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Chromian jadeite, phengite, pumpellyite, and lawsonite in a high-pressure metamorphosed gabbro from the French Alps

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SUMMARY. Small ophiolitic bodies are enclosed in the calcschists of the Piemont zone (western Alps). They have been metamorphosed in the blueschist facies during the alpine orogeny. One of them, the Roche Noire massif, includes gabbro breccias. The magmatic mineralogy of the gabbro was plagioclase + clinopyroxene + minor chromite. There was no chemical homogenization during metamorphism because of the lack of penetrative deformation and on the site of previous chromites, chromium-rich high-pressure and low-temperature minerals (jadeite, phengite, pumpellyite, and lawsonite) were formed. The $Al \rightleftharpoons Cr$ substitution does not affect other P- and T-dependent substitutions.

IN the western Alps the calcschists of the Piemont zone enclose numerous bodies of ophiolitic rocks. One of them, the Roche Noire massif (Lat. 44° 38′ N; Long. 6° 53′ E) is mainly composed of serpentinites enclosing small masses of pillow-lavas and gabbro breccias (Lemoine, 1971). The breccia is composed of big blocks of gabbro cross-cut by diabasic dykes, and smaller fragments of gabbro and minor diabase in a matrix made up of the same material but finely broken. It contains no fragment of the enclosing calcschists. This suggests that the breccia formed very early, in an oceanic environment, probably along a fault scarp in the oceanic crust. Diabase breccias with a matrix of finely broken plagioclase and clinopyroxene crystals have been dredged, for example, in the Romanche fracture zone in the Atlantic ocean (personal observations of rocks from cruise 7309 of the School of Marine and Atmospheric Sciences, Miami). Lemoine and Tricart (1979) suggest that the inclusion of the gabbros in the serpentinites might be the result of serpentinite diapirs in an oceanic fracture zone environment.

During the alpine orogeny, the Roche Noire massif suffered a high-pressure and low-temperature metamorphism in the blueschist facies. The characteristic assemblage in the basic rocks is jadeite + glaucophane + lawsonite (Caby *et al.*, 1978).

Petrography

The main characteristic of the metamorphism in the gabbro breccias is the lack of penetrative deformation contrasting with the strong foliation developed in the enclosing rocks (serpentinites, calcschists). This is probably related to the fact that the gabbros are much more competent. Magmatic textures are perfectly preserved. The gabbros are very coarse-grained and rather leucocratic. The magmatic assemblage was plagioclase + clinopyroxene + minor chromite. Relict clinopyroxene and chromite are still present. Because of the lack of deformation, the metamorphic phases crystallizing are highly dependent on the nature of the magmatic minerals that they replace. Clinopyroxene is replaced by glaucophane ± jadeite, plagioclase by lawsonite + phengite ± jadeite. Green patches, up to 5 mm in size, are scattered in the gabbro. They are dark green in hand specimen and are seen in thin section to consist of jadeite, lawsonite, phengite, and pumpellyite, characterized by very high chromium contents. Sometimes a chromite grain is still present in the centre of the patch (fig. 1*a*). Jadeite, phengite, and lawsonite occur in the rest of the rock as non-chromian varieties and attest the equilibrium blueschist paragenesis. From textural relationships, pumpellyite seems in equilibrium with chromian phengite but it does not occur as a low-chromium variety.

Two samples were selected for more detailed study of chromian minerals:

A 243 is a coarse-grained gabbro in which plagioclase recrystallized to lawsonite + phengite + minor jadeite. Several green patches in the rock consist of green phengite + pumpellyite + lawsonite

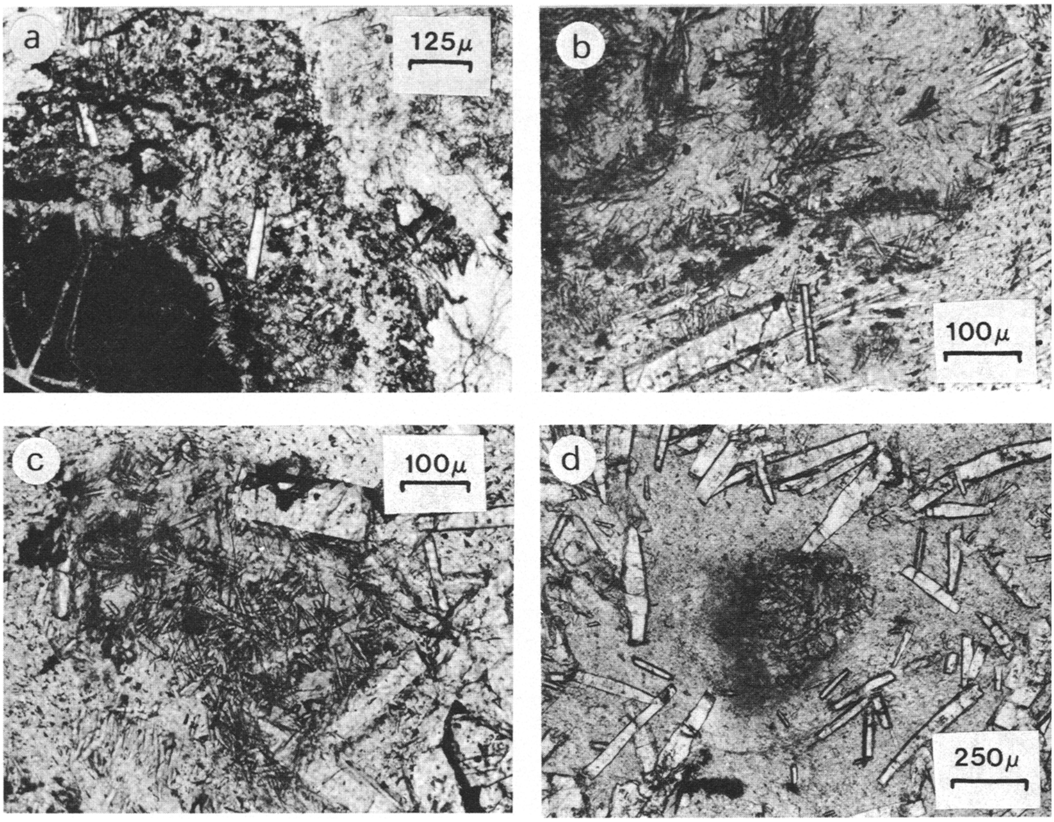

FIG. 1. (*a*) Portion of a relict chromite (black) surrounded by a green patch composed of chromian phengite + lawsonite (white prisms) and tiny grains of sphene. On the right side of the photo occur non-chromian phengite and jadeite (light grey). (*b*) Chromian pumpellyite crystals (dark grey) scattered in very fine-grained chromian phengite. Pure phengite (light grey) is seen on the right side of the photo, (*c*) Chromian pumpellyite (dark-grey needles), phengite and lawsonite (light-grey prisms). (*d*) Green patch (dark grey) composed of chromian jadeite plus minor chromian phengite. Around the patch occur non-chromian phengite + lawsonite.

(fig. 1*b* and 1*c*) with tiny rims of sphene at the periphery.

A 247 is a gabbro fragment in the breccia in which plagioclase recrystallized to jadeite + minor lawsonite and phengite. Two types of chromian mineral assemblages occur: (1) green phengite + minor lawsonite rimming a relict chromite (fig. 1*a*), (2) green jadeite + green phengite (fig. 1*d*).

The conditions of the alpine metamorphism can be evaluated from the mineral paragenesis. The presence of glaucophane and jadeite together with phengite with a phengitic substitution of 3.6 (Velde, 1967) and lawsonite suggest a temperature between 300 and 400 °C and a minimum pressure of 8 kb.

Chromian minerals

Minerals have been analysed with a CAMECA microprobe, using natural minerals as standards. Element concentrations have been calculated using the EMPADR VII program (Rucklidge and Gasparrini, 1969). As the minerals are always extremely small, it was almost impossible to determine their optical properties.

Chromian jadeite. Chromian jadeite occurs as small crystals ($< 75\ \mu$), strongly pleochroic from bright grass-green to yellow. Because of the small size of the crystals, the strong colour, and the high dispersion, it was very difficult to determine the position of α and γ. In one crystal, however, the grass-green was definitely parallel to α and the yellow to γ as in acmite and ureyite.

The analyses (Table I) show a high Cr_2O_3 content (up to 8 %) together with high Na_2O values. Cr concentrations in the pyroxenes are highly variable but decrease from the centre to the edge of the patch. The brightness of the green decreases simultaneously. This can be explained by a very limited diffusion of Cr during the metamorphism.

The structural formulae show that there is no Al in the tetrahedral position. Fig. 2*a* demonstrates the substitution Al $\rightleftharpoons$ Cr (up to a Cr/(Cr + Al) ratio of 0.28). This suggests the replacement of jadeite by a NaCr component, ureyite (Deer *et al.*, 1978) which varies from 8 to 23 %. Pure ureyite is known only in meteorites. Cr-rich clinopyroxenes have been reported in kimberlites from Yakutia (Sobolev *et al.*, 1975) but they are poor in jadeite and rich in diopside component.

The system $NaAlSi_2O_6$–$NaCrSi_2O_6$ has been investigated at 800 °C (Abs-Wurmbach and Neuhaus, 1976). The authors found that at this temperature the complete solid solution between jadeite and ureyite exists only at very high pressures (above 18 kb). In the system $NaAlSi_3O_8$–$NaFe^{3+}Si_3O_8$, Popp and Gilbert (1972) have shown that the field of complete solid solution between acmite and jadeite is highly dependent on the temperature. Decreasing the temperature enlarges the field of the complete solid solution toward lower pressures. In the Roche Noire massif the temperature has been estimated at between 300 and 400 °C for a minimum pressure of 8 kb. Under these conditions and in the presence of 15% diopside component occurs a solid solution of jadeite–ureyite with a low ureyite component. By analogy with the acmite–jadeite relationships, this suggests an enlargement of the complete jadeite–ureyite solid solution field toward lower pressures with decreasing temperature. Further investigations are necessary, however, to support this supposition.

Chromian phengites. Phengite is widespread in the gabbros. In the green patches it is replaced by a Cr-rich variety distinctly green in thin section despite the tiny size of the crystals (< 10 μ). Deer *et al.* (1962) recommend the use of the name mariposite for chromian phengites, restricting fuchsite to chromian muscovites.

Chromian phengites have been analysed in both A 243 and A 247 (Table II). Cr contents are very high, up to 16%. The phengitic substitution (3.5 to 3.6) are similar in the chromian phengites and the normal adjacent phengites. It is balanced mainly by Mg while the iron content is always very low.

In fig. 2*b* the negative correlation between Al^{VI} and Cr suggests again that the Al $\rightleftharpoons$ Cr substitution occurs in the octahedral sites. The Cr/(Cr + Al)

TABLE I. *Chromian jadeite compositions (sample A 247)*

	1	2	3	4	5	6	7
SiO_2	57.01	57.23	56.39	58.46	58.83	58.57	57.80
Al_2O_3	15.00	16.63	15.60	17.10	18.43	18.72	17.71
Cr_2O_3	8.38	6.76	6.74	6.13	4.02	3.64	2.83
FeO*	0.54	0.49	0.57	0.44	0.37	0.46	0.62
MnO	0.06	0.03	0.03	0.03	0.03	0.03	0.00
MgO	2.89	2.61	2.68	2.30	2.90	3.21	2.21
CaO	3.65	3.28	3.78	2.96	3.33	3.96	2.77
Na_2O	12.96	13.04	12.92	12.94	13.03	13.04	13.17
Total	100.50	100.08	98.71	100.36	100.94	101.65	98.12
Numbers of ions on the basis of 6(O)							
Si	1.991	1.992	1.997	2.016	2.007	1.989	2.021
Al^{IV}	0.009	0.008	0.003	—	—	0.011	—
Al^{VI}	0.609	0.674	0.648	0.695	0.741	0.738	0.771
Cr	0.232	0.186	0.189	0.167	0.108	0.098	0.078
Fe*	0.016	0.014	0.017	0.013	0.011	0.013	0.018
Mn	0.002	0.001	0.001	0.001	0.001	0.001	0.000
Mg	0.150	0.135	0.142	0.118	0.147	0.163	0.115
Ca	0.137	0.122	0.143	0.109	0.122	0.144	0.104
Na	0.878	0.880	0.887	0.866	0.862	0.869	0.893
Σ	2.024	2.012	2.027	1.969	1.992	2.016	1.979
Ureyite	23.0	18.4	18.9	17.0	10.9	9.7	8.0
Jadeite	61.2	67.4	65.1	71.0	74.5	74.0	79.0
Acmite	1.6	1.2	1.7	0.4	1.1	1.2	1.8
Diopside	14.2	12.8	14.3	9.6	13.5	15.1	11.2

ratio reaches 0.64. The highest Cr_2O_3 values were found in crystals adjacent to a relict chromite (fig. 1*a*). At the edge of the green patches the Cr content of the phengites decreases abruptly to less than 1.5%. This emphasizes again the limited diffusion of Cr.

Chromian phengites have been described in rocks from Calabria (De Roever and Kieft, 1970; De Roever, 1972), together with chromian pumpellyite and chlorite, presumably pseudomorphing magmatic chromian spinels in metaporphyrites. These rocks, which contain no jadeite, formed under lower pressure conditions, in the lawsonite-albite facies (De Roever, 1972). The phengitic substitution in the micas is lower than in the Roche Noire massif (~ 3.3) and consistent with the pressure conditions (Velde, 1967). The trivalent cations in the octahedral sites are thus more abundant and include appreciable Fe^{3+}. In fig. 2*b*, the Calabrian mariposites plot on a line parallel to Roche Noire, showing again (though the small number of analyses) an $Al \rightleftharpoons Cr$ substitution.

These observations demonstrate that the $Al \rightleftharpoons Cr$ substitution affects only the octahedral site and that Cr does not enter the tetrahedral site.

TABLE II. *Representative analyses of phengites*

	1	2	3	4	5	6
SiO_2	51.39	51.33	51.71	49.07	51.20	53.43
Al_2O_3	10.71	13.96	13.91	13.22	14.70	22.86
Cr_2O_3	16.25	13.32	12.35	13.94	12.73	0.24
FeO*	0.54	0.76	0.69	0.08	0.07	0.12
MgO	5.14	4.74	5.35	5.08	5.26	5.95
K_2O	10.74	10.61	10.54	10.98	10.95	11.80
Total	94.78	94.92	94.54	92.34	94.91	94.39
Numbers of ions on the basis of 22(O)						
Si	7.249	7.175	7.203	7.069	7.133	7.165
Al^{IV}	0.751	0.825	0.797	0.931	0.887	0.835
Al^{VI}	1.030	1.466	1.487	1.315	1.520	2.779
Cr	1.812	1.466	1.360	1.588	1.398	0.025
Fe*	0.064	0.088	0.080	0.010	0.008	0.014
Mg	1.081	0.984	1.111	1.092	1.089	1.190
Σ	3.387	4.004	4.038	4.005	4.015	4.008
K	1.993	1.885	1.873	2.019	1.940	2.018

1, 2, and 3: chromian phengites from A 247—highest, intermediate and lowest Cr content; 4 and 5: chromian phengites from A 243—highest and lowest Cr content; 6: phengite from A 243.

* Total Fe as FeO.

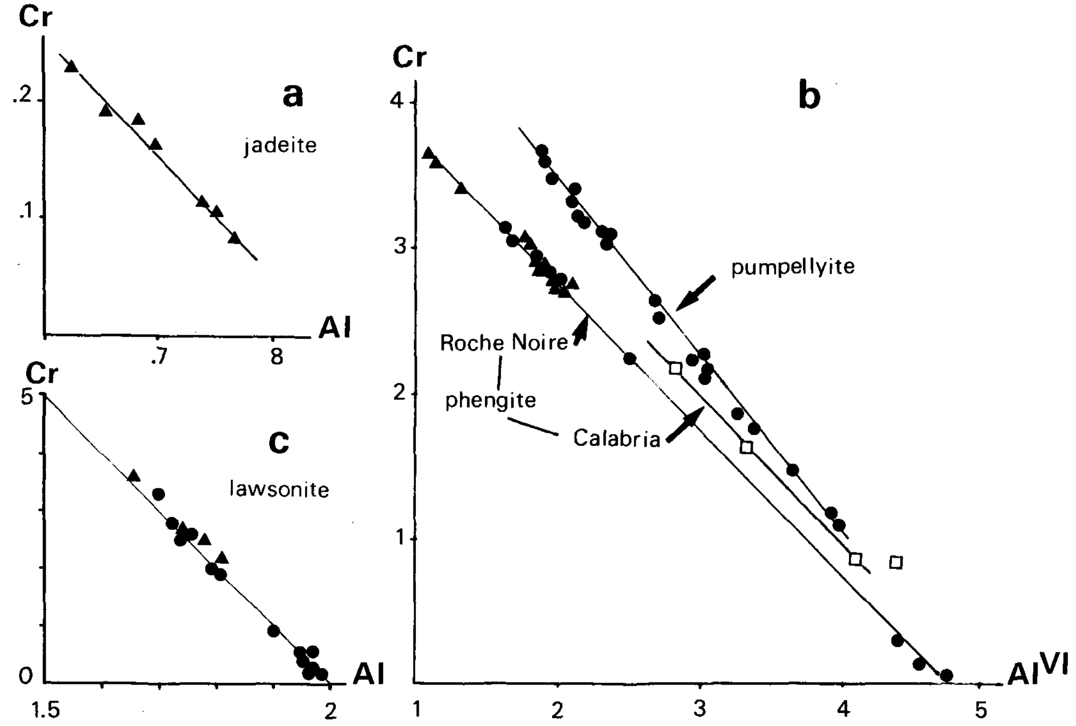

FIG. 2. Compositional variation in an Al *vx*. Cr diagram for (*a*) jadeite, (*b*) pumpellyite and phengite (phengites from Calabria are shown for comparison—see text for explanation), (*c*) lawsonite (solid circles: A 243, solid triangles: A 247).

Apparently the phengitic substitution in chromian phengites, like in pure phengites, is mainly dependent on the physical conditions.

Chromian pumpellyite. Chromian pumpellyite occurs in A 243 as small crystals ($< 75\ \mu$), with low birefringence and high dispersion, scattered in the phengite. Unlike the green phengite and jadeite, chromian pumpellyite is distinctly pink, a feature already observed for moderately chromian pumpellyite from Calabria (De Roever and Kieft, 1970).

TABLE III. *Representative analyses of chromian pumpellyites and lawsonites*

	1	2	3	4	5
SiO_2	34.60	36.34	37.15	36.43	37.77
Al_2O_3	9.05	20.02	26.21	26.26	31.53
Cr_2O_3	26.48	9.32	8.57	7.70	0.01
FeO*	1.69	1.22	n.d.	n.d.	n.d.
MnO	0.66	0.38	n.d.	n.d.	n.d.
MgO	2.99	3.84	n.d.	n.d.	n.d.
CaO	18.25	21.17	17.10	16.32	16.98
Total	92.71	92.30	89.03	86.71	86.29
Si	6.005	5.990	1.992	1.997	2.021
Al	1.859	3.892	1.657	1.697	1.989
Cr	3.633	1.214	0.363	0.334	0.000
Fe*	0.245	0.168	—	—	—
Mn	0.097	0.053	—	—	—
Mg	0.773	0.943	—	—	—
Σ	6.600	6.270	2.020	2.031	1.989
Ca	3.394	3.739	0.983	0.959	0.973

Pumpellyites (1 and 2: A 243, highest and lowest Cr content) and lawsonites (3: A 247, 4 and 5: A 243, highest and lowest Cr content). The structural formulae of pumpellyites are calculated assuming Σ cations = 16, those of lawsonites on the basis of 8(O).

* Total Fe as FeO.

The Cr content reaches 26% but varies widely from one crystal to the other (Table III). As the water content is not known, the structural formulae were calculated on the basis of sixteen cations, as suggested by Coombs *et al.* (1976). The formulae depart somewhat from common pumpellyite (Passaglia and Gottardi, 1973) by their high Cr and low Ca contents. Al and Cr show a good negative correlation and as the *Z* positions are filled with silica we can assume an $Al \rightleftharpoons Cr$ substitution in the octahedral sites, but it is impossible to know whether it occurs in the *X*- or *Y*- position. The Cr/(Cr+Al) ratio reaches 0.66. Ca varies from 3.39 to 3.85 but never fills the *W*- site. Passaglia and Gottardi (1973) suggest a shift in Mn and Fe^{2+} to fill this site. In this case it is not sufficient to fill the *W*- site and this suggests that some Mg may enter this site also.

The Fe content of the pumpellyites is very low. Many authors have found that the Al/Fe ratio in pumpellyites increases with increasing grade of metamorphism (Seki, 1961; Iwasaki, 1963; Ernst *et al.*, 1970; Kawachi, 1975). The Roche Noire massif is in the glaucophane–lawsonite facies and the pumpellyite compositions are consistent with previous results in spite of the $Al \rightleftharpoons Cr$ substitution.

It has been noted that pumpellyite occurs only in the green patches, as a Cr-rich variety. The texture suggests no evidence of desequilibrium with phengite (fig. 1*b* and *c*). More likely, pumpellyite forms only in these patches because of local chemical conditions.

Chromian lawsonite. Lawsonite is not abundant in the green patches but when it occurs it contains Cr also. It forms elongated prisms, up to 0.2 mm in size, slightly pinkish.

Chromian lawsonite has been analysed both in A 243 and A 247 but the given compositions (Table III) are mainly indicative for the crystals are quickly burnt under the beam, even when defocused. The structural formulae, though, are consistent.

Chromian lawsonite occurs only at the periphery of the patches and is consequently never rich in Cr. The highest content is only 8.5% (Cr/(Cr+Al) = 0.18). Fig. 2*c* demonstrates again the $Al \rightleftharpoons Cr$ substitution.

Discussion

One gabbro sample (A 243) has been analysed. Its composition (SiO_2 46.72%, TiO_2 0.24, Al_2O_3 22.04, Fe_2O_3 1.23, FeO 2.45, MnO 0.02, MgO 8.40, CaO 6.97, Na_2O 2.65, K_2O 3.42, Cr_2O_3 0.09, P_2O_5 tr, H_2O^+ 6.33, H_2O^- 0.10) is quite different from common ophiolitic gabbros, particularly for its H_2O, K_2O, and CaO content. The high water content suggests that the rock composition has been strongly modified by secondary processes. The high Al content together with low Fe and Mg contents can be explained by the high proportion of plagioclase relative to clinopyroxene and is probably primary. Such compositions are known in cumulate gabbros from ophiolitic sequences (Coleman, 1977). But the fact that phengite occurs with lawsonite and jadeite replacing magmatic plagioclase shows that the potassium content is secondary. Low-temperature interaction between sea-water and the oceanic crust is known to induce hydration, leaching of Ca, and K enrichment (Hart, 1970, 1973; Matthews, 1971; Aumento *et al.*, 1976; Robinson *et al.*, 1977;

etc.). It is related to progressive replacement of plagioclase by potassic zeolites (phillipsite) and even K feldspar. If these gabbro breccias formed, as suggested previously, along a fault scarp in the oceanic crust, they have been in contact with sea-water at low temperature and may have been altered. It is important to point out that the pillow-lavas enclosed in the same serpentinite body are also hydrated, Ca-poor, and strongly enriched in K (up to 4%) (Mevel, 1975).

Though the Cr content of the gabbro is very low, the Cr content of some of the metamorphic minerals is extremely high, reaching values never described before. The occurrence of such Cr-rich minerals is related to particular conditions. As observed in every ophiolitic massif in the western Alps, the high-pressure and low-temperature metamorphism did not favour the chemical homogenization of the rocks, especially of the gabbros. The metamorphic event was probably rather short and at low temperature the diffusion rate of Cr seems to be very slow. The few magmatic chromites scattered in the rocks provided Cr-rich environments allowing the crystallization of highly chromian metamorphic minerals. The green patches in the gabbros represent the chromite pseudomorphs plus probably a small area of Cr diffusion, the Cr content of the minerals decreasing toward the periphery. The Cr-rich assemblages in Calabria formed in a similar situation (De Roever and Kieft, 1970). The Roche Noire massif demonstrates that during glaucophane-lawsonite-facies conditions, the substitution Al$\rightleftharpoons$Cr may occur to a very high extent in jadeite, phengite, pumpellyite, and lawsonite. It is important to point out that this substitution does not affect the compositional characteristics of the minerals related to external conditions (diopside content of jadeite, phengitic substitution in mica, Al content of pumpellyite).

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