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PORE FLUID AND SEISMOGENIC CHARACTERISTICS OF FAULT ROCKS WITHIN THE VILARIÇA FAULT ZONE (NE PORTUGAL): EVIDENCES FOR DEEP FLUID CIRCULATION DURING THE UPLIFT OF THE VARISCAN CONTINENTAL CRUST

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Abstract

The study of two sectors belonging to the main nucleation domain of the Vilariça Fault, shows that the tectonic events responsible for the evolving steps of the fault zone trigger off notorious hydrothermal activity at different crustal levels, and were determined by the regional stress fields of late-D_3 and D_4 variscan phases. The superposition of fault rocks generated at distinct P-T conditions strongly suggest that the evolving path of the fault zone may be used as a marker of the continental uplift that took place after D_3. The bidimensional model developed by Koons (1987) seems to be appliable to the available data, suggesting that a moderate crustal uplift (≈5mm/a) occurred in the surrounding region of the Vilariça Fault in late-D_3 times. We predict that the uplift rate should increase westwards, reaching a maximum in the adjoining region of Porto-Tomar Shear Zone. Given that, in continental collision, moderate to fast uplift of crustal blocks will produce anomalously hot regions within the crust and consequent surface heat flow anomalies, our interpretation might explain the hydrothermal activity associated to most of the late-variscan strike-slip faults in this domain of the Iberian Terrane.

The Vilariça Fault Zone (VFZ) is one of the major left-lateral NNE-SSW structures of the Late-Variscan strike-slip fault network in NW Iberia. Its nucleation/propagation events, determined by the regional stress fields of late-D_3 and D_4 variscan phases, induced the generation of different fault rocks (including hydrothermal siliceous precipitates) and typical associations of (micro-) macrostructures, whose development denounce either polyphasic seismic activity or cyclic fluid pumping to the fault zone under distinct crustal conditions (*e.g.* Ribeiro, 1974; Mateus, 1995). The VFZ evolving P-T-t path provides therefore important information on the thermal and mechanical behaviour of the crust during the variscan continental uplift that took place after D_3.

Multidisciplinary studies carried out in two sectors belonging to the main nucleation domain of the VFZ (Quintas Vale do Meão and Terrincha - fig.1), revealed that the fault zone geometry is strongly constrained by the pre-existence of sin-D_3 anisotropies, particularly those related to the development of ductile/semi-ductile shear zones. Far from the VFZ, the ductile sin-D_3 deformation registered by the synorogenic granites (305±10 Ma) is usually restricted to narrow NNE-SSW to NE-SW bands, where the preserved microstructures are attributed to cyclic, continuous-discontinuous yielding mechanisms at the grain scale, and early mineral transformations due to the circulation of late-magmatic oxidising fluids with pH $\geq$ 5. Strain heterogeneity is favoured by the development of mechanical instabilities at the microscale, mainly from: (1) distinct recovery mechanisms acting upon various minerals, for each set of P-T conditions; (2) initiation and quasi-static propagation of intra- and intergranular cracks; (3) strain features related to grain-boundary mechanisms. According to the available data, the P-T conditions required to the establishment of this mixed deformation pattern and the correlative hydrothermal alteration is of the order of 3-5 kbar and 450±50°C. An average yielding flow rate scattered in the most probable range 10^{-14} to 10^{-12} s^{-1} should be expected, considering the subgrain and recrystallized quartz grain dimensions and the equations experimentally deduced by White (1979) and Hansen & Carter (1982) for deformed quartz and wet granite, respectively (fig.2B).

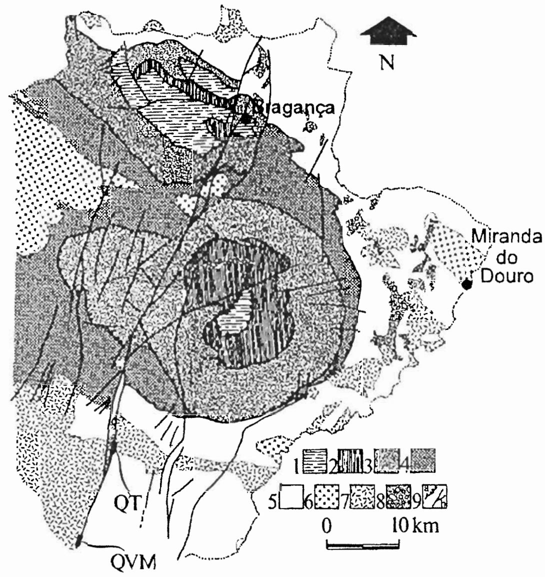

Fig.1 - Synthetic geological setting of the **VFZ** northern segment (simplified after Ribeiro, 1974) and localisation of the studied fault segments (**QVM** - Quinta Vale do Meão; **QT** - Quinta da Terrincha). **1** - Upper Allochthonous Unit; **2** - Ophiolite Complex; **3** - Lower Allocthonous Unit; **4** - Para-autochthon; **5** - Autochthonous Domain; **6** - Late-hercynian granites; **7** - Hercynian granites; **8** - Cenozoic cover deposits; **9** - **a)** Major thrust plane; **b)** Main fault trace.

Comprehensive petrography of the outcropping fault rocks enabled the establishment of a relative chronology between fracturing/sealing events of the protomylonite relics and quartz fillings; the main conclusions of this study are summarised in fig.2**A**. P-T-t evolving paths presented in figs. 3**A**, **B** relate the data obtained from the micro-thermometry analysis of the slightly deformed and undeformed quartz generations, and from the evaluation of the chemical conditions required to the successive hydrothermal mineral parageneses stability. In this context, it is worth noting that rock alteration is largely dependent of the intensity of brittle deformation and that secondary mineral parageneses could be generally given by the association quartz + sericite ± chlorite ± illite ± hematite. From the available data, one may conclude the following: (**a**) The earlier sin-D_4 seismic events occurred in a semi-ductile regime under temperatures ranging from 300 to 350°C and global pressures lower than 3 kbar. Strain ratios of the order of 10^{-11} s^{-1} and an average depth for the brittle-ductile transition regimes near 10±0.5 km can be pointed out, assuming the most probable size range of quartz subgrains and recrystallized grains in protomylonites, and fluid pressures near the lithostatic pressure (fig.2**B**). The metasomatic processes contemporaneous of this deformation step denote the circulation of aquo-carbonic, reduced and acidic fluids with low to moderate salinity of probable metamorphic origin; in the course of quartz ***II*** deposition, significant changes of the fluid composition occurred, probably due to system depressurization via seismic yielding. (**b**) Seismic events in semi-brittle regime took place under P-T conditions of the order of 1-2 kbar and 250-300°C. The deformation/alteration pattern correlative of this important evolving step suggests that acidic, and reducing metamorphic aquo-carbonic fluids with low salinity were present. (**c**) The transition to the deformation cycles in brittle regime is underlined by

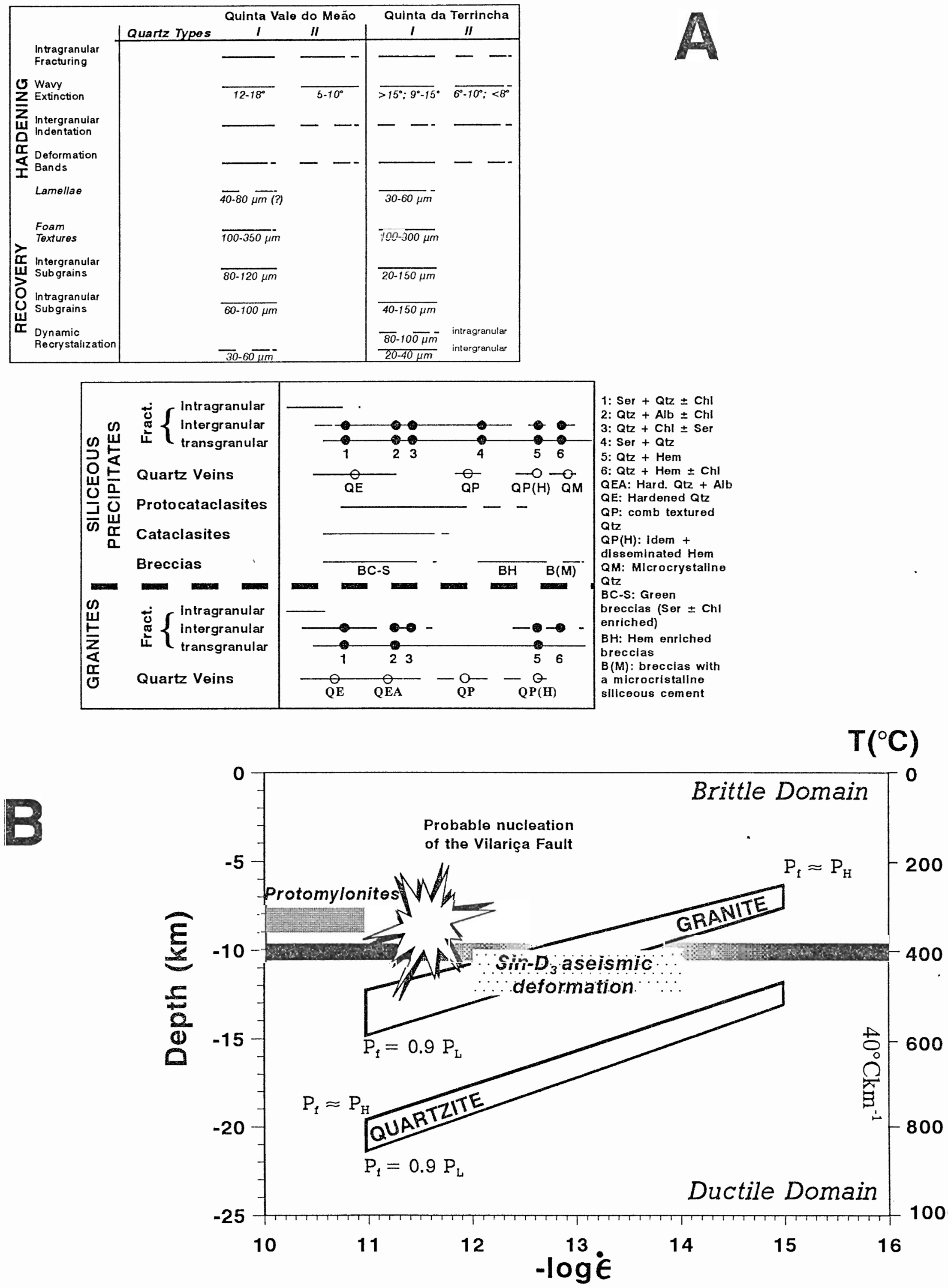

Fig.2 - **A**: Main microstructural characteristics of quartz generations **I** and **II** (the remaining quartz types do not show petrographic features due to plastic and/or semi-brittle deformation) and synthesis of the relative chronology between fracturing/sealing events (of the hidrothermal siliceous precipitates and host granites) and fault rocks development. **B**: *-log* ($\delta\varepsilon/\delta t$) - *T* - *depth* diagram showing the relative position of the most probable strain rate values required to granite sin-D_3 deformation and granitic protomylonite development (sin-D_4). The geotherm 40°Ckm^{-1} is consistent with the available microthermometric data. The white fields illustrate the strain rate amplitude experimentally obtained for granite and quartzite under fluid pressures (P_f) equivalent to hydrostatic and 0.9 of the lithostatic pressures (P_H and P_L, respectively).

significant decrease of fluid pressures and gradual increase of deviatoric stress under P-T values near 1-1.5 kbar and 200°C. Fluids pumped to the fault zone include typically aqueous and acidic solutions of low salinity with a low density carbonic phase. (**d**) Temperatures below 200°C and global pressures not above 1 kbar characterise the deformation cycles that occurred in near-surface crustal levels. The mineralogical record of the fluid/rock interaction contemporaneous of this evolving step suggests the percolation of aqueous, oxidising, and relatively acidic fluids of probable meteoric origin.

Taking into consideration the depth-P-T-time path obtained from fluid inclusion data and mineral stability relationships (fig.3**C**), one may conclude that the average temperature drop for a large part of the uplift is relatively small. This is quite obvious for the transition between the evolving steps **1** and **2** (where an average depth change of 5.5 km corresponds to a cooling gradient near $15°Ckm^{-1}$), which contrasts with a ≈ $50°Ckm^{-1}$ cooling gradient over de last 4 km of uplift. Although in a fault zone one might expect temperature variations through time largely dependent on the temperature of the fluid, we think that the detected cooling path, with the two very distinct intervals, coupled with the regional constraints, may be interpreted as follows. Using the numerical approach of Koons (1987), the depth-temperature-time path obtained corresponds to a record of a nearly isothermal decompression due to a moderate uplift rate (≈ 5 mm/year) immediately after D_3. This will contribute to the weakening of the crust by raising the depth of the brittle-ductile transition regime, and so explains the development of protomylonite rocks at the above mentioned P-T conditions, as reported in fig. 3**C**.

The geological plausibility of the previous interpretation is stressed by the eastward development of a continental clastic sedimentary sequence of Carboniferous age, comprising a basal conglomerate with sin-D_3 granite pebbles. The unconformity, dated of 296 Ma, is consistent with the above model in which 300 Ma is assumed as the starting time for the uplift increment. Moreover, the geological context of the continental sediments of Carboniferous age, as well as the geodynamic evolving path of the Carboniferous Trough and Porto-Tomar Shear Zone, strongly suggest that the uplift rate should increase westwards, reaching a maximum in the crustal block eastbounded by the latter shear zone.

It should also be noted that sustained moderate to fast uplift of crustal blocks will produce anomalously hot regions within the crust and consequent surface heat flow anomalies which may explain the hydrothermal activity associated to most of the late-variscan strike-slip faults in this domain of the Iberian Terrane. Also the concentration of strain within the lithospheric weakened domains should promote a decrease in the depth and frequency of large earthquakes. The vertical transfer of stress from the crust to the upper mantle, should therefore induce an intermediate depth seismicity.

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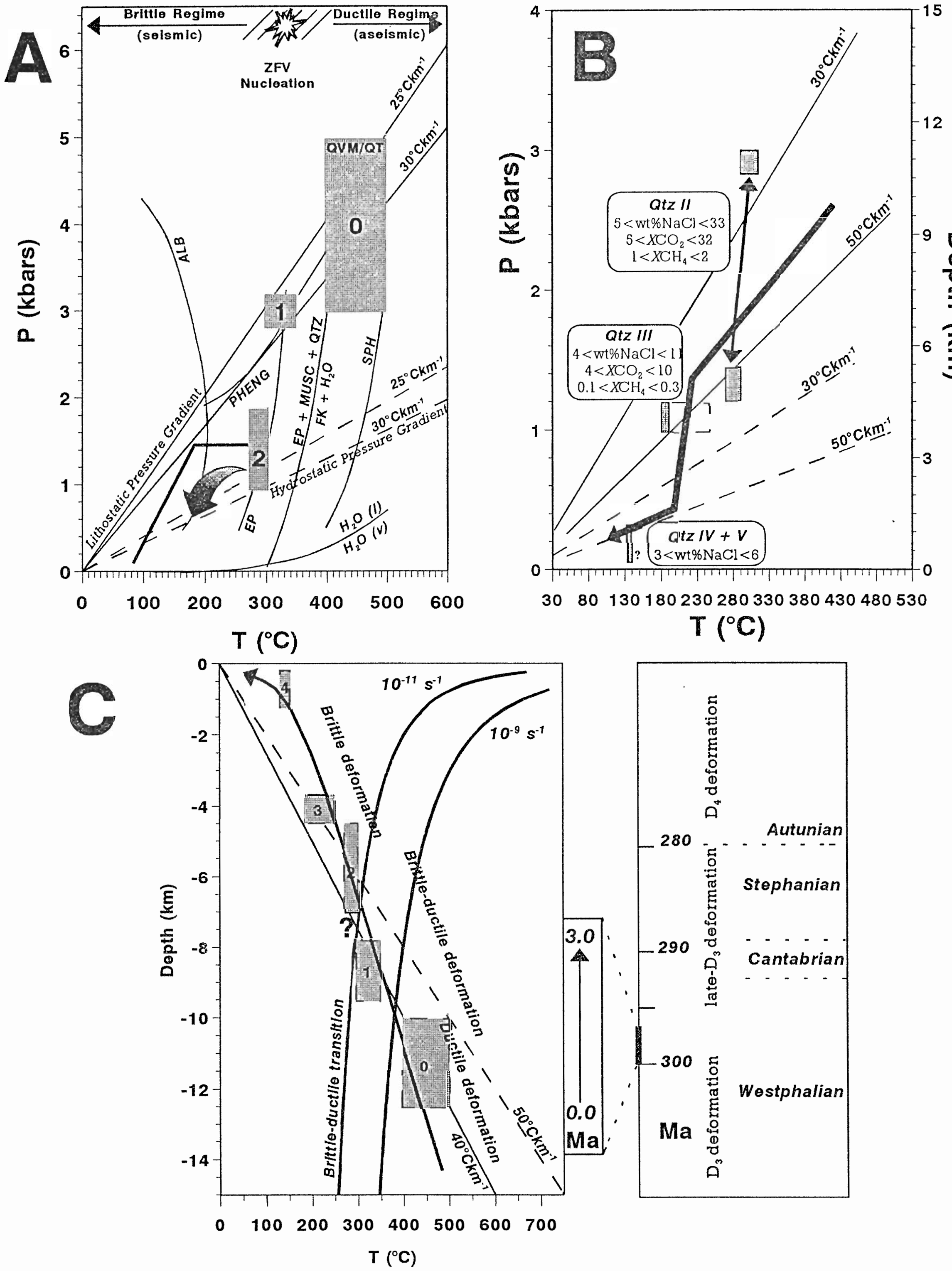

Fig.3 - **A**: P-T-t evolving path for the **VFZ** according to fluid inclusion data and the P-T stability domains of the hydrothermal mineral parageneses as well as the observed microstructures. **B**: Chemical parameters obtained from fluid inclusion studies (strong plastic deformation displayed by quartz ***I*** prevent its microthermometric characterisation). **C**: **P-T-t** evolving path; the line labelled *Brittle-ductile transition* was calculated from the equations of Sibson (1984), assuming a strike-slip model for a constant fluid pressure (λ=0.36) and a strain rate ranging from 10^{-11} (present study) to 10^{-9} s^{-1} (considering the different cartographic rejection of the Vila Real-Carviçais and Santa Comba de Vilariça granitic batholiths - 5 km in $\approx$ 5 Ma). The right column shows the predicted position of the brittle-ductile transition at millions of years after initiation of the uplift, according to the model of Koons (1987) for moderate uplift rates (5 mm/year).