The Peña Negra Anatectic Complex

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photo: anatectic granites and migmatites, Peña Negra

Introduction

The Variscan belt of the Iberian Peninsula is part of the larger, late Paleozoic, European Variscan Chain which runs some 3000 km from western Iberia to Poland ((Matte, 2001 and references therein). Deformation, metamorphism and magmatism associated with the orogen, which formed as Laurasia and Gondwana collided, are observed in the pre-Mesozoic basement along the length of the mountain belt. The overall structure of the Iberian Massif reflects the general pattern throughout the Western European Variscan chain. Namely, metamorphic and magmatic expressions of the collision are principally concentrated in a wide axial zone flanked by low grade metamorphic rocks and Devonian-Carboniferous syn-tectonic sediments (Pérez-Estaún and Bea, 2004).

Geological setting

The axis of the Central Iberian Zone includes the Avila batholith which crops out over 13,000 km^2 (Fig. 1). The batholith is divided into two sectors: Guadarrama to the east and Gredos to the west (Bea, 1985; Bea et al., 1999). The Gredos Sector, is made up of amalgamated plutons of peraluminous S-type granitoids and, in the core of the batholith, large low-pressure anatectic complexes (Bea and Pereira, 1989; Pereira, 1993) (Fig. 1). Cutting the granitoids in the Gredos Sector are primitive camptonitic and more evolved bostonitic alkaline lamprophyre dikes that form a broadly north-south trending swarm (Bea and Corretgé, 1986; Bea et al., 1999; Scarrow et al., 2011).

The Avila batholith, like practically all the Central Iberian batholiths, is hosted by the Schist-Greywacke Complex (SGC), the dominant metasedimentary formation of the Central Iberian Zone (San José et al., 1990). The SGC is a monotonous sequence of Late-Proterozoic to Cambrian shales and sandstones with minor conglomerates and limestones with a thickness of ~8000 to 15000 meters. The shales and sandstones have the same major mineralogy comprising different proportions of quartz, albitic plagioclase, muscovite-illite and chlorite, with accessory zircon, apatite, monazite, occasional xenotime, huttonite, and U-bearing minerals such as uraninite, betafite, pirochlore, etc. and, locally, abundant graphite. The metamorphic grade far from Variscan batholiths is usually below the biotite-in isograde, but in the neighborhood of the batholiths it increases up to the breakdown of muscovite. The large fragments of the SGC enclosed within the batholiths are strongly migmatised and form anatectic complexes, the largest of which is the Peña Negra (Fig. 1) with gradational contacts towards the batholithic granitoids. The increase of metamorphic grade occurred at a roughly constant pressure of 4 to 4.5 kbars, and can therefore be related to the mid-crustal thermal anomaly that generated the granites (Bea et al. 2003).

Single zircon evaporation and ion-microprobe dating of migmatites and anatectic granites in the Peña Negra Complex of Central Iberia, reveals that the Variscan anatexis occurred continuously from 352 to 297 Ma, with a maximum at 335 to 305 Ma.

Garnet geothermobarometry (Pereira, 1993; Pereira, 1998) coupled with zircon dating (Montero et al., 2004) indicate that the peak of anatexis occurred at ca. 325 Ma with a T of around 800 °C and a P of some 4.5 kbar. After that, the pressure decreased rapidly, so that the rims of retrograde garnets were equilibrated at about 500 °C and 1.5 to 2 kbar at ca. 295 Ma.

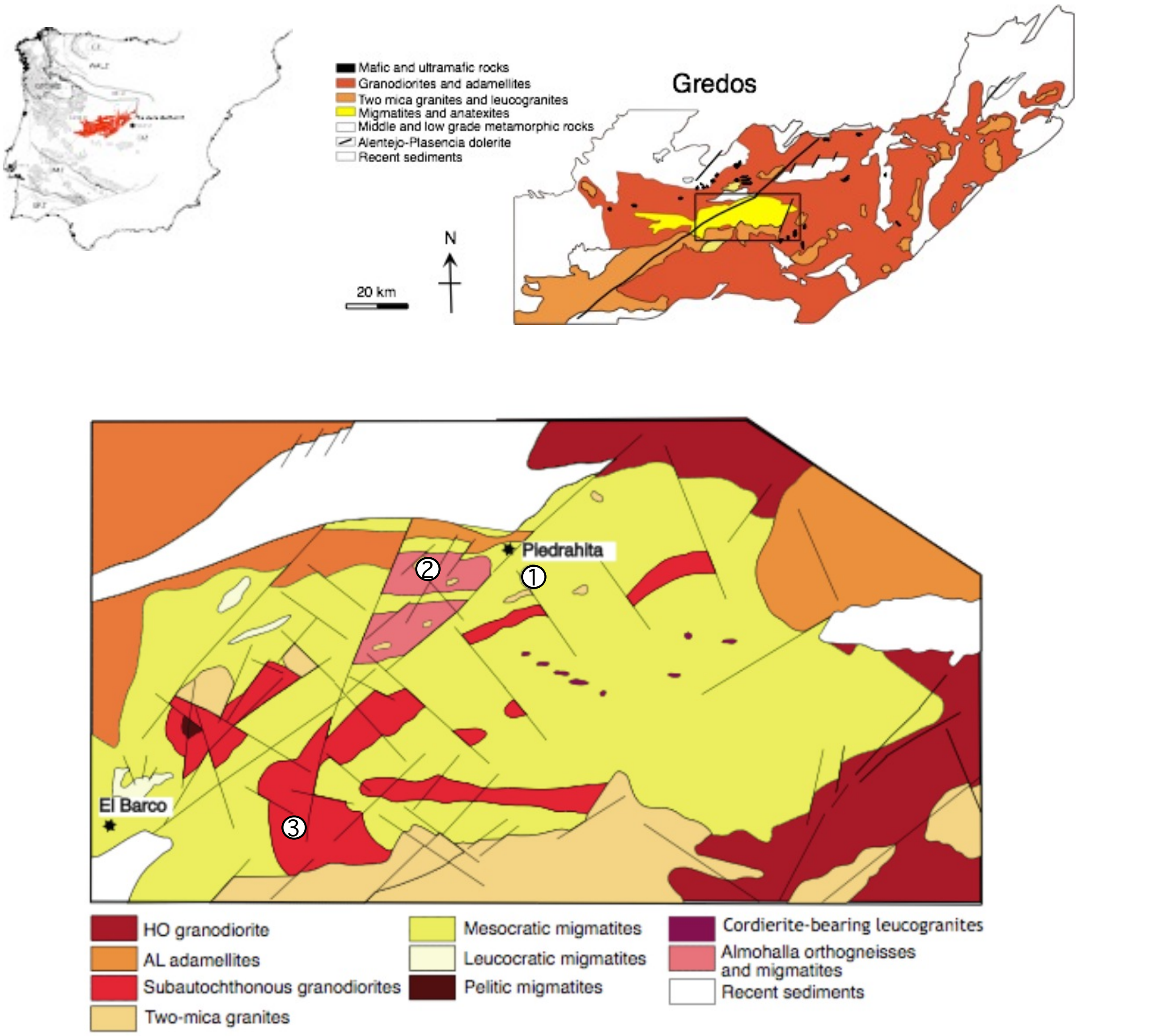

Fig. 1 Geological sketch of the Peña Negra Anatectic Complex of Central Iberia (Montero et al., 2004). SPZ, OMZ, CIZ, WALZ and CZ are the zones of the Iberian Massif, respectively: South Portuguese, Ossa Morena, Central Iberia, Western Asturian-Leonian, and Cantabric

Field relations

Peña Negra is the largest anatectic complex of the Avila batholith (Fig. 1), it originated during the long-lived Variscan anatectic event and represents the source layer of Central Iberian granites (Bea et al., 2003). Comprising about 90% of migmatised, mostly terrigenous, metasediments and 10% Cadomian meta-rhyolites and orthogneisses, the latter being quite rare in low-grade metamorphic areas, its main lithologies are:

i. Diatexitic mesocratic migmatites contain cordierite + biotite + sillimanite ± garnet, with a composition similar to strongly peraluminous granodiorites or monzogranites.

ii. Metatexitic pelitic migmatites, subordinate, and a few marbles, calc-silicate schists and quartzites, which can be tracked from the neighbouring low-metamorphic SGC of the northern part of the batholith (García de Figuerola, 1981).

iii. Leucocratic migmatites, concordant layers of meta-rhyolites finely interbedded with metasediments (Bea and Maldonado, 1983).

iv. Gneissic granitoids of Late-Proterozoic age. The largest, the Almohalla orthogneiss crops out over 15 km^2 in the northern part of complex. This coarse-grained biotite-bearing locally migmatised augen-gneiss still has recognizable primary magmatic features: enclaves, intrusive contacts and aplo-pegmatitic dykes (Bea et al., 1990).

v. Anatectic subauthochtonous granodiorites that form 1-2 km long, 100-200 m thick tabular bodies with gradational contacts with the host migmatites. They consist of high melt-fraction monzogranites to granodiorites, with little or no separation of restites, whose chemical composition overlaps that of the mesocratic migmatites. Subauthochtonous granodiorites always occur in subhorizontal shear zones, so that they seem to be a consequence of locally-enhanced melting of mesocratic migmatites.

vi. Anatectic cordieritic leucogranites that represent low melt-fraction segregates with a limited restitic component; they form pods or small plutons with a diameter rarely over 50-100 m; they have also gradational contacts with the mesocratic migmatites.

Fig. 2 (a) Calc-silicate resister in the Peña Negra diatexitic mesocratic migmatite (b) Almohalla orthogneiss.

Geochronology

The pre-Variscan anatexis Almohalla orthogneiss has been precisely dated at 543 ± 6 Ma (Bea et al., 2003) and is, therefore, Cadomian in age. These authors also suggested that immature sediments derived from the Cadomian orthogneisses were the most important component of the protolith of the Peña Negra mesocratic migmatites.

Single zircon evaporation and ion-microprobe dating of migmatites and anatectic granites in the Peña Negra Complex, reveals that the Variscan anatexis occurred continuously from 352 to 297 Ma, with a maximum at 335 to 305 Ma (Montero et al., 2004). Anatexis began coeval with the main collision of continental masses. A limited melting event, probably related to the beginning of migmatization in syn-collision crustal-scale shear zones, produced a population of zircons with ages of ~350 Ma only found in nebulitic migmatites. The production of new zircons decreased to a minimum at ~343 Ma but then increased swiftly as the internal thermal evolution of the thickened Central Iberian crust led Peña Negra to widespread anatexis, mesocratic migmatite formation, at 332 Ma. Shortly after this, the melt resident in the migmatites was locally segregated into small bodies that crystallized as cordierite leucogranites at 321 Ma. Simultaneously, extensional subhorizontal shear zones were preferentially developed over layers of the migmatite series that, owing to their elevated heat production and fertility, had the highest melt fraction. Shearing provoked further anatexis and viceversa, this contributed significantly to the in situ production of high-melt fraction anatectic subauthochtonous granodiorites and adamellites from transitional mesocratic migmatites. This process occurred from 325 to 305 Ma, notably 15 Ma later than the peak of anatexis, with a maximum at 309 Ma marking the peak of the Variscan extensional collapse in Central Iberia, indicating that indication that granite generation and emplacement were not solely controlled by the thermal evolution of the migmatite series. After ~305 Ma the melt fraction decreased quickly, so that the production of new zircons was insignificant at 300 Ma and had stopped completely by 297 Ma.

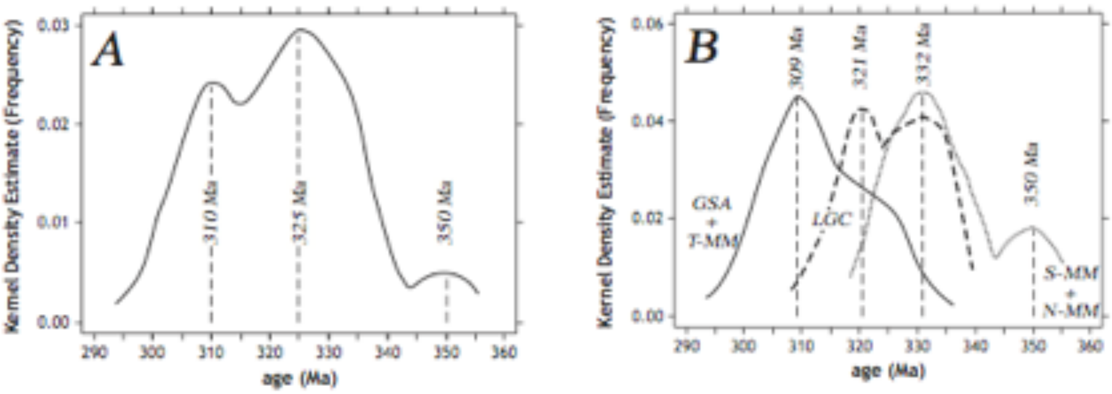

Fig. 3 (a): Frequency distribution of Variscan ages recorded in zircons of migmatites and anatectic granites, if the fraction of new zircons is a function of the melt fraction, 325 Ma would thus represent the peak of anatexis, (b) common mesocratic migmatites, schlieren (S-MM) and nebulitic (N-MM), are bimodal with a population at ca. 350 Ma that represents a limited melting event, probably related to syn-collision crustal-scale shear zones; The leucogranites (LGC) are also bimodal, with a population of restitic Variscan crystals inherited from the migmatites and another population at 321 Ma corresponding to the crystallization age of leucogranites; subautochthonous granodiorites (GSA) and the spatially related transitional migmatites (T-MM) are younger, with a maximum at 309 Ma, and were generated within subhorizontal extensional shear zones that were active from ca. 325 Ma to ca. 305 Ma.

Petrography

Migmatites

Mesocratic migmatites are diatexitic, with a medium to coarse-grained granodioritic to monzogranitic leucosome dominant over a fine-grained restitic melanosome; they contain little or no recognizable mesosome. The leucosome has a hypidiomorphic to granoblastic texture and is mainly composed of quartz, plagioclase (core An_{20-26} rim An_{11-18}), cordierite, subordinate K-feldspar, rare biotite and sillimanite, and occasional garnet and muscovite. The melanosome comprises alternate granoblastic and schistose bands defining a folded foliation; granoblastic layers are formed of quartz + oligoclase ± cordierite ± lozengic sillimanite; schistose layers are formed of biotite and fibrolitic to lozengic sillimanite accompanied by 5 to 10 vol.% of ilmenite and, locally, Fe (Cu) sulfides and graphite. Other accessory minerals are apatite, zircon, monazite, huttonite, and rare xenotime, uraninite and betafite. Accessories, except apatite, mostly appear as inclusions into biotite (Bea, 1996).

These mesocratic migmatites are divided into three facies: schlieren, nebulitic and tran-sitional on the basis of their mesoscopic structures. Schlieren migmatites still preserve a re-cognizable compositional leucosome-melanosome banding with visible fold and shear structures. Nebulitic migmatites are more homogeneous; the melanosome appears within the leucosome either as small enclaves or diffuse schlierens. Transitional migmatites appear between subauthochtonous granodiorites and nebulitic or, less frequently, schlieren migmatites; they are characterized by the appearance of megacrysts of K-feldspar oriented along the foliation. Despite these differences, the three facies have identical modal and chemical compositions.

Metapelitic migmatites consist of fine-grained dark-colored metatexitic migmatites with abundant dyktionitic structures. The mesosome has well-developed grano-lepidoblastic textures and is composed of dominant quartz and biotite, with subordinate sillimanite, cordierite and plagioclase (An_{17-62}), and rare K-feldspar and muscovite. The leucosome appears as thin veins; its major minerals are quartz, K-feldspar, acid oligoclase and rare cordierite, biotite and, locally, muscovite and tourmaline. Accessory minerals are ilmenite, Fe-sulfides, apatite, zircon, monazite and rare huttonite.

Leucocratic migmatites have the same mineralogy as the mesocratic migmatites, but the proportion of leucosome is notably higher, and its composition is more leucogranitic. The melanosome appears either as planar streaks or, more commonly, rounded nodules (Ø ~ 10 to 15 cm) generally oriented according to the foliation. For this reason, some authors have called them “nodular granites” (Bea and Maldonado, 1983).

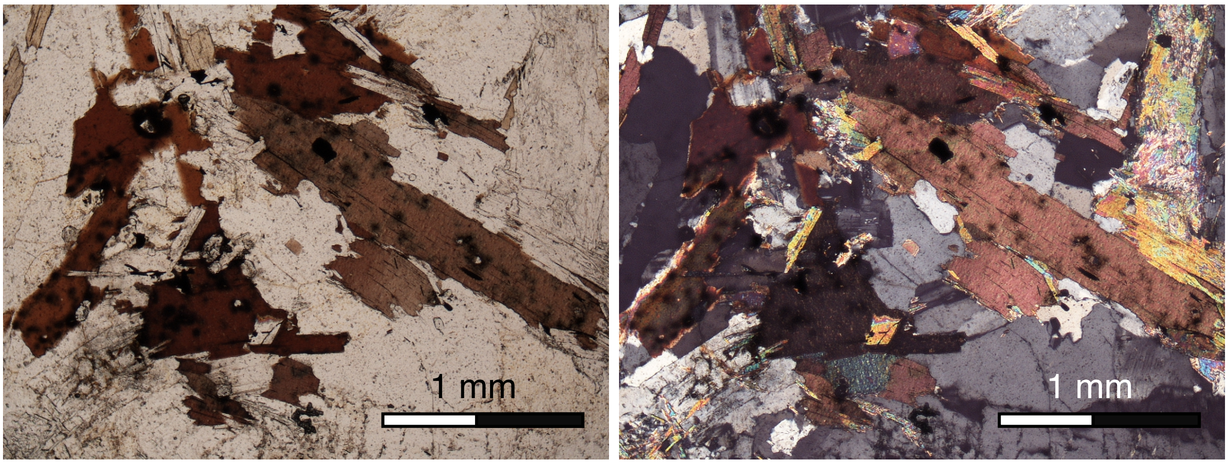

Fig. 4 (a) photomicrograph, ppl, of the Peña Negra migmatite (b) same view in xpl.

Orthogneisses

The orthogneisses form the km-sized Almohalla unit (Fig. 5) and several other small bodies dispersed throughout the Complex (Bea et al., 1990). These rocks are locally slightly migmatised coarse-grained, intensely deformed and recrystallized mesocratic rocks. Textures are gneissose granoblastic, locally oftalmitic. Quartz, plagioclase (An_{23-48}), K-feldspar and biotite are the major minerals; myrmekites are locally abundant. Accessories include ilmenite, titanite, apatite, zircon and monazite. The migmatization is usually metatexitic and results in the formation of 5-10 cm wide veins of fine-grained neosome, within the otherwise untransformed orthogneiss. There is no recognizable melanosome. The neosome has almost the same mineralogical and chemical composition as the mesosome; it is composed of large crystals of restitic plagioclase within an aplitic groundmass with abundant micropegmatitic structures (Bea, 1989).

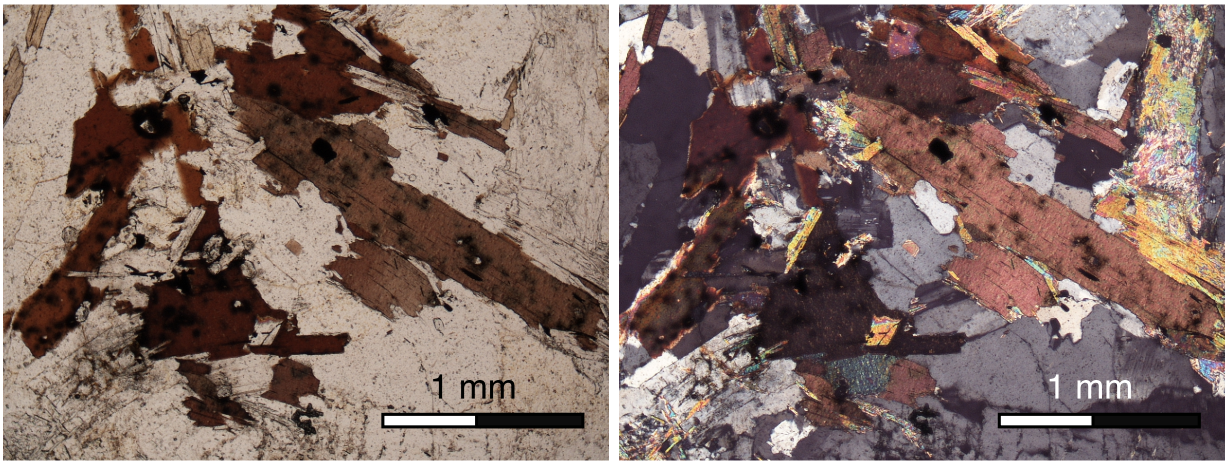

Fig. 5 (a) photomicrograph, ppl, of the Almohalla orthogneiss (b) same view in xpl.

Subauthochtonous granodiorites

The subauthochtonous granodiorites are, after the mesocratic migmatites, the most abundant rocks of the Peña Negra Complex. They are medium to coarse-grained rocks with a hypidiomorphic granular groundmass composed of quartz, plagioclase (core An_{29-40}, rim An_{12-17}), rare K-feldspar, aluminous biotite, euhedral prisms of cordierite and occasional sillimanite or andalucite, and large megacrysts of K-feldspar. The average modal composition corresponds to a monzogranite or, rarely, a true granodiorite. Accessory minerals are ilmenite, Fe (Cu) sulfides, rare graphite, abundant apatite, zircon and monazite, rare huttonite and occasional xenotime. The granodiorites usually have a planar subhorizontal fabric concordant with the external shape of the body. Shear structures are common, especially at the top and bottom contacts of the plutons, where they grade into transitional migmatites.

Cordieritic leucogranites

These rocks are medium to coarse-grained leucocratic, with hypidiomorphic textures and large prismatic crystal of cordierite. Major minerals are quartz, K-feldspar, plagioclase (core An_{20-25}, rim An_{13-17}), cordierite and occasional biotite and sillimanite. Accessory minerals are scarce; they include ilmenite, rare sulfides, apatite, zircon, monazite and occasional xenotime. Mineral proportions vary so the rock composition ranges from syenogranite to alkali-feldspar leucogranite. The fabric is either homophanous or tenuously planar subvertical.

Whole rock compostion

Host metasediments of the Schist-Graywacke-Complex

The chemical composition of the low-grade metasediments of the SGC is highly variable, SiO_2 ranges from 50% to 92%, Al_2O_3 from 3% to 27%, Fe_2O_3T from 0.8% to 12%, MgO from 0.05% to 9%, CaO from 0% to 2.3% Na_2O from 0% to 4.4% and K_2O from 0.4% to 7%. Elemental correlations reflect the effect of the mechanical sorting and indicate that these rocks were mature sediments with only a small proportion of components directly derived from igneous rocks (Beetsma, 1995, Ugidos et al., 1997). Their potential granite fertility, calculated as the fraction of haplogranitic component, i.e. 3.33 times the percentage of the least abundant CIPW-normative mineral among quartz, orthoclase and albite, is rarely greater than 50% and often close to zero (Bea et al. 2003). Their heat production, calculated at 330 Ma from K, Th and U analytical data, is in the range of 0 to 2 µW m-3, with an average of 1.4 µW m-3 (Bea et al., 2003).

Peña Negra Series

The chemical composition of the metasediments from which the migmatite series of Peña Negra was derived is, by far, less varied than the low-grade SGC metasediments. Zircon data, element ratios and the close spatial relation indicate that the protolith of the Peña Negra series were immature sediments derived mainly from Cadomian orthogneisses (Bea et al., 2003). Compared to equivalent rocks of the SGC, Peña Negra metasediments are richer in CaO, Na_2O, K_2O, Rb, Cs, Sr, Ba, Ni, Mo, Pb, Th, U and LREE but poorer in Y and HREE, isotopically they are more juvenile and, of special interest for us, have higher potential fertility, ca. 70%, and heat production, 2.7 µW m^{-3}. In the following sections we shall describe the chemical composition of the different rock-types of Peña Negra, emphasizing their similarities and dissimilarities with respect to anatectic granitoids.

Pelitic migmatites are less silicic, richer in Al_2O_3, FeOT and Mg, and notably poorer in CaO, Na_2O and K_2O, with ASI from 1.6 to 2.9. Their continental crust (CC)-normalized trace element patterns are similar to those of mesocratic migmatites, although with deeper negative anomalies in such trace elements as Pb, Ba, Sr and Eu that mainly reside in feldspars. The contents of REE are also smaller, but with nearly parallel Chondrite-normalized REE patterns; some samples, however, have very elevated Th, U and REE with a marked negative Eu anomaly . Their average potential fertility is ca. 50%, and the average heat production is ca. 3.2 µW m^{-3}.

Leucocratic migmatites have the per-aluminous K-rich leucogranite compositions with SiO_2 commonly in the range 71-75 wt.%, CaO 0.4-0.9 wt.%, Na_2O 2.4-3.7 wt%, K_2O 4.4-6.3 wt.%, and the aluminum saturation index 1.17-1.29. Their CC-normalized trace-element patterns reveal they are depleted in all elements, except U and Rb, with respect to both, the mesocratic migmatites and the average continental crust. Th, Sr and V show negative anomalies whereas Li has a positive anomaly. The leucocratic migmatites are the only Peña Negra materials with Th/U < 1. Their chondrite-normalized REE patterns decrease almost uniformly from La_N 18 - 30 to Lu_N 1.5-3.5, and in most cases they do not have a Eu anomaly or even have a small positive one. The average potential fertility is high, 85%, and the average heat production is ca. 1.6 µW m^{-3}.

The distribution of $^{87}Sr/^{86}Sr_{(320\ Ma)}$ in Peña Negra migmatites range from 0.706 to 0.720 with a peak at 0.712. ε320 Ma(Nd) varies between -2.5 and -9, with the majority of values clustering around -5. The orthogneisses have $^{87}Sr/^{86}Sr_{(320\ Ma)}$ in the range 0.708 to 0.710 and ε320 Ma(Nd) ca. -2.4 and -3.5.

Orthogneisses

Orthogneisses have the composition of slightly peraluminous granodiorite and are richer in plagioclase cations, Na + Ca, than any other rock type of Peña Negra. SiO_2 is commonly in the range 65-70 wt.%, CaO 2.6-4.1 wt.%, Na_2O 3.5-3.9 wt%, K_2O 2.8-4.1 wt.%, and the aluminum saturation index 1.0-1.2. They have higher contents of REE, Zr and Ba, but lower concentration of Cs, Rb. U, V, Sc and Ni than the mesocratic migmatites. The average potential fertility is 67%, and the average heat production is 2.1 μW m^{-3}.

Subauthochtonous granodiorites

The composition of the subauthochtonous granodiorites is comparable to that of the mesocratic migmatites with SiO2 commonly in the range 63-67 wt.%, CaO 0.9-2.3 wt.%, Na_2O ~2.1-4.2 wt%, K_2O ~3.2-6.5 wt.%, and the aluminum saturation index (ASI) 1.06-1.98. A Hotelling's T-test on major elements comparing subauthochtonous granodiorites with transitional migmatites revealed that the vectors of means are the same for the two groups. When compared with nebulitic and schlieren migmatites, however, subauthochtonous grano-diorites have a different vector mean, with higher CaO, Na_2O, K_2O and P_2O_5, but lower MgO. The trace element composition is also almost identical to that of the transitional migmatites, except for somewhat highest Ba and Ce contents, and significantly higher values of REE and Th, but not in U. The average heat production is ca. 3.3 μW m^{-3}.

Cordieritic leucogranites

Cordieritic leucogranites commonly have SiO_2 in the range 70 to 76 wt.%, CaO 0.3 to 1.6 wt.%, Na_2O 2.2 to 4.5 wt%, K_2O 4.0 to 7.0 wt.%, and the aluminum saturation index 1.00 to 1.49. They are only superficially analogous to the leucocratic migmatites, being sinificantly richer in TiO_2, MgO, and CaO. Their trace-element composition is highly variable, changing systematically with the volume of the body. Low-volume bodies are depleted in all trace elements; their CC-normalized patterns reveal positive anomalies of the K-feldspar-compatible elements Pb, Ba and Eu and Li. Their chondrite-normalized REE patterns have La_N 30-50, then decrease smoothly until Dy, show a positive Eu anomaly, and are flat from Ho to Lu at a level about 4x-7x chondrite. The concentration of trace elements increases in high-volume bodies which, in some places, can reach REE, Th and U levels higher than in the mesocratic migmatites from which they segregated. Granites of the largest bodies have negative Eu anomalies, caused by the incorporation of substantial amounts of monazite, either dissolved or included in restitic crystals, into the segretate. All cordieritic leucogranites are characterized by the positive slope from Cs to Pb, reflecting the subordinate role of micas in their genesis and composition.

Subauthochtonous granodiorites and cordieritic leucogranites have the same $^{87}Sr/^{86}Sr$(320 Ma), from 0.708 to 0.717 with an average of 0.714. Nd isotopes, however, are different. Whereas in the subauthochtonous granodiorites ε320 Ma(Nd) range from -3.4 to -5 with an average of -4.5, cordieritic leucogranites have ε320 Ma(Nd) -2.7 to -9.9 with an average of -5.5.

Petrogenetic model

Melt existed at Peña Negra uninterruptedly for about 55 million years. The crystallization of Variscan zircons started at 352 Ma, reached a maximum between 335 and 305 Ma and ended at 297 Ma. The initial ~350 Ma melting event was roughly coeval with the main Variscan collision, estimated at 350-360 Ma (Ferreira et al. 1987; Serrano Pinto et al. 1987), it was probably associated with frictional heating related to syn-collision crustal-scale shear zones. Following on from this at ca. 320 Ma leucosome segregation formed cordierite leucogranites in small-sized, poorly communicated melt reservoirs of migmatites. Subsequently, subautochthonous granodiorites represent high-melt fraction magmas with little residuum-melt segregation, produced by a combination of local enhancement of melting by focused shear zones and the existence of zones with increased heat production and fertility: the increase of the melt fraction above the rheologically critical point was initially caused by local anomalies in heat production, the changes in the rock rheology facilitated the development of shear zones, and shearing provoked further melting so producing high-melt fraction granites from the mesocratic migmatites. The evolution of the partially molten rock within the shear zones to produce the granodiorites would have been very protracted so producing a complex sequence of zircon dissolution and precipitation, as revealed by the existence of grains with Variscan cores rimmed by a discordant and younger rims from ca. 325 Ma to ca. 305 Ma with a peak at 310 Ma.

Stop 1: Peña Negra mountain pass

At this locality we leave the coach at the Peña Negra mountain pass and walk some two kilometres east along shallow gradient track and through low shrubby vegegation. We begin our trip in mesocratic migmatites, with their characterisitic schlieren and nebulitic structures and resister enclaves of marbles, calc-silicate schists and quartzites, then pass progressively through leucosome segregate cordierite leucogranites into the subathocthonous granoriorites (Fig. 1).

Fig. 6 Peña Negra Complex, looking to the south from the village of Piedrahita.

Stop 2: Almohalla orthogneiss

At this locality, we observe a pre-Variscan coarse-grained augen orthogneiss and irregular, subauthochtonous bodies of Variscan garnet-bearing leucogranites.

Fig. 7 Almohalla orthogneiss with pre-Variscan foliation folded during the second Variscan deformation event.

Stop 3: Lastra del Cano

At this locality, the subauthochtonous granodiorites have a planar subhorizontal fabric that is concordant with the external shape of the body. Shear structures are common, especially at the top and bottom contacts of the plutons, where they grade into transitional migmatites.

Fig. 8 Lastra del Cano, looking to the south.

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