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HIGH-PRESSURE K-FELDSPAR – VESUVIANITE-BEARING ASSEMBLAGE IN THE CENTRAL METASEDIMENTARY BELT OF THE GRENVILLE PROVINCE, SAINT JOVITE AREA, QUEBEC

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ABSTRACT

A lens consisting largely of calcite, microcline, vesuvianite, quartz, diopside, calcic plagioclase, and wollastonite occurs within calcite marble of the Central Metasedimentary Belt (CMB) of the Grenville Province, in the Saint Jovite area of Quebec. This unusual assemblage exhibits a polygonal granoblastic texture and reflects high-grade phase equilibrium during a Grenvillian metamorphic event. The coarse grain-size of the calcite, microcline, vesuvianite and quartz in patchy zones within the lens is attributed to grain growth in macro-pressure shadows during shearing. There is no evidence for fluid infiltration, but water may have concentrated by solution-transfer into the patches. A T–$X(CO_2)$ phase diagram constructed for ≥6 kbar total pressure suggests temperatures in the order of ≥750°C and $X(CO_2)$ at ~0.2.

Keywords: K-feldspar, vesuvianite, high pressure, Grenville Province, Saint Jovite, Quebec.

SOMMAIRE

Nous décrivons une lentille contenant l'assemblage calcite + microcline + vésuvianite + quartz + diopside + plagioclase calcique + wollastonite dans une séquence de marbre à calcite près de Saint-Jovite, Québec, dans la ceinture métasédimentaire centrale de la Province du Grenville. Cet assemblage inusité définit une texture polygonale granoblastique et témoigne d'un équilibre de ces phases lors de l'événement métamorphique grenvillien. On attribue la granulométrie grossière de la calcite, du microcline, de la vésuvianite et du quartz dans des domaines individualisés de la lentille à la croissance des cristaux dans des zones protégées à pression isotrope lors d'un cisaillement. Nous ne trouvons aucune indication d'infiltration d'une phase fluide, mais il est possible que l'eau se soit concentrée par solution et tranfert vers ces domaines individualisés. Un diagramme de phases T–$X(CO_2)$ construit pour une pression totale de 6 kbar ou plus indique une température de l'ordre de 750°C et une valeur de $X(CO_2)$ d'environ 0.2.

(Traduit par la Rédaction)

Mots-clés: feldspath potassique, vésuvianite, pression élevée, Province du Grenville, Saint-Jovite, Québec.

INTRODUCTION

Vesuvianite is a constituent of contact metamorphic calc-silicate rocks. To date, it has only rarely been reported within regional metamorphic rocks, where it occurs, generally in minor amounts, in all facies. Many of the high-pressure – high-temperature occurrences are in the Central Metasedimentary Belt of the Grenville Province in Ontario and Quebec (Wynne-Edwards 1972), a terrane that represents juvenile Grenvillian crust metamorphosed to a peak of granulite-facies conditions (100 MPa and 950°C), as recorded within gneiss complexes (Boggs *et al.* 1994). Other areas, including that west of Saint Jovite, have been reactivated and do not reflect peak conditions of metamorphism (Corriveau & van Breemen 1994).

Experimental and theoretical phase-equilibrium studies of vesuvianite suggest that it is stable over a

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wide range of temperatures and pressures. In the presence of quartz, its stability at low pressures seems limited to temperatures near or below 400°C and very low $X(O_2)$ (Hochella *et al.* 1982).

In this study, we examine an unusual lens-shaped body consisting of calcite, K-feldspar, vesuvianite, quartz, clinopyroxene, wollastonite and calcic plagioclase, entrained within granulite-facies marble of the Central Metasedimentary Belt. It is located along Highway 117, some 12 km northwest of Saint Jovite, Quebec). The association of vesuvianite with K-feldspar and quartz as major phases in a high-grade assemblage has not been previously reported. A prominent feature that characterizes the lens is the very coarse grain-size of the K-feldspar, vesuvianite, quartz and calcite.

GEOLOGICAL SETTING

The Meso- to Neoproterozoic rocks (Grenvillian) in the Saint Jovite area of western Quebec consist of two main groups: the Central Metasedimentary Belt (CMB) to the west, and the Morin igneous complex, dominantly charnockitic rocks of the Central Granulite Terrane (CGT), to the east. These are separated by the Labelle shear belt (LSB), a north–south-trending unit traversing lithologies of both the CMB and the Morin complex (Rivers *et al.* 1989), folded in this area into an S-shaped kilometer-scale reclined fold (Martignole & Corriveau 1991).

The CMB includes calcite marble units meters to hundreds of meters thick, which contain heterogeneously distributed diopside, titanite, and accessory dolomite, plagioclase, tremolite, vesuvianite, and wollastonite (Martignole & Corriveau 1991, 1993). Thinner calc-silicate units within the marble are rich in diopside, with variable amounts of grossular, wollastonite, titanite, scapolite, quartz, K-feldspar and plagioclase. Titanite ages from marble and calc-silicate units occurring ~30 km to the west range between 1133 and 1165 Ma (Boggs *et al.* 1994). Most of the area lies within the granulite facies, with maximum temperatures and pressures in the order of 740–790°C and 8 kbar (Boggs *et al.* 1994, Martignole & Corriveau 1991).

A marble and calc-silicate unit occurring within and near the eastern boundary of the LSB is bordered to the west (~200 m) by charnockite, and to the east it is covered by glacial sediments. The assemblage described here occurs along a road-cut of Highway 117 (now largely quarried by mineral collectors) in a lens approximately 2.5 m long and up to 50 cm wide within coarse-grained granoblastic calcite marble. The lens is parallel to the trend of nearby calcite-bearing calc-silicate layers.

MINERALOGY

The main minerals in the lens are calcite (80–90%), K-feldspar (5–10%) and vesuvianite (~2–5%); quartz, clinopyroxene and calcic plagioclase together form up to 5%, whereas wollastonite is sporadic, locally reaching 1–2%. Accessory minerals are graphite and titanite. The rock is typified by the extreme heterogeneity in grain size. Thus calcite varies from mm size to 2 cm, microcline, from ~0.5 mm to 3 cm (Fig. 1), vesuvianite, from mm size to 8 cm, quartz, from ~0.2 mm to 3 cm, and plagioclase, from ~0.2 to 5 mm. Clinopyroxene (0.1–2 mm), wollastonite (0.5 –2 mm), graphite (0.5–3 mm), and titanite (0.1–0.2 mm) are more or less equigranular. The coarser-grained minerals tend to occur together as nebulous patches within the lens, although their distribution could not be mapped because of the abundance of enveloping calcite.

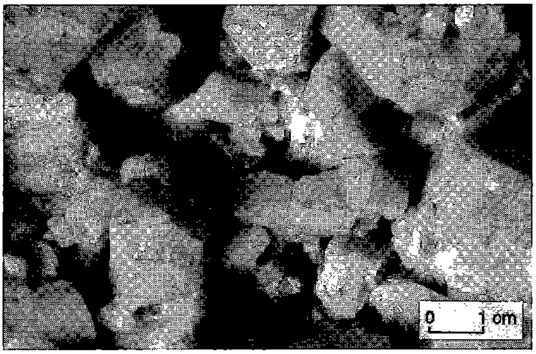

FIG. 1. Photograph of coarse-grained, subhedral to euhedral microcline. Spaces between crystals are the result of acid-leaching of calcite.

Crystal boundaries are straight to slightly curved (equilibrium boundaries; Spry 1969), and 120° triple-point junctions are common, even where the grains are coarse. The overall texture is thus massive, inequigranular, polygonal granoblastic (Fig. 2). The following equilibrium assemblages of minerals were observed petrographically: Cal–Kfs–Cpx, Kfs–Cpx, Cal–Kfs, Ves–Cal, Ves–Qtz–Kfs, Kfs–Ves, Cal–Cpx, Qtz–Wo, Kfs–Qtz–Cpx, Ves–Cal–Cpx, Wo–Ves–Kfs,

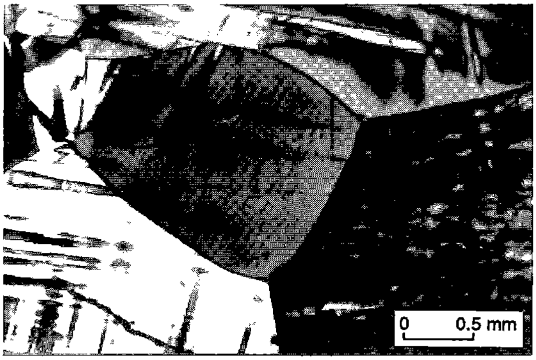

FIG. 2. Photomicrograph of microcline with typical polygonal granoblastic texture. Crossed nicols.

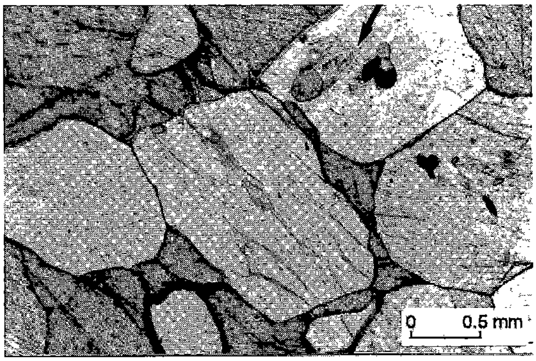

FIG. 3. Photomicrograph of calcite (light grey), microcline (medium grey) and pyroxene inclusions (arrow). Plain light.

and Kfs–Qtz–Cal (minerals for each assemblage listed in decreasing order of relative abundance). The symbols are those of Kretz (1983).

Calcite shows twin lamellae in two, and locally in three planes. It is coarser grained where associated with the silicate minerals, and finer where it is the dominant phase, although in the latter, it is still at least twice as coarse as in the host marble. In single sections, it occurs both as a coarse-grained major phase with straight to curved boundaries with the silicate species, and as a finer-grained interstitial phase, particularly with K-feldspar, which it also envelops (Fig. 3).

The K-feldspar (perthitic microcline) exhibits typical cross-hatched twinning with elliptical to lobate shapes outlining crystal boundaries. A section fortuitously cut parallel to (010) exhibits pericline twinning with elongate "patches" representing cross-sections of coarse plate- or vein perthite (with minor albite twinning). Most of the albite present occurs as film perthite parallel to the Murchison plane. In local domains of seemingly untwinned microcline, the albite lamellae appear to be longer (~2×) than in zones of cross-hatching. Certain zones of film perthite appear to be distorted, apparent plate perthite exhibits z-forms, and a microfault slightly displacing some, but not all of the film perthite it crosses, is itself filled with albite. These features suggest albite exsolution during rock deformation, as suggested by Evans & Guidotti (1966) based on a "spiral" arrangement of perthitic albite. Eskola (1952) and others (as summarized in Smith 1974) suggested that shearing stress is important for the formation of microcline.

On a fresh surface, the vesuvianite is honey-brown, with a vitreous luster. It forms "stocky" prisms, in general with a length-to-width ratio of 2–3:1, and where relatively fine-grained, occurs as rectangular forms in thin section. A distinct cleavage is absent, and the fracture is irregular. In one crystal observed under the microscope, remnant crystal forms, partly outlined by fractures and with subtle changes in the greyish shade (plane-polarized light) suggest replacement of an earlier mineral.

The quartz prisms show marked striations. In general, quartz is coarse-grained where associated with microcline, and finer in the calcite-dominated masses. Euhedral to subhedral crystals of wollastonite were observed in contact with all major phases (Fig. 4). Subhedral to euhedral grains of clinopyroxene occur randomly as a poikilitic phase largely within microcline, calcite and vesuvianite. Their form and optical properties are similar to the clinopyroxene occurring within calc-silicate rocks in the area. Flakes of graphite have a similar distribution. Calcic plagioclase occurs sporadically as large crystals up to ~0.5 cm in sharp contact with microcline, calcite, quartz, and vesuvianite, and is locally replaced by the quartz. Small subhedral to anhedral grains also are embedded within calcite and microcline. Titanite is rare, occurring as rounded grains within vesuvianite and microcline.

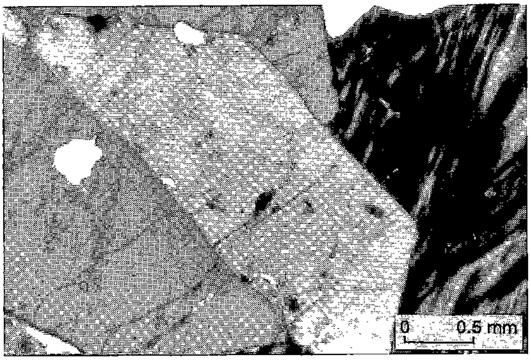

FIG. 4. Photomicrograph of vesuvianite (grey), wollastonite (light grey, center), microcline (cross-hatching) and quartz (white, top). Crossed nicols.

MINERAL CHEMISTRY

Pulverized concentrates of the minerals were scanned using a Philips PW1730/1710 X-ray diffractometer with CuK radiation. Chemical analyses of those minerals were made using a JEOL 840 SEM with an attached Link 10000 energy-dispersion spectrometer (EDS; ZAF4 program) on polished sections (comparison with standard block files). The accuracy is ±5%. Concentrations of major and trace elements in selected samples of vesuvianite and K-feldspar were measured by inductively coupled plasma – atomic emission spectroscopy (ICP–AES) and inductively coupled plasma – mass spectrometry (ICP–MS), and K_2O and Na_2O by atomic absorption spectroscopy (AAS). For the major elements, samples

TABLE 1A. CHEMICAL COMPOSITION OF VESUVIANITE, SAINT JOVITE, QUEBEC: MAJOR ELEMENTS

	1	2	3	4	5	6	7
SiO_2	37.8	36.8	40.0	37.11	37.3	38.4	37.5
TiO_2	1.8	1.9	1.8	1.77	2.0	2.0	2.0
Al_2O_3	16.5	17.4	16.3	17.06	17.3	17.2	17.5
Fe_2O_3	4.0	3.9	3.9	3.62	3.4	3.5	3.4
MnO	0.04	0.04	0.04	-	0.03	0.03	0.03
MgO	1.9	1.9	1.8	2.01	1.9	1.9	1.8
CaO	34.0	35.0	33.8	34.74	35.5	34.3	35.1
Na_2O	0.2	0.5	0.2	0.43	0.1	0.1	0.2
K_2O	-	0.1	-	0.27	-	0.06	0.05
SO_3	0.6	-	0.2	-	0.5	0.1	-
P_2O_5	0.1	0.1	0.1	-	-	-	-
LOI	3.6	2.8	2.8	-	2.6	2.6	1.6
Total	100.5	100.4	100.9	97.01	100.6	100.1	99.2

Number of ions based on 50 total cations

	1	2	3	4	5	6	7
Si^{4+}	18.47	18.36	19.88	18.23	18.59	19.23	19.40
Al^{3+}	9.50	10.23	9.55	9.88	10.17	10.15	10.67
Ti^{4+}	0.66	0.71	0.67	0.66	0.75	0.75	0.78
Mg^{2+}	1.38	1.41	1.33	1.47	1.41	1.42	1.39
Mn^{2+}	0.02	0.02	0.02	-	0.01	0.01	0.01
Fe^{3+}	1.47	1.46	1.46	1.34	1.28	1.32	1.32
Ca^{2+}	17.79	18.70	18.00	18.29	18.96	18.40	19.45
Na^{+}	0.19	0.49	0.19	0.41	0.10	0.10	0.20
K^{+}	-	0.07	-	0.17	-	0.04	0.03
P^{5+}	0.04	0.04	0.04	-	-	-	-
S^{6+}	0.22	-	0.07	-	0.19	0.04	-
OH^{-}	11.73	9.31	9.28	10.91	8.64	8.68	5.52
ΣX	17.98	19.26	18.19	18.87	19.06	18.54	19.68
ΣY	13.07	13.87	13.07	13.35	13.62	13.65	14.17
ΣZ	18.47	18.36	19.88	18.23	18.59	19.23	19.40

Proportion of major-element oxides quoted in wt.%. - Not detected. Total iron expressed as Fe_2O_3. Analytical techniques: 1, 2, 3, 5, 6, 7: ICP–AES + AA; 4: EDS.

TABLE 1B. CHEMICAL COMPOSITION OF VESUVIANITE, SAINT JOVITE, QUEBEC: TRACE ELEMENTS

	1	2	3	4	5	6	7
Co	20	14	60	-	11	10	10
Cr	90	103	140	-	168	90	95
Ni	28	20	19	-	10	10	10
V	-	-	-	-	260	220	230
Pb	-	-	-	-	8.4	11.6	7.7
Zn	93	107	105	-	90	95	94
Cu	20	10	<5	-	25	7	<5
Mo	-	-	-	-	<10	<10	<10
Cd	-	-	-	-	<3	<3	<3
Rb	<10	10	<10	-	10	12	10
Be	7	8	7	-	7.8	7.7	8.8
Sr	320	300	270	-	280	280	275
Ba	-	-	-	-	2	9	7
Li	-	-	-	-	280	300	315
B	-	-	-	-	58	50	58
U	-	-	-	-	5.4	5.1	5.4
Th	-	-	-	-	23	20	24
Y	52	63	62	-	53	57	53
La	62	75	76	-	75	81	69
Ce	113	135	140	-	143	155	138
Pr	-	-	-	-	17	19	17
Nd	-	-	-	-	64	71	66
Sm	-	-	-	-	13	14	13
Eu	2.6	2.8	2.8	-	3.0	3.4	2.8
Tb	-	-	-	-	1.9	2.0	2.0
Gd	-	-	-	-	12	13	13
Dy	-	-	-	-	11	11	11
Ho	-	-	-	-	2.2	2.3	2.2
Er	-	-	-	-	6.8	7.2	6.8
Tm	-	-	-	-	1.0	1.0	1.0
Yb	5.6	6.8	6.7	-	7.0	7.4	6.7
Lu	-	-	-	-	1.1	1.1	1.1

Concentration of trace elements quoted in ppm. - Not measured. Analytical techniques: 1, 2, 3: ICP–AES; 5, 6, 7: ICP–AES + ICP–MS.

were heated to 1050°C (loss on ignition, LOI), fused with $LiBO_2$, and dissolved in HNO_3. For trace elements, samples were sintered with Na_2O_2 and dissolved in HNO_3. Accuracy for major elements is better than 2%, and for trace elements, 10%.

The microcline (Ab_{7-14}) and albite (Ab_{92-96}) are close to end-member compositions, consistent with retrogression to a lower temperature, and the plagioclase is calcic ($An_{\sim 75}$). The clinopyroxene within the lens is (ferroan) diopside; within nearby calcite-bearing calc-silicate layers, it is apparently slightly richer in Ca and total Fe at the expense of Mg. The wollastonite typically contains 53% SiO_2, 45% CaO, 1% Fe_2O_3 and 0.1 to 0.5% each of Al_2O_3, K_2O, and Na_2O.

Compositions of the vesuvianite are presented in Table 1. There are minor variations in the composition of the vesuvianite taken from different parts of the lens. Compared to an average of the twenty-four compositions of vesuvianite in Deer *et al.* (1982) and the twenty compositions in Groat *et al.* (1992), our samples are slightly elevated in their Ti contents and depleted in Mg and Ca, although they are within ranges of those reported therein. The magnesian vesuvianite of Valley *et al.* (1985) is not significantly different, containing more Al, less total iron, and slightly more Mg.

There has only been limited trace-element data reported for vesuvianite. Unusually high enrichments in vesuvianite have been reported for B, Be, Bi, Pb, Cr, *REE*, Cl, Cu, Zn, Sb, Li, Cr, U and Th (Deer *et al.* 1982, Groat *et al.* 1992). In certain cases, metal enrichment in vesuvianite may relate to the host lithology [*e.g.*, Cu, Zn, and Be at the Franklin, New Jersey chalcophile metal deposit, *REE* in association with alkaline rocks: Deer *et al.* (1982), and transition metals in vesuvianite from ultramafic settings: Economou & Marcopoulos (1980)], and perhaps to the nature of skarn-forming fluids. The trace-element data for vesuvianite from the lens hints at slightly anomalous values for Ni + V, Zn + Cu, and Sr.

DISCUSSION

The coarse grain-size of the K-feldspar, vesuvianite, quartz and calcite within the lens are reminiscent of contact-metasomatic skarns, which are present throughout the Grenville, especially where marble is found, and are common in regions of high-grade metamorphism (Shaw *et al.* 1963). Nevertheless, a regional metamorphic origin is preferred for the following reasons: 1) The host marble in the area are not intruded by syn- or late-tectonic granite massifs, such as those noted by Martignole & Corriveau (1993). 2) "Classic" skarns or skarn-like bodies are absent in the area, and textures of the host marbles and spatially associated calc-silicate rocks are those encountered in regionally metamorphosed rocks. Skarns tend to have irregular textures indicative of disequilibrium (Spry 1969). 3) Geochemical evidence for skarn-related vesuvianite, such as high Be contents (~800 ppm: Watters & Brooks 1982), are lacking (<10 ppm Be in vesuvianite from lens). 4) The calcite marble in the Saint Jovite area originated as shallow marine sediments (Rivers *et al.* 1989), within which are thin layers and erratic pods of calc-silicate rocks likely derived by the metamorphism of marls (Martignole & Corriveau 1991). All minerals within the lens are present, as major components or as accessories, within either the regional metamorphic calc-silicate rocks or calc-silicate-bearing marbles. Although the assemblage within the lens differs in terms of mineral proportions from both of these rocks, its overall chemical composition would be compatible with, for example, illite-bearing marls. It is thus not necessary to invoke an "outside" source (such as a skarn fluid) for any of the major elements present in the lens. The level of concentration of *REE* and most other trace elements are of the same order of magnitude of those reported in the NASC (North American Shale Composite: Gromet *et al.* 1984). A plot of the *REE* data normalized to the NASC shows a fairly smooth, near-horizontal distribution (Fig. 5), thus suggesting a similar precursor for the *REE* in vesuvianite from the Saint Jovite lens.

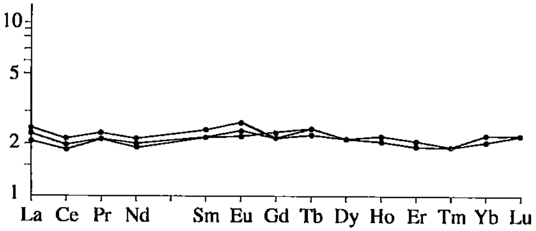

FIG. 5. Plot of the *REE* data normalized to the North American shale composite (Gromet *et al.* 1984).

As defined by metallurgists (references cited by Karcz 1964), grain growth is a process of migration of grain boundaries by which the grain mosaic adjusts itself to the requirements of minimum surface-tension. In sedimentary dolomites, grain-growth fabrics are indicated by (i) a high proportion of triple-point junctions at angles in the 100–140° range, and (ii) boundaries at the junctions that are usually concave away from the smallest angle (incomplete adjustment). Both these features are found within the coarse-grained "patches" in the lens. Karcz (1964) also found that features of grain growth are common near "planes of dislocation" and suggested that tectonic stress may have supplied the energy necessary to "unlock" the boundaries. For the lens assemblage, deformation in the LSB may have initiated crystal-face re-adjustments, with the shape of the grain boundaries controlled by grain-boundary energy (Spry 1969) to produce the polygonal granoblastic texture. The regional and local lithologies lie within the granulite facies (Boggs *et al.* 1994, Martignole & Corriveau 1991), and all minerals within the lens are individually stable within granulite-facies terranes. Coarse grain-sizes in high-grade calc-silicate rocks may be enhanced by the presence of abundant calcite, which could promote ionic mobility (Spry 1969).

An additional enhancement for coarsening may relate to the presence of areas of varying rigidities, depending, for example on differential compaction of the sediment matrix (Spry 1969) or original heterogeneous mineral distributions. Assuming opposing-sense shearing near the walls of the lens, these "rigid heterogeneities" or "rigidity contrasts" could yield relatively low-pressure zones, similar to pressure shadows (Spry 1969) on a macroscopic scale. This could explain the "patchy" nature of the coarse-grained minerals.

T–X(CO_2) phase relations

Hochella *et al.* (1982) and Valley *et al.* (1985) have shown that the stability field of vesuvianite + quartz at a fluid pressure less than 2 kbar is restricted to low T (≤400°C) and low $X(CO_2)$ (≤0.06). However, since the quartz – vesuvianite association is found in amphibolite-facies rocks, Valley *et al.* (1985) suggested that solid solutions in vesuvianite (principally the incorporation of F, Fe^{3+}, Ti^{4+}) may extend the thermal stability of the assemblage vesuvianite + quartz.

In an attempt to constrain the conditions of metamorphism, we have made calculations of T– $X(CO_2)$ equilibria involving the mineral assemblages. The calculations are made using the end-member compositions rather than measured compositions. This approach allows the equilibria to be represented as a series of stable univariant reactions, and seems preferable to a more complicated analysis involving the calculation of divariant and univariant equilibria. The T–$X(CO_2)$ equilibria were calculated for 6 kbar using the program Thermocalc v2.3 (Powell & Holland 1988, Holland & Powell 1990) in the KCMASH system ($CaO–K_2O–MgO–Al_2O_3–SiO_2–H_2O–CO_2$) using end-member phases: calcite (cal), vesuvianite (ves), potassium feldspar (kfs), quartz (qtz), diopside (di), wollastonite (wo), anorthite (an), muscovite (ms), CO_2, and H_2O. The equilibria are plotted in Figure 6. The mineral assemblage in the lens is approximately centered around invariant point (I) (ms-absent; wo-present), with $X(CO_2)$ of ~0.2 and T close to 740°C. The field of stability of the whole assemblage is delimited by the reactions forming muscovite on the low-temperature and low-$X(CO_2)$ sides. The shaded area shows the more restricted stability field in terms of T– $X(CO_2)$ for the assemblage kfs + wo + ves (Fig. 6).

The choice of 6 kbar for the T– $X(CO_2)$ calculation is meant to give a representative value for the 4- to 8-kbar range of pressure, at which the assemblage could have formed. The position of the invariant point is dependent on pressure; for example, with a pressure of 8 kbar, the point is moved to 820°C and $X(CO_2)$ = 0.27. This is a slightly higher temperature than the estimated maximum regional temperature of metamorphism, 750–790°C. However, bearing in mind that the calculations have used end-member phases (*i.e.*, are not activity-corrected for real compositions), conditions of

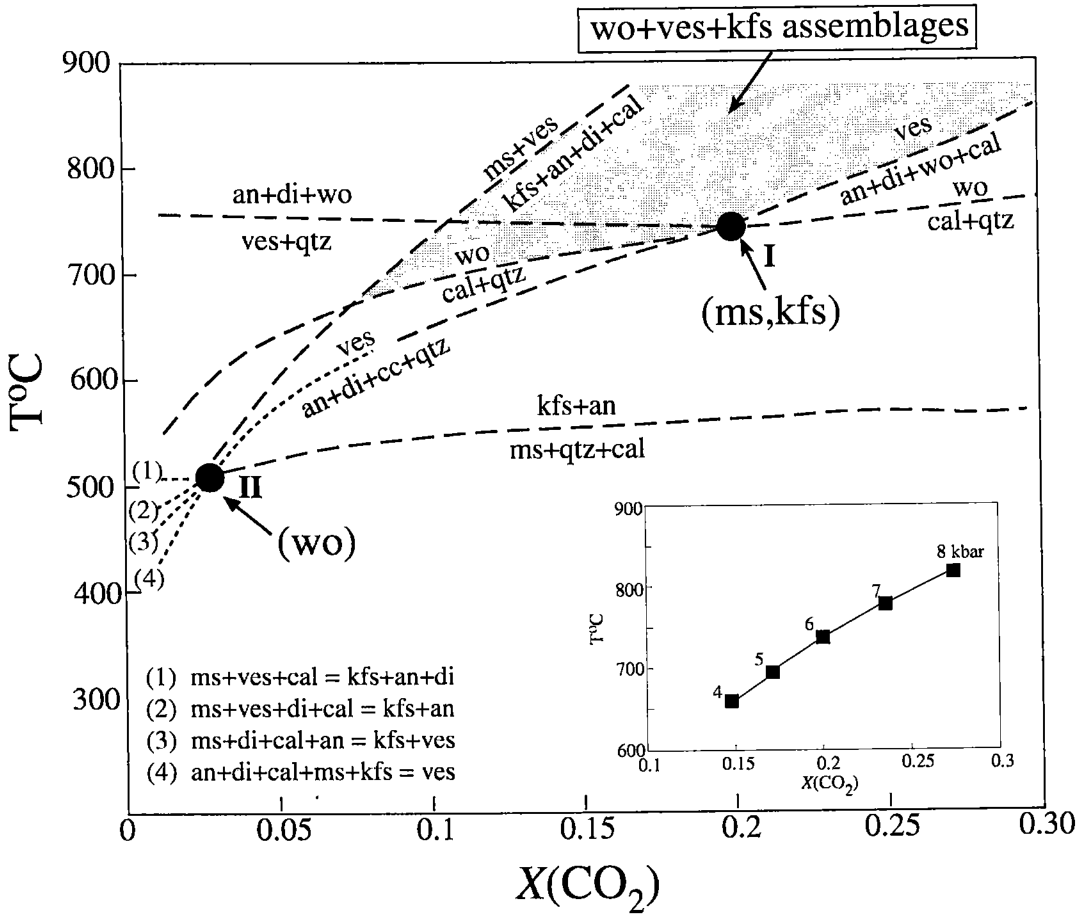

FIG. 6. Calculated univariant T– $X(CO_2)$ equilibria diagram at 6 kbar for the system $CaO–K_2O–MgO–Al_2O_3–SiO_2–H_2O–CO_2$. End-member phases used in the calculations are muscovite (ms), potassium feldspar (kfs), wollastonite (wo), calcite (cal), quartz (qtz), diopside (di), anorthite (an), vesuvianite (ves), CO_2 and H_2O. Invariant point (I): all phases present, ms and kfs absent; invariant point (II): all phases present except wo. Inset shows how position of invariant point I varies with pressure. The shaded area shows the stability field for the critical assemblage kfs–ves.

750–800°C, 6–8 kbar and $X(CO_2)$ in the range 0.2 to 0.27 for the invariant-point assemblage are seen to be consistent with those of regional metamorphism. The fluid phase is thus seen to be H_2O-rich, as noted in other studies on the stability of vesuvianite–wollastonite-bearing assemblages (Valley *et al.* 1985).

The presence of a mineral assemblage that is close to or at an invariant point condition suggests that the fluid composition was "rock"-buffered. This does not eliminate the possibility of infiltration of metamorphic fluid, but may be taken as further support for the notion that there is no involvement of an externally derived fluid.

The "formation water" within the sediments that formed the lens (trapped by the host marble, an impenetrable barrier) may have been locally concentrated by solution-transfer (Durney 1972) into the relatively low-pressure zones that resulted in the formation of the coarse-grained vesuvianite-bearing assemblage.

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