Evidence of Protolith Contamination in the Generation of an Anatectic Complex: Peña Negra, Central Spain

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Abstract: The Peña Negra complex, in central Spain, provides a superb opportunity for the study of Variscan partial melting processes. The heat source for the anatexis has been controversial. The presence of mafic rocks in the vicinity has given rise to the suggestion that mafic magmas of mantle origin provided the requisite heat for the generation of the anatectic granites. Experimental petrology can be used to support this concept, but the volumes of mafic magma necessary for the anatexis appear improbably large. Geophysical models for Central Iberia do not support the presence of such large basic complexes at depth. Furthermore radiometric dating of the scarce mafic outcrops indicates that they are too old to have been involved in the granitic magma genesis. The alternative interpretation is that melting of the protolith was promoted by the radioactive decay of K, U and Th. Anatexis was enhanced by the existence of a fertile protolith and by the presence of shear structures that permitted volatile fluxing. The situation is believed to have been analogous to that in other European Variscan terrains.

Key Words: Peña Negra, anatexis, protolith contamination, radiogenic heat.

INTRODUCTION

The geology of Peña Negra has been described and discussed in a series of papers (e.g. [1-3]). The Peña Negra anatectic complex (PNAC) lies in the middle of the Gredos sector (Fig. **1**) and comprises high-grade metamorphic rocks, mostly migmatites, and autochthonous or sub-autochthonous granitic bodies. These occur either as small, lens-shaped bodies or as subhorizontal sheets interlayered with the migmatites. The PNAC has a sub-horizontal disposition resulting from the second phase of Variscan deformation that produced sub-horizontal structures including isoclinal folds, foliation and shear zones. The anatectic complex is surrounded by several granite plutons with contacts ranging from concordant to intrusive (Fig. **2**). Mafic rocks are very scarce in the Complex and the field relationships of those do not support the idea that they played an important role in the evolution of PNAC, due to the sharp contacts between lithologies (Fig. **3**).

The Schist-Greywacke Complex (SGC), in the northwestern part of the Iberian Central System, has been described by numerous authors (e.g. [4-12]). It comprises Neoproterozoic - Lower Cambrian metasedimentary rocks considered as a possible protolith of the Peña Negra complex and many other granitic complexes in central Iberia [3,13].

Previously published geological, geochemical, thermobarometric and chronological data for rocks within the PNAC are taken into consideration in this paper which examines the hypothesis that the anatectic complex formed as a result of radiogenic heat production from the fertile protolith. Considering the high content of radiogenic elements and the lack of physical evidence for intrusion of mantle-derived magmas into the source region, radiogenic heat is inferred to have provided the energy for partial melting.

GEOLOGICAL BACKGROUND

Regional Setting

PNAC is located within the Gredos sector of the Avila Batholith (Fig. **1**). It consists mainly of migmatites, granodiorites, leucogranites, orthogneisses and sillimanite-rich restite. Gabbros and diorites occur as small outcrops in a nearby area [14] cut by the granodiorites. Smaller outcrops of mafic rocks were found within the PNAC but show no interaction with the granitoids. All the lithologies have been described in previous papers (i.e., [2,3,15]) and in this work we consider only the mafic rocks in the complex. These have not hitherto been studied.

The Rocks

Although the PNAC lithologies have been described elsewhere (*cf*. [3,15]), a summary of their characteristics is provided here for clarity and understanding. In volumetric terms, the migmatites are the most important rock type in the PNAC [16-18]. In outcrop they are mesocratic rocks composed of a granodioritic leucosome (quartz, plagioclase, potassic feldspar, cordierite and biotite) and a melanosome (sillimanite, biotite and cordierite, locally with a high content of ilmenite) that forms small enclaves or schlieren interlayered with the leucosome. On the basis of their mesoscopic aspect we distinguish three different facies: l) schlieren, 2) nebulitic and 3) transitional. Each facies has the same mineralogy and geochemistry, but differs texturally. All underwent the same petrogenetic processes but with different degrees of segregation and textural evolution, as we will explain below. The schlieren facies has compositional layering on a cm scale, defined by melanocratic and leucocratic layers. In places the schlieren display complex folding as "wild migmatite", which

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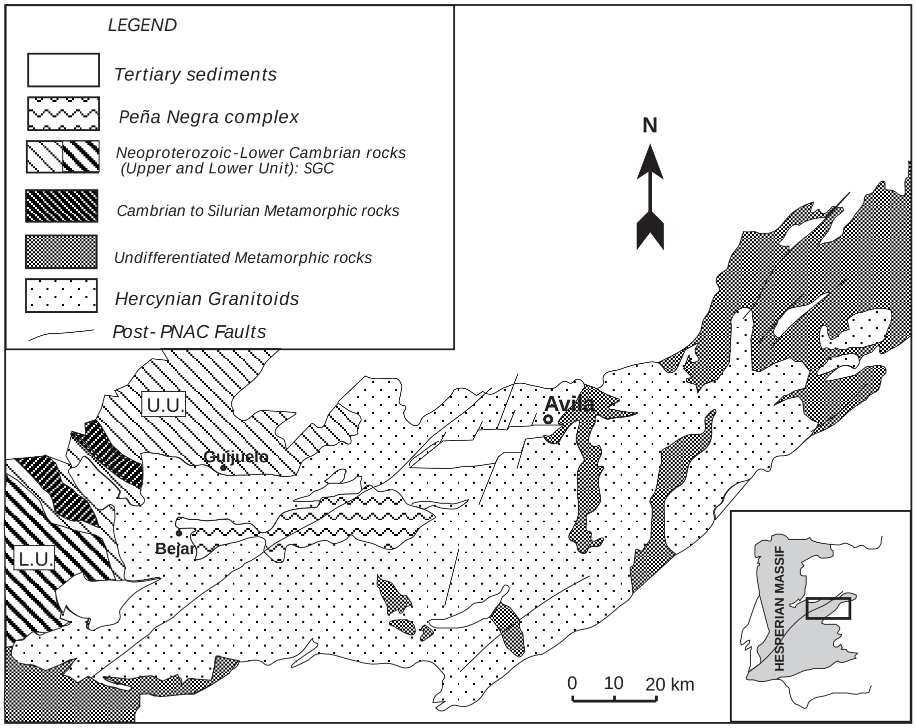

Fig. (1). Location of PNAC within the Avila Batholith.

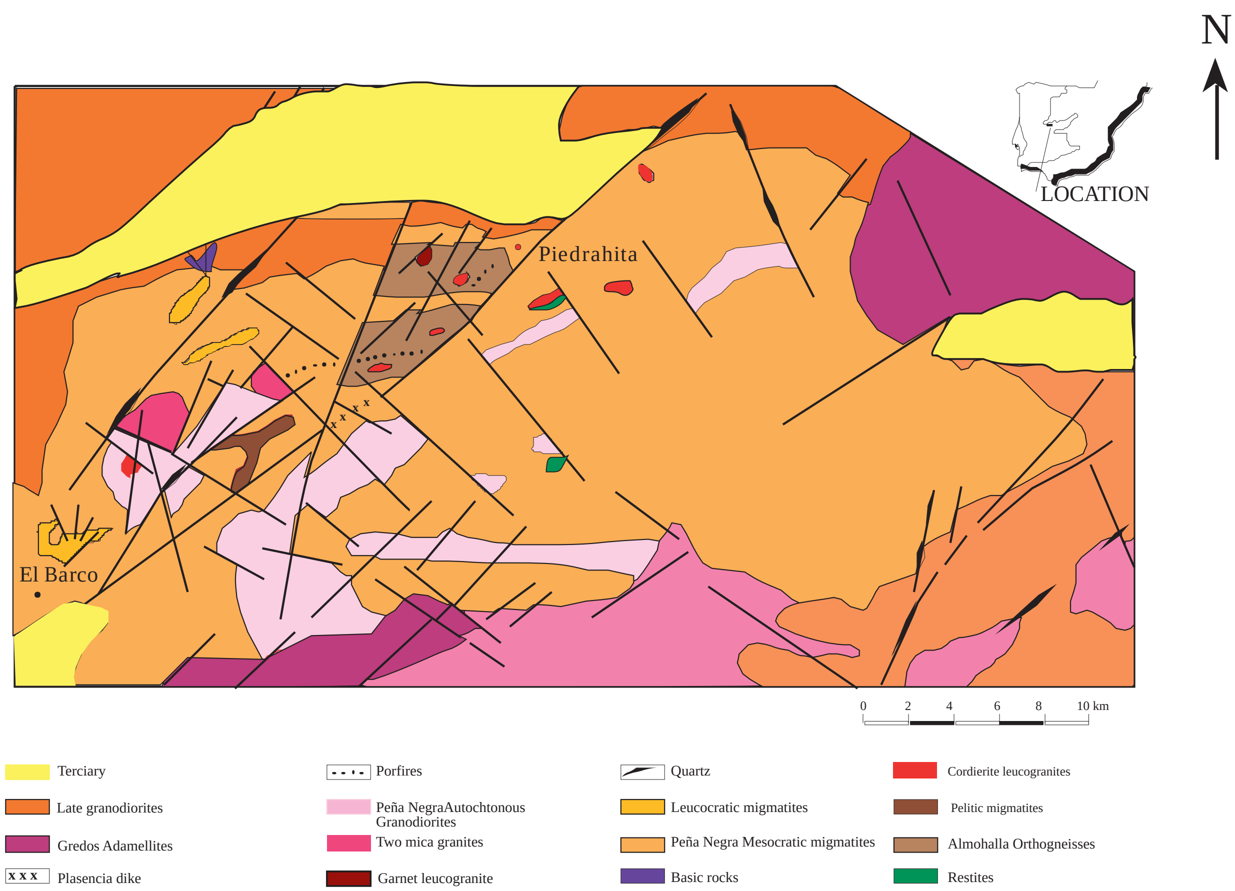

Fig. (2). Geological sketch of Peña Negra anatectic complex, showing lithologies described in text. Modified from [3].

exhibits subhorizontal deformation from the second phase of the Variscan Orogeny. Nebulitic and transitional facies reveal the subhorizontal structures albeit to a lesser degree because the higher intensity of anatexis has caused their partial obliteration. Transitional facies occur between the migmatites and granodiorites, invariably with gradational contacts. The transitional facies has some feldspar phenocrysts: this is also the main petrographic feature of the granodiorites and consequently it is difficult to decide whether they should be called migmatites or diatexitic granodiorites. Relative textural maturity was established on the different facies of migmatites [19] and the results indicate that the degree of anatexis increases from the schlieren to the nebulitic and transitional facies [16].

Thin layers of orthogneisses, intercalated with the migmatites, are leucocratic, strongly foliated, and show the structures produced by the different phases of the Variscan deformation [6]. The orthogneisses have been affected by several stages of migmatization [18] and augen structures are common. They consist of quartz, plagioclase, alkali feldspar and biotite, with zircon, apatite, monazite and ilmenite as accessory phases. Muscovite and chlorite occur as secondary products.

Migmatites and orthogneisses gave a Rb-Sr age of 528 Ma [18]. However, recent investigations obtained ages from 350 to 332 Ma through zircon dating [20]. Either Rb-Sr ages are dating previous materials or the migmatites were formed or reactivated during the Cadomian-Avalonian activity, as in other Iberian regions [21], and subsequently re-set during the Variscan orogeny. This second possibility has not been documented on the studied area, though.

The porphyritic granodiorites crop out as medium- to coarse-grained rocks, with abundant tabular potassic feldspar megacrysts and prismatic, commonly pinitized, cordierite. The fabric of the granodiorites is subhorizontal, concordant with the migmatites and the general structure of the PNAC. The strong sub-horizontal foliation is defined by feldspar megacrysts, biotite and prismatic cordierite. The granodiorites gave a Rb-Sr age of 310 Ma [18,22]. This age coincides with the 309 Ma zircon age obtained by [20]. Granodiorites represent the most important anatectic product of the migmatites, with respect to volume, and their age also dates the most intense period of partial melting of the Complex.

Mineralogical compositions of the migmatites and granodiorites are similar. Both contain quartz, plagioclase, alkali feldspar, biotite, cordierite and sillimanite as principal phases. The leucosomes of the migmatites have hypidiomorphic textures, composed of quartz + plagioclase + cordierite + biotite + alkali feldspar. The melanosome is composed of alternating granoblastic cordierite ± quartz ± plagioclase ± alkali feldspar layers and the schistose layers of sillimanite + biotite + ilmenite ± cordierite. All contain accessory apatite, zircon, ilmenite, tourmaline, monazite and xenotime. We find garnet as a minor phase in one outcrop of the schlieren migmatites that appears as a narrow band coinciding with the largest outcrop of cordierite leucogranite generated from melting of the migmatites. Specific studies on this outcrop are being carried out to gain better understanding of this anomaly. Otherwise, the mineralogy of this garnetiferous rock is the same, and will be used to determine more precise P and T conditions in a future work.

The leucogranites are spatially related to the mesocratic migmatites. They consist of cordierite-bearing leucocratic rocks that crop out as small bodies within the migmatites, with contacts ranging from transitional to intrusive (Figs. **4** a, b: [3]). The leucogranite rocks comprise quartz, alkali feldspar, plagioclase and cordierite, with the same accessory minerals in the granodiorites and migmatites. Cordierite is commonly euhedral to subhedral. Locally, small (< 1 m diameter) intrusive bodies of garnet leucogranite occur which are unrelated to the anatexis. Cordierite leucogranites gave Rb-Sr ages in the range of 305 to 295 Ma. These data are in disagreement with the 321 Ma obtained by [20] for new zircons crystallizing from the granitic melt. Our younger age coincides with the age that these authors obtained for the end of the anatexis at Peña Negra. The different ages could well reflect polymetamorphism in the area, which has been recorded for other Variscan terrains, *e.g.* the Massif Central in France [23], indicating a reactivation of the melting at the end of the process. In any case, the field evidence support the younger ages for the leucogranite.

Sillimanite-rich restites form small, irregular bodies, typically in contact with the migmatites and close to the leucogranites (Fig. **2**). They are characterized by conspicuous sillimanite crystals 3-4 cm long. The restites have granoblastic textures and a modal content of sillimanite between 30 and 60%. The mineral assemblage is as in the melanosomes: biotite and cordierite, in addition to sillimanite, occur as principal phases, augmented by quartz and potassic feldspar. Ilmenite (locally abundant), pyrite, muscovite, zircon and apatite represent accessory phases that are commonly hosted by biotite crystals.

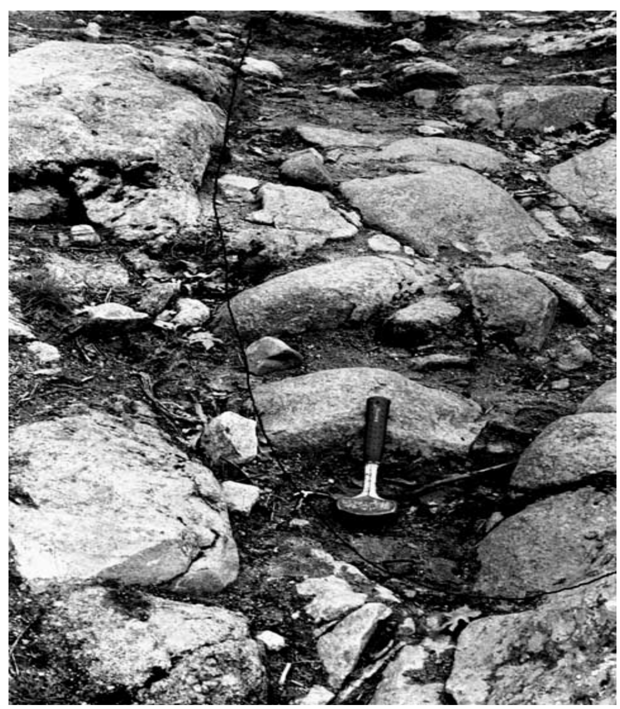

Fig. (3). Mafic rocks emplaced within migmatites from PNAC. Limit between the two lithologies are outlined in ink.

Basic-intermediate rocks are very scarce within the complex and have not previously been described. A very small outcrop of tonalitic rocks at the extreme north of Peña Negra (Fig. **2**) may be related to the same mafic complex as Puente del Congosto [24]. It includes dark grey, medium-grained rocks, with biotites of 4-5 mm, and a slight foliation concordant with the surrounding rocks. The rocks are made up of plagioclase, biotite, amphibole and some quartz with accessory apatite, zircon, allanite, titanite and opaque oxides, commonly included in biotite. The basic to intermediate rocks outcrop as large enclaves within the granodiorites and show no interaction with them.

Previous works showed that these mafic rocks are considerably older than the melting products (416 Ma, [18]), and agrees with the lack of mixing that these rocks show in the field, when included in migmatites or granodiorites [18]. Therefore, it cannot be supportted that a mafic magmatism was involved in the generation of the anatectic complex. Partial melting of crustal protoliths requires intrusion of at least an equivalent mass of basic magma, and in this case it would lead to hybridization [25,26], which is not the case at PNAC.

Rb-Sr data calculated for the mafic rocks described in this paper (Table **2**) give an age of 447 Ma ($^{87}Sr/^{86}Sr$ initial ratio = 0.703). Rb-Sr dating is not a very reliable dating method due to the limited range of chemical composition of the samples. Nevertheless, mafic plutonism and volcanism at 437 Ma has been described by several authors in different European settings (e.g. Scotland [27], Norway [28]). Although highly speculative, it could be that Cadomian basic magmatism affected the metasediments found in all these regions. This is consistent with the existence of a mantle component in the chemical composition of the Gredos granitoids, as shown by the granodiorites (high Ca content ; low $^{87}Sr/^{86}Sr$ values (0.709, [18]) and the experiments proposed by [24]. Alternatively, the high Ca content in the granodiorites could be explained by the existence of amphibolitic layers within the SGC, ultimate protolith for PNAC.

Sm-Nd dating has been attempted but the homogeneous values for these elements (Table **2**) did not permit construction of a significant isochron.

The Protolith of the PNAC

Carbonate and calc-silicate lenses in the migmatitic series indicate that the migmatites of the PNAC were derived from a metasedimentary source [18]. Field relationships suggest that the Neoproterozoic-Lower Cambrian metasedimentary rocks, outcropping within extensive antiforms between very tight Ordovician synclines in the northern and western surroundings of the PNAC area, are the potential sources for the migmatites and other Variscan granites. These metasedimentary rocks and the associated magmatism record a continuous Neoproterozoic-Cambrian sedimentation. However, in most areas sedimentation is not preserved beyond the Precambrian-Cambrian limit, which took place in the northern margin of Gondwana, between the end of the Cadomian cycle and the beginning of the Cambro-Ordovician cycle. This event records the passage from an active margin regime during the Neoproterozoic-Cambrian limit, to the rifting and fragmentation of this margin, which became passive in Cambrian-Ordovician times [29]. The same occurred in other marginal areas of northern Gondwana [30,31]. The Neoproterozoic-Lowermost Cambrian (Corduban) succession consists of a thick (6000-11000 m) siliciclastic sequence with very few interlayered carbonates. These sediments have always been considered to form a Schist-Greywacke Complex (SGC) in which two main informal units can be described: the Lower Unit and the Upper Unit, interpreted as a continuous process of siliciclastic sedimentation with the development of turbiditic facies, which evolved upward into mixed-siliciclastic-carbonate slope-platform environmental conditions within a tectonic-controlled basin and associated with volcanic activity [5] and references therein; [29]. Both units are interpreted as two depositional sequences separated by a disconformity of the type 1 boundary sequence and organized in twelve lithostratigraphic units [8,9]. The SGC grades upward into a Lower Cambrian (Ovetian) shallow marine sandy succession (Tamames Sandstone Fm) that marks the beginning of the Cambrian transgression [32,33] and is followed by platform carbonates (Tamames Limestone Fm) with trilobites, archaeocyathids and ichnofossils. Apparently, they accumulated continuo until an episode of late Cambrian diastrophism folded and locally uplifted the whole sequence. Finally, the Ordovician-Silurian sediments and its volcanic-volcaniclastic associated rocks are unconformably deposited over different levels of the Neoproterozoic-Cambrian succession [5,33].

Petrological studies show that gray to black laminated shales and their metamorphic equivalents are the most abundant group of rocks within the whole Neoproterozoic-Lower Cambrian succession, followed by sandstones, conglomerates and carbonate intercalations. Among the sandstones, quartz-, lithic- and feldspathic-greywackes, together with lithic sandstones, quartz-arenites and volcanoclastic sandstones are found. Conglomerates are both grain- and matrix-supported, and also oligo- and polymictic in composition. The rock fragments and quartz grains in sandstones and conglomerates reveal different provenance areas: sedimentary (siliciclastic), metamorphic and plutonic, together with mixtures of juvenile volcanic components [3,4]. The carbonate materials include calcareous breccias and thin-bedded carbonate facies consisting mainly in crystalline arenaceous limestones and dolomites with very few allochemical components [4]. Occasionally, phosphate-rich horizons or nodules and cherts are also present.

Evidence of magmatism contemporaneous with the Neoproterozoic-Lowermost Cambrian sedimentation is provided by the presence of coherent, massive volcanic rocks (metabasalts, meta-andesites and meta-rhyolites), volcaniclastic mudstones, sandstones, conglomerates and breccias. Other evidence is the presence of volcanogenic lithic fragments and crystals mixed in different proportions with siliciclastic constituents and within calcareous components in the sedimentary succession [29].

GEOCHEMICAL FEATURES

Full descriptions of analytical methods for geochemistry are given by [3] together with whole-rock compositions of lithologies. The methodology for the analysis of oxygen isotopes in zircons is fully described in [34].

Geochemical studies on the protolith show that Neoproterozoic-Lower Cambrian sandstones and shales [8-12,35] reveal a great homogeneity in the composition through the CIZ and WALTZ [7,36] as well as in areas of Central and Western Europe. These authors agree on the evidence that the sedimentary series record two provenance areas: a detrital material derived from recycled orogens and an important juvenile contribution, which governs their isotopic signature. This is confirmed by the geochemical results reported from the volcanic and volcaniclastic rocks interlayered with the sedimentary facies, which support tectonic and magmatically active settings as direct contributors of Neoproterozoic-Lower Cambrian sequences in the CIZ. Some samples display calc-alkaline affinity, although most of them show tholeitic character, suggesting a magmatic evolution within an active margin setting [29], placed in the northern margin of Gondwana that featured both magmatic arc and a variety of back-arc basins in Neoproterozoic times. Sm/Nd, Nb/Yb and Ta/Yb ratios support such possible evolution [29]. All of these features favour the proposed model involving the Avalonian-Cadomian arc as the tectonic setting for the Neoproterozoic-Lower Cambrian of NW Iberia [37].

The major-element composition of the mesocratic migmatites and sub-autochthonous granodiorites are almost identical (Table **1** in [3]) although CaO is always higher in the granodiorites (2.57 % for granodiorites ; 1.50 for migmatites). The orthogneisses have compositions very close to those of the migmatites, except for their enrichment in CaO, in which they resemble the granodiorites. This feature could point to a possible mafic influence in the generation of the granodiorites, invoking the presence of mafic bodies that have been found in areas nearby [24,38]. However, other explanations are preferable as will be discussed. The protolith is very heterogeneous and contains, among other materials, layers of amphibolites that are found within the Complex, as evidence of its source [29].

Seven samples of mafic rocks have been studied for the present work. Their major elements show that they have a high potassium calc-alkaline character (Table **1**).

These rocks are metaluminous (ASI ≈ 0.63). Their chondrite-normalized REE patterns (Fig. **4**) have a negative slope ($La_N/Lu_N \approx 8$) with a small negative Eu anomaly (Eu*/Eu) ≈ 0.8). These mafic rocks could resemble the mafic precursors described by [38] and [24], although some differences related with age are discussed below.

Oxygen isotopes were investigated in the different lithologies. The maximum $\delta^{18}O$ is obtained for migmatites: 16.23 ‰ (leucosome: 12.98 ‰, melanosome: 12.31 ‰). Mafic rocks have a value of 8.45 ‰ and the granodiorites give a value of 9.57 ‰. Preliminary results for oxygen isotopes in zircons in some PNAC lithologies show values that clearly indicate an I-type source. Zircons in the migmatites have $\delta^{18}O$=6.49 ‰ whereas those from the granodiorites have $\delta^{18}O$=5.37 ‰. Sillimanite and quartz from these rocks gave values between 9.69 to 9.97 ‰ and between 11.49 and 12.42 ‰ for the two minerals respectively. From these data it is deduced that the zircons record an early magmatic composition whereas the other phases could represent a magmatic value after a later event. This would imply that a enrichment in $\delta^{18}O$ took place after the crystallization of zircons [34,39,40].

The mafic rocks were analyzed for Rb, Sr, Sm and Nd isotopes (Table **2**). These isotopic ratios show very constant values, more appropriate for crustal rocks than for mantle-derived material. This is a common feature in the mafic rocks from the Spanish Central system and could be attributed to contamination with meta-sediments affected by the Cadomian orogeny. The field relationships observed between these mafic bodies and their host rocks do not suggest any later elemental exchange. Although it is not the best dating method for these lithologies, we used these data to estimate the age of the basic magmatism (see above).

GRAVIMETRIC AND MAGNETIC DATA

No geophysical work has been done on this specific area, although there are several papers on regions close by [41,42]. In the National Geographic Service general maps of Spain and maps of ENRESA (Spanish national company for radioactive waste management) there is no evidence of large masses of high density (i.e. mafic rocks) in the studied area, except small maxima on the Free Air Anomaly map. Gómez-Ortiz described a relative maximum on his studied area coinciding with the northeast limit of the Spanish Central system [41]. This maximum coincides with the presence of orthogneisses outcropping in the region, whose densities contrast with those of the sediments in the area [41]. These images agree with the field observations.

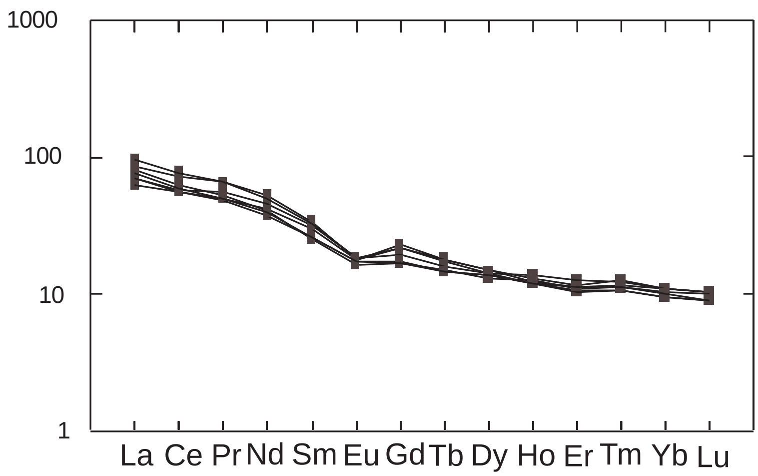

Fig. (4). REE for mafic rocks, normalized to chondrite.

Table 1. Geochemical Composition of Mafic Rock Samples Found at the PNAC

	Grelo-57	Grelo-58	Grelo-59	Grelo-60	Grelo-61	Grelo-62	Grelo-65
Major Elements							
SiO_2	57.10	59.71	56.18	58.77	55.85	55.28	55.09
Al_2O_3	16.69	16.81	18.25	17.93	15.99	16.10	16.16
Fe_2O_3	7.41	6.71	7.75	7.04	8.45	8.46	8.43
MnO	0.12	0.11	0.12	0.11	0.13	0.13	0.14
MgO	3.72	3.30	3.45	3.28	5.33	5.70	6.02
CaO	4.89	4.90	5.39	5.59	5.62	5.88	6.13
Na_2O	3.09	3.13	3.39	1.77	1.78	1.92	1.72
K_2O	3.25	2.71	2.83	2.80	2.76	2.67	2.68
TiO_2	1.24	1.13	1.15	1.20	1.48	1.45	1.33
P_2O_5	0.45	0.38	0.33	0.33	0.28	0.28	0.27
LOI	1.30	0.75	0.81	1.08	1.55	1.35	1.51
Total	99.25	99.63	99.65	99.90	99.22	99.48	99.22
Trace Elements							
Li	67	55	59	94	70	72	66
Rb	127	110	121	182	158	152	165
Cs	6.72	6.50	7.04	8.61	8.06	8.14	8.86
Be	2.27	2.78	2.70	2.88	2.53	2.57	2.28
Sr	330	316	326	466	344	346	348
Ba	667	516	590	698	495	396	473
Sc	20	17	21	23	26	27	28
V	112	107	113	96	134	145	147
Cr	160	148	117	37	225	247	271
Co	20	18	19	45	67	51	55
Ni	34	25	20	11	76	84	90
Cu	27	19	17	14	67	31	31
Zn	79	79	95	87	98	97	93
Ga	21	21	23	21	20	20	20
Y	31	29	31	33	30	32	31
Nb	15	14	14	11	13	14	13
Ta	1.14	1.01	1.06	0.95	1.30	1.26	1.17
Zr	58	68	81	265	186	213	197
Hf	1.88	2.08	1.95	3.11	4.91	4.23	3.90
Mo	1.27	2.13	1.55	0.28	0.74	1.22	1.47
Sn	5.58	4.22	4.83	3.51	4.17	4.04	4.01
Tl	0.80	0.71	0.76	1.28	1.08	1.00	1.01
Pb	16	18	18	6.48	9.50	9.09	8.73

(Table 1) contd….

	Grelo-57	Grelo-58	Grelo-59	Grelo-60	Grelo-61	Grelo-62	Grelo-65
Trace Elements							
U	2.18	1.96	1.60	1.59	4.08	2.39	2.30
Th	7.57	5.97	5.94	8.33	6.08	7.30	6.89
La	31	23	26	35	26	30	28
Ce	72	53	57	75	54	60	57
Pr	9.10	7.12	7.66	9.18	6.79	7.31	6.97
Nd	38	30	32	36	27	29	29
Sm	7.93	7.03	7.30	7.49	6.01	5.94	6.07
Eu	1.60	1.60	1.62	1.63	1.56	1.47	1.54
Gd	7.25	6.58	6.81	6.09	5.33	5.28	5.26
Tb	1.06	1.01	1.06	0.95	0.86	0.87	0.86
Dy	5.73	5.35	5.71	5.54	5.26	5.03	5.21
Ho	1.06	1.04	1.13	1.18	1.04	1.07	1.04
Er	2.89	2.71	2.99	3.15	2.61	2.79	2.84
Tm	0.43	0.39	0.46	0.45	0.39	0.42	0.41
Yb	2.79	2.41	2.76	2.76	2.37	2.56	2.49
Lu	0.39	0.34	0.40	0.39	0.34	0.38	0.34

Major elements are given in %; trace elements in ppm.

Table 2. Rb, Sr, Sm and Nd Concentration in Mafic Rocks, and Isotopic Ratios

Sample	(Sr)	Error (2σ)	(Rb)	Error (2σ)	^{87}Rb/^{86}Sr	Error (2σ)	^{87}Sr/^{86}Sr	Error (2σ)
Grelo-61	465.8	9.3	181.9	3.6	1.131	0.032	0.710206	0.000050
Grelo-62	344.1	6.9	157.8	3.2	1.329	0.038	0.711524	0.000058
Grelo-63	347.9	7.0	164.8	3.3	1.372	0.039	0.711397	0.000060
Grelo-65	346.0	6.9	151.8	3.0	1.271	0.036	0.711079	0.000054

Sample	(Nd)	Error (2σ)	(Sm)	Error (2σ)	^{149}Sm/^{144}Nd	Error (2σ)	^{143}Nd/^{144}Nd	Error (2σ)
Grelo-61	29.68	0.42	6.02	0.06	0.123	0.001	0.512300	0.000013
Grelo-62	23.09	0.32	5.09	0.05	0.134	0.001	0.512236	0.000024
Grelo-63	25.73	0.36	5.28	0.06	0.125	0.001	0.512357	0.000017
Grelo-65	23.71	0.33	5.27	0.06	0.134	0.001	0.512402	0.000021

Aeromagnetic maps supplied by ENRESA, the Spanish national company for radioactive waste management, show some maxima in areas close to the PNAC that could represent bodies of high magnetism. These bodies have not been identified in the field and the image could indicate that large mafic bodies underlie the rocks at the surface. This could be the case if the leucogranites formed during an extensional period when the crust would have been thinner and mantle material had been closer to the surface (Fig. **5**).

Further work on this subject is needed to make a three-dimension picture of the situation at the PNAC regarding mafic rocks at depth.

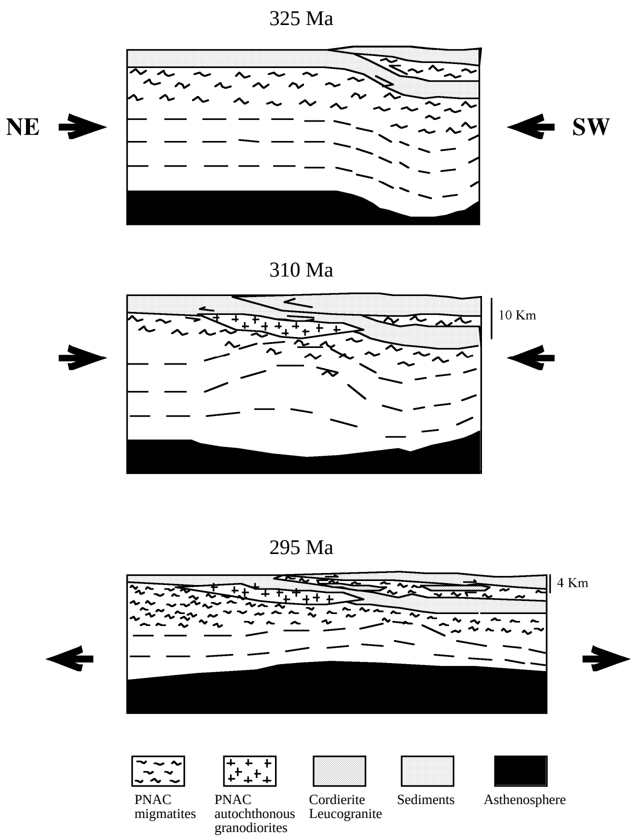

Fig. (5). Evolution of Peña Negra complex during the Variscan orogeny. From Pereira (2003).

RADIOGENIC HEAT PRODUCTION

Radiogenic heat production is dependent on lithology and its effectiveness can vary with depth. The metasedimentary SGC, the ultimate protolith of the Peña Negra anatectic complex, is enriched in K, U and Th, as are the granites formed by its partial melting. Many papers dealing with economic deposits have revealed their conspicuous enrichment in U in the SGC. This enrichment is shared by the migmatites although to a lesser extent. U-depletion during anatexis was noted by [43] who showed that the U is located neither in accessory minerals nor in the crystal structures of the major rock-forming minerals and is readily leached by migrating fluids. We have calculated the average heat production using the composition of a wide selection of samples of all lithologies [3,8,18,35] and densities published for these rocks (Table **3**).

The heat production obtained for all lithologies is higher than the average heat production of the Upper Crust (2 $\mu W/m^3$, [45]). The data used here are from surface rocks collected during the study. Radiogenic U, Th and K had a long period of decay, and the increase of heat production with depth is notable [46]. It is therefore reasonable to consider that the heating values in Proterozoic and Variscan times would be at least 10% higher than values shown on Table **3**, high enough to cause melting of a fertile rock. In terms of fertility, it has been demonstrated that a source composed of a mixture of metasediments plus orthogneisses gives the optimum composition for anatexis to occur [3]. Although [47] suggested that pelitic material is the most likely provider of radiogenic heat, due to its K-Th-U composition, Fig. (**6**) shows that a quartz-feldspathic material buried at an appropriate depth can generate an increase in temperature more efficiently than metasediments alone. This figure is modified from Figure 14 in [16], and was made using the radiogenic heat production equation proposed by [48]. This author proposed that a rock enriched in Rb, K, U and Th can generate heat, which, if not dissipated, can produce generalized melting [49] without large thermal gradients. Using this figure, enough heat would be produced at a depth of 10 km. This is approximately the depth at which the granodiorites were produced during the Variscan orogeny, as calculated from the P-T path for these rocks [22].

Table **3** shows that restite produces the greatest heat (2.95 $\mu W/m^3$). Restites are high-density rocks occurring in association with leucogranites and migmatites and it is debatable whether heating produced by restites at ~ 4 km depth

Table 3. Radiogenic Elements in Average Compositions for the Presumed Protolith and PNAC Lithologies, Together with Calculated Heat Production

Lithology	Density	U (ppm)	Th (ppm)	K_2O (%)	Radiogenic Heat Production ($\mu W/m^3$)
Schists	2.74	3.60	12.8	3.70	1.48
IBRC*	2.76	3.80	16.1	5.60	2.26
IBRP*	2.76	2.90	10.8	4.00	1.62
Metapelites	2.76	2.95	10.9	4.20	1.70
Migmatites	2.76	2.64	9.94	3.48	1.41
Gneisses	2.68	4.30	10.9	2.68	1.05
Granodiorites	2.66	2.47	12.94	4.72	1.84
Leucogranites	2.64	3.32	12.34	4.86	1.88
Restites	2.87	8.25	21.49	7.03	2.95

Data from [3,7,8,18,35]. IBRP* and IBRC*: Iberian Range Precambrian Shale and Iberian Range Cambrian Shale [36]. Densities are from [41] and [44].

could cause melting of an already depleted source to yield leucogranite melts as a low melt-fraction [50].

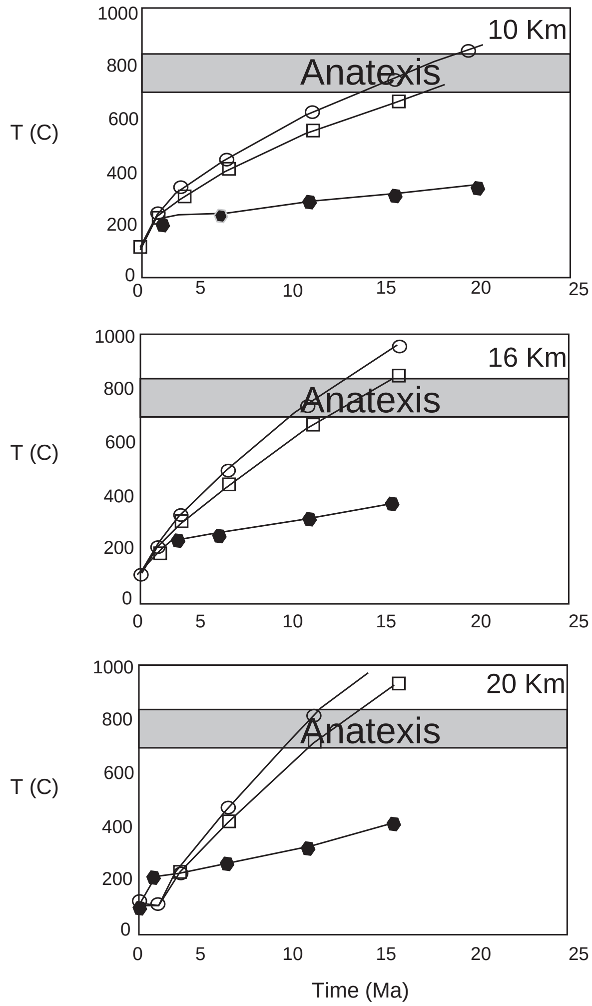

Fig. (6). Production of anatexis at different depths, depending on the protolith. Open symbols represent quartzfeldspathic material; solid circles represent pelithic lithologies. Modified from [16].

2D numerical modeling of the thermal structure of collisional orogens has been done by [51] running a series of models with heat production values in the sediments varying between 2 (standard value) and 6 $\mu W/m^3$ and basal (mantle) heat flow values between 20 and 55 μWm^{-2}. Sediment thicknesses have also been varied between 7 and 10 km. The effect of changing heat production from 2 to 6 $\mu W/m^3$ in a 7 km thick layer (thickness proposed by [38], as the most probable for the migmatite source layer) is of the order of 100-130 ºC. If we consider a thickness of 10 km, the heat production increases the temperature to 170 ºC. An increased basal heat flow entering the crust from the mantle was needed to get high enough temperatures at a depth of 20 km to produce anatexis. Although [52] suggested that a heat production of the order of the one obtained by the restites composition was a viable mechanism in granite generation, [51] conclude that even elevated heat production, on its own, cannot be the origin of widespread melting for those depths proposed by [38]. Therefore, it is even less feasible for the depths calculated from the P-T conditions by [50] for the Peña Negra anatectic products. For realistic average heat production values of 3-4 $\mu W/m^3$, a basal heat flow of 50-55 mWm^{-2} is needed.

DISCUSSION

The existence of fertile protoliths in the crustal profile and the distribution of heat producing elements are necessary conditions if melting within the crust is to take place. The migmatites in the Peña Negra anatectic complex were produced by the partial melting of a highly heterogeneous protolith, the Schist Greywacke Complex, wherever a high volume of orthogneisses was present. The anatectic event took place during an extent period (55 Ma, suggested by 20), starting with the main Variscan collision and giving granitic products out of the migmatites.

The second phase of the Variscan orogeny had a very important role in the generation of melts. This phase was the response to a compression stage, and was translated into sub-horizontal structures. As a generality for the PNAC, the granodiorites define sub-horizontal sheets of 1 - 10 km length (Figure 2 in [1]) and up to 200 m thick. Sub-horizontal structures affect both the migmatites and the granodiorites and it is clear that these structures acted as conduits for fluids that promoted the partial melting and controlled the geometry of the melt [53,54]. A subsequent extensional event produced the collapse of the migmatitic series. Locally, the planar fabric was affected by sub-vertical folding and sub-vertical shear zones [6]. However, the anatexites developed at these steep structures are of minor importance.

U-Pb dates on zircons from the gneisses give Cadomian to Cambrian ages [55]. More recently, [21] have proposed on the basis of zircon dates from the orthogneisses of north-western Iberia that the provenance of basement rocks range from Palaeoproterozoic to Neoproterozic in age. Local homogenization of the protolith (SGC + orthogneisses) prior to the Variscan anatexis gave rise to a compositional mixture in which all the rocks (except for extreme lithologies, e.g. sandstones, calc-silicate rocks and limestones, found as enclaves within the PNAC) were progressively unified.

The melting (or re-melting) of the migmatites during the Variscan orogeny involved breakdown of hydrous minerals. The presence of cordierite and the addition of boron and other volatile species [54] led to lowering of the solidus and the minimum-melt composition was shifted to the left of the melt-production curve, producing peraluminous granodiorites and, at lower temperatures, leucogranites [1,56]. The source contains enough radiogenic isotopes to have brought about the partial melting of migmatites at a depth of ~10 km, but only when facilitated by the existence of a fertile protolith affected by shear zones providing additional frictional heat and volatile conduits [53].

Published data on geochemistry ([14] and references therein) corroborates the anatectic hypothesis for the generation of granodiorites and leucogranites, the latter leaving a residue made up by sillimanite + biotite. This high-density restite contained a high proportion of radiogenic elements, probably due to the high concentration of biotite, which is a conspicuous host for accessory phases, mainly zircon, monazite, allanite and apatite [26]. This high concentration of radiogenic elements could have been brought about by leachable fluids including, e.g. boron [2], coming from the protolith. The existence of such radiogenic element-enriched material would have provided a heat-source for low partial melting, such as leucogranite generation, and has to be taken into account.

Oxygen isotopes in the migmatite and granodiorite zircons give values typical for I-type igneous rocks and from these data we deduce that the zircon records an early magmatic composition whereas oxygen in the other phases reflects magmatic values after a later event. This would imply that enrichment in $\delta^{18}O$ took place after the crystallization of zircons. Although it could be argued that the zircons were inherited from a more basic source, in either case, it is clear that zircon was in isotopic disequilibrium with everything else. Although other chemical anomalies in the anatectic rocks show a possible influence of mafic material, these relate to earlier magmatic events (see above), because there is no physical evidence of mafic components at the present erosion level. Furthermore, the available geophysical data do not indicate the existence of large enough mafic bodies at depth. Therefore, we exclude the involvement of basic magma in the anatectic process, as [24] had proposed based on experimental data.

CONCLUSIONS

Variscan collision started at around 350 Ma in southeastern Europe, affecting first the metasediments from the Bohemian region. The effect propagated towards the west, piling up radiogenic isotope-enriched metasediments that produced enough heat to help to start melting the migmatites at about 10 km depth, thus producing the granitoids. Extensional collapse after some 15 Ma produced a second generation of shearing permitting the accumulation of fluids and volatiles. These, together with the heat generated by fertile rocks at about 4 km depth, could trigger melting of the protolith, giving more anatectic products through anatexis. There is no requirement for basic magma to generate the anatectic complex, although as the leucogranites were formed during the extensional collapse of the sequence, mantle heat could be considered to help by conduction, as this mantle would be closer to the melting region. Some authors do not agree with the idea that radiogenic heat would produce anatexis [51,57] and the present work here does not prove the case. However, it sets out the complementary circumstances including: 1) the concentration of volatiles in shear zones; 2) fertility of the protolith; and 3) the high content of heat producing elements in specific lithologies which, in combination, can cause anatexis of metasedimentary source rocks, without the involvement of mafic magmas. [57] demonstrated with their models that heating through shearing is efficient in triggering the partial melting of a protolith, providing that it is fertile enough to produce granitoids. Horizontal shearing affecting migmatites and granodiorites during the second phase of the Variscan orogeny has been described in several papers [3,53] and demonstrated their effectiveness in the generation of melt. In any case, there is enough evidence for protolith contamination at the Peña Negra complex to consider its partial melting origin, without looking for external heating related to basic magmatism to produce the anatectic complex.

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