CALCULATED MINERAL EQUILIBRIA FOR ANTHOPHYLLITE-STAUROLITE-GARNET SCHISTS OF THE MORAIS OPHIOLITE COMPLEX (TRÁS-OS-MONTES, PORTUGAL)

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Resumo: O topo da unidade superior do ofiolito de Morais é constituida por metassedimentos marinhos e meta-precipitados químicos, representados por xistos pelíticos (ky-st-g-plag) e antofilíticos (oamp-st-g), que ocorrem imediatamente abaixo da zona de carreamento dúctil que marca o contacto com o terreno alóctone superior. A evolução metamórfica dos xistos antofilíticos é inferida através do cálculo de pseudosecções P-T para composições apropriadas no sistema FeO-MgO-Al_2O_3-SiO_2-H_2O. Estas rochas atingiram T ≈ 630 – 650 ºC e P ≈ 9 – 10 kbar, a que se seguiu arrefecimento (sob descompressão moderada) e intensa re-hidratação das paragéneses de elevada-T. O percurso metamórfico inferido é consistente com o ambiente tectónico dos xistos antofilíticos, onde a sequência ofiolítica é rapidamente sobre-espessada e (inicialmente) aquecida devido à transferência de calor das unidades alóctones superiores (de alto-grau). O arrefecimento subsequente é promovido pela exumação tectónica e por extensa circulação de fluidos, esta última gradualmente focalizada ao longo do carreamento principal (reactivado) e estruturas subsidiárias.

Abstract: The upper unit of the Morais ophiolite preserves marine sediments and hydrothermal chemical precipitates that have been metamorphosed to ky-st-g-plag and anthophyllite (oamp)-st-g schists immediately below the main ductile thrust contact with the upper allochthonous terrane. The metamorphic evolution of the oamp schists is inferred from calculated P-T pseudosections for bulk compositions appropriate for these rocks in the model system FeO-MgO-Al_2O_3-SiO_2-H_2O. The oamp schists experienced a clockwise P-T path that reached T ≈ 630 – 650 ºC and P ≈ 9 – 10 kbar; this was followed by cooling (under moderate decompression) and extensive re-hydration of high-T assemblages. The inferred metamorphic path is consistent with the oamp schists tectonic setting, where the top of Morais upper ophiolite unit was buried and initially heated up because of the downward heat conduction from the overlying (high-grade) upper allochthonous thrust units. Subsequent cooling was promoted both by tectonic exhumation and extensive fluid circulation, the latter progressively focused along the (re-activated) Main thrust zone and subsidiary structures.

1. Introduction

The NW Iberia preserves one of the best sections of the European Variscan Belt. Main tectonic units comprise three stacked allochthonous terranes that, from bottom to top, represent: 1) a poly-orogenic continental sequence; 2) a tectonically dismembered and metamorphosed ophiolite suite; and 3) a basal metasedimentary sequence including different horizons of bimodal metavolcanic rocks. The ophiolitic allochthonous terrane is particularly well represented in the Morais Massif (NE Trás-os-Montes) and is known as the Morais Ophiolite Complex. Detailed fieldwork and petrography (e.g. Ribeiro & Pereira, 1997) enable to divide the Morais Ophiolite Complex in two different units. The anthophyllite-garnet-staurolite schists addressed here are preserved in the upper ophiolite (Morais-Talhinhas) unit. This study provides a new petrogenetic grid for these rocks, enabling P-T pseudosection analysis of their metamorphic evolution path.

2. Geological setting

The examined anthophyllite schists can be observed in the critical Ponte do Azibo outcrop of the Morais Massif, near the confluence of the Azibo and Sabor rivers. Here, along the Main Thrust zone (that locally shows talc infillings), ortogneisses of the upper allochthonous terrane (the Lagoa augen gneisses) were brought to contact with and a strongly deformed rock sequence belonging to the upper unit of the Morais Ophiolite Complex (e.g., Coelho, 2002). The outcropping ophiolite sequence is mainly composed of a thick series of retrograded amphibolites showing a well-defined metamorphic layering. A few meters below the Main Thrust, a narrow sequence of meta-pelites are covered by anthophylllite schists (quite often sulphide-rich) and, together, form a fault-bounded intercalation within the ophiolite amphibolites. The meta-pelites develop three different levels that show slightly textural differences (from granoblastic to grano-lepidoblastic, the latter sometimes banded) and a relatively uniform mineral composition: garnet porphyroblasts (usually comprising quartz inclusions) in a matrix essentially made of quartz, muscovite and plagioclase, including biotite and abundant staurolite and kyanite, largely replaced by late stage chlorite. The upper anthophyllite schist is coarse-grained and includes interstitial chalcopyrite, pyrrhotite and pyrite-marcasite aggregates. The quartz-rich matrix of this rock encloses anthophyllite, (helicitic) staurolite and garnet porphyroblasts; minor ilmenite and biotite are also observed. Garnet preserves (rare) chlorite inclusions and is (locally) seen giving way to staurolite and anthophyllite; late stage chlorite is widespread, replacing the higher-T assemblages. Meta-pelites and anthophyllite schists are interpreted as marine sediments and hydrothermal chemical precipitates on top of an oceanic crustal sequence that have been metamorphosed during Variscan thrusting.

3. Phase equilibria

Metamorphosed mafic rocks, particularly in amphibolite facies terranes, involve high-variance (apparently simple) assemblages, which are stable over large regions of the P-T-X space, making it difficult to obtain precise P-T constraints on their genesis. However, the Morais anthophyllite schists include garnet + staurolite assemblages that have greater potential for constraining equilibration conditions, reaction history and P-T evolution. Calculated mineral equilibria (e.g., Powell et al., 1998) focusing on these assemblages should improve our understanding of the phase relationships as a function of pressure and temperature. The major minerals of interest in this study include those of a "common" assemblage in Ca-Na-K poor, aluminous amphibolites, i.e., anthophyllite-gedrite, chlorite, garnet, staurolite, cordierite, kyanite, sillimanite and quartz; other minor minerals would include ilmenite, sulphides and paragonite, plagioclase and biotite. Among the chemical components necessary to describe the system, Na_2O, K_2O, TiO_2 and S are mainly restricted to one minor mineral (e.g. paragonite/albite, biotite, ilmenite and sulphides) and it may be assumed that they have little effect on the phase equilibria relationships of the major silicate minerals. MnO and CaO may expand the stability of garnet and plagioclase; however, because plagioclase is absent from the studied rocks and garnet has generally low Mn and Ca contents, these components are excluded from the model system. All the remaining components FeO-MgO-Al_2O_3-SiO_2-H_2O (FMASH) are important in reflecting the main compositional substitutions in the principal minerals of anthophyllite schists; quartz and an aqueous fluid are taken to be in excess, so that phase relations among major minerals can be illustrated in an effective ternary system (FMA). End-member compositions of the major minerals (referred above) are listed in Holland & Powell (1998) and solution activity models were taken from Vance & Holland (1993), Holland et al. (1998) and Arnold et al. (2000). We address the dependence of the phase relations in anthophyllite schists on P, T and bulk composition using the software THERMOCALC (Powell et al., 1998); THERMOCALC version 3.21 is used with the internally consistent thermodynamic database of Holland & Powell (1998). The program allows direct calculation of phase compositions along boundary lines/reactions, points and fields of any variance in P-T space; however, the relative stability of univariant and invariant equilibria are determined, manually, by applying Schreinemakers Rule (e.g. Zen, 1966) to the univariant lines around each invariant, then putting the invariant points together. The P-T projection for FMASH (fig. 1A) shows the univariant and invariant equilibria for all bulk compositions that have excess quartz + H_2O. The P-T grid in figure 1(A) includes 4 invariant points (3 on the ky-sill univariant); Schreinmakers analysis makes sense with [cd, sill] at high-P and [cd, chl] at high-T. The large stability field of the critical assemblage staurolite-anthophyllite is dominated by the univariants chl + g = st + oamp and st + oamp = g + ky/sill. Using the AFM (+ quartz + H_2O) projection for FMASH, a series of compatibility diagrams is given in figure 1(B). As usual with P-T projections, the compositions of the phases vary along the univariant reaction lines and ferromagnesian minerals are seen to become more Mg-rich with increasing pressure; compositions of the phases at invariant equilibrium [cd, sill] are given in Table 1.

Table 1: P-T conditions and mineral compositions at invariant [cd, sill] in fig. 1(A)

P(kbar)	T(°C)	x(chl)	y(chl)	Q(chl)	x(st)	x(g)	x(oamp)	y(oamp)
11.79	633.5	0.3168	0.5517	0.4482	0.7552	0.7364	0.4767	0.1993

x (i) = Fe/(Fe+Mg); y(i)= Al on M2; Q(chl) = order parameter (Holland et al.,1998)

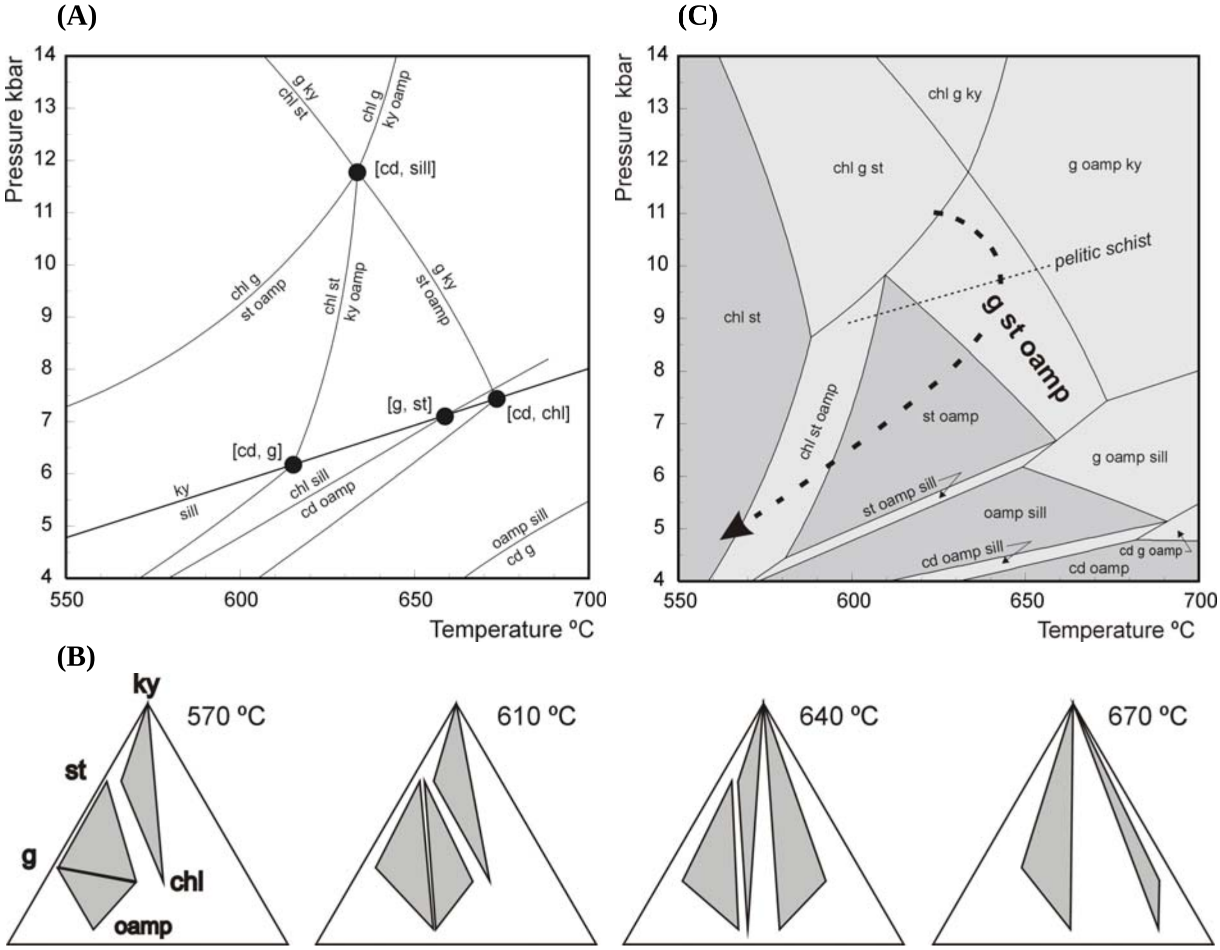

Figure 1 – (A): *P-T projection for the system FMASH with quartz + H_2O in excess; solid circles = invariant points, labelled with the absent phases in square brackets (cd cordierite; chl chlorite; g garnet; ky kyanite; oamp anthophyllite-gedrite; sill sillimanite; st staurolite).* **(B):** *Schematic representation of AFM (+ quartz + H_2O) compatibility diagrams for divariant assemblages at 9 kbar.* **(C):** *P-T pseudosection for a typical anthophyllite schist bulk composition (Al_2O_3:MgO:FeO = 23.69: 34.52: 41.79); divariant (3 phases) and trivariant (2 phases) fields are characterized by different shades of grey. P-T relationships for plagioclase (an 30%) + garnet (gr 15 %) + kyanite + quartz equilibrium in associated st-ky-g pelitic schist (see text) are also shown. Thick dashed line = inferred P-T path for anthophyllite schists.*

Pseudosections involve the invariant and univariant equilibria they inherit from P-T projections, as well as additional boundary lines and points (see Powell et al., 1998). A significant advantage of P-T pseudosections is that the bulk rock composition serves as an additional constraint, implying that the inherited equilibria are just those parts of the P-T projection that are relevant to the bulk composition being considered. Thus, by using pseudosection analysis, the sequences of mineral assemblages inferred from thin section observation can be compared with the thermodynamically predicted P-T stability fields of these assemblages on the pseudosection, which is calculated for that particular rock composition. A P-T pseudosection for a typical anthophyllite schist bulk composition is shown in figure 1(C). A prominent feature of figure 1(C) is the large number of divariant fields (which are widespread over the P-T space); this is the topological reflection of the anthophyllite schist bulk composition, which has "seen" 2 invariant {[cd, chl], [cd, sill]} equilibria, as well as several univariant reactions (8). The large divariant field involving garnet, staurolite and anthophyllite (fig. 1C) represents the P-T conditions at which the main part of the anthophyllite schist developed. Within this divariant field it is difficult to define the precise P-T conditions at which the mineral assemblage developed. However, by combining mineral chemistry and modal contents of anthophyllite schists with geobarometric constraints from the associated meta-pelites (see fig. 1C), it is inferred that peak metamorphic conditions reached ≈ 630 ºC - 650 ºC at 9 – 10 kbar. Petrographic observations provide further constraints on the P-T metamorphic path. Thus, early chlorite inclusions preserved in garnet are best illustrated by the divariant field chlorite – staurolite – garnet, (located at the high-P end of the inferred P-T path; fig. 1C), suggesting that the rocks underwent prograde heating and decompression, before reaching the thermal peak. Subsequent (partial) replacement of garnet by staurolite + anthophyllite (in the absence of sillimanite) and late (widespread) development of chlorite require initial cooling under moderate decompression, such that the rocks remained at depth, below the staurolite-anthophyllite-sillimanite stability field (fig. 1C).

4. Discussion and conclusions

The upper unit of the Morais ophiolite preserves marine sediments and hydrothermal chemical precipitates that have been metamorphosed to kyanite-staurolite-garnet-biotite-plagioclase and anthophyllite-staurolite-garnet schists, respectively, immediately below the main ductile thrust contact with the upper allochthonous terrane (Lagoa augen gneiss). The metamorphic evolution of the anthophyllite schists is inferred from calculated P-T pseudosections for bulk compositions appropriate for these rocks in the model system $FeO\text{-}MgO\text{-}Al_2O_3\text{-}SiO_2\text{-}H_2O$. The anthophyllite schists experienced a clockwise P-T path that reached T ≈ 630 – 650 ºC and P ≈ 9 – 10 kbar; this was followed by cooling (under moderate decompression) and extensive re-hydration of the high-T assemblages. The inferred P-T metamorphic path is consistent with the tectonic setting of the anthophyllite schists, at the top of the Morais upper ophiolite unit; this was rapidly buried and initially heated up because of downward heat conduction from the overlying (high-grade) upper allochthonous thrust units. Subsequent cooling should have been promoted by tectonic exhumation and extensive fluid circulation. The latter was increasingly focused along the Main Thrust zone and its subsidiary structures; these were generated during succeeding re-activation events, as recorded by the late development of talc lenses.

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