Petrology, Vol. 6, No. 6, 1998, pp. 555–563. From Petrologiya, Vol. 6, No. 6, 1998, pp. 606–614.

P–T Conditions of Generation of the Peña Negra Anatectic Complex, Central Spain*

M. Dolores Pereira
Depto. de Geología, Facultad de Ciencias, Universidad de Salamanca, 37008 Salamanca, SPAIN;
e-mail: mdp@gugu.usal.es

Received April 21, 1998

Abstract—Geothermobarometry has been applied on materials from the Peña Negra anatectic complex using assemblages containing garnet. The used calibrations show that the climax of anatexis took place at 750°C and 4 kbar. Retrograde metamorphism led to minimum temperature conditions of about 500°C and a pressure between 1 and 2 kbar. Garnet is a very rare mineral within the complex and seems to have formed through the incongruent melting of biotite during the thermal paroxysm. Afterwards, retrogression of the garnet produced a rim of biotite plus cordierite; these are less magnesian than normal prograde biotite and cordierite. The obtained results coincide with published data by different authors for areas nearby, which are always near the anatexis isograd.

INTRODUCTION

The Peña Negra anatectic complex (PNAC) is located in the middle-western part of the Avila batholith, in central Spain (Fig. 1) (Bea and Pereira, 1990; Pereira, 1992; Pereira and Bea, 1994). It crops out over 350 km^2, and it is made up of high–medium grade metamorphic rocks, mainly migmatites, and anatectic products derived from the melting of those migmatites during the Hercynian orogeny. Generation and coexistence of the different products is mainly the result of the locally composition variation of a highly heterogeneous source. A fertile lithology is the main feature to take into account, although the presence of shear structures, controlling the role of volatile elements, is a very important factor in triggering the partial melting of the migmatites (Pereira and Shaw, 1996, 1997).

Migmatites have a nonvariable mineralogy, characteristic of low pressure conditions: quartz + plagioclase + alkali feldspar + biotite + cordierite ± sillimanite as main phases. Ilmenite, apatite, zircon, pyrite, chalcopyrite and tourmaline are common accessory minerals. This paragenesis does not contain an association that can be used as a good thermobarometric sensor. However, there is a restricted and narrow band of migmatites, close to the high part of the complex, where we have identified garnet as an accessory phase (Pereira, 1992, 1993). This fact will be crucial when applying some geothermometric calculations, calibrated by different authors on the pairs cordierite–garnet (Bhattacharya *et al*., 1988), biotite–garnet (see Spear and Peacock, 1990), and on the association garnet–plagioclase–sillimanite–quartz to calculate pressure conditions (Hodges and Spear, 1982).

* This article was submitted by the author in English.

The purpose of this paper, therefore, is the study of pressure and temperature conditions under which the rocks from the PNAC were generated and to compare these results with the ones obtained by other authors for the generation of similar complexes.

THE SAMPLES

Mesocratic migmatites are the most abundant material in the PNAC, and sheets of granodiorite and small lens-shaped bodies of cordierite leucogranite can be found interlayered with them (Pereira, 1992; Pereira and Bea, 1994; Pereira and Shaw, 1996, 1997). These migmatites are high-grade, mostly neosomatic, and can be called diatexites (in the sense of Mehnert, 1987). They are made up of: (1) a granodioritic leucosome, with hypidiomorphic texture, containing quartz, plagioclase, alkali feldspar, cordiente, and biotite as main phases; and (2) a restitic melanosome, which appears as small enclaves or as schlieren within the leucosome, and it is made up by sillimanite, cordierite, and biotite, with very abundant ilmenite and very rare alkali feldspar.

Chemical and mineralogical composition of migmatites is identical in every part of the PNAC, but garnet is only found in a specific outcrop, where it appears as subhedral big crystals (1 cm in size) with poikilitic textures (Fig. 2). Garnet has a tendency for the leucosome, although composition is the same as the few found in melanosome (Table 1; Fig. 3).

ANALYTICAL METHOD

Electron microprobe analyses were done for major elements on biotite, cordierite, garnet, sillimanite, muscovite, feldspar, ilmenite, and sulfides. Facilities used

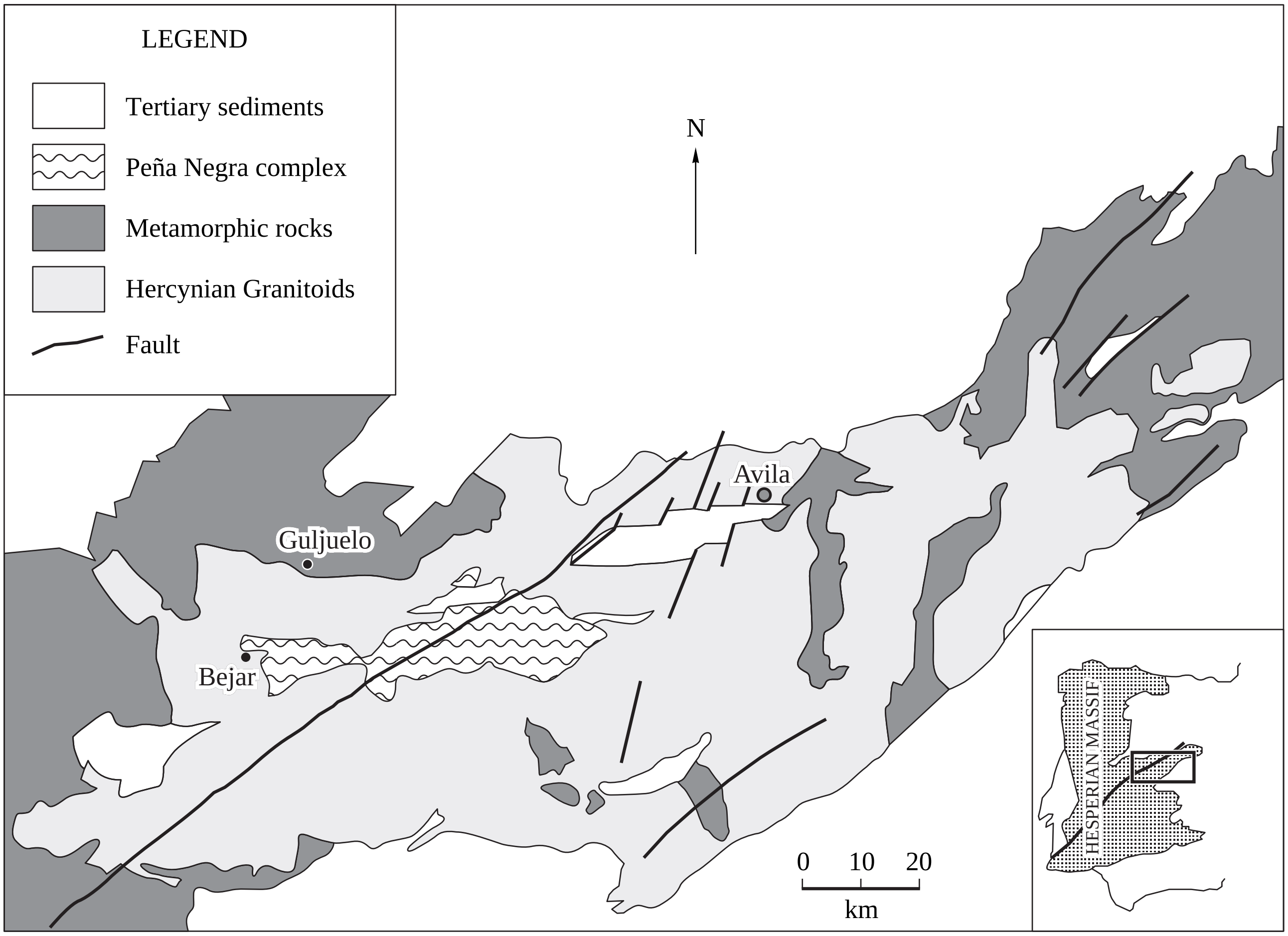

Fig. 1. Location of the Peña Negra anatectic complex within the Avila batholith (Central Iberia, Hercynian massif).

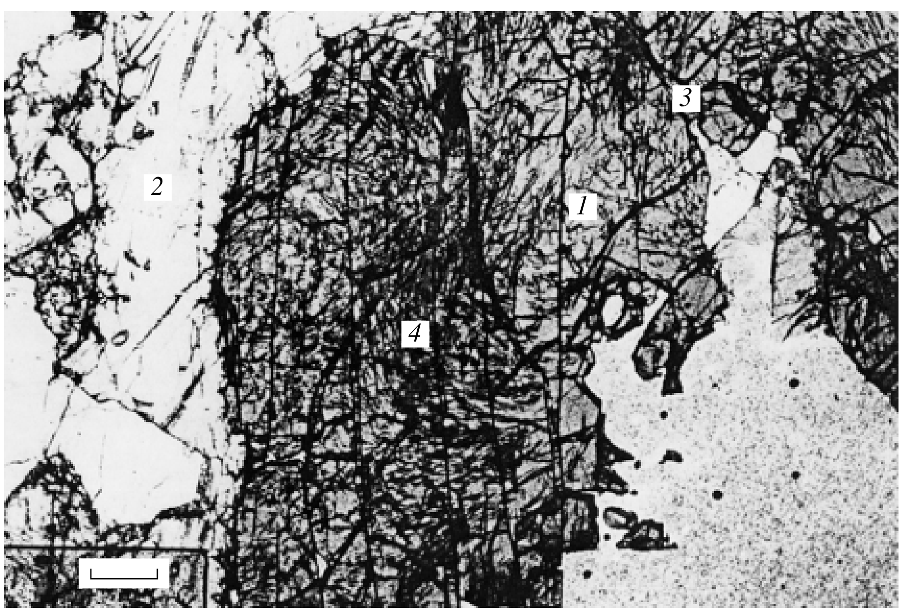

Fig. 2. Characteristic texture of garnet in migmatites from Peña Negra complex (see text). (*1*) Garnet; (*2*) cordierite; (*3*) biotite; and (*4*) sillimanite (fibrolite). Scale bar: 1 mm.

Table 1. Analyses of garnet from Peña Negra migmatites

Components	1			2		3			4		
	rim	mid	core	rim	mid	rim	mid	core	rim	mid	core
SiO_2	36.73	37.03	37.08	36.38	37.33	36.79	36.33	37.02	36.23	36.83	36.46
TiO_2	0.04	0.04	0.02	0.03	0.04	0.01	0.04	0.00	0.00	0.00	0.04
Al_2O_3	20.78	20.58	20.68	20.53	21.00	20.75	20.83	20.98	20.77	20.67	20.66
FeO	36.16	36.91	35.92	36.72	35.17	34.24	35.03	34.08	34.29	35.46	35.05
MgO	1.18	1.90	2.56	1.18	3.41	1.88	2.03	3.06	0.61	1.71	1.70
MnO	5.76	4.29	3.75	5.22	3.13	4.91	4.54	3.81	6.59	5.00	4.89
CaO	0.71	0.81	0.74	0.66	0.83	0.78	0.82	0.80	0.69	0.71	0.79
Na_2O	0.01	0.00	0.01	0.00	0.00	0.02	0.04	0.06	0.09	0.08	0.09
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.00
Total	101.4	101.5	100.8	100.7	100.9	99.38	99.66	99.82	99.29	100.47	99.68
Structural formulae based on 12 oxygens											
Si	2.98	2.98	2.99	2.97	2.98	3.00	2.97	2.99	2.99	2.99	2.98
Al	1.98	1.95	1.96	1.97	1.98	2.00	2.00	2.00	2.02	1.98	1.99
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	2.45	2.49	2.42	2.51	2.35	2.34	2.39	2.30	2.37	2.41	2.40
Mg	0.14	0.22	0.30	0.14	0.40	0.22	0.24	0.36	0.07	0.20	0.20
Mn	0.39	0.29	0.25	0.36	0.21	0.34	0.31	0.26	0.46	0.34	0.33
Ca	0.06	0.07	0.06	0.05	0.07	0.06	0.07	0.06	0.06	0.06	0.06
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X_{Fe}	0.80	0.80	0.79	0.81	0.77	0.78	0.79	0.76	0.79	0.79	0.79
X_{Mg}	0.04	0.07	0.10	0.04	0.13	0.07	0.08	0.12	0.02	0.06	0.06
X_{Mn}	0.13	0.09	0.08	0.11	0.07	0.11	0.10	0.08	0.15	0.11	0.11
X_{Ca}	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02

were CAMEBAX microprobes at the University of Oviedo (Spain) and Hannover (Germany). Similar analytical programs were used for the silicates and the parameters were: accelerating voltage: 15.00 kV; filament tension: 8.00 kV; image energy: 10 nA.

As standards were used (1) corundum, (2) hematite, (3) periclase, (4) TiMn, (5) orthoclase, (6) albite, (7) wollastonite, (8) andradite, and (9) apatite. Counting conditions were adjusted to obtain a precision better than ~0.5 % in all elements.

Tables 1–4 show the analyses obtained for garnet, cordierite, biotite, and plagioclase, respectively.

CHEMISTRY OF THE GARNET

Garnet from the PNAC migmatites has an almandine composition with a high content of spessartine (up to 8%). MnO is concentrated preferentially in the rim, the core is slightly depleted in this component (Fig. 3). Profiles are similar to those described by several authors in rocks from sillimanite–alkali feldspar metamorphic conditions. However, garnet from the literature shows a large core without zoning, and all the zoning is concentrated in the rim (e.g., Tracy *et al.*, 1976;

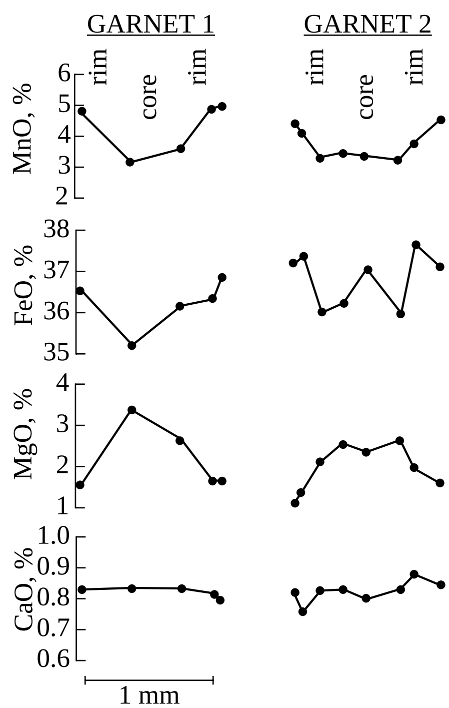

Fig. 3. Zoning profiles for MnO, FeO, MgO, and CaO in garnets from migmatites in the Peña Negra complex.

Table 2. Analyses of cordierite from Peña Negra. Crystal 3 is a cordierite coexisting with garnet. In the structural formulae, ΣT, ΣM, ΣCh represent the sum of tetrahedric, octahedric and channel cations respectively. mg# = Mg/(Fe + Mn + Mg)

Components	1	2	3	4	5
SiO_2	47.64	48.25	48.17	48.53	47.83
TiO_2	0.00	0.02	0.01	0.00	0.00
Al_2O_3	32.04	32.85	31.64	32.27	32.86
FeO	11.95	10.41	13.08	11.58	10.77
MgO	6.10	6.50	5.34	6.09	6.08
MnO	0.23	0.22	0.33	0.27	0.26
CaO	0.00	0.01	0.00	0.00	0.01
Na_2O	0.18	0.39	0.15	0.08	0.25
K_2O	0.00	0.01	0.00	0.00	0.00
Total	98.14	98.66	98.72	98.82	98.06
Structural formulae based on 18 oxygens					
Si	5.004	5.004	5.053	5.045	4.998
Al	3.966	4.014	3.910	3.953	4.046
ΣT	8.970	9.019	8.963	8.997	9.043
Ti	0.000	0.002	0.001	0.000	0.000
Fe	1.050	0.903	1.147	1.006	0.941
Mg	0.954	1.004	0.835	0.943	0.946
Mn	0.021	0.019	0.030	0.024	0.023
ΣM	2.025	1.928	2.012	1.974	1.910
Ca	0.000	0.001	0.000	0.000	0.001
Na	0.037	0.078	0.031	0.016	0.051
K	0.000	0.001	0.001	0.000	0.000
ΣCh	0.037	0.081	0.032	0.016	0.052
Σcat.	11.032	11.027	11.007	10.987	11.005
mg#	0.471	0.521	0.415	0.478	0.495

Table 3. Analyses of biotite from Peña Negra migmatites. Crystals 1 and 2 are in contact with garnet

Components	1	2	3	4
SiO_2	34.40	34.60	35.03	34.72
TiO_2	2.34	2.30	2.43	2.39
Al_2O_3	19.80	19.46	18.29	19.13
FeO	22.67	23.13	21.31	20.62
MgO	5.82	5.90	8.06	8.10
MnO	0.21	0.06	0.20	0.22
CaO	0.01	0.04	0.00	0.00
Na_2O	0.23	0.22	0.08	0.20
K_2O	9.03	9.21	9.98	8.86
Total	95.51	94.92	95.38	94.24
Structural formulae based on 11 oxygens				
Si	2.681	2.692	2.705	2.686
Al(IV)	1.319	1.308	1.295	1.314
Al(VI)	0.500	0.477	0.369	0.430
Ti	0.137	0.135	0.141	0.139
Fe	0.676	0.684	0.927	0.933
Mg	1.477	1.505	1.376	1.334
Mn	0.014	0.004	0.013	0.014
ΣM	2.804	2.803	2.825	2.851
Ca	0.002	0.004	0.000	0.000
Na	0.036	0.033	0.012	0.030
K	0.898	0.914	0.983	0.874
ΣA	0.935	0.951	0.995	0.904
$\frac{Fe}{Fe + Mg}$	0.686	0.688	0.597	0.588

Yardley, 1989). Garnets from the PNAC migmatites show a continuous zoning from core to rim, although some irregularities are found in the middle part of the largest crystals (Fig. 3).

The FeO profile is similar to the MnO one: concentration of these components increases toward the rim. Regarding MgO, there exists a depletion toward the rim, although in some cases, there are zones between showing an enrichment in comparison to the core. The depletion of MgO toward the rim can be explained by cordierite generation at the expense of garnet.

In general, a reverse zoning is observed on the garnets from the PNAC migmatites related to its resorption and generation of cordierite and biotite at their expense.

GEOTHERMOBAROMETRIC STUDY

There is a large collection of references dedicated to the calibration of geothermometers based on the same mineralogical association that is found in the materials used for the present study (e.g., Perchuk, 1967, 1969, 1970a, 1970b; Hensen and Green, 1973; Currie, 1974; Holdaway and Lee, 1977; Perchuk, 1977; Ferry and Spear, 1978; Perchuk, 1981; Hodges and Spear, 1982; Perchuk and Lavrent'eva, 1983; Ganguly and Saxena, 1984; Indares and Martignole, 1985; Bhattacharya *et al*., 1988; Spear and Peacock, 1989). However, only few were used to calculate *P* and *T* conditions for the PNAC (Table 5) avoiding those that gave aberrant results. More specifically, for the pair garnet–cordierite, the algorithm of Bhattacharya *et al*. (1988) was used, and for the pair garnet–biotite, Ferry and Spear (1978), Hodges and Spear (1982), Ganguly and Saxena (1984),

Table 4. Analyses of plagioclase from Peña Negra

Components	1	2	3	4
SiO_2	63.80	62.50	62.61	63.17
TiO_2	0.00	0.00	0.01	0.00
Al_2O_3	22.66	23.39	24.64	22.83
FeO	0.01	0.06	0.05	0.04
MgO	0.02	0.00	0.01	0.00
MnO	0.01	0.03	0.05	0.03
CaO	4.22	4.85	5.15	4.11
Na_2O	9.10	8.62	7.89	8.93
K_2O	0.20	0.20	0.21	0.17
P_2O_5	0.10	0.14	0.14	0.20
Total	100.12	99.79	100.76	99.48

Table 5. Results from the application of several geothermometers (°C) for an invariable *P* of 3 kbar

Thermometer	Core	Middle	Rim	Observation
1	741	622	513	
2	785	643	488	
3	795	652	496	
4	764	658	535	dWMn = 3000 cal
5	678	610	525	
6	676	555	430	
7	782	644	494	

Note: Cordierite-garnet pair: 1—(Bhattacharya *et al.*, 1998). Biotite-garnet pair: 2—(Ferry and Spear, 1978); 3—(Hodges and Spear, 1982); 4—(Ganguly and Saxena, 1984); 5—(Perchuk and Lavrent'eva, 1983); 6—Indares and Martignole, 1985); 7—(Ferry and Spear, 1990).

Perchuk and Lavrent'eva (1983), Indares and Martignole (1985), and Spear and Peacock (1990). The geobarometer used was the one by Hodges and Spear (1992), using the association garnet–sillimanite–plagioclase–quartz.

GEOTHERMOMETRY

Cordierite–Garnet Pair

Some of the calibrations considering the pair cordierite–garnet did not offer a reasonable result for the metamorphic climax. That is probably due to the lack of spessartine component of the garnet used for the calibration, which in garnet from the PNAC can be very high (see above) with a high and constant enrichment toward the crystal rim (Table 1).

Only the thermometer calibrated by Bhattacharya *et al*. (1988) has been applied, yielding reasonable temperature values (Table 5):

(1) The range of temperature values is 513–741°C. *T* has been calculated for a constant *P* of 3 kbar, as this variable does not affect the temperature calculation.

(2) Depletion of MgO toward the rim has been explained as a consequence of cordierite generation (Grant and Weiblen, 1971; Tracy *et al*., 1976; Hollister, 1977; Tracy, 1982; Pereira and Bea, 1994).

(3) It can be observed that when using rim composition, the highest X_{Fe}/X_{Mg} values are obtained, together with the lowest temperatures. However, when using garnet core composition, where the lowest values for X_{Fe}/X_{Mg} are found, we get the maximum values of *T*, for a constant *P* = 3 kbar. It is highly recommended to use core analyses when dealing with zoned minerals to get equilibrium temperatures, so we can conclude that the value around 740°C is the temperature for the equilibrium crystal–melt.

Biotite–Garnet Pair

Distribution of FeO and MgO between the garnet core and biotite from the matrix is more appropriated to estimate temperature conditions in prograde metamorphism (Tracy *et al*., 1976; Chipera and Perkins, 1988). This is due to the high diffusion rate of biotite in comparison to garnet, in the way that while zoning can be determined on the latter, biotite in contact with garnet does not show any zoning, as diffusion has deleted it (Robinson *et al*., 1982; Spear, 1989).

Several thermometers have been applied, using the program developed by Spear and Peacock (1990) on the biotite–garnet pair. Analyses from core, middle, and rim have been used, attending to the garnet zoning, from leucosome and melanosome of migmatites of the PNAC. Although there is agreement when using most of them, thermometers calibrated by Perchuk and Lavrent'eva (1983) and Indares and Martignole (1985) gave much lower values than the others. Temperatures obtained when using core or rim analysis are similar to the ones obtained with the calibrated method by Bhattacharya *et al*. (1988) on the garnet–cordierite pair.

Therefore, we can accept that the maximum *T* values obtained (750°C for constant *P* = 3 kbar) represent the climax of metamorphism.

GEOBAROMETRY

Due to the mineralogical composition of the PNAC, only the barometer calibrated by Hodges and Spear (1982) has been used on the association garnet–plagioclase–sillimanite–quartz. Composition of plagioclase in the migmatites is rather constant: core $An_{20–26}$, rim $An_{11–18}$. Chemical data of plagioclase can be found on Table 4.

Although in temperature calculation, we used a constant *P* of 3 kbar because of the independence of the thermometers on this variable, a difference has been observed when calculating pressure for equilibrium conditions. For garnet core analyses, the maximum value of 4 kbar was obtained, which drops down to 1–2 kbar when using the rim analyses.

Also using the middle garnet analyses, we have represented all the values on a *P–T* diagram, obtaining a retrogressive path, from the equilibrium garnet–melt (*P* ≈ 4 kbar and *T* ≈ 750°C) to the end of retrogression of the garnet (*P* ≈ 1–2 kbar and *T* ≈ 500°C) (Table 6, Fig. 4).

On Fig. 4, the triple point is the one from Bohlen *et al*. (1991): *T* ≈ 530°C; *P* ≈ 4.2 kbar. H_2O concentration curves are from Johannes and Holtz (1990); muscovite (*Ms*) and biotite (*Bt*) melting curves are from Petö (1976) and Le Breton and Thompson (1988), respectively. Relevant mineral equilibrium regarding paragenesis in the PNAC materials are:

(a) *ms* + *qtz* = *sil* + *Kfs* + vapor, Chaterjee and Johannes (1974) modified by Holdaway and Lee (1977);

(b) *bt* + *sil* + *qtz* = *crd* (*M* = 0.5) + *Kfs* + vapor,

bt + *sil* + *qtz* = *crd* + *grt* + *Kfs* + vapor, and

grt + *sil* + *qtz* + vapor = *crd* (*M* = 0.5), *M* = Mg/(Mg + Fe) (Holdaway and Lee, 1977); nnd

(c) *bt* + *crd* + *qtz* = *Kfs* + *grt* from Thompson (1982).

P–T TRAJECTORY

We have not found preanatectic parageneses within the PNAC, but in areas nearby, there are very similar materials, where the anatexis isograde has not been reached (see Franco, 1980; Beetsma, 1995), and the association biotite + sillimanite + quartz can be found to be stable. This point is taken as the first reference in the *P–T* trajectory of the metamorphism (point *A* in Fig. 5).

Garnet is a very rare component of migmatites from PNAC (see above). It has only been identified in a very restricted area, made of migmatite of schlieren facies. The first question to answer is whether there is a chemical difference between migmatites with and without garnet, specially regarding the aluminum index (ASI) and X_{Fe} value. Chemistry of all migmatites is virtually the same (Pereira, 1992), so we have to accept that generation of garnet was not due to a compositional peculiarity, but to the change of *P–T* conditions that allowed this material to reach one of the equilibrium curves that represent the garnet generation reaction. From the geothermobarometric study, we can conclude that garnet was generated through the incongruent melting of biotite in the presence of sillimanite during the metamorphic paroxysm of the PNAC (point *B* in Fig. 5).

The scarce garnet one can find in the migmatites from the PNAC always presents the same texture (Fig. 2), being surrounded by cordierite and biotite. These biotite and cordierite have a different composition (less magnesium, more iron) than the other biotite and cordierite coexisting in the same samples (Tables 1–3). Besides, garnet zoning profiles regarding FeO and MnO are always reverse, implying the effect of retrograde metamorphism. Retrogression of garnet was produced following a continuous reaction where cordierite and biotite were formed at the expense of garnet (point *C* in Fig. 5) (Pereira, 1992, 1993; Pereira and Bea, 1994):

alkali feldspar + $garnet_1$ + $biotite_1$ + $cordierite_1$ = $garnet_2$ + $biotite_2$ + $cordierite_2$ + quartz.

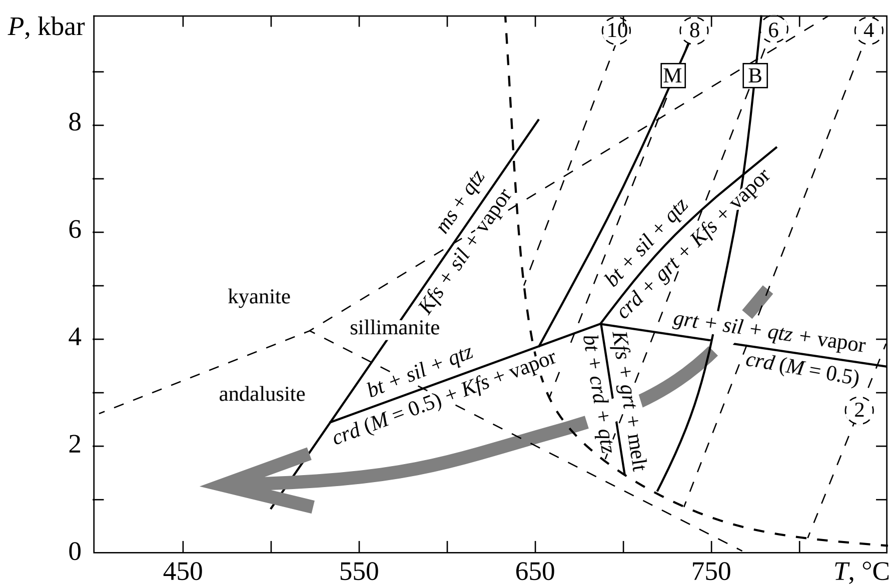

Fig. 4. *P–T* evolution in the Peña Negra complex defined through the analytical study of garnet profiles: from the climax of metamorphism to the retrogression conditions. Abbreviations as in (Kretz, 1983).

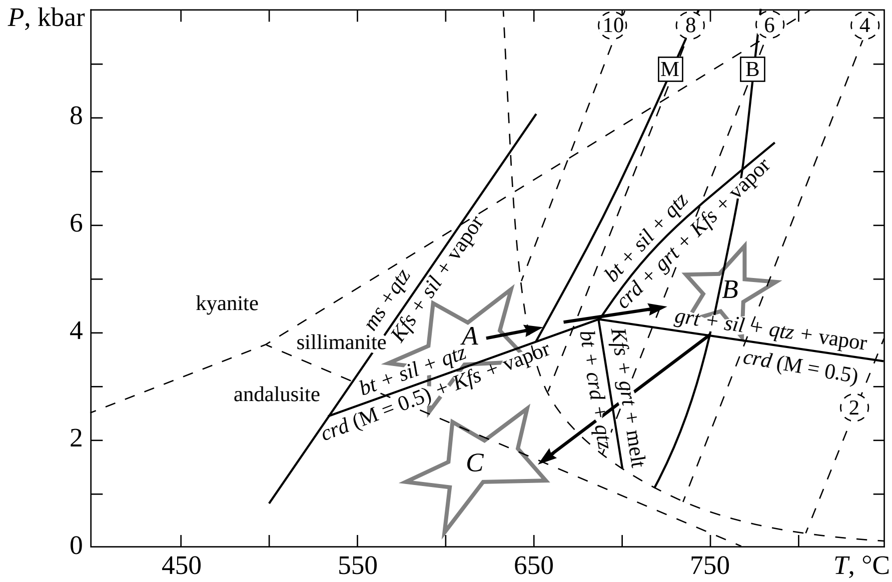

Fig. 5. Metamorphic evolution of the Peña Negra complex.
M and *B* curves are muscovite (Petö, 1976) and biotite (Le Breton and Thompson, 1988) melting respectively. *M* = Mg/(Fe + Mg) in cordierite. Dashed lines: water concentration curves are from Johannes and Holtz (1990).

From this reaction it is obtained:

(1) $Garnet_2$ is more ferrous and more manganesiferous than $garnet_1$. $Garnet_2$ is represented by the rim of the largest garnet crystals.

(2) $Biotite_2$ is less magnesian and less titaniferous than $biotite_1$, because it is generated, at least partially, at the expense of garnet.

(3) $Cordierite_2$ is less magnesian and less manganesiferous than $cordierite_1$, because it is generated partially at the expense of garnet, and this mineral is getting more and more avid for the coordination of Mn.

GEODYNAMIC IMPLICATIONS

Figure 5 shows the conditions under which the PNAC was generated. The same clockwise *P–T* path has been described in other Hercynian areas nearby (Gil Ibarguchi and Martínez, 1982; Barbero, 1995; Yenes, 1996), responsible for the generation of important volumes of peraluminous granitoids. It has been interpreted as indicative of brief intervals of rapid tectonic thickening, followed by exhumation of materials, as explained by Hollister (1994). Tectonic thickening was the result of thrusting during the compression taking place during the first phases of the Hercynian orogeny, and as a response of these event, granitic products would have been produced from partial melting of migmatites. An extensional collapse of the series at the end of the orogeny had an effect in decreasing pressure to produce another stage of anatexis, generating low melt fraction granites from a source already depleted in fertile components.

SUMMARY

From the geothermobarometric studies on the migmatites from the Peña Negra anatectic complex, a *P–T* trajectory is obtained indicating that the metamorphic paroxysm took place under maximum conditions of $T \approx 750°C$ and $P \approx 4$ kbar. Afterward, a drop of conditions took place and a retrometamorphism was achieved under minimum conditions of $T \approx 500°C$ and $P \approx 1–2$ kbar.

The observed *P–T* path in this region is very similar to the one described for areas nearby, using the same mineral associations (Gil Ibarguchi and Martínez, 1982; Barbero, 1995; Yenes, 1996), indicating a stage of isobaric heating, followed by a stage of decompression and cooling, which is reflected by the retrogression of garnet. Jamieson (1991) described these trajectories as characteristic of compressive orogens, and correspond to: (I) the isobaric heating during the thermal stage that follows the thickening of the crust and (II) decompression and cooling due to the late exhumation stage.

ACKNOWLEDGMENTS

The author thanks T. Gerya and A. Graphchikov for revision of the manuscript.

REFERENCES

Barbero, L., Granulite-facies Metamorphism in the Anatectic Complex of Toledo, Spain, *J. Geol. Soc.*, London, 1995, vol. 152, pp. 365–382.

Beetsma, J.J., *The Late Proterozoic/Paleozoic and Hercynian Crustal Evolution of the Iberian Massif, N Portugal, as Traced by Geochemisty and Sr–Nd–Pb Isotope Systematics* *of pre-Hercynian Terrigenous Sediments and Hercynian Granites*, PhD Thesis, Vrije Universiteit, 1995.

Bea, F. and Pereira, M.D., Estudio petrológico del Complejo Anatéctico de la Peña Negra, Batolito de Avila, *Rev. Soc. Geol*., España, 1990, vol. 3, pp. 87–104.

Bhattacharya, A., Mazumdar, A.C., and Sen, S.K., Fe–Mg Mixing in Cordierite: Constraints from Natural Data and Implications for Cordierite–Garnet Geothermometry in Granulites, *Am. Mineral*., 1988, vol. 73, pp. 338–344.

Bohlen, S.R., Montana, A., and Kerrick, D.M., Precise Determination of the Equilibria Kyanite = Sillimanite and Kyanite = Andalusite and a Revised Triple Point for Al_2SiO_5 Polymorphs, *Am. Mineral*., 1991, vol. 76, pp. 677–680.

Chatterjee, N.D. and Johannes, W., Thermal Stability and Standard Thermodynamic Properties of Synthetic 2M1-Muscovite $KAl_2(AlSi_3O_{10}(OH)_2)$, *Contrib. Mineral. Petrol*., 1974, vol. 48, pp. 89–114.

Chipera, S.J. and Perkins, D., Evaluation of Biotite–Garnet Geothermometers: Application to the English River Subprovince, Ontario, *Contrib. Mineral. Petrol*., 1988, vol. 98, pp. 40–48.

Currie, K.L., A Note on the Calibration of the Garnet–Cordierite Geothermometer and Geobarometer, *Contrib. Mineral. Petrol*., 1974, vol. 44, pp. 35–44.

Ferry, J.M. and Spear, F.S., Experimental Calibration of Partitioning of Fe and Mg between Biotite and Garnet, *Contrib. Mineral. Petrol*., 1978, vol. 66, pp. 113–117.

Franco, M.P., *Estudio petrológico de las formaciones metamórficas y plutónicas al norte de la depresión Corneja-Amblés (Sierra de Avila)*, PhD Thesis, Universidad de Salamanca, 1980.

Ganguly, J. and Saxena, S.K., Mixing Properties in Aluminosilicate Garnets: Constraints from Natural and Experimental Data and Applications to Geothermobarometry, *Am. Mineral*., 1984, vol. 69, pp. 88–97.

Gil Ibarguchi, I. and Martinez, F.J., Petrology of Garnet–Cordierite–Sillimanite Gneisses from the el Tormes Thermal Dome, Iberian Hercynian Foldbelt (W Spain), *Contrib. Mineral. Petrol*., 1982, vol. 80, pp. 14–24.

Grant, J.A. and Weiblen, P.W., Retrograde Zoning in Garnet near the Second Sillimanite Isograde, *Am. J. Sci*., 1971, vol. 270, pp. 281–296.

Hensen, B.J. and Green, D.H., Experimental Study of the Stability of Cordierite and Garnet in Pelitic Compositions at High Pressures and Temperatures: III. Synthesis of Experimental Data and Geological Applications, *Contrib. Mineral. Petrol*., 1973, vol. 38, pp. 151–166.

Hodges, K.V. and Spear, F.S., Geothermometry, Geobarometry and the Al_2SiO_5 Triple Point at Mt. Moosilauke, New Hampshire, *Am. Mineral*., 1982, vol. 67, pp. 1118–1134.

Holdaway, M.J. and Lee, S.M., Fe–Mg Cordierite Stability in High-Grade Pelitic Rocks Based on Experimental, Theoretical and Natural Observations, *Contrib. Mineral. Petrol*., 1977, vol. 63, pp. 175–198.

Hollister, L.S., The Reaction Forming Cordierite from Garnet, the Khtada Lake Metamorphic Complex, British Columbia, *Can. Mineral*., 1977, vol. 15, pp. 217–229.

Hollister, L.S., Clockwise *P–T–t* Paths: the View from the Coast Orogen, British Columbia, *EOS, Trans. Am. Geophys. Union*, 1994, vol. 75, no. 16, p. 186.

Indares, A. and Martignole, J., Biotite–Garnet Geothermometry in the Granulite Facies: the Influence of Ti and Al in Biotite, *Am. Mineral*., 1985, vol. 70, pp. 272–278.

Jamieson, R.A., *P–T–t* Paths of Collissional Orogens, *Geol. Rundsch*., 1991, vol. 80, no. 2, pp. 321–332.

Johannes, W. and Holtz, F., Formation and Composition of H_2O Undersaturated Granitic Melts, *High T Metamorphism and Crustal Anatexis*, Ashworth and Brom, Eds., Unwin Hyman, 1990, pp. 87–104.

Kretz, R., Symbols for Rock-forming Minerals, *Am. Mineral*., 1983, vol. 68, pp. 277–279.

Le Breton, N. and Thompson, A.B., Fluid-absent (Dehydration) Melting of Biotite in Metapelites in the Early Stages of Crustal Anatexis, *Contrib. Mineral. Petrol*., 1988, vol. 99, pp. 226–237.

Mehnert, K.R., The Granitization Problem—Revised, *Fortschr. Mineral*., 1987, vol. 65, pp. 285–306.

Perchuk, L.L., Biotite–Garnet Geothermometer, *Dokl. Akad. Nauk SSSR*, 1967, vol. 177, pp. 411–414.

Perchuk, L.L., The Effect of Temperature and Pressure on the Equilibrium of Natural Iron–Magnesium Minerals, *Int. Geol*., 1969, part II, pp. 875–901.

Perchuk, L.L., *Equilibria of Rock-forming Minerals*, Moscow: Nauka, 1970a.

Perchuk, L.L., Equilibrium of Biotite with Garnet in Metamorphic Rocks, *Geochem. Int.*, 1970b, vol. 7, pp. 157–179.

Perchuk, L.L., Thermodynamical Control of Metamorphic Processes, *Energetics of Geological Processes*, Saxena, S.K. and Bhattacharji, S., Eds., Springer-Verlag, 1977, pp. 285–352.

Perchuk, L.L., Correction of Biotite–Garnet Thermometer in Case Mn = Mg + Fe Isomorphism in Garnet, *Dokl. Akad. Nauk SSSR*, 1981, vol. 256, pp. 38–41.

Perchuk, L.L. and Lavrent'eva, I.V., Experimental Investigation of Exchange Equilibria in the System Cordierite–Garnet–Biotite, *Kinetics and Equilibrium in Mineral Reactions*, Saxena, S.K., Ed., Springer-Verlag, 1983, pp. 199–239.

Pereira, M.D., *El complejo Anatectico de la Perla Negra (Batolito de Avila): un estudio de la anatexia cortical en condiciones de baja presion*, Tesis Doctoral. Universidad de Salamanca, 1992.

Pereira, M.D., Termometria de rocas con la asociación granate–cordierita–biotita; trayectorias *P–T* en el Complejo Anatéctico de la Peña Negra (Batolito de Avila). Implicaciones sobre el metamorfismo hercínico en la zona centroibérica, *Rev. Soc. Geol. España*, 1993, vol. 6, nos. 1–2, pp. 131–140.

Pereira, M.D. and Bea, F., Cordierite-producing Reactions at the Peña Negra Complex, Avila Batholith, Central Spain: the Key Role of Cordierite in Low Pressure Anatexis, *Can. Mineral*., 1994, vol. 32, no. 4, pp. 763–780.

Pereira, M.D. and Shaw, D.M., Boron and Lithium Distribution in the Peña Negra Complex: An Alpha-track Study, *Am. Mineral*., 1996, vol. 81, pp. 141–145.

Pereira, M.D. and Shaw, D.M., Behaviour of Boron in the Generation of an Anatectic Complex: the Peña Negra Complex, Central Spain, *Lithos*, 1997, vol. 40, pp. 179–188.

Pető, P., An Experimental Investigation of Melting Relations Involving Muscovite and Paragonite in the Silica Saturated Portion of the System $K_2O–Na_2O–Al_2O_3–SiO_2–H_2O$ to 15 kbar Total Pressure, *Prog. Exp. Petrol. NERC Rept*., 1976, vol 3, pp. 41–45.

Robinson, P., Hollocher, K.T., Tracy, R.J., and Dietsch, C.W., High Grade Acadian Regional Metamorphism in South–Central Massachusetts, in *NEIGC 74th Ann. Meeting*., 1982, pp. 289–340.

Spear, F.S., Relative Thermobarometry and Metamorphic *P–T* Paths, *Evolution of Metamorphic Belts*, Daly, J.S., Cliff, R.A., and Yardley, B.W.D., Eds., *Geol. Soc. London Spec. Publ*., 1989, vol. 43, pp. 63–81.

Spear, F.S. and Peacock, S.M., Metamorphic Pressure–Temperature–Time Paths, *Evolution of Metamorphic Belts*, Daly, J.S., Cliff, R.A., and Yardley, B.W.D., Eds., Washington, D.C.: Am. Geophys. Union, 1989.

Spear, F.S. and Peacock, S.M., *Metamorphic P–T–t Paths: Program Manual and Computer Exercises for the Calculation of Metamorphic Phase Equilibria, Pressure–Temperature–Time Paths and Thermal Evolution of Orogenic Belts*, Washington, D.C.: Am. Geophys. Union, 1990.

Thompson, A.B., Dehydration Melting of Pelitic Rocks and the Generation of H_2O-Undersaturated Granitic Liquids, *Am. J. Sci*., 1982, vol. 282, pp. 1567–1595.

Tracy, R.J., Compositional Zoning and Inclusions in Metamorphic Minerals, *Rev. Mineral*., 1982, vol. 10, pp. 355–397.

Tracy, R.J., Robinson, P., and Thompson, A.B., Garnet Composition and Zoning in the Determination of Temperature and Pressure of Metamorphism, Central Massachusetts, *Am. Mineral*., 1976, vol. 61, pp. 762–775.

Yardley, B.W.D., *An Introduction to Metamorphic Petrology*, Longman, 1989.

Yenes, M., *Estructura, geometría y cinemática del emplazarniento de lo granitoides del área de La Alberca-Bejar (Sistema central español, zona centroíberica)*, PhD Thesis, Universidad de Salamanca, 1996, 229 p.