



THE OCCURRENCE AND THERMAL DISEQUILIBRIUM OF CUMMINGTONITE IN PLUTONIC ROCKS OF NAHUELBUTA MOUNTAINS

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INTRODUCTION

The “cummingtonite series” (Leake, 1978) are characterised by magnesio-cummingtonite ($\text{Mg}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$) and grunerite ($\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$) end-members. Cummingtonite is mainly produced under amphibolite-facies conditions, but the entire stability range cover at least a field of 400 to 800° C, at pressures between <1 to 15 kbar (Evans and Ghiorso, 1995, Ghiorso *et al.*, 1995). Natural cummingtonite occurs in several metamorphic rock types (i.e. Kisch & Warnaars, 1969, Choudhuri, 1972) and also can coexist with incipient melt in high-grade gneisses in deep-crustal levels (Kenah and Hollister, 1983). For igneous rocks, cummingtonite had been described in some rhyolites at Taupo Zone, New Zealand (Wood & Carmichael, 1973) and as a stable phase in plutonic rocks (e.g. Bues *et al.*, 2002). In the present study, we describe the occurrence of cummingtonite in Upper Palaeozoic plutonic rocks and their amphibolite xenoliths from the Nahuelbuta Mountains, south central Chile (37°-38°S, for location see fig. 1 in Creixell *et al.*, this volume). We discuss its P-T conditions of formation and its implication for the petrogenesis of Upper Palaeozoic intrusive rocks of the area.

GEOLOGICAL SETTING

Nahuelbuta plutonic rocks containing cummingtonite are part of a Late Palaeozoic orogenic belt, composed by metamorphic and intrusive rocks. Metamorphic rocks are separated into *Eastern* and *Western Series* (Aguirre *et al.*, 1972) which are affected by regional metamorphism developed mainly during Mid to Late Carboniferous times. Granitoids constitute the major part of the *Southern Coastal Batholith* (SCB, Hervé *et al.*, 1987, 1988). In the studied area, plutonic rocks range from quartz-diorites to granites. SiO_2 content varies from 51.4 to 75.9 wt% (Creixell *et al.*, in prep.), following a calc-alkaline trend. Amphibolite xenoliths are mainly concentrated in tonalites and diorites at the northeastern part of the area and are absent in granitic rocks, which contains only metapelitic xenoliths.

OCCURRENCE AND COMPOSITION OF CUMMINGTONITE

Cummingtonite occurs near the towns of Santa Juana and Caramávida, in tonalitic to quartz-dioritic intrusives as well as in amphibolite xenoliths, contained in the intrusives. The plutonic

rocks are mainly composed of plagioclase (An₅₃₋₄₂), calcic amphibole (Fe-tschermakite to Mg-hornblende) with cummingtonite cores (fig. 1), biotite and quartz. Minor K-feldspar (<5%) is also present. Amphibolite xenoliths have a similar mineralogy, with some plagioclase (An₅₄) and calcic amphibole (Al-tschermakite) porphyroblasts in a weakly foliated matrix of quartz + plagioclase + calcic amphibole. *Cummingtonite occurs as relict cores surrounded by Ca-amphibole (fig 1) in both intrusive and metamorphic rocks.* These coronas indicate a disequilibrium state between cummingtonite and intensive conditions of late magmatic or metamorphic paragenesis. Most of the observed crystals show an extensive development of Ca-amphibole lamellae exsolutions, with at least two-preferential orientations (fig 1). Cummingtonites also contain apatite, quartz and ilmenite inclusions. The twenty-two microprobe analyses (EMPA) of cummingtonite show a marked homogeneity in TiO₂, Cr₂O₃, MnO and FeO contents. Low-range heterogeneity can be observed in the SiO₂ content (48.6 to 51.9 wt%), CaO (0.63 to 1.92 wt%), Al₂O₃ (1.6 to 5.1 wt%) and MgO (13.0 to 14.8 wt%). These heterogeneities suggest a possible effect of contamination by fine Ca-amphibole exsolutions that cannot be discriminated by the EMPA beam. CaO, Al₂O₃, K₂O, Na₂O contents can be considered high as compared with exsolution-free analyses of cummingtonite published by Klein *et al.* (1997). Mg/(Mg+Fe²⁺) ratios are largely homogeneous and were apparently not affected by exsolutions; they range from 0.49 to 0.51 in cummingtonite from tonalites and their xenoliths. Cummingtonite from more mafic amphibolite xenoliths is Mg-rich, with Mg/(Mg+Fe²⁺) near 0.57.

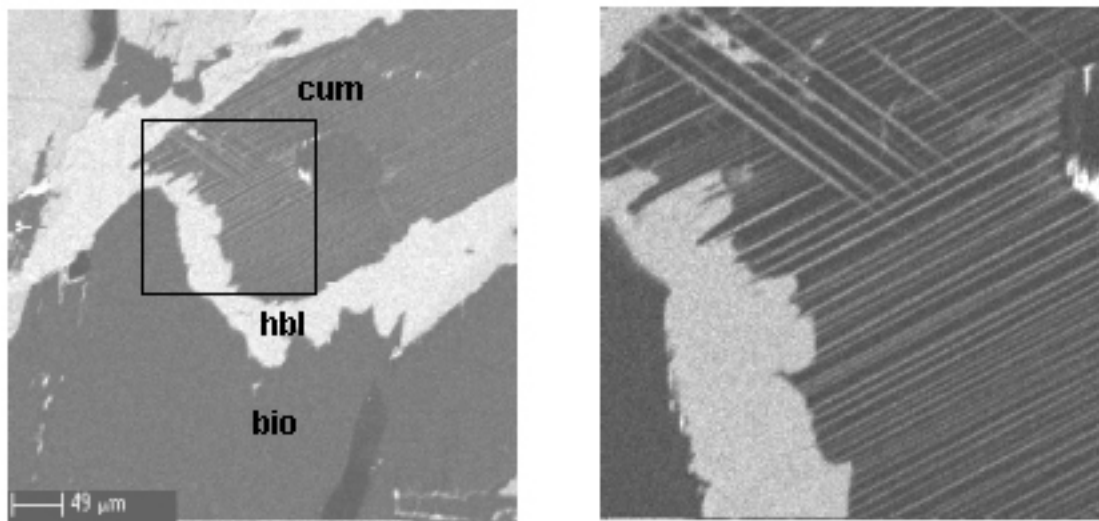
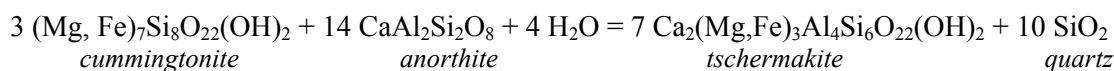


Figure 1: back-scattered electron image for Ca in cummingtonite crystal from a tonalite sample (00-83). Square delimits the area of detailed image to the right, where Ca-amphibole lamellae exsolutions can be observed.

THERMAL DISEQUILIBRIUM OF CUMMINGTONITE

A possible reaction that can explain the formation of the Ca-bearing rims is described by Evans and Ghiorso (1995) for the CMFASH system:



With the aim to know intensive conditions at that the reaction occur, we performed a thermodynamic modelling using the software TWEEQU (Berman, 1991). Although in tonalites,

cummingtonite and tschermakite compositions are relatively well fixed, quartz and water activities are hard to constrain from a single reaction and remain as variables, giving an important state of variance for the equilibrium. Quartz activity can be considered < 1 in tonalites and equals to 1 in the amphibolites, where there is quartz saturation associated to the reaction (quartz neoblasts in corroded plagioclase porphyroblasts). For tonalites, near water saturated conditions ($a_{\text{H}_2\text{O}} \sim 0.9-1$), this reaction occurs at approximately 750 to 790°C in the pressure interval from 3.5 to 5 kbar (curve 2 in fig. 2), assuming $a_{\text{qtz}} \sim 0.7$ (arbitrary). In amphibolites, the same reaction is produced at lower temperature in the amphibolite facies (curve 1 in fig. 2), mainly owing to an increase in quartz activity (= 1). Therefore, thermal stability of cummingtonite is controlled by compositional parameters for different magmatic and metamorphic systems. Effects of $f\text{O}_2$ remain unknown in this case.

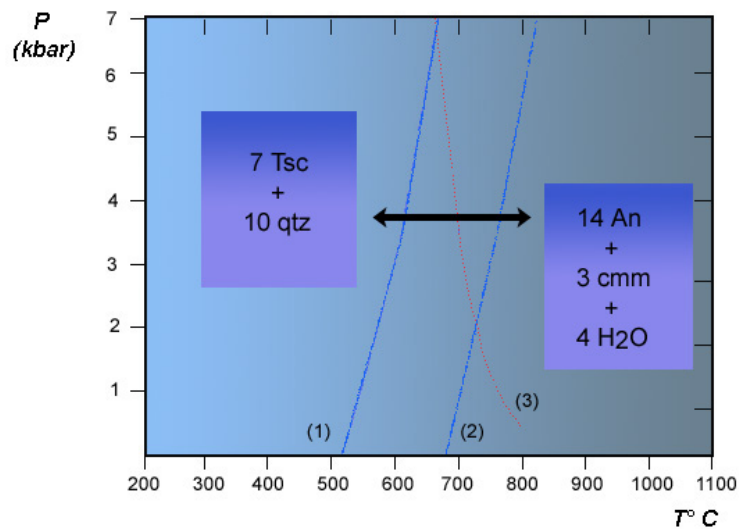


Figure 2: P-T space with the reaction *cummingtonite* + *anorthite* = *tschermakite* + *quartz* modelled with TWQ (Berman, 1991) for amphibolite data (curve 1) and tonalite data (curve 2). Standard state data and solution models for cummingtonite were taken from Ghiorso *et al.* (1995), and are consistent with the database of Berman (1988). Solution models for plagioclase are from Fuhrman and Lindsley (1988), and for tschermakite W parameters of Mader *et al.* (1994). Wet tonalite solidus (curve 3) was taken from Schmidt and Thompson (1996).

PETROGENETIC IMPLICATIONS

The thermodynamic computation of the reaction involving cummingtonite in tonalites and amphibolites can be compared with thermobarometrical data obtained from Ca-amphibole-plagioclase equilibrium (rim compositions, Creixell *et al.*, in prep.). In the tonalites, geothermometry using the equations of Holland and Blundy (1994) and semi-quantitative Ti isopleths of Ernst and Liu (1998), yield temperatures in the range from 688 to 645°C. For Ca-amphibole portions near the contact with cummingtonite, Ernst and Liu Ti isopleths give temperatures from 720 to 670°C (near the hydrated solidus). From the thermobarometrical data, we can interpret that in tonalites, cummingtonite was destabilised at hyper-solidus conditions (~750°C) to form tschermakite and these Ca-amphibole continued to grow to reach final equilibrium near solidus to sub-solidus conditions (688 to 645°C).

The thermodynamic disequilibrium of cummingtonite with respect to the rest of the magmatic system can be result of two different processes, i.e. cummingtonite cores was an early magmatic

phase or represent material incorporated by the tonalitic magma, in both cases destabilised under magmatic conditions. In spite of that there is a very close spatial relationship between the occurrence of cummingtonite in the granitoids and xenoliths, our present data and thermal relations modelled are not sufficient to discriminate about the origin of cummingtonite crystals.

ACKNOWLEDGEMENTS

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