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Full Length Research Paper

Chemical Mobility and Mineralogical Variability in the Mica Schists of Edough Massif (Annaba, Northeast Algeria)

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ABSTRACT

Mineralogical as well as compositional changes are often due to changes in metamorphic grade. The insignificant changes of thermo-barometric conditions of the mica schists did not influence the mobility of the elements. The slight variation in bulk rock composition and the homogeneity of the alteration index allow to exclude alteration as major process for mass transfer and change of the phase assemblages encountered along the section. The mica schists however experienced strong tectonic constraints with increasing strain along the E-W transect. The isocons show that Si, Fe, Al and K where mobile during deformation and the transformation from garnet mica schists to andalusite mica schists. This transition leads to loss of Fe and gain of Al, Si and K. The element mobility correlates with deformation that favored fluid circulation and the growth of andalusite in the zone of strongest shear stress.

Key words: Isocons, Metamorphism, Mass transfer, *Edough Massif*, Algeria

1. INTRODUCTION

The *Edough Massif*, located in the oriental part of the Algerian coastline, is a dissymmetric "core complex" (Caby & Hammor 1992) oriented NE-SW with a length of about 50 km and a width of 20 km (Figure 1). The conditions of metamorphism, geochronology and geology studies of the massif have been the subject of several papers (Hilly, 1962; Gleizes et al. 1988; Ahmed-Said & Leake 1993; Laouar et al. 2002). The *Edough* metamorphic rocks consist of two tectonically superposed units composed of gneiss (the lower unit) and mica schists (the upper unit). The metamorphic assemblages indicate high temperatures for both units and show that the lower unit recorded medium pressure conditions, whereas the upper unit showed lower pressures. Characterization and quantification of mass transfer by fluids is based on research of mineralogical and chemical witnesses. The presence of metastable minerals indicates an incomplete re-equilibration to metamorphic conditions. Deformation and P-T condition are very important factors in the process of re-equilibration because they have the effect of accelerating or slowing down chemical processes and can influence the redistribution of fluids in the rocks. The studied zone is characterized by variations of mineralogical composition of the rocks, which may be related to variations of deformation (schistosity and

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foliation). This paper aims to evidence fluid rock interaction in the mica schists of the upper unit.

2. GEOLOGICAL BACKGROUND

The core of the *Edough Massif*, so-called "lower unit" is composed of biotite gneiss and two mica augen-gneiss of Neoproterozoic age (Hammor & Lancelot 1998). The gneisses are altered diatexites and have an arkosic origin (Hadj Zobir & Mocek 2012, Hadj Zobir 2012). They sometimes contain benches of leucogneisses and marbles (Hilly 1962; Gleizes et al. 1988; Ahmed-Said & Leake 1993) (Figure 1). Overlying the gneiss a so-called "intermediate unit" is composed of garnet mica schists with kyanite, sillimanite and andalusite mica schists and metric benches of marbles. The uppermost unit, "alternating series", is composed mainly by an alternation of feldspathic quartzite and aluminous *mica schist* with some andalusite levels.

The sedimentary envelope of the metamorphic massif is allochtone. It is represented by flysch facies: the Cretaceous flysch, composed mainly of dark blue schistose argillite, alternating with benches (20 to 50 cm) of sandy limestone, blue-grey micro-breccieted limestone of Maestrichtian age (Marignac & Zimmermann 1983) and the Numidian formation of Oligo-Miocene age (Lahondère et al. 1979) that corresponds to a quartzic sandstone formation with thin clayey levels (Hilly 1962). The metamorphic rocks and the sedimentary formations have been cut up during Miocene (Langhian) by magma of high to intermediate acidic composition and rhyolitic to microgranodioritic subvolcanic rocks (Figure 1).

The *Edough Massif* underwent a polycyclic metamorphism characterized by three major events (i) a high grade metamorphism (HT-HP) corresponding locally to conditions of the granulites facies, (ii) an intermediate degree of prograde metamorphism (MP-MT) and (iii) a low-pressure – high-temperature (Brunnel et al. 1988; Ahmed Said & Leake 1993; Caby et al. 2001). The different metamorphic units underwent first oblique deformation characterized by syn-metamorphic folds followed by flexural shear generating upright folds of N140° direction, anticlines with direction N50° to N60° and shear senses of N120° to N160° direction. The rocks of the *Edough Massif* present foliations and lineations that show deformation along gently dipping planes.

3. ANALYTICAL METHODS

A subset of 5 samples out of ten was chosen for analysis at the Center of Research and Development (CRD), SONATRACH (Boumerdes, Algeria). The major element compositions were determined by X-ray fluorescence (XRF).

4. RESULTS AND DISCUSSION

4.1. *Whole-rock and samples description*

Whole-rock samples have been systematically collected across the mica schists showing variable deformation and change in mineral composition. The sampling was done at 10 meters distances along an E-W section.

The studied area is characterized by monotone mica schists. In these biotite mica schists we note the successive apparition, from east to west, of new specific minerals, indicators of a metamorphic gradient such as garnet, staurolite, and andalusite. Foliation varies from NE-SW to E-W respectively from east to west. The eastern part of the studied zone with a NE-SW foliation is characterized by an abundance of white micas, some garnets and rare biotite. The coexistence of rare biotite and white micas indicates a relatively low degree of metamorphism. These rocks (sample

E36) are the least deformed and least metamorphosed of the whole section. The middle part of the studied section (samples E37'a, E37", E38) is characterized by the development of staurolite and small pockets of pink andalusite, associated with quartz, some biotite and rare muscovite. The western part showing E-W foliation (sample E41), is characterized by biotite and pockets of pink andalusite, associated with clear, transparent quartz (exudates ≥ 5cm in diameter) as well as feldspathic "nodules". Some lithologic levels carry indication of more intense deformation. Farther to the west of the study area, feldspar associated with andalusite is abundant and coexistence of sodic and potassic feldspar is observed.

Sample E36: is a garnet *mica schist* (Figure 2a) representing the protolith with the weakest deformation and thus metamorphic conditions representative for the area. Major phases found in this sample are garnet, white mica, biotite quartz and as accessory staurolithe. Garnet is only found in this sample (E36). It generally forms transparent; millimeter sized globular crystals that may comprise corroded rims: Rare biotite coexist with muscovite and form aureoles around garnet. Staurolithe s extremely rare in this samples and only one crystal was found in the thin section. This slightly deformed mineral is homogeneous.

Samples E37'a, E37" and E38: these samples stem from the central part of the section and are characterized by the growth of andalusite and feldspar while garnet disappears. Staurolithe and biotite are more abundant than in sample E36 (Figure 2b, 2c). Muscovite seems to be consumed by biotite. Andalusite forms small rose crystals, which are associated with quartz and potassic feldspar. The size of the staurolithe crystals augments.

Sample E41: this sample represents the zone with the strongest deformation and exhibits a mineralogical composition similar to samples E37'a, E37" and E38. The mica schists of this zone show andalusite phaenoblasts from 2 to 3cm, potassic feldspar and quartz. The difference to the other samples is obvious from the abundance of andalusite, staurolithe, potassic feldspar and biotite (Figure 2c). Twinned plagioclase is albitic and occurs as randomly distributed laths. Orthoclase dominates over plagioclase and the blasts are often broken. Biotite forms layers of various lengths which may attain 1cm.

4.2. whole-rock chemistry and chemical alteration

The successive petrographic samples contain variable element abundances (Figure 3). At the centre of the section a clear decrease of SiO_2 (62.08 – 66.89 wt%) is obvious. The highest values (69.12 wt%) can be found in sample E36 while E41, the sample with the strongest deformation contains less SiO_2 (67.46 wt%). This variation expresses the mobility of silica and explains the frequent formation of quartz exudates in the zone of strong deformation. The drop of Fe_2O_3 (7.88 – 4.82 wt%) and MgO (1.54 – 0.94 wt%) in the intermediate part goes along with disappearing of ferromagnesian minerals like garnet, while the drop of Al_2O_3 (17.70 – 16.64 wt%), CaO (0.44 – 0.41 wt%), K_2O (4.27 – 2.96 wt%), and Na_2O (1.37 – 1.08 wt%) correlates with the decrease of aluminous and alkaline minerals. The most deformed sample E41 is characterized by high values of Al_2O_3 (18.69 wt%) and K_2O (4.8%) corresponding to its mineralogy (large andalusite crystals and potassic feldspar).

The chemical evolution (Table.1) of the samples shows two rock groups (Figure 4): a first group that encloses samples E36, E37'a and E37", corresponds to weakly deformed rocks and low metamorphic grade. The second group with samples E38 and E41 corresponds to highly deformed rocks. The mica schists show a relatively homogenous chemical composition. The rocks are rich in Al_2O_3 (13.54 – 18.69%) and K_2O (3.02 – 4.8%), but show low contents of CaO (1.7 - 0.66) and Na_2O (1.5 – 1.54%). The distribution of major elements along the section, from little to strongly deformed rocks show a zigzag trend suggesting mass transfer due to chemical alteration, metamorphism or deformation. During chemical alteration Ca, Na and K are preferentially leached (Nesbitt & Young 1982). These elements are thus good indicators of alteration processes. The chemical alteration index (CIA) (CIA = Al_2O_3 / (Al_2O_3+CaO+Na_2O+K_2O) (Nesbitt & Young 1982) of the mica schists is elevated but shows only a low degree of variation: CIA_{E36} =0.69, $CIA_{E37'-E38}$ =0.74-0.79 and CIA_{E41} =0.74. These show that the weathering effect was insignificant and cannot be the cause of the mineral variations.

4.3. *Thermo-barometry*

P-T condition were calculated using the program THERIAK-DOMINO version 140205 of C. de Capitani (2005), using the database Jun92.bs (Berman et al. 1985; Perkins et al. 1986). The *mica schist* register temperatures in the range 500–600 °C (Figure 5). The least transformed sample (E36) containing garnet, white mica and biotite equilibrated at 500-550 °C and 0.15 – 0.25 GPa (Figure 5a). According to our model data the rocks from the middle part of the studied section registered temperatures from 500-525° C (samples E37'a) to 525- 575°C (sample E38). The most transformed sample E41 containing andalusite, staurolite and biotite points towards equilibration at T: 500-550°C, P: 0.15-2.5 GPa (Figure 5b). Thus calculations of stable assemblages using the bulk rock composition of the least and the most deformed *mica schist* and assuming equilibrium conditions indicate a homogenous P-T evolution, the effect of which was insignificant as far as mobility of the elements is regarded. The thermodynamics result shows that metamorphic conditions did not cause the mineralogical variability observed in the studied mica schists.

4.4. *Mass Transfer*

The chemical evolution from the less deformed rocks to a more deformed imprint expresses a transfer of matter evidenced by the appearance of biotite, andalusite or the disappearance of muscovite and garnet. The degree of deformation and mineralogical change of the rock is obvious from the enrichment or impoverishment of some elements and in the conservation of others. In the study area the deformation appears progressive and develops from East to West. Grants (1986) isocon method has been used to calculate mass transfer. Sample E36 has been taken as reference because it presents the lowest degree of metamorphism, deformation while bulk rock composition is similar to the deformed samples. The comparison is illustrated in figure 6. Al and Ti are considered as immobile and little soluble elements at conditions experienced during deformation and weathering (Tobisch et al. 1991, Erslevs & Ward 1994). However the *Edough* rocks show by their mineralogical changes that Al is mobile. Ti remains unchanged during the metamorphic changes (Gresens 1967; Fisher 1970; Ferry 1982). Since Ti is not involved in the phase transitions we define the line crossing Ti as the isocon. The gains and the losses of elements in the mica schists are progressive as they can directly be linked to the variation in the degree of deformation. The variations in the Gresens diagrams show open fans suggesting significant amounts of mass transfer (Figure 6).

The most chemical elements are constantly washed away when there is an increase in the deformation gradient. Mg and Na show a very weak mobility and seem not affected by deformation processes. Fe behaves irregular; there is a tendency of loss of this element during the different stages of mineralogical transformation and deformation. The enrichment of K expresses the formation of biotite and potassic feldspar in highly deformed rocks.

Quantification of the constituents that have undergone gains and losses is done using the general equation proposed by Grant (1986).

$$C_i^A = (M^0 / M^A) * (C_i^0 + DC_i)$$

At constant mass, this equation becomes:

$$DC_i / C_i^0 = (C_i^A / C_i) - 1$$

DC_i / C_i^0: relative gain or loss of element "I" during transformation of the original rock;

M^0: original mass of the rock;

M^A: mass of the transformed rock;

C_i^0: mass or weight of the element in the original rock;

C_i^A: mass or weight of the element in the transformed rock

The balance of the gains and losses in chemical elements is summarized in Table 2. According to the Figure 4, the majority of elements are mobile. The Ti being immobile, the mass balance of the different samples can be calculated as:

1) 100g (E36) -19.75g SiO_2 + 0.79g Al_2O_3 +1.12g Fe_2O_3-1.40g CaO + 0.19g MgO +0.01g MnO + 0.45g K_2O - 0.41g Na_2O = 81g E37'a
2) 100g (E36) -13.15g SiO_2 + 2.02g Al_2O_3 + 0.81g Fe_2O_3-1.45g CaO + -0.09g MgO + 0.00g MnO+ 0.00g K_2O- 0.13g Na_2O = 88g E37''
3) 100g (E36) -11.93g SiO_2 + 0.84g Al_2O_3 -1.18g Fe_2O_3 -1.40g CaO - 0.26g MgO + 0.02g MnO - 0.49g K_2O - 0.59g Na_2O = 85g E38
4) 100g (E36) + 47.35g SiO_2 + 18.96g Al_2O_3 -1.86g Fe_2O_3 + 0.86g CaO + 0.9g MgO - 0.03g MnO + 5.34g K_2O + 0.45g Na_2O = 171.97g E41

During the increase of deformation (from sample E37"a to E38) (Figure 7), the loss in mass of SiO_2 is very important, suggesting the dissolution of quartz and white mica. The gain in mass of Al is continuous and increases until the sample E41, this variation can be correlated with the apparition and modal increase of aluminous minerals such andalusite.

5. CONLUSION

Mineralogical as well as compositional changes are often due to changes in metamorphic grade. The insignificant changes of thermo-barometric conditions of the mica schists did not influence the mobility of the elements. The slight variation in bulk rock composition and the homogeneity of the alteration index allow to exclude alteration as major process for mass transfer and change of the phase assemblages encountered along the section. The mica schists however experienced strong tectonic constraints with increasing strain along the E-W transect. The isocons show that Si, Fe, Al and K where mobile during deformation and the transformation from garnet mica schists to andalusite mica schists. This transition leads to loss of Fe and gain of Al, Si and K. The element mobility correlates with deformation that favored fluid circulation and the growth of andalusite in the zone of strongest shear stress.

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FIGURE CAPTIONS

Figure 1: Schematic geologic map of the *Edough Massif* (according to Hilly, 1962; Caby and Hammor, 2001; Laouar et al., 2002).

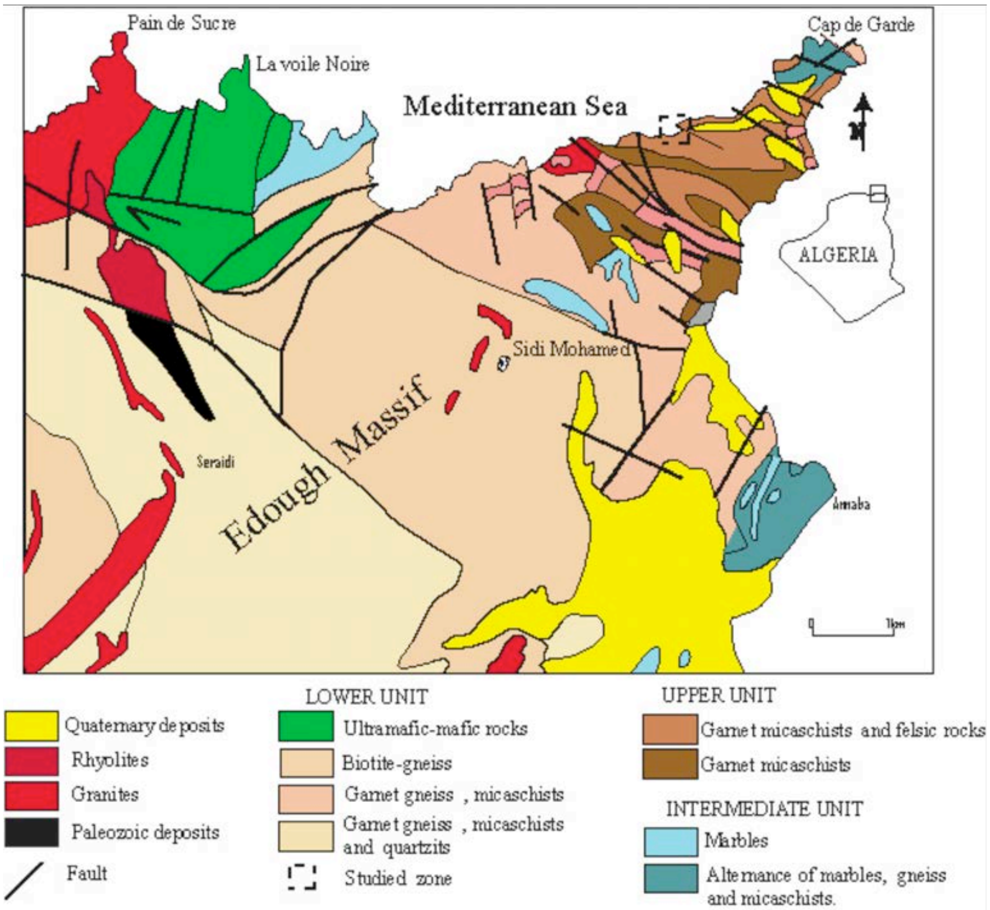
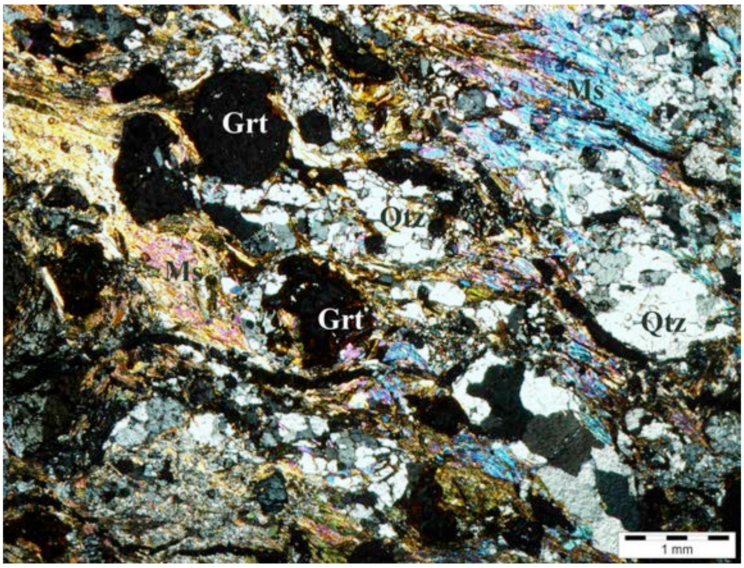


Figure 2: Mineralogical evolution and deformation of the « upper unit » in the *Edough Massif*. And: andalusite, Bt: biotite, Fsp: feldspar, St: Staurolite, Qtz: quartz (mineral abbreviations after Kretz, 1983)

a)



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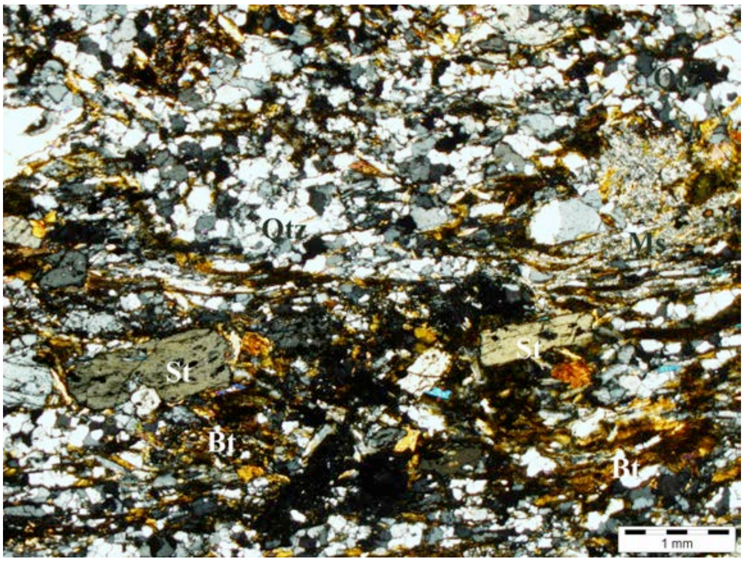

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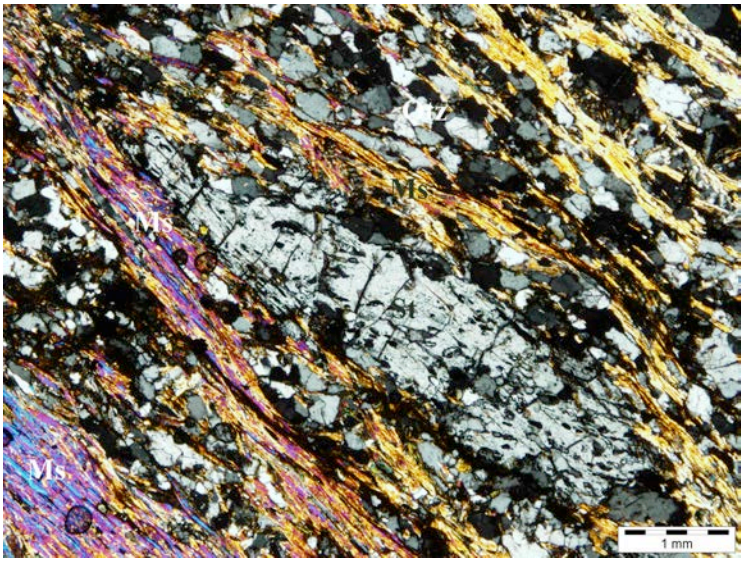

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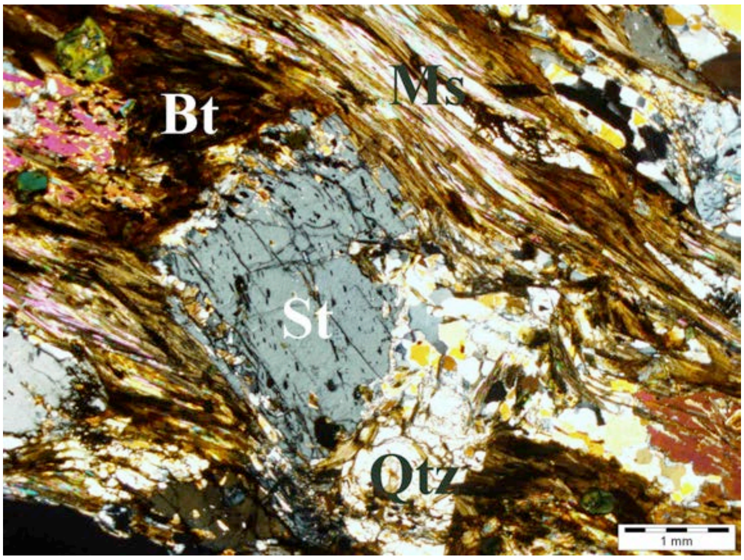


Figure 3: Harker diagrams showing major element variation along the transect

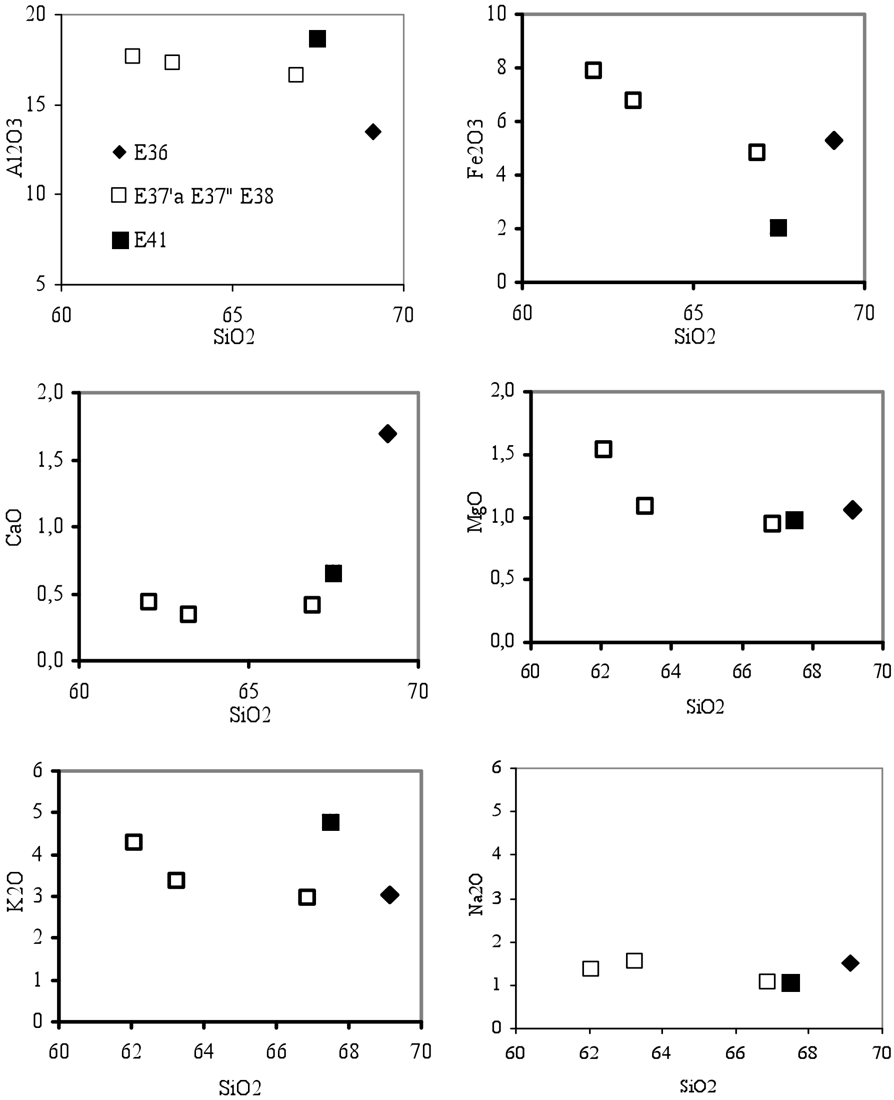


Figure 4: Fluctuations of the bulk chemical composition along the E-W transect

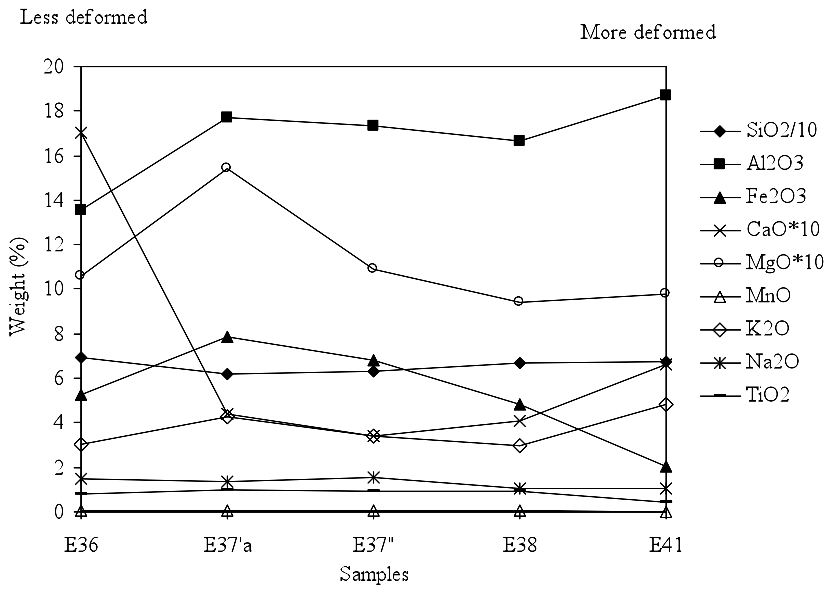
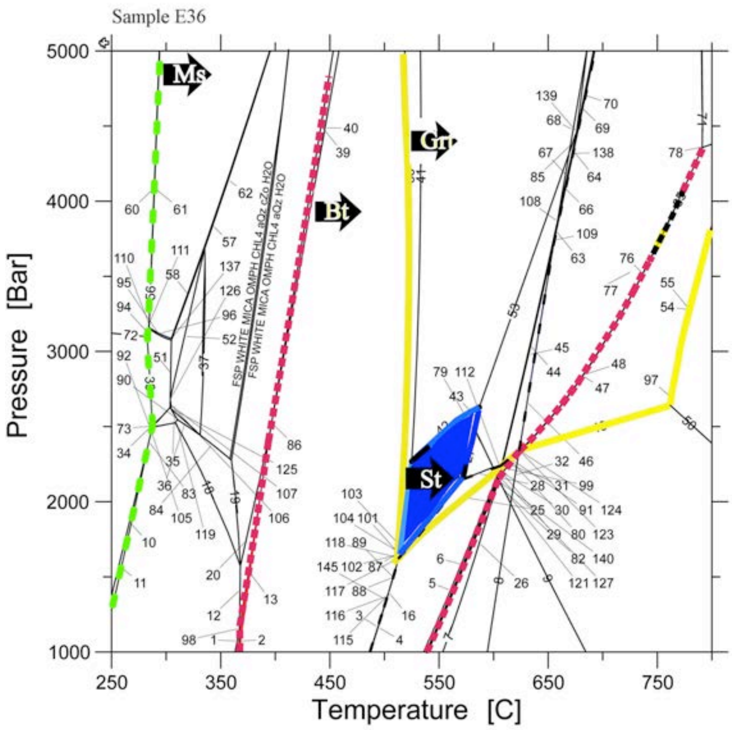
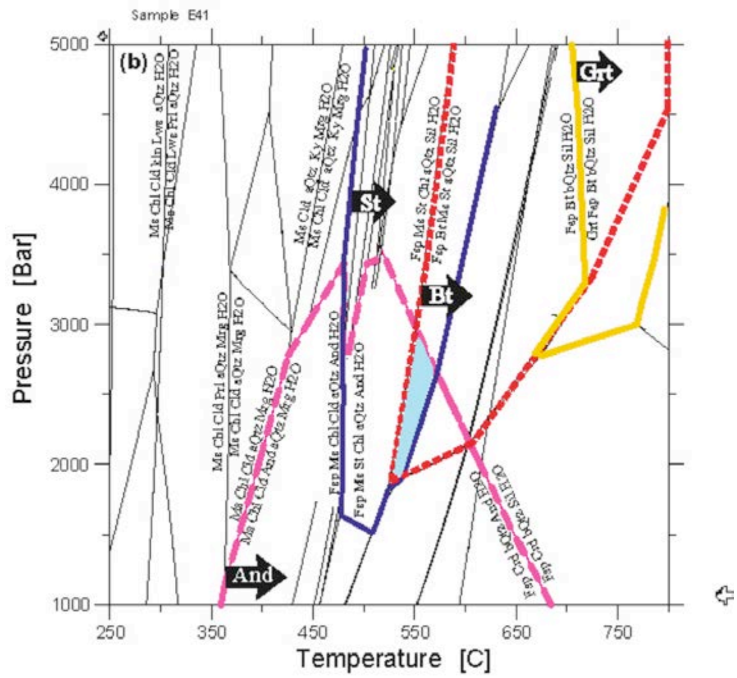


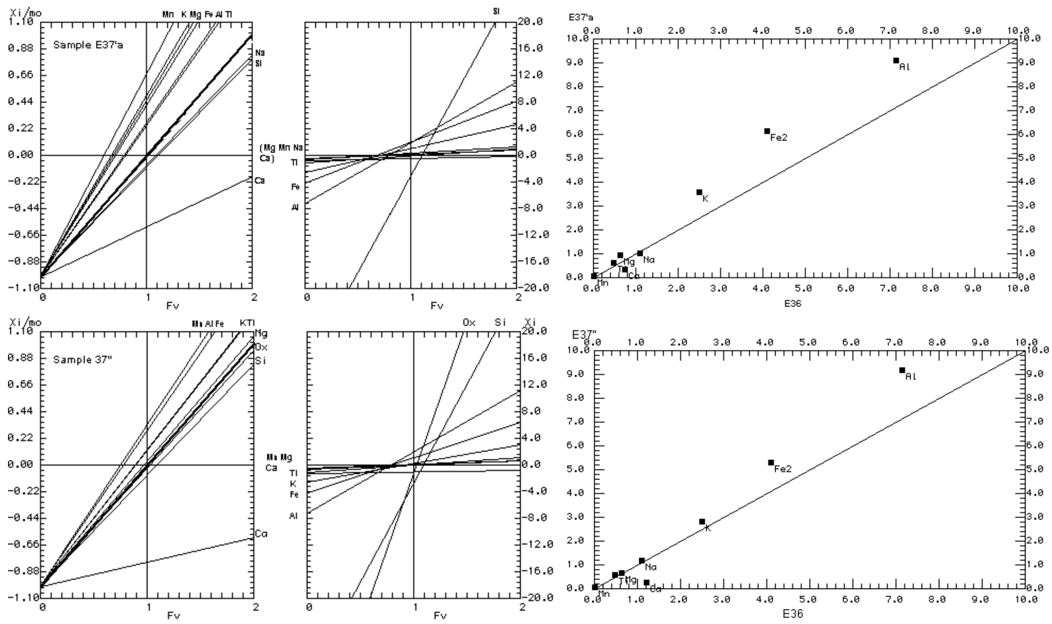
Figure 5: Thermobarometric conditions: a) for the less deformed rock (E36), b) for the most deformed (E41) made with Theriak-Domino. Mineral abbreviations (Kretz, 1983): And: andalusite, Bt: biotite, Chl: chlorite, Czo: clinozoisite, Crd: cordierite, Cld: chloritoid, Fsp: feldspar, Grt: garnet, H_2O: water, Ky: kyanite, Lws: lawsonite, Mrg: margarite, Ms: muscovite, Omp: omphacite, Prl: pyrophyllite, Qtz: quartz, Sil: sillimanite. Arrows indicate the appearance of a mineral





/ / / / = stability fields of minerals, ■P-T area of sample (E36), ■P-T area of sample (E41)

Figure 6: Composition–volume diagrams and isocons of the chemical transfers along the cross section in the mica schists



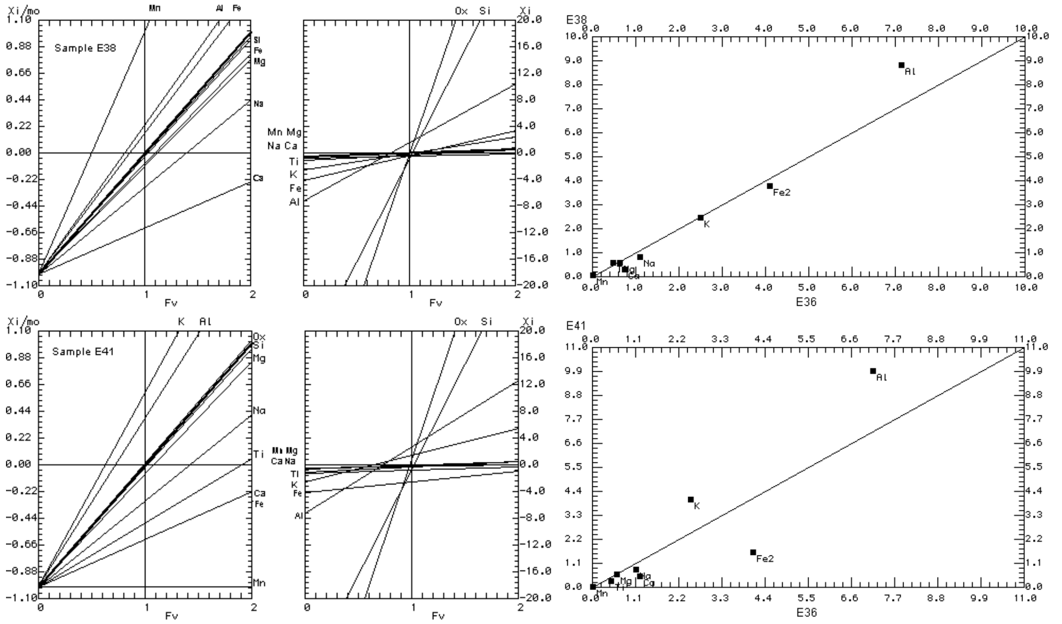


Figure 7: Histograms of the gains and relative losses during the transformation of the rock

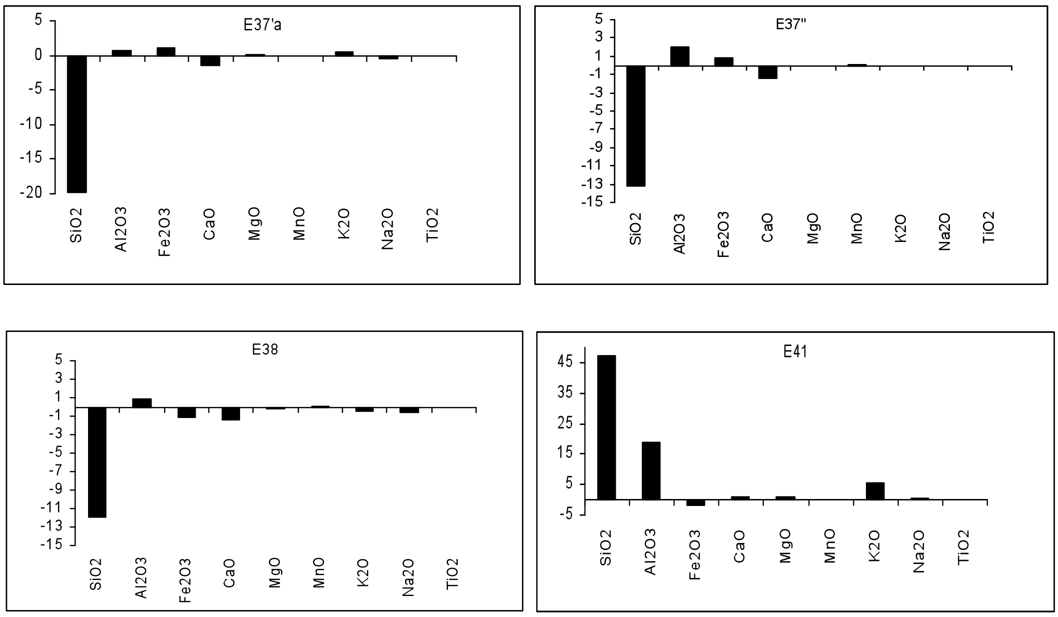


TABLE CAPTIONS

Table 1: Whole-rock geochemistry for the mica schists of the *Edough Massif*

Samples	E36	E37'a	E37"	E38	E41
SiO_2	69,12	62,08	63,25	66,89	67,46
Al_2O_3	13,54	17,70	17,33	16,64	18,69
Fe_2O_3	5,29	7,88	6,79	4,82	2,06
CaO	1,70	0,44	0,34	0,41	0,66
MgO	1,06	1,54	1,09	0,94	0,98
MnO	0,03	0,05	0,04	0,06	0,00
K_2O	3,02	4,27	3,38	2,96	4,80
Na_2O	1,50	1,37	1,54	1,08	1,06
TiO_2	0,82	1,02	0,92	0,95	0,43
L.O.I	3,65	4,25	4,00	3,90	3,40
Total	99,73	100,60	98,68	98,65	99,54

Table 2: Balance of the gains and relative losses during the transformation of the rocks subject to deformation

Sample	SiO2	Al2O3	Fe2O3	CaO	MgO	MnO	K2O	Na2O
E37'a	-19,75	0,79	1,12	-1,40	0,19	0,01	0,45	-0,41
E37"	-13,15	2,02	0,81	-1,45	-0,09	0,00	0,00	-0,13
E38	-11,93	0,84	-1,18	-1,40	-0,26	0,02	-0,49	-0,59
E41	47,35	18,96	-1,86	0,86	0,90	-0,03	5,34	0,45