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Early deformation and metasomatic evolution of the Barranco da Gravia metagabbros as recorded by amphibole and plagioclase chemistry[1]

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Palavras-Chave: Complexo Ofiolítico de Beja-Acebuches; metagabros; condições P-T de deformação e metamorfismo varisco.

Resumo: A caracterização mineralógica e textural dos metagabros pertencentes ao COBA revela que estas rochas foram alvo de recristalização precoce sob condições de elevada T (800-900ºC) e baixa P (< 5 kbar) e posteriormente objecto de metamorfismo na fácies anfibolítica (600-620ºC), por vezes seguido de retrogradação para condições de transição entre as fácies anfibolítica e xistos verdes alta (450-500ºC). Os últimos estádios deste percurso de arrefecimento são correlativos da génese das zonas de cisalhamento precoce em regime de transição semi-dúctil – semi-frágil. O reconhecimento de todas estas características permite distinguir as rochas metagabróicas do BAOC dos gabros constituintes do Complexo Ígneo de Beja.

Key-words: Beja-Acebuches Ophiolite Complex; metagabbros; P-T conditions of variscan deformation and metamorphism

Abstract: The characterization of mineral paragenesis and textural features displayed by metagabbros of BAOC reveal that these rocks experienced an early recrystallization event under high-T (800-900ºC) and low-P (< 5 kbar) conditions, and were afterwards subject to metamorphism of amphibolite facies (600-620ºC), followed in some places by retrogradation to transitional amphibolite – high-T greenschist metamorphic conditions (450-500ºC). The last stages of this cooling path are coeval with the genesis of the earlier semi-ductile – semi-brittle shear zones. The recognition of all these features enables the distinction between metagabbroic rocks of BAOC and gabbros of the Beja Igneous Complex.

INTRODUCTION

The intermediate section of the reconstructed ophiolite sequence outcropping in the Beja-Acebuches belt is mainly composed of metagabbroic rocks, forming the Barranco da Gravia Unit in the Guadiana Valley area (*e.g.* FONSECA, 1995). According to QUESADA *et al.* (1994), the entire succession shows evidence for an early recrystallization event under high temperature and low pressure conditions (coeval to an early, north-directed penetrative fabric), and was afterwards subject to metamorphism under amphibolite facies conditions, followed in some places by retrogradation to transitional amphibolite – high-T greenschist metamorphic conditions. The first event of the outlined evolution is tentatively ascribed to the ophiolite hot emplacement (D_1 phase of deformation) and the lower grade metamorphic episodes to the collisional stage of the Variscan orogeny (D_2 and succeeding deformation phases).

This study addresses the chemical behaviour of some main primary silicates (such as plagioclases, clinopyroxenes and amphiboles) during metamorphism, in the basic rocks of BAOC. Mineral chemistry and other essential petrographic data (particularly of microstructural nature), are evaluated to unravel the relationships between metamorphism and shear zone development in these rocks and the physical and chemical conditions associated with the Variscan orogenesis.

GEOLOGICAL SETTING

Samples were collected at Melrinas, Moinho dos Machadinhos and Sete Pés in the Guadiana Valley. Left-lateral shear zones, generally striking WNW-ESE and dipping North, are common in this area, are underlined by polyphasic carbonate-silica hydrothermal precipitates, and bring to contact distinct sections of the ophiolite sequence.

Detailed mapping and geological reconnaissance of the surrounding areas revealed a complex network of shear zones whose development can be assigned mainly to D_2 and D_3 deformation phases previously identified in BAOC (*e.g.* GONÇALVES *et al.*, 1997). The meso- and macrostructures ascribable to the late-D_2/D_3 deformation events are the best preserved, and comprise mainly semi-brittle to brittle ENE-WSW shear zones. This system, which experienced late polyphasic reactivation with transcurrent left-lateral movement, clearly post-dates the development of (syn-D_2) N120 ductile to semi-ductile shears subparallel to the major WNW-ESE accidents. Right-lateral N-S shear zones seem to be the latest expression of the Variscan deformation, being usually associated with D_3 or late-D_3 structures.

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There is a deformation continuum between all the above tectonic events, giving rise to a complex pattern of shear zones, closely associated with severe mineralogical transformations in the metagabbroic rocks. Indeed, the development of amphibole and plagioclase, with or without quartz precipitation, is restricted to these shear zones, which in turn record several yielding events during D_2 deformation. Of particular interest are the early-D_2 NNW-SSE left-lateral shear zones which, most probably, led to the development of the earlier microstructures observed and of several right-lateral syn-D_2 ENE-WSW shears and their N-S conjugates, locally marked by mylonitic textures.

MACRO- AND MICROSCOPIC FEATURES OF THE EXAMINED METAGABBROIC ROCKS

The examined metagabbroic rocks (mainly former gabbros and gabbronorites) consist essentially of Ca-rich plagioclase, relics of diopsidic clinopyroxene and brown hornblend; ilmenite and titanium-rich magnetite, sometimes accompanied by small amounts of badly preserved olivine, and disseminated sulphides (mostly pyrrhotite, chalcopyrite and pyrite), are the main accessory minerals. In these rocks, metamorphic textures are dominantly grano-nematoblastic; extremely fresh samples from Moinho dos Machadinhos display typically a granoblastic texture with tiny variations resulting from the presence of subidioblastic amphibole (which often shows a decussate texture), and from mineralogical transformations caused by successive metasomatic events that modify (sometimes severely) primary relationships.

The granoblastic texture is most of the times due to the presence of interlocking irregular/equigranular crystals of plagioclase that display rare serrated boundaries, but usually show bent or kinked twin lamellae, deformation bands and wavy extinction; the ubiquitous twinned crystals also show periodic to quasi-periodic exsolution lamellae substructures (segregation bands). The mechanical origin of the plagioclase twins is clearly demonstrated by: 1) the lenticular shape of most lamellae, wedging out within the grains; 2) the occasional development of twin lamellae restricted to marginal areas, especially in boundary domains where stress concentration might be expected; and 3) the spatial coexistence with other optical features or microstructures due to intracrystalline plastic strain. Two different twinning laws are observed; and tentatively identified as the albite and pericline laws. There is no textural evidence for subgrain development; recrystallized annealed grains of plagioclase are also absent.

Primary clinopyroxene and brown amphibole are usually corroded and partially substituted by greenish amphiboles + quartz and chlorite + quartz, respectively, which appear to be synchronous of non-twinned plagioclase rims around the earlier deformed crystals of this silicate. All these mineral transformations occurred apparently before the genesis of the NNW-SSE semi-ductile – semi-brittle shear zones, which sometimes comprise remnants of mylonitic rocks developed under temperature and stress conditions that have simultaneously favoured brittle behaviour of plagioclase crystals and strong plastic deformation followed by dynamic recrystallization of quartz aggregates; local fluid inflows, coeval with or later than the strain accommodation (via geometrical or chemical softening) trigger plagioclase saussuritization and quartz + chlorite deposition. Within the mylonitic rocks, asymetric sigma structures demonstrate a left sense of shear, relating these structures to the macrocospic NNW-SSE early-D2 shears. Subsequent low-temperature reactivation of these shear zones enabled the development of microstructures typical of brittle regime, easily correlated with those present in the adjoing metagabbroic rocks. Most are fractures filled by chlorite ± carbonate which show a wide range of directions making it difficult to relate them unambigously to the macroscopic late fractures and shears. Nevertheless, it must be emphasized that the ENE-WSW-striking fractures are responsible for local cataclasis in several plagioclase crystals; their shear sense was not determined. The NE-SW fractures show left sense of shear, as indicated by the development of en échelon tension gashes is some plagioclase crystals. Finally, a set of N-S fractures is observed without any noticeable microstructures present.

MINERAL CHEMISTRY

Primary amphiboles (brown hornblendes) are generally characterized by SiO_2 values ranging from near 43.0 to 49.0 wt% and relatively homogeneous CaO and Cr_2O_3 values (10.6-11.9 wt% and 0.0-0.1 wt%, respectively); they also have relatively higher TiO_2 (1.04-2.34 wt%) and alkali concentrations ($0.77 \leq Na_2O \leq 1.95$ wt% and $0.17 \leq K_2O \leq 0.48$ wt%) than late amphiboles. The latter (Mg-hornblendes – actinolites-tremolites) have SiO_2 values in the range ≈ 48.0-56.0 wt%, and are commonly relatively enriched in MgO (14.2-21.9 wt%), showing extremely variable CaO and Al_2O_3 values (0.8-12.2 wt% and 1.0-5.4 wt%, respectively). These major compositional differences suggest that the chemical variability of brown hornblendes represents a primary (magmatic) feature, whereas for late amphiboles it is due not only to the chemical nature of the primary clinopyroxene, but also to the metamorphism experienced.

It should be stressed that clinopyroxenes are only preserved as magmatic relics. Their chemical composition is fairly homogeneous, showing only slight variations from core to rim of individual crystals; they are typically diopsidic pyroxenes (21.5 ≤ CaO ≤ 22.9 wt%; 13.6 ≤ MgO ≤ 14.2 wt%) with little Al_2O_3 (≤ 2.4 wt%) and almost no TiO_2 (≤ 0.5 wt%). Thus, their transformation during the main stage of Variscan metamorphism would preferentially give rise to Mg-hornblendes which grade further into actinolitic compositions as temperature decreases.

A general review of the available chemical data for plagioclases together with the petrographic information, shows that those typical of metaggabbroic rocks outcropping at Sete Pés and Melrinas display weak chemical zonation and a relatively constant anorthitic content (ranging from An_{56} to An_{59} on average); the obtained deviations from the ideal compositional lines are most of the times within analytical errors. Conversely, the plagioclases included in characteristic metagabbroic rocks of Moinho dos Machadinhos are zoned, exhibiting tenuous chemical variations in undeformed core domains (An_{60} to An_{58}) and An-poor rims of variable composition (usually ranging from andesine, adjoining the deformed cores, to oligoclase, in the outer domains of the crystal); note that the rims just referred to are compositionally similar to the non-twinned and undeformed plagioclase aggregates that usually fill up some relatively late irregular microfractures, and that many segregation bands have oligoclase composition.

A comprehensive examination of the available analytical data for plagioclases included in metagabbros of the Moinho dos Machadinhos sector, also reveals that more or less significant chemical variations (particularly concerning Si and Al distributions) are observed in some of the undeformed crystal cores. Subsequent hydrothermal metasomatism, often controlled by microfracturing, may as well lead to evident chemical changes in the plagioclase, as documented by some strongly corroded and/or fractured crystals. It must be emphasized, however, that all these compositional deviations apparently do not follow any consistent tendency, which makes it difficult to determine any particular chemical trend for each case.

DISCUSSION

The intermediate section of the BAOC sequence consists mainly of metagabbroic rocks (essentially former gabbros and gabbronorites), whose primary mineral assemblage comprises Ca-rich plagioclase + diopsidic clinopyroxene + brown hornblend + ilmenite + titanium-rich magnetite ± olivine ± sulphides (mostly pyrrhotite, chalcopyrite and pyrite). Detailed petrographic characterization of these rocks, shows that a tectonic fabric, representing an early phase of deformation (labelled D_1 – *e.g.* QUESADA *et al.*, 1994) is preserved in some places of the Beja-Acebuches belt. According to QUESADA *et al.* (1994), this tectonic fabric was formed under pressure conditions below 5 kbar and initial recystallizing temperatures of 800-900ºC, as may be deduced from the occurrence of Ca-plagioclase, olivine, ortho- and clinopyroxene, from the chemical composition of pyroxenes and from the absence of coronitic garnet/spinel on plagioclase; this tectonic event is tentatively ascribed to the hot emplacement of the ophiolite. The examined metagabbroic rocks from Sete Pés, Melrinas and Moinho dos Machadinhos are probably more differentiated, because olivine and orthopyroxene are scarce, but this cannot be confirmed by chemical data on these minerals due to their extreme alteration. Nevertheless, the evaluation of the "exact" conditions under which plagioclase intracrystalline deformation took place (inferred from the presence of wavy extinction, bent or kinked twin lamellae, deformation bands, quasi-periodic exsolution lamellae substructures, and of mechanically twinned grains) may provide some complementary information about the physico-chemical environment of the D_1 deformation phase.

Comparison of the published data set on plagioclase with the main microstructural characteristics shown by this silicate in the observed metagabbroic rocks, suggests that two different twin laws are present. If, as usual, the albite law predominates over the pericline law, then mechanisms involving dislocation pile-ups on (010) slip planes would have been favoured, since the albite and pericline laws require almost the same amount of macroscopic shear deformation, there is no inhomogeneous global chemical composition of the plagioclase, as is shown by the relatively constant chemical compositions obtained, and there is no reason to admit a primary preferred orientation of the crystals. There is no evidence for subgrain development and recrystallized annealed grains seem also to be absent. Therefore, one may conclude that the temperatures under which the earlier deformation phase took place did not favour either the recovery mechanisms of plagioclase (promoted by the stability of intermediate disordered structures), or the chemical nucleation of deformation-free crystals accomplished by strain enhanced diffusion rates during later (after D_1 deformation) static recrystallization processes. Since these features are not observed in the most recrystallized gabbroic rocks, we interpret the relatively dry environment and minimum temperatures ranging from 550 to 600ºC that may be inferred from them as a record of the final stages of the high-T recrystallization event referred to by QUESADA *et al.* (1994). This interpretation is corroborated by the lack of significant boundary diffusion leading to static recrystallization, indicating that these temperature conditions did not last a very long time.

Subsequent mineral transformations, involving mainly some chemical re-adjustments of primary plagioclases, clinopyroxene alteration and quartz deposition, mark the onset of variscan metamorphism, prior to the development of the earlier semi-ductile – semi-brittle shear zones.

In general, plagioclases display weak oscillatory core zonation and An-poor rims (particularly well developed in metagabbros of Moinho dos Machadinhos). This oscillatory zonation from, on average, An_{56} to An_{60} is believed to be a remnant of the magmatic stage. The inner rims, with andesine compositions, should represent the initial metamorphic re-equilibrium; the outer rims of oligoclase might therefore result from the subsequent cooling stage. Pyroxenes are only preserved as magmatic relics; the dominant pyroxene is chemically fairly homogeneous and has diopsidic composition with little Al and almost no Ti. It was gradually transformed in Mg-hornblendes in the course of the initial stages of Variscan metamorphism. During retrogradation, the metamorphic amphibole formed has actinolitic compositions, and is correlative of the later plagioclase growth. Applying the amphibole-plagioclase geothermometer of HOLLAND & BLUNDY (1994) to the pair andesine bands in plagioclase crystals and Mg-hornblende, temperatures around 600-620ºC will be obtained for the initial stages of the variscan metamorphism. Temperatures ranging from 450 to 500ºC are obtained for coexisting actinolites and oligoclase rims, which is consistent with the observed breakdown of primary amphiboles and with the estimations of QUESADA *et al.* (1994) for the greenschist-amphibolite transitional mineral assemblages of BAOC (400-500ºC under pressure conditions not exceeding 2-3 kbar).

The genesis of the earlier semi-ductile – semi-brittle shear zones should have occurred during the last stages of the above mentioned cooling path, as documented by brittle deformation of plagioclase crystals coeval with plastic deformation and dynamic recrystallization of quartz aggregates, which denotes a most probable temperature of 350-400ºC. Under these thermal conditions, quartz + chlorite deposition and the more or less evident plagioclase saussuritization are ascribable to syn- and/or relatively late fluid inflows into these structural corridors. Later reactivation of these corridors enables the development of typical brittle microstructures and the deposition of chlorite and carbonate aggregates somewhat enriched in quartz. These late microstructural re-adjustments and their correlative mineral paragenesis, reflecting temperatures below 300ºC, can easily be correlated with the final mineral and textural alterations experienced by the adjoing metagabbroic rocks.

As a final remark it should be emphasized that the deformation history recorded by metagabbroic rocks of BAOC is longer than the one presented by primitive gabbros of the Beja Igneous Complex (BIC). The main deformation phase recorded in the former rocks is underlined by a conspicuous mineral stretching lineation materialized by parallel elongated non-igenous (green) Mg-hornblende crystals, which trends subparallel to the magmatic fabrics often displayed by the later gabbros. Therefore, if both the magmatic fabric of BIC gabbros and the structural fabric of BAOC metagabbros are taken to be the expression of the same deformation event (*e.g.* SILVA, 1997), then a gros temperature inconsistency appears, which, however, may be easily removed postulating a model where the initial stages of BIC intrusion occurred during the variscan orogenic metamorphic peak.

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