mg/(Mg + Fe) mineral compositions of the coarse and deformed peridotites overlap but with the olivines and pyroxenes tending to have higher Mg/(Mg + Fe) in coarse nodules. Similar relations are seen in bulk rock analyses of the two groups. Another distinction in bulk rock chemistry between the coarse and deformed groups is a tendency for the deformed peridotites to show higher TiO2 contents. These features correspond to those seen in nodules from other kimberlite pipes (e.g. Gurney and Harte 1980). Derivation of the deformed rocks from originally coarse rocks is indicated texturally, and the rare presence of spinel exsolution lamellae in some orthopyroxene porphyroclasts is particularly interesting in that it suggests derivation from relatively low-temperature coarse rocks; perhaps in a process of the type suggested by Gurney and Harte (1980). However, the coarse protoliths for the deformed nodules do not appear to be the rocks represented by the common coarse nodules. This is indicated by the modal differences of the two groups of nodules, since the abundance of garnet and clinopyroxene porphyroclasts in the deformed'rocks makes it unlikely that the modal differences are solely a product of metasomatism.

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CORUNDUM-BEARING GARNET PYROXENITES AT BENI-BOUSERA (MOROCCO): AN H9 EXCEPTIONNALLY AL-RICH CLINOPYROXENE FROM "GROSPYDITES" ASSOCIATED WITH **ULTRAMAFIC ROCKS.**

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First described by Milliard (1950) the ultramafic Beni-Bousera body (northern Morocco) exhibits spinel-lherzolites and harzburgites associated with spinel and/or garnet pyroxenite layers. The main assemblages belong to the "ariegite subfacies" (O'Hara, 1967) and have been ultimately equilibrated under high pressure granulite facies conditions (10-12 Kbar ; 900°C) together with the surrounding paraderived country rocks, before their tectonic uplift to their present geological environment (Kornprobst, 1969). The various pyroxenite layers have been interpreted as the crystallization products of a melt extracted from the surrounding peridotites during an adiabatic diapiric rise of a fragment of the upper mantle. This interpretation is supported by experimental (Kornprobst, 1970) and geochemical (Javoy, 1970 ; Loubet and Allegre, 1979) data.

The primary crystalls precipitated from the melt most generally recrystallized in the solid state but could be recognized and their compositions approximately recalculated; they appear to be mainly Mg-rich clinopyroxenes involving a large range of Mg-Tschermak solid solution and up to 10% A1203 contents. A new primary assemblage has been recently discovered, characterized by the presence of corundum associated with Ca-rich garnet and Ca-Tschermak- and jadeite-rich clinopyroxene (A1203 up to 20%).

I/ THE PRIMARY ASSOCIATION : A CORUNDUM BEARING "GROSPYDITE"

The corundum-bearing rocks have not been found in place and the structural relationships with the peridotites are unknown. They are layered and exhibit sharp compositional variations across a few cm. The



- Fig.1: The "grospydites" from the Beni Bou-sera body : solid symbols ; stars = bulk rock compositions ; squares = garnets ; triangles = clinopyroxenes.
 - 1A- Molecules % : comparison with the grospydites from Yakutia (Sobolev et al., 1965 ; 1968); same symbols as above, open.
 - 1B- Weight % : comparison with Boyd's ex-perimental results (1970) ; same symbols as above, open.

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corundum is visible on hand specimens as small idiomorphic rubies (a few mm long) more or less parallel to the layering. The primary pink garnet is relatively scarce whereas clinopyroxene, as large (1 cm or more) xenomorphic crystals, is the main phase in the rocks. Representative compositions of the primary minerals are given in the Table. More data are plotted in fig. 1.

TABLE

	bulk- rock	срх	срх	gt	со
Si02	41.70	45.87	45.75	41.72	0.02
TiO ₂	0.35	0.12	0.24	0.05	0.0
A1203	22.40	19.61	16.78	23.73	99.05
Cr203	n d	0.0	0.04	0.0	0.21
FeÕ	4.50	2.44	3.11	8.91	0.38
MnO	0.05	0.05	0.0	0.09	0.0
MgO	10.30	9.28	10.11	16.70	0.09
NiO	n d	0.0	0.0	0.0	0.10
CaO	18.00	20.42	21.42	8.30	0.0
Na ₂ 0	1.60	2.31	1.92	0.03	0.0
K ₂ Õ	0.25	0.0	0.0	0.0	0.0
н ₂ 0+	1.02				
total	100.17	100.11	99.38	99.52	99.92
	Analyses of minerals by CAMEBAX probe at				
Museum d'Histoire Naturelle de Paris					

High Ca-Tschermak and jadeite contents as found in the primary clinopyroxene, and grossular content in the associated pyrope-rich garnet have never been recorded from "eclogites" (ariegites and griquaites) related to the ultramafic bodies, but are known from corundum-eclogites and grospydites, Ca-Al-rich xenoliths associated with kimberlites in South-Africa (Williams, 1932; 0'Hara, 1966) and Yakutia (Bobrievich et al., 1960). The original grospydites contain kyanite but corundum-bearing rocks have been also described. On the other hand they have a clinopyroxene richer in jadeite and a garnet more calcic (Sobolev et al., 1968) than observed in the rocks at Beni Bousera (fig. la).

II/ THE SECONDARY ASSEMBLAGES : CORUNDUM + CLINOPYROXENE UNSTABILITY.

The primary association became unstable during the rock history. Exsolution features in the clinopyroxene (garnet, corundum, spinel, sapphirine and plagdoclase lamellae) as well as coronitisations around the corundum crystals underline this unstability. Two main types of coronites have been observed (fig.2) :



Fig. 2: Coronitisation textures around corundum crystals.
2A- Plagioclase-bearing coronite;
2B- Sapphirine-bearing coronite.

a- The plagioclase-bearing coronites : three envelopes appear around the corundum ; an inner spinel rim is separated from the outer garnet rim by



Fig. 3: The grospydite subfacies and the reaction : gt+pl+sp → cpx+co. 3A- Al- and Ca-rich garnet-granulites in

- 3A- Al- and Ca-rich garnet-granulites in the ariegite subfacies (cpx+sp+gt+pl). The cpx-co tie line pierces the plane at-pl-sp in z.
- 3B- The grospydite subfacies : sp-grospydites (cpx+sp+gt+co) and ky-grospydites (cpx+gt+co+ky).
- The dotted surfaces emphasize the griquai-
- tes (cpx+sp+gt) volume.

a thin plagioclase rim. It can be interpreted as the result of a reaction : CPX + COP = -CT + PI + SP (1)

 $CPX + COR \longrightarrow GT + PL + SP$ (1) which can take place on the Ca-Al-rich side of the griquaite plane (fig. 3) at increasing temperature and/or decreasing pressure (Kushiro, 1969 ; Royd, 1970 ; Thompson, 1979).

b- The sapphirine-bearing coronites : They differ from the former by showing a sapphirine rim instead of the plagioclase zone. This type is not yet fully understood.

'II/ CRYSTALLIZATION CONDITIONS OF THE CORUNDUM-BEARING GARNET PYROXENITES AT BENI BOUSERA ("GROSPYDITES" L.S.).

Sobolev et al. (1966) considered that pressures between 20 and 30 Khar account for the grospydite assemblages and associated kyanite and/or corundum eclogites. Boyd (1970) crystallized a 3 phases association (cpx + gt + cor) at 30 Khar and 1200 °C, from a glass slightly richer in Ca than the "grospydites" described here (fig. 1); a synthetic garnet significantly richer in Ca than the natural one suggests that the experimental temperature was lower and/or pressure higher than the condition experienced by the natural samples. Kushiro (1969) demonstrated that plagioclase disappears from Na- and Ca-rich compositions of the system diopside-anorthite-albite at pressures above 28 Khar at 1150 °C. Temperatures of equilibration of the clinopyroxene + garnet pairs can be estimated (Ellis and Green, 1979) : the primary association would have crystallized at about 1325 °C (at 20 Kbar) or 1370 °C (at 30 Kbar).

The crystallization of sapphirine from cor + sp + gt assemblages has been studied in a Fe- and Ca-free system involving water (Ackermand et al., 1975). At temperatures mentionned above the primary association would have crystallized out of the stability field of sapphirine, under pressures as high as 30 Kbar, i.e. in the garnet-lherzolite field (0'Hara et al., 1971): it is time to recall that pressures between 27 and 30 Kbar have been advocated to account for the possible partial melting event in the ultramafic body (Kornprobst, 1970).

(Kornprobst, 1970). Even if the pressure of equilibration of the primary association cannot be accurately determined, it is possible to consider that reaction (1) could play an important role in the mineral facies of the mafic rocks at mantle depth : as clinopyroxene, garnet and spinel are costable on the low pressure side of the equilibrium, this reaction may occur at pressure greater than required for the crystallization of the ariegite association from the reaction :

 $OPX + PL + SP \longrightarrow CPX + GT.$ (2) Then, as already suggested by Sobolev et al. (1966), a grospydite subfacies must be emphasized (fig. 3), characterized by the breakdown of plagioclase in Caand Al-rich compositions. Because of the lack of reliable experimental data it is not yet possible to define accurately the limits of this subfacies.

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H10 SULFIDE MINERALOGY AND CHEMISTRY IN SOME FRENCH SPINEL-LHERZOLITE XENOLITHS

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Sulfides are the only opaque phases present as traces (0,01 to 0,06 %) in the unaltered spinel-lherzolite xenoliths trapped by the alkali-basalts from the Massif Central and Languedoc volcanic suites (120 samples from 23 localities). The sulfides occur mainly as inclusions (10 to 100 μ) in the silicates, less frequently as relatively abundant interstitial grains.

Independant of locality, texture (coarse-grained pokilitic, equant or tabular, porphyroclastic and granuloblastic) and equilibrium temperatures of the parent silicates (900° to 1200°C), the inclusions are composed of the same primary phases : Ni-rich pyrrhotites, pentlandite (Ni/Fe at. rat.~1,3) with small amounts of chalcopyrite. Pyrrhotites crystallize in two optically distinct phases, both with the same range of sulphur/metal atomic ratio (MgS10 to M/S8) : - "grey pyrrhotite" (Po_{ss}]), as mono - or polyphase inclusions, showing the highest nickel con-

- "grey pyrhotite" (Po_{SS}) , as mono - or polyphase inclusions, showing the highest nickel contents ever found in natural pyrhotites (20 to 27 weight %), with an average composition (18 inclusions) of Fe_{36,4} Ni_{23,7} Co_{0,3} Cu_{0,1} S_{39,1} wt. %;

- "pink pyrhotite" ($Po_{ss}2$), which shows more variable Ni-contents (7 to 19 wt. %) but is always Ni-poorer than the coexisting $Po_{ss}1$. The "pink pyrhotite" is always directly associated to the "grey" type, most frequently intimately intergrown, leading to bulk compositions (defocused beam microprobe analyses) which spread in the range (23 inclusions) : Fe : 37-47; Ni : 13-24; Co : 0,1-0,5; S : 38-40 wt. %.

The modal proportions (200 inclusions) show an unimodal distribution between : $Po_{ss}(1+2)$: 70-100 %; Pn : 0-30 %; Cp : 0-20 %, giving an average mode : Po_{ss} : 82 %; Pn : 12 %; Cp : 6 %.

Phase analysis were done for 45 inclusions, giving bulk compositions with a range : Fe : 33-47; Ni : 13-29; Co : 0, 1-0, 5; Cu : tr.-7; S : 36-39, 5 wt. \mathbb{Z} and resulting in an average bulk pyrthotite composition (MgS₁₀) : Fe_{37,7} Ni_{21,0} Co_{0,3} Cu_{1,6} S_{38,3} wt. \mathbb{Z} .

Experimental phase diagrams in the Fe-Ni-Cu-S system, indicate that such an average composition, as well as the compositions of most individual inclusions, totally crystallized as monosulfide solid solutions (Mss) at 1000°C. The bulk chemical differences observed among the inclusions could be explained by some local differentiations, during deformations, at temperatures between 1000° and 1100°C, where the Mss coexist with more or less Ni and Cu enriched liquids. Present parageneses result from a suite of reactions in the solid state continuing down temperatures between 250° and 300°C, well below those which control the last equili-

Where sulfides are predominant as interstitial grains, their mineralogy and chemistry differ markedly from those of the inclusions, even if both coexist in the same rock sample. In the type suite selected here (Montferrier, Herault), interstitial grains are composed of pentlandite (Ni/Fe \sim 1) associated to a Ni-poor (≤ 0.5 %) pyrrhotite (Fe7Sg) and minor amounts of chalcopyrite.

Although broadly different from one grain to the other, the mean modal proportions measured in each individual sample (17 inclusions) remain in a relatively restricted unimodal field. Thus, the average mode can be determined to : Po : 47 %; Pn : 48 %; Cp : 5 %, with a corresponding bulk chemical composition : Fe45,3 Ni16,1 Co0,4 Cu1,7 S36,0. These characteristics are believed to result essentially from an early desulphurization of a primary liquid akin to the average composition of the inclusions. This event could have occured during the main episode of deformation and re-crystallization of the host rocks, at temperatures between at least 1200° and 1000°C.

The relative sulphur decrease of the pristine interstitial sulfide phase and its differenciation in an open system, may explain both the great modal variation on a small scale and the final crystallization of Po+Pn+(Cp) instead of $Po_{SS}+(Pn)+(Cp)$ at the same low temperature (250°-300°C). It should be noted that both the interstitial and enclosed assemblages are quite different from the sulfide paragenesis due to secondary thermal mobilizations directly related to the basalt eruption.