

## OCCURRENCE AND PETROLOGICAL SIGNIFICANCE OF LOVERINGITE IN THE WESTERN LAOUNI LAYERED COMPLEX, SOUTHERN HOGGAR, ALGERIA

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### ABSTRACT

*Loveringite* (Ca, REE) (Fe, Ti, Cr)<sub>21</sub>O<sub>38</sub> is an accessory but not a rare mineral in layered complexes. It has been identified in the lower banded zone of the Western Laouni intrusive complex, southern Hoggar, Algeria. It occurs mainly in two distinct petrographic and geochemical settings, in olivine - chromite orthocumulates and in anorthosite adcumulates. In the lowermost orthocumulates, *loveringite* is closely associated with chrome spinel in the intercumulus spaces, where it coexists with Ti-rich pargasite, (Na, K)-phlogopite, magnesian ilmenite, rutile and magnesian pseudobrookite. It is richer in Ti and poorer in REE than previously known examples. In the anorthosite adcumulates, at the top of the lower banded zone, the *loveringite* crystallized away from the chrome spinel; it coexists with zirconolite CaZrTi<sub>2</sub>O<sub>7</sub>, zircon, and a minor amount of ilmenite and rutile. As a result, it is strongly depleted in Ti and enriched in Zr and the REE. It may be fully enclosed in the cumulus plagioclase and is free of late-magmatic minerals. Its distribution and compositional variations from the base of the lower banded zone to the top are accounted for by percolation of strongly evolved liquids expelled from the pile of cumulates by filter pressing. After the accumulation of the Ti-rich oxides in the intercumulus spaces of the lowermost orthocumulates, these liquids became depleted in Ti but enriched in Zr and the REE. They were arrested during upward migration by the anorthosite adcumulates that formed a stagnant layer in the magma chamber; also, they infiltrated along grain boundaries of the plagioclase as the latter was still undergoing adcumulus growth. The two processes are likely responsible for the inclusions of *loveringite* in plagioclase.

**Keywords:** *loveringite*, Western Laouni, basic layered complex, orthocumulates, anorthosites, infiltration metasomatism, Hoggar, Algeria.

### SOMMAIRE

La *loveringite* (Ca, REE) (Fe, Ti, Cr)<sub>21</sub>O<sub>38</sub> est un minéral accessoire mais non rare dans les complexes basiques stratifiés. Elle a été identifiée dans la zone inférieure litée du complexe intrusif de Laouni-ouest, Hoggar méridional, Algérie. Elle est principalement présente dans deux con-

textes pétrologiques et géochimiques différents, les orthocumulates à olivine et chromite et les adcumulates d'anorthosites. Dans les orthocumulates inférieurs, la *loveringite* est étroitement associée au spinelle chromifère dans les espaces intercumulus, coexistant avec pargasite titanifère, phlogopite sodico-potassique, ilménite magnésienne, rutile et pseudobrookite magnésienne. Elle est plus riche en Ti et plus pauvre en Zr et en terres rares que dans les compositions publiées. Dans les adcumulates d'anorthosite au sommet de la zone inférieure litée, la *loveringite* peut cristalliser loin du spinelle chromifère et coexiste avec zirconolite CaZrTi<sub>2</sub>O<sub>7</sub>, zircon et de petites quantités d'ilménite et rutile. En conséquence, elle est fortement appauvrie en Ti et enrichie en Zr et terres rares. Certains grains de *loveringite* sont totalement inclus dans le plagioclase cumulus et dissociés des minéraux magmatiques tardifs. La distribution et les variations de composition de la *loveringite* de la base au sommet de la zone inférieure litée sont expliquées par la percolation de liquides fortement évolués, expulsés lors de la compaction de l'empilement des cumulates. Après l'accumulation d'oxydes riches en Ti dans les espaces intercumulus des orthocumulates inférieurs, ces liquides ont été appauvris en Ti mais enrichis en Zr et terres rares. Ils ont été arrêtés pendant leur migration vers le haut par les adcumulates d'anorthosites formant un lit stagnant dans la chambre magmatique et se sont infiltrés le long des limites de grain du plagioclase alors que celui-ci était encore en cours de croissance adcumulus. L'effet combiné de ces deux processus est probablement responsable des inclusions de *loveringite* dans le plagioclase.

**Mots-clés:** *loveringite*, Laouni-ouest, complexe intrusif basique stratiforme, anorthosites, infiltration, metasomatisme, Hoggar, Algérie.

### INTRODUCTION

*Loveringite* (Ca, REE) (Ti, Fe, Cr)<sub>21</sub>O<sub>38</sub> is the Ca end-member of the crichtonite group, of general formula AM<sub>21</sub>O<sub>38</sub>. It was first described as a mineral species by Gatehouse *et al.* (1978) and Campbell & Kelly (1978) from bronzitites and olivine - plagioclase orthocumulates of the Lower Layered Series in the Jimberlana igneous intrusive complex, Australia. Cameron (1978) reported a complex Ca - REE - Ti oxide in anorthosites and bronzite from the Criti-

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cal Zone of the eastern Bushveld Complex, the major and minor element chemistry of which is similar to that of loveringite. This mineral is closely associated with chrome spinel, ilmenite and rutile. Because of the absence of X-ray data, Cameron could not decide whether his oxide mineral is loveringite or armalcolite. Another locality in the Bushveld Complex was recently revisited by Johan & Watkinson (1986), who confirmed the presence of loveringite, but their identification relies exclusively on microprobe data.

In this paper, we describe the third occurrence of loveringite in an igneous layered complex. This mineral has been identified by X-ray diffraction and microprobe investigation in the Laouni layered complex, southern Hoggar, Algeria. It coexists either with Nb - Zr-rich rutile, Mg-rich pseudobrookite and magnesian ilmenite, or with zirconolite (Lorand & Cottin 1987a, b). Such a diversity of oxide minerals in basic rocks has only been described in the *KREEP* lunar basalts (Haggerty 1973). The textural relationships, compositional range and conditions of crys-

tallization of loveringite are discussed by reference to the percolation of intercumulus liquids that take place in magma chambers (Irvine 1980). As pointed out by Campbell & Kelly (1978) and Haggerty (1983), the members of the crichtonite group have the structural flexibility to accept all the large-radius incompatible elements (*e.g.*, Zr, Ti, *REE*, Th and Nb) that are concentrated in residual liquids or fluids of cumulates. Indeed, they are powerful petrogenetic indicators to trace the circulation of these liquids through the cumulus pile of layered basic complexes.

GEOLOGICAL SETTING

The Pan-African Laouni igneous complex (600 - 540 Ma), 250 km south of Tamanrasset, Algeria, crops out as four small intrusive massifs within granitic and metamorphic formations of the Polycyclic Central Hoggar area (Caby & Bertrand 1977, Cottin 1985). The samples studied come from the massif described as the "Western Laouni" by Donville

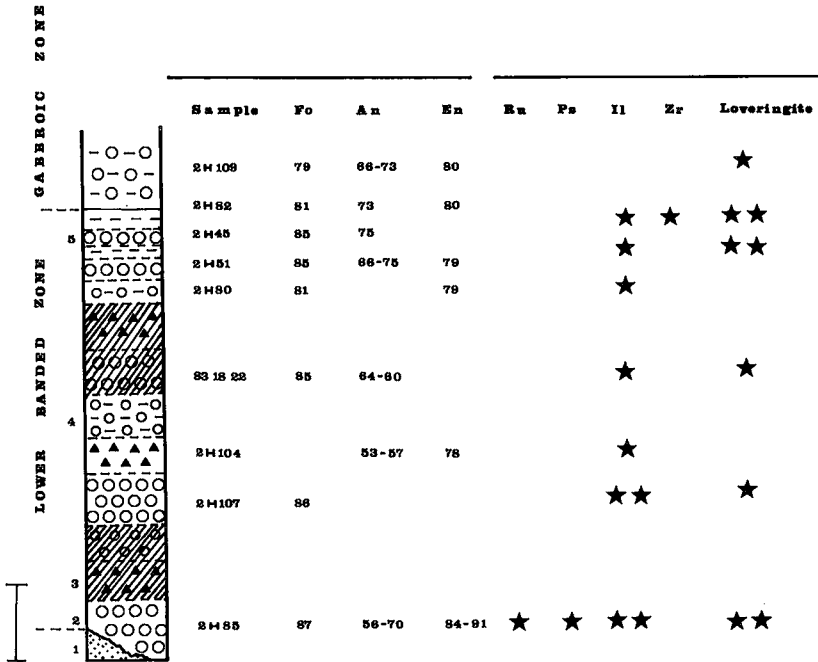


FIG. 1. Schematic lithology of the lower banded zone of the Western Laouni massif, showing the distribution of loveringite and associated opaque minerals (Ru rutile, Ps Mg-rich pseudobrookite, Il ilmenite, Zir zirconolite). The number of stars is proportional to the relative abundance of each mineral. Key to zones: 1 unutilized gabbros, 2 olivine - chromite cumulates, 3 bronzite orthocumulates, 4 plagioclase - olivine cumulates, and 5 anorthosites. The shaded areas correspond to intensely serpentinized zones. Fo, An, En are the forsterite, anorthite and enstatite contents of olivine, plagioclase and orthopyroxene, respectively. Scale bar 20 metres.

(1962). The southern part of this massif is a concentrically zoned body, about 20 km<sup>2</sup> in size, surrounded by uralitized gabbros. Apart from the considerable difference in size, the western Laouni body exhibits close similarities with the Jimberlana and Bushveld complexes in terms of both petrography and order of crystallization of the cumulus phases (Cottin & Lorand 1986).

In spite of local serpentinization, the lower part of the massif (the lower banded zone) displays layering well defined by the cyclic repetition of olivine - chromite cumulates, bronzite cumulates and plagioclase - olivine cumulates over a thickness of a few hundred metres (Fig. 1). The lower banded zone is overlain by massive olivine gabbro and troctolite free of layering; the transition between layered and massive rocks is marked by centimetre-sized anorthosite layers. Textural evidence shows that the order of crystallization of the cumulus minerals in the silicate melt parental to the lower banded zone was olivine and chrome spinel, then orthopyroxene and, finally, plagioclase and clinopyroxene. A mantle source for the magma is suggested by the olivine composition of the earliest cumulates (Cottin & Lorand 1986). Multiple injections of the same tholeiitic magma are considered to account for the limited decrease of the forsterite content in the lower banded zone (Cottin 1985). On the contrary, the order of crystallization of the main massive zone involves plagioclase as the earliest cumulus phase, whereas orthopyroxene follows later; this may reflect the flotation of plagioclase in dense liquids separated during the fractional crystallization of tholeiitic magmas, a point that is discussed below.

#### PETROGRAPHIC FEATURES OF THE SAMPLES INVESTIGATED

Fifteen samples from the lower banded zone and the massive zone have been investigated in reflected light. The number of polished thin sections studied for each sample ranged from 2 to 7 except for sample 2H85, which was studied using 12 polished thin sections in order to obtain a better estimate of the abundance of loveringite.

According to the descriptive classification of Irvine (1982), bronzite - and olivine - chromite cumulates range from meso- to orthocumulates. Olivine - chromite cumulates show more than 25% by volume of intercumulus material composed of orthopyroxene, clinopyroxene, plagioclase, titanian pargasite and phlogopite. The cumulus Cr-Al-spinel has extensively reacted with the intercumulus liquid and resembles spinel from the Jimberlana orthocumulates discussed by Roeder & Campbell (1985). Unlike the latter occurrence, however, spinel has entrapped numerous solid inclusions during the postcumulus growth, consisting of intercumulus minerals (orthopyroxene, albite, (Na,K)-phlogopite, pargasite, Fe-Ni-Cu sulfides, magnesian ilmenite, rutile, Mg-rich pseudobrookite) and typical late-stage minerals like apatite as well (Lorand & Cottin 1986).

The olivine - plagioclase cumulates are poikilitic adcumulates; their pore space, commonly less than 10% by volume, is filled with ortho- and clinopyroxene, pargasitic amphibole and biotite. The anorthosites show an adcumulus texture and contain less than 5% by volume of intercumulus orthopyroxene, clinopyroxene and biotite.

TABLE 1. X-RAY DIFFRACTION PATTERNS FOR LOVERINGITE COMPARED WITH OTHER CRICHTONITE-GROUP MINERALS

This study			Loveringite		Lindsleyite		Titanate 3094		
h k l	dmes	dcal.	f(*)	dmes	l	dmes	l	dmes	f(*)
0 2 4	3.392	3.390	s	3.384	89	3.37	30	3.37	m
2 0 5	3.054	3.046	w	3.037	89	3.04	40	3.03	s
3 0 0	3.006	2.998	m	2.984	33				
1 1 6	2.875	2.874	m	2.867	90	2.87	70	2.877	s
2 1 4	2.834	2.841	m	2.831	74	2.83	70	2.84	m
1 3 1	2.476	2.476	ms	2.465	76	2.47	30	2.426	
2 0 8	2.243	2.243	ms	2.238	46	2.24	40	2.243	ms
3 1 5	2.134	2.136	w	2.129	65	2.13	100	2.134	ms
1 3 10	1.593	1.593	m	1.589	97	1.59	100	1.591	s
5 2 0	1.438	1.440	m	1.433	100	1.44	100	1.441	v

(\*) visual estimates. The X-ray diffraction patterns of loveringite, lindsleyite and titanate 3094 are from Kelly et al. (1979), Haggerty et al. (1983) and Jones & Ekambaran (1985), respectively.

Data from this study are refined in the hexagonal system; hexagonal cell-parameters:  $a = 10.385 + 0.019$ ,  $c = 20.702 + 0.019$  (in Å).

## IDENTIFICATION OF LOVERINGITE

Loveringite occurs mainly in the layered cumulates from the lower banded zone, but it is very rare in massive olivine gabbro and troctolite (Fig. 1). It is encountered as grains less than  $70 \times 40 \mu\text{m}$  in size that show optical properties closely similar to those of ilmenite, namely a weak reflectance and a greyish white color in reflected light. However, no confusion exists when viewed under oil immersion at the highest magnifications ( $\times 500$ ,  $\times 1000$ ): ilmenite is readily distinguished by its pinkish to purplish pleochroism in plane-polarized light and by its strong anisotropism.

The nomenclature of the crichtonite group, of general formula  $AM_{21}O_{38}$ , is based on the large cation occupying the A site (Gatehouse *et al.* 1978,

Haggerty *et al.* 1983): landauite Na, loveringite Ca, senaite Pb, crichtonite Sr, davidite U + REE, mathiasite K, lindsleyite Ba. Thus full identification of any crichtonite-group mineral requires both X-ray-diffraction and electron-microprobe data.

One grain large enough to be removed from a polished thin section was analyzed using a Gandolfi camera (Philips PW 1050/25 diffractometer,  $\text{CuK}\alpha$  radiation, Ni filter, 96 hours exposure). The least-squares refinement of the powder data was performed by computer program LSQ82 (Hubbard *et al.* 1982); the results and the cell dimensions are given in Table 1. The *d*-values of the Laoui loveringite are similar to those of kimberlitic crichtonite (lindsleyite and titanate 3094) (Haggerty *et al.* 1983, Jones & Ekambaram 1985) and to those of the loveringite of Kelly *et al.* (1979).

TABLE 2. REPRESENTATIVE CHEMICAL COMPOSITIONS OF THE LAOUI LOVERINGITE

Samples	2H807 (*)	2H107 (*)	2H85	2H85	2H85	8318.22 (*)	8318.22	2H51	2H45 (**)
Weight %									
TiO <sub>2</sub>	72.22	70.44	70.79	68.00	64.96	61.74	61.35	66.25	61.69
ZrO <sub>2</sub>	0.14	0.14	0.51	1.18	3.22	7.90	7.31	2.84	7.35
Al <sub>2</sub> O <sub>3</sub>	0.88	0.74	0.75	0.97	1.58	1.84	1.71	1.55	1.21
Cr <sub>2</sub> O <sub>3</sub>	4.76	6.02	4.75	5.56	7.00	6.42	6.40	4.78	0.48
Fe <sub>2</sub> O <sub>3</sub>	15.81	15.37	15.09	16.96	15.47	17.67	19.40	20.34	23.58
MgO	1.77	1.91	2.57	2.11	1.65	1.44	1.48	0.43	0.49
MnO	0.37	0.63	0.73	0.46	0.30	0.22	n.d.	0.33	0.44
CaO	3.90	3.94	4.11	3.64	3.02	3.33	3.30	3.68	3.14
Na <sub>2</sub> O	n.d.	0.18	0.16	0.24	0.04	n.d.	0.04	0.01	0.03
K <sub>2</sub> O	n.d.	0.03	0.04	0.05	0.07	0.02	0.02	0.02	0.02
ZnO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
La <sub>2</sub> O <sub>3</sub>	n.d.	n.d.	0.07	0.08	0.23	0.17	0.09	0.22	0.18
Co <sub>2</sub> O <sub>3</sub>	n.d.	n.d.	0.17	0.14	0.49	0.26	0.14	0.30	0.33
Pr <sub>2</sub> O <sub>3</sub>	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Nd <sub>2</sub> O <sub>3</sub>	n.d.	n.d.	0.02	0.07	0.08	0.25	0.01	n.d.	0.09
Y <sub>2</sub> O <sub>3</sub>	n.d.	n.d.	0.01	0.10	0.18	0.04	0.03	0.05	0.20
UO <sub>2</sub>	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ThO <sub>2</sub>	n.d.	n.d.	n.d.	n.d.	0.14	n.d.	n.d.	0.05	0.06
Nb <sub>2</sub> O <sub>5</sub>	n.d.	n.d.	n.d.	n.d.	0.02	0.21	n.d.	0.02	0.09
V <sub>2</sub> O <sub>5</sub>	n.d.	n.d.	n.d.	n.d.	0.05	n.d.	0.37	n.d.	0.07
Total	99.85	99.43	99.77	99.29	98.30	101.51	101.68	100.87	99.70
Number of cations based on 38 oxygen atoms									
Ti	16.544	14.409	14.435	14.029	13.667	12.791	12.661	13.616	13.078
Zr	0.018	0.023	0.067	0.158	0.439	1.061	0.978	0.378	1.010
Al	0.280	0.237	0.240	0.314	0.455	0.597	0.553	0.499	0.402
Cr	1.015	1.295	1.018	1.206	1.548	1.398	1.388	1.033	0.107
Fe	3.208	3.146	3.079	3.446	3.257	3.663	4.006	4.183	5.055
Mg	0.711	0.774	1.039	0.863	0.688	0.591	0.605	0.175	0.206
Mn	0.085	0.145	0.168	0.107	0.071	0.051	-	0.076	0.105
Ca	1.127	1.148	1.194	1.070	0.905	0.983	0.970	1.078	0.948
Na	-	0.095	0.084	0.128	0.022	-	0.021	0.005	0.016
K	-	0.010	0.014	0.017	0.025	0.007	0.007	0.007	0.007
Zn	-	-	-	-	-	-	-	-	-
Ce	-	-	0.017	0.014	0.050	0.026	0.014	0.030	0.034
La	-	-	0.007	0.008	0.023	0.017	0.009	0.022	0.019
Nd	-	-	0.002	0.007	0.008	0.025	0.001	-	0.009
Pr	-	-	-	-	-	-	-	-	-
Y	-	-	0.001	0.015	0.027	0.006	0.004	0.007	0.030
U	-	-	-	-	-	-	-	-	-
Th	-	-	-	-	0.003	-	-	0.003	0.004
Nb	-	-	-	-	0.009	0.026	-	0.002	0.011
V	-	-	-	-	-	-	0.067	-	0.013
Total	21.087	21.282	21.365	21.381	21.206	21.245	21.286	21.117	21.055

Electron-microprobe data. (\*) inclusions of loveringite in Cr-spinel, (\*\*) inclusion of loveringite in plagioclase; other analyses: loveringite adjacent to chrome spinel; n.d.: below the detection limit of the electron microprobe. : All Fe as Fe<sup>3+</sup>

Loveringite has been analyzed with a fully automated CAMEBAX electron microprobe at the Muséum National d'Histoire naturelle de Paris. A preliminary scan by wavelength dispersion (WDS) led to the detection of Ti, Zr, Al, Cr, Fe, Mg, Mn, Ca, Th, U, Nb, Y and rare-earth elements. These elements have been determined by two separate procedures, using the WDS mode. The detailed analytical procedures are given by Lorand & Cottin (1987b). The microprobe data given in Table 2 show that Ca is invariably the dominant cation entering the *A* site. The value  $Ca/(Ca + U + REE)$ (atomic) is always much higher than 0.5, suggesting that the proportion of davidite is low in our samples; the proportion of the other end-members is negligible.

#### TEXTURAL RELATIONSHIPS

Loveringite occurs mainly in two distinct petrographic and chemical settings, the olivine – chromite orthocumulates and the anorthosite adcumulates

(Fig. 1). Loveringite has also been observed in one olivine gabbro (sample 2H109) but is lacking from the gabbroic zone above this sample (Fig. 1). An average of five grains of loveringite has been found per polished thin section; its textural relationships are a function of the host rock.

In the olivine – chromite orthocumulates, loveringite grains are up to 40  $\mu\text{m}$  in diameter. It is never included in olivine, pyroxenes or plagioclase, and belongs to the intercumulus paragenesis. Loveringite is invariably adjacent to spinel grains, disseminated in the intercumulus spaces, generally in the vicinity of amphibole or phlogopite. In the lowermost samples (2H85, 2H107; Fig. 1), loveringite coexists with magnesian ilmenite (up to 37 mole %  $\text{MgTiO}_3$ ), Nb–Zr-rich rutile, and Mg-rich pseudobrookite (Lorand & Cottin 1987a). The characteristic features of these samples is the heterogeneous distribution of the accessory Ti-rich oxides. Grains of spinel a few millimetres apart in the same polished section differ markedly in the nature of the associated oxide, which

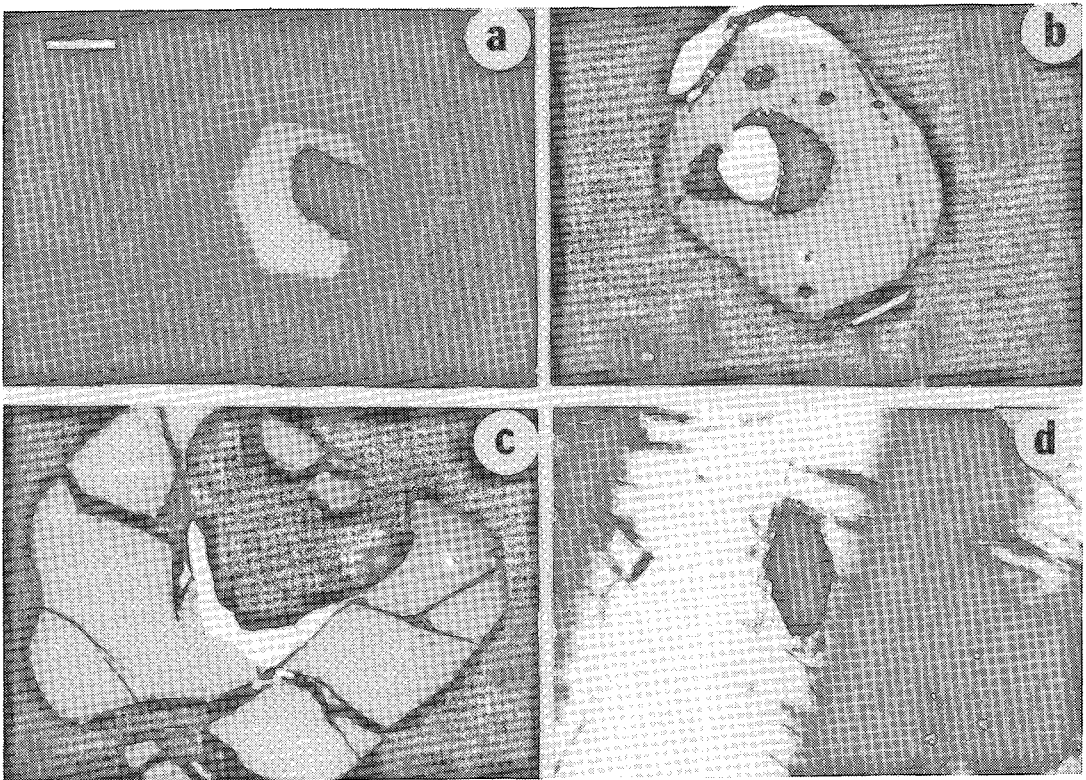


FIG. 2.a. Inclusion of euhedral loveringite (light grey) with phlogopite (dark) in chrome spinel (medium grey). Plane-polarized reflected light, oil immersion (sample 2H107). The scale bar is 30  $\mu\text{m}$ ; it applies to all photomicrographs. b. Round inclusion of loveringite (light grey) in chrome spinel (medium grey) with pargasite, phlogopite and orthopyroxene (dark). Plane-polarized reflected light, oil immersion (sample 83–18–22). c. Loveringite (light grey) adjacent to chrome spinel (medium grey). Plane-polarized reflected light, oil immersion (sample 2H85). d. Inclusion of loveringite (dark) in cumulus plagioclase (black and white) from anorthosite (sample 2H45). Crossed-polarized transmitted light.

may be ilmenite, ilmenite + rutile, rutile, loveringite, or Mg-rich pseudobrookite. Unlike ilmenite, rutile and Mg-rich pseudobrookite are neither found adjacent to loveringite nor present in loveringite-bearing spinel grains. Such a distribution suggests that the crystallization of Ti-rich oxides was controlled by local physicochemical parameters (Williams 1978, Cameron 1979).

Regardless of its textural sites, loveringite may be fully enclosed within chrome spinel. If predominant in the inclusion, then loveringite is polyhedral and displays smooth grain-boundaries and, locally, a thin rim of ilmenite (Fig. 2a). The inclusions in spinel may

be cavities as well, in which round grains of loveringite have been trapped together with orthopyroxene, pargasite, (Na,K)-phlogopite and, locally, Fe-Ni-Cu sulfides (Fig. 2b). The other grains of loveringite are adjacent to spinel and rimmed by pargasite or phlogopite (Fig. 2c).

The loveringite from the anorthosite adcumulates and from olivine gabbros differs from that in the olivine - chromite orthocumulates in both the nature of the assemblage of associated oxide minerals and its textural relationships. Mg-rich pseudobrookite is lacking, whereas the abundance of ilmenite and, especially, rutile, decreases considerably. On the

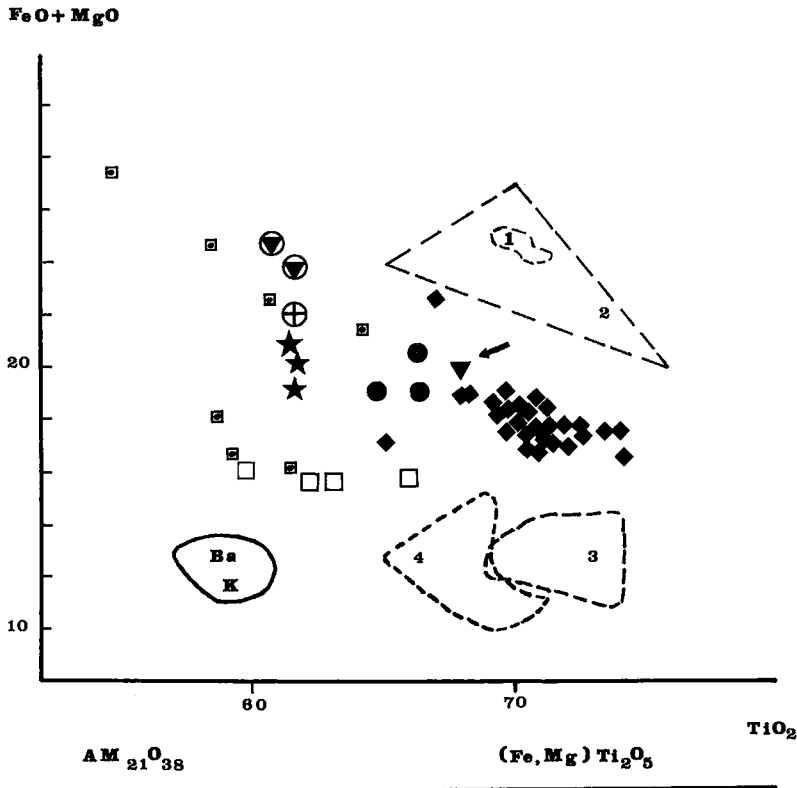


FIG. 3. Plot of FeO + MgO versus TiO<sub>2</sub> showing the composition of loveringite (wt. %). Filled symbols: this study, open squares: loveringite from the Bushveld Complex (Cameron 1978), squares with a dot: loveringite from the Jimberlana intrusive complex (Campbell & Kelly 1978). Diamond-shaped symbols: lowermost olivine - chromite cumulates (samples 2H85 and 2H107), stars: uppermost olivine - chromite orthocumulate sample (83-18-22), circle: sample 2H51, inverted triangle: sample 2H45 (the arrow indicates the X-rayed grain), cross: sample 2H109; the inclusions of loveringite in plagioclase are circled. The other data-points are from Haggerty (1983). (Fe, Mg)Ti<sub>2</sub>O<sub>5</sub>: armalcolite series; AM<sub>21</sub>O<sub>38</sub>: crichtonite series. Numbers 1 to 4 indicate the compositional fields of kimberlitic Cr-armalcolite, Zr-lunar armalcolite, kimberlitic Ca-Cr (Zr) (Nb) armalcolite and lunar Ca-Cr-Zr armalcolite, respectively. The (Ba, K) compositional field corresponds to kimberlitic crichtonite.

other hand, zirconolite and zircon coexist with loveringite in sample 2H45 (Lorand & Cottin 1987b) (Fig. 1). The change in the assemblage of oxide minerals indicates an overall decrease of Ti and an increase of Zr from the base to the top of the lower banded zone.

Loveringite from the plagioclase-rich adcumulates may be adjacent to Cr-spinel but is never included in that mineral. Moreover, some grains of loveringite are fully enclosed in cumulus plagioclase (Fig. 2d); they occur as discrete inclusions free of Cr-spinel and late-magmatic minerals. Loveringite, zirconolite, zircon and ilmenite occupy different textural sites in the host rocks and, except for ilmenite, are

never associated within a single grain. As for the olivine - chromite orthocumulates, it seems likely that the Ti-Zr-rich oxides crystallized as systems isolated from each other (Lorand & Cottin 1987b).

MINERAL CHEMISTRY

The composition of loveringite closely reflects the variation of Ti and Zr occurring in the assemblage of coexisting opaque minerals from the base to the top of the lower banded zone. As a general rule, Ti is negatively correlated with Zr (Fig. 5), a distinctive feature of loveringite (Campbell & Kelly 1978, Cameron 1978). The Cr-Fe correlation is not as well

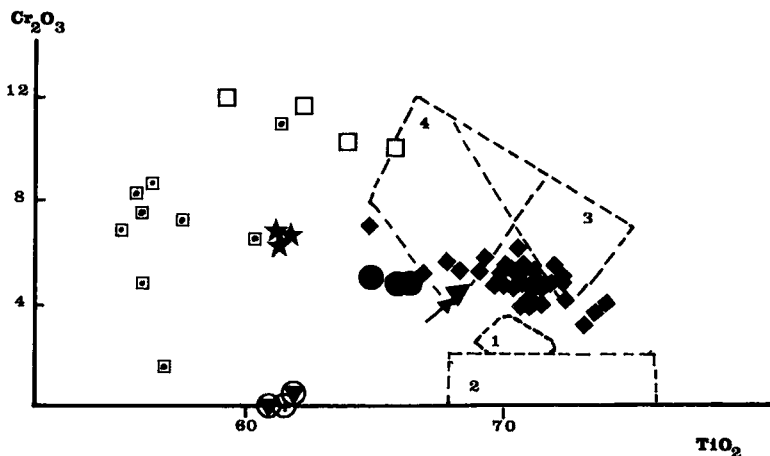


FIG. 4. Plot of Cr<sub>2</sub>O<sub>3</sub> versus TiO<sub>2</sub> showing the composition of loveringite (wt. %). Symbols as in Figure 3.

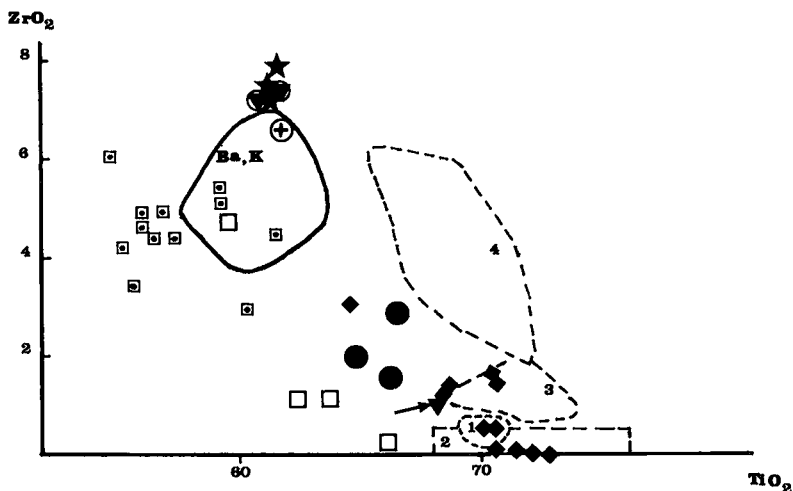


FIG. 5. Plot of ZrO<sub>2</sub> versus TiO<sub>2</sub> showing the composition of loveringite (wt. %). Symbols as in Figure 3.

marked as in the Jimberlana occurrence, suggesting that the  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratio, though not yet determined, could be variable. Assuming, however, that all Fe is present as  $\text{Fe}^{3+}$ , the sum of the cations in the Laouni loveringite is about 21, in agreement with the results of Campbell & Kelly (1978) and Cameron (1978) (Table 2). The other elements entering the loveringite are minor amounts of Al, Mg and Mn that show erratic grain-to-grain variations.

In agreement with the Ti-rich nature of the associated oxide minerals, loveringite from the lowermost olivine – chromite cumulates (samples 2H85, 2H107) has the highest Ti-content and the lowest Fe- and Zr- contents. Its Mg/Fe value is very low compared to that in the coexisting ilmenite and pseudobrookite (Lorand & Cottin 1987a), suggesting that the loveringite postdates these oxides and crystallized late during the solidification of the intercumulus liquid.

The compositional range of the Laouni loveringite overlaps that of armalcolite (Figs. 3,4,5). However, the occurrence of the latter mineral can be ruled out for four reasons. Firstly, unlike loveringite, the reflectance of armalcolite is lower than that of ilmenite (Lévy *et al.* 1972). Secondly, armalcolite displays remarkable Cr-Ti and Ca-Zr correlations that are not observed in loveringite (Haggerty 1983).

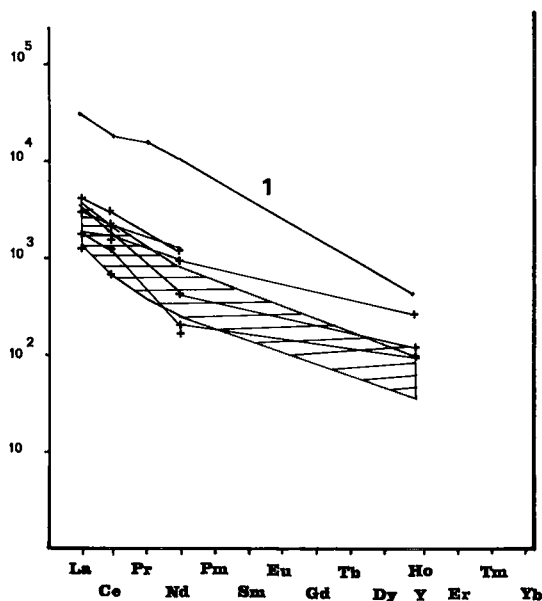


FIG. 6. REE distribution in loveringite normalized to C1 chondrite abundances (Nakamura 1974), with Y used in place of Ho as proposed by Jones & Ekambaram (1985). 1: loveringite from Jimberlana; crosses: this study. The lined area refers to kimberlitic crichtonite (Haggerty 1983, Haggerty *et al.* 1983).

Thirdly, the Ti content of the grain isolated for X-ray analysis plots well within the range attributed to armalcolite, but it is loveringite (Figs. 3,4,5). Fourthly, the distinction between armalcolite and loveringite relies on genetic considerations; the persistence of armalcolite implies that the host rocks have been quenched from 1000°C (El Goresy 1981), a temperature that seems unlikely for intrusive igneous cumulates. Therefore, the present data extend the compositional range of loveringite toward compositions richer in Ti than indicated by the published data.

Within a single sample of orthocumulate, the Ti/Zr value of loveringite is higher in grains included in chrome spinel than in grains outside the inclusions (Table 2). One sample (83-18-22) departs from this trend because the inclusions of loveringite in chrome spinel have the same Ti/Zr value as the discrete grains isolated in cumulus plagioclase from the anorthosite layers (Table 2). Both have the highest Zr content (up to 7.9 wt.%  $\text{ZrO}_2$ ; Table 2) yet found for the crichtonite group (whether loveringite or a kimberlitic crichtonite) (Fig. 5) and the lowest concentration of Ti. Figure 1 shows that the sample 83-18-22 is situated just beneath the anorthosite layers and thus, the composition of loveringite would be premonitory to the drop of the Ti/Zr ratio occurring in the assemblage of opaque minerals at this level in the lower banded zone. It is evident from the above observations that this ratio is not bulk-rock-controlled. Such is also the case for Cr; the inclusions of loveringite in cumulus plagioclase are nearly devoid of Cr, so that the entry of this element into loveringite would depend only on whether the loveringite is in close contact with Cr-spinel or not (Table 2).

Taken as a whole, the chemical composition of the Laouni loveringite differs from the Jimberlana and Bushveld compositions mainly by its low content of incompatible trace-elements (Table 2). Uranium, thorium and vanadium are often below the detection limit of the electron microprobe. The sum of the rare-earth elements is lower than at Jimberlana (Fig. 6); as for Zr, the REE content of loveringite increases from inclusions in chrome spinel to grains located outside in the lowermost orthocumulates and from the base to the top of the lower banded zone (Table 2).

The REE distribution of crichtonite-group minerals is not well established in the recent literature. According to Campbell & Kelly (1978) and Haggerty (1983), loveringite should have a U-shaped chondrite-normalized REE pattern, with enrichment in both LREE and HREE such as holmium, whereas Jones & Ekambaram (1985) published a negatively sloping chondrite-normalized pattern (Fig. 6). The latter authors argued that yttrium, which has an atomic radius closely similar to that of holmium, should be



a good indicator of the abundance of the heavy *REE*. When applied to our samples, this method provides a negatively sloping chondrite-normalized *REE* pattern for loveringite also, consistent with that proposed by Jones & Ekambara (1985) (Fig. 6). Though the *REE* have not been determined because of complex peak-overlaps (Roeder 1985), the analytical totals near 100 wt. % are considered to be evidence for the absence of *HREE* enrichment in the Laoui loveringite.

#### DISCUSSION

##### *Loveringite as an evidence for infiltration metasomatism*

Campbell & Kelly (1978), Cameron (1978) and Kelly *et al.* (1979) were in agreement in proposing that loveringite is a late-magmatic mineral that crystallizes from isolated volumes of intercumulus liquid, provided that the latter is Cr-saturated. At Jimberlana, the major evidence for the above model is the concentration of loveringite in orthocumulates rather than in adcumulates (Kelly *et al.* 1979). This is also valid for our orthocumulate samples. In addition to textural and chemical criteria, loveringite is a late-magmatic mineral because it has crystallized as a result of locally imposed physicochemical parameters. Such conditions are fulfilled when pockets of intercumulus liquid are isolated from each other at the end of the solidification process and behave as isolated systems (Williams 1978).

Unlike the Jimberlana occurrence, the Cr-saturation of the intercumulus liquid was, however, not necessary to stabilize loveringite at Laoui since Cr-free loveringite occurs far from the spinel grains. Actually, loveringite requires only a high activity of Ti, together with sufficient amounts of Ca to fill the A site in its medium of crystallization, regardless of the content of Cr, Zr and *REE*. On the other hand, its compositional range is so wide that it can adapt itself to a great diversity of conditions in orthocumulates and adcumulates as well.

If valid for the orthocumulates, a simple model of increase of Ti in pockets of intercumulus liquid fails, however, to account for the occurrence of loveringite as inclusions in cumulus plagioclase from the anorthosite layers. Thus we propose that such inclusions were produced by strongly evolved liquids coming from beneath, that infiltrated the anorthosites at different stages of solidification. A similar process was invoked ten years ago to explain the unusual quantities of incompatible elements like sulfur at given levels of layered basic complexes (Vermaak 1976). Since the work of Irvine (1980), this is known as "infiltration metasomatism" and ascribed to filter-pressing of intercumulus liquids under the effect of the compaction of the cumulus pile. At Laoui, the infiltration metasomatism is supported

by at least two features: 1) the inclusions of loveringite in plagioclase from the anorthosites and in chrome-spinel from the underlying orthocumulates have the same Ti/Zr ratio and *REE* contents, which indicates a common medium of crystallization, 2) the anorthosite layers probably behaved as an impermeable cap for the incompatible elements since loveringite, zirconolite and the other Ti- and Zr-rich oxides are lacking above the lower banded zone. Accordingly, the distribution of loveringite would reflect the percolation of filter-pressed residual liquids that mixed to various degrees with the resident liquids of the cumulates. We propose the following model that, even if only qualitative, tries to account for the opposite behavior of two strongly incompatible elements such as Ti and Zr.

The orthocumulates are sites of preferential accumulation of evolved liquids during infiltration metasomatism (Tait *et al.* 1984). The lowermost samples were infiltrated by a Ti-rich filter-pressed liquid while the resident liquid was still magnesian, thus producing Mg-rich ilmenite (Lorand & Cottin 1987a). After the segregation of ilmenite, the medium of crystallization was depleted in Mg but high enough in Ti to produce loveringite. The textural relationships between loveringite, pargasite and phlogopite suggest that these three minerals have crystallized in the same range of temperature, *e.g.*, 1050 to 900°C (Holloway 1973, Roeder & Campbell 1985), though no experimental data are available for loveringite. At this stage, the intercumulus liquid was not enriched in Zr and *REE*, as indicated by the inclusions of loveringite in chrome-spinel.

After the deposition of Ti-rich oxides (ilmenite, pseudobrookite, Ti-rich loveringite and rutile), the liquid remaining in the lowermost orthocumulates would have been depleted in Ti but enriched in Zr, which behaves as a nearly perfectly incompatible element (Eales & Robey 1976). This is demonstrated by the grains of loveringite outside the grains of spinel. Upward migration of this liquid explains the occurrence of Ti-deficient, Zr-rich loveringite in the uppermost orthocumulates from the lower banded zone. This is likely inasmuch as the migration of filter-pressed liquids may affect a cumulus pile over a thickness of 100 to 300 metres (Irvine 1980), which roughly corresponds to the thickness of the lower banded zone (Fig. 1).

It has been postulated that plagioclase is not sufficiently dense to be deposited by gravity-settling during the crystallization of tholeiitic melts (Campbell 1977); rather, it forms stagnant layers floating at different levels of magma chambers that give rise to the anorthosite layers (McBirney & Noyes 1979). Owing to its particular behavior, plagioclase may have been first responsible for the creation of an incompatible-element-enriched closed system beneath the anorthosite layers. Then, on cooling, the evolved

liquid probably infiltrated the overlying stagnant layer along the grain boundaries of plagioclase crystals, perhaps because of variation in its density (Hupfert & Sparks 1980) or of the increase in the fluid pressure. The core-rim compositional zoning indicates that plagioclase was still growing at this stage. The combined effect of these two processes (infiltration of evolved liquids introducing Ti and Zr and the adcumulus growth of plagioclase) could be responsible for the entrapment of loveringite in plagioclase. At a lower temperature, the magmatic growth was relayed by solid-state readjustment of grain boundaries of plagioclase meeting at 120° (Lorand & Cottin 1987b); the displacement of pockets of residual liquids by this secondary growth would account for the occurrence of zirconolite a few millimetres apart from loveringite in the same polished section and the absence of late-magmatic minerals associated with loveringite in plagioclase adcumulates.

#### CONCLUSIONS

Loveringite is not as rare as believed in cumulative rocks from the layered basic complexes. Its compositional field is wider than indicated by published data, especially in terms of Ti/Zr value. It may crystallize provided that the medium is rich in Ti, together with sufficient amounts of Ca to fill the A site, and regardless of the Cr, Zr and REE contents. Such is generally the case in late-magmatic liquids trapped in the cumulates.

Unlike the Jimberlana occurrence, the above conditions were fulfilled in two distinct petrographic and chemical settings of the Laouni body, the olivine-chromite orthocumulates and the anorthosite adcumulates. The composition of loveringite is not bulk-rock-controlled but shows an overall decrease in Ti/Zr from the base to the top of the lower banded zone, which is strongly correlated with the nature of the associated Ti-Zr oxides.

The crystallization of Ti-rich, Zr- and REE-poor loveringite coexisting with magnesian ilmenite, Mg-rich pseudobrookite and rutile in the lowermost orthocumulates is attributed to the accumulation of a Ti-rich liquid. The occurrence of Ti-deficient, Zr- and REE-rich loveringite, locally associated with zirconolite, at the top of the lower banded zone is ascribed to infiltration metasomatism by a Ti-depleted and Zr-enriched evolved liquid expelled from the underlying cumulus pile by filter-pressing after the deposition of Ti-rich oxides. The anorthosite adcumulates may have acted as an impermeable cap for this liquid because they formed a stagnant layer in the magma chamber. The adcumulus growth of plagioclase is considered to be responsible for the trapping of loveringite.

The present data suggest that loveringite can record subtle variations of the chemistry of strongly

evolved liquids trapped in the cumulates. Accordingly, loveringite is to be added to the list of trace minerals potentially useful for the study of the processes taking place after magma genesis in the layered basic complexes.

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