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LATE-VARISCAN CRUSTAL UPLIFT OF THE IBERIAN TERRANE AS A RESPONSE TO ISOSTATIC REBOUND; IMPLICATIONS FOR THE BRITTLE-DUCTILE TRANSITION , FLUID CIRCULATION AND METALLOGENESIS.

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Introduction

The thermal and mechanical evolution of continental lithosphere during and after continental collision severely constrains the generation and development of different metallogenetic systems, including those related to the advance of regional metamorphism, granite magma emplacement and of relatively late hydrothermal processes that involve the circulation and mixtures of fluid from distinct sources in a wide range of temperatures. This evolution, however, is strongly influenced by the crustal uplift rates attained after the main orogenic deformation events, and divergent results will be expected if uplifting is considered to be merely due to an isostatic-viscoelastic response function (<2 mm/year) and chiefly controlled by erosion rates, or related to an isostatic rebound of the crust (5 to 10 mm/year). The thermal structure of the crust resulting from these two isostatic recover alternatives have also serious repercussions on the time-dependent mechanical response of the continental lithosphere, since the fast increase of the thermal advection component due to sustained rapid uplift favours the rise of the brittle-ductile transition (BDT) and suppresses the thermal effects due to heat production through radioactive decay (Koons 1987).

An increasing amount of evidence from different studies recently carried out in active and palaeo-orogenic belts, namely in Variscan Belt, strongly suggests that rapid crustal uplift caused by isostatic rebound is much more common than firstly thought. From these investigations, it is also possible to conclude that sustained high uplift rates will not proceed uniformly in the entire collision belt, occurring preferentially in crustal domains with lateral dimensions around 100-300 km by 10-50 km and usually bounded by deep tectonic structures. That seems to be also the case of the central-northern part of the Iberian Terrane in the Variscan Belt.

Geology

In NW Iberia, during the major Variscan collisional event (corresponding to D_1 and D_2 deformation phases, 387 to 352 Ma), clockwise P-T metamorphic paths were completed, suggesting a nearly isothermal decompression immediately after the emplacement of the Allochthonous Terranes. In the course of the initial steps of this decompression, large volumes of peraluminous granite magmas were generated under 650-700 °C and low pressure conditions (<5 kbar) by crustal anatexis of metasediments and metavolcanoclastic rocks at an average depth of 14-15 km. Results from detailed gravity surveys reveal that the emplacement of these two-mica granites (320-315 Ma) is mainly controlled by local tectonics and that many of them show numerous feeder channels (Vigneresse 1999 and references therein). The deflection of regional schistosity in rock domains adjoining the boundaries of these intrusives, and the correlative development of many brittle structures, enable also to conclude that most of these syntectonic granites were quickly intruded in crustal horizons that roughly correspond to the BDT (13-14 km). Further magmatic activity led to the emplacement of late (310-305 Ma) to post-tectonic (290-280 Ma) Variscan granitoids that represent products of a complex lower-crust melting and possible mixture with mantelic magmas. They form usually plutons with a localised root zone, around which aureoles of contact metamorphism (2 kbar; 500-550°C) and an intricate pattern of fractures can be found (Sant'Ovaia 2000). During this orogenic evolution, different shear zones were developed and successively reactivated, forming a complex crustal network of pathways that enabled the circulation of distinct fluids in time.

The studied cases

In order to evaluate the importance of the Late-Variscan crustal uplift on the generation of surface heat flow anomalies that can provide for significant fluid circulation and generate distinct geochemical systems suitable for the development of different types of mineralisations with time, P-T-t paths determined for different domains of the Central-Iberian Zone through fluid inclusion studies were used and compared with the available structural and petrological (both metamorphic and igneous) data.

Average P-T conditions of peraluminous granites emplacement (3-3.5 kbar, 500-550°C) correlate quite well with the P-T conditions inferred for the entrapment of H_2O-CO_2(-CH_4) fluids in quartz aggregates that fill early veins in metamorphic rocks (3.5-4 kbar, 500-550°C).

The mechanical and thermal instabilities caused by the polyphasic emplacement of peraluminous granites favoured the development of thermally (frequently narrow, <3m thick) softened bands along the contacts with strongly deformed metasedimentary rocks, thus creating the adequate conditions for the nucleation and propagation of ductile or semi-brittle shear zones that will accommodate preferentially further deformation. The P-T conditions under which these structural corridors evolve (<4 kbar, 450-500°C) can be inferred from the presence of microstructures ascribable to cyclic, continuous-discontinuous deformation mechanisms at the grain scale acting in presence of late-magmatic fluids; strain rate values ranging from 10^{-14} to 10^{-12} s^{-1} can be determined by using the dimensions of subgrain and recrystallized quartz grains and the equations experimentally deduced for quartz and wet granite. At this time, the BDT depth would be around 12 km, considering the time-dependent mechanical response of the crust to be effectively dominated by feldspar rheology and assuming an average thermal gradient of 40°Ckm^{-1}; consequently, the expected surface heat flow values would be about 120 mW.m^{-2}. All these estimations strongly suggest that the development of shear zones at the margins of peraluminous granite massifs is correlative of the last increments of their crystallisation and cooling. Fluid circulation is therefore restricted to rock domains where an increase of permeability is expected to develop mainly as a result of a regional stress field locally modified by the intrusion stress configuration The geochemical systems meanwhile developed support different types of mineralisations (particularly Sn, or P and/or Li (Fe, Mn, Nb Ta) bearing pegmatites) that are primarily dominated by residual magmatic fluids further gradu-

ally mixed with “metamorphic solutions” variably enriched in C-phases (as documented by correlative W-skarn deposits and pegmatites).
The subsequent reactivation of many ductile/semi-ductile shear zones in P-T-t conditions that successively favours the relative predominance of brittle deformation mechanisms, leads to the generation of superimposed fault rocks and hydrothermal precipitates, thus indicating a sudden increase of the crustal uplift rates and a notable migration of aqueous-carbonic fluids of “ metamorphic origin” towards dilational structures intimately related to strain accommodation within shear zones or to strain partitioning in the metamorphic sequences. During this sustained rapid uplift, which is believed to begin at circa 300 Ma (the age of the basal continental conglomerate that mark the Stephanian unconformity is 296 Ma), the rising of the BDT results in significant reduction of the crustal strength, since the mechanisms responsible for the generated thermal anomalies occurred much more faster than does dissipation of heat by conduction and fluid advection. Consequently, the emplacement of late- and post-tectonic granitoids immediately above the BDT occurs at progressively shallower depths.
The intricate pattern of fractures developed around the late- and post-tectonic granitoids, mostly reflecting the evolution of a local stress field often dominated by the intrusion stress configuration, represents adequate conduits for fluid flow derived from the inevitable dissipation of the thermal anomaly closely associated with these intrusives by means of heat conduction and fluid convection. This leads frequently to the development of many ore-forming systems that involve the circulation of large volumes of aqueous solutions variably enriched in metals and in other chemical components under P-T conditions usually below 2 kbar and 450ºC; the main lode-tungsten deposits are paradigmatic examples.
In presence of significant crustal surface heat flow anomalies (>120 $mW.m^{-2}$), the major reactivated shear zones should sustain also significant ore-forming systems intimately related to the conspicuous convective fluid flow that took place in the upper 5 km of the crust. This will favour the circulation of SiO_2-saturated metamorphic solutions variably enriched in CO_2 (CH_4-N_2) under P-T conditions below 2.5 kbar and 450ºC, respectively, and their subsequent channelling through the main structural conduits, especially those oriented NE-SW (coarsely the direction of the maximum remote Variscan compression). In this structural context, successive fracturing/sealing events controlled by the cyclic build-up of fluid pressure and/or by repeated seismic events are responsible for many characteristics displayed by the trapped fluids, specifically those induced by depressurisation processes (such as the loss of volatile components, variations of density and salinity in coeval fluid inclusions). Structural evidence coupled with fluid inclusion studies of late barren quartz- and gold-bearing veins indicates that the waning stages of this pervasive Late-Variscan fluid circulation involve mostly the circulation of aqueous solutions of meteoric origin under P-T conditions below 0.7 kbar and 200ºC.

Discussion

Variable mixing of residual magmatic and “metamorphic fluids” characterise the initial steps of some ore-forming Variscan systems, although the major hydrothermal-mineralising events were typically developed under lower temperatures (<350ºC, on average) and related to fluid fluxes dominated by “metamorphic or deeply modified interstitial/meteoric waters”; this is particularly evident in geochemical systems associated to post-tectonic granitoids emplaced at relatively shallow depths (4-5 km).

The extent of fluid mixing and/or singularities achieved during the evolution of a particular geochemical system related to a major reactivated shear zone, may alter considerably the chemical composition of the circulating fluids in a given decreasing temperature gradient, or modify suddenly some key-parameters (like pH, Eh, pCO_2, pO_2 or pS_2). These physical-chemical variations will determine the deposition of sulphides (usually arsenopyrite, pyrite pyrrhotite, and accessory amounts of galena and chalcopyrite), sulphosalts, gold and/or carbonates in the polyphasic hydrothermal infillings that often can be found in many Variscan shear zones. In all of the P-T-t paths obtained, the major fluid fluxes evolve under a decreasing temperature gradient below 300ºC characterised by remarkable pressure drops.

As a final remark, it is also worth noting that the steep thermal gradients induced by rapid uplift also affected the metamorphic pile outside any significant influence of granitic orebodies, and may have generated convective systems of its own, mineralising or otherwise.

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