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High-grade metamorphic rocks and peridotites along the Leiza Fault (Western Pyrenees, Spain)

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With 6 figures and 5 tables

Zusammenfassung

Typische Gesteine entlang der Leiza-Störung (Navarra, Spanien), im äußersten Westen des pyrenäischen Gürtels, sind saure und basische Granulite, Migmatite und Lherzolithe. Die Ausgangsgesteine der sauren Granulite waren von granodioritischer Zusammensetzung. Texturelle und mineralogische Untersuchungen lassen darauf schließen, daß sich die sauren Granulite aus einer frühen, synkinematischen Mitteldruck-Granulitfazies-Phase [Granat-Biotit I-Kfsp] bis zu einer postkinematischen Granulitfazies-Phase niedrigeren Drucks und höherer Temperatur [Granat-Biotit II-Cordierit-Kfsp-(Spinel?), Kinzingite] herleiten lassen. Die Ausgangsgesteine der basischen Granulite waren tholeitische bis alkaline Basalte. Als Charakteristikum weisen die basischen Granulite millimetergroße subidiomorphe Granate verteilt in der Matrix auf, sowie kleinere kranzartigte Granate zwischen opaken Mineralen oder Orthopyroxenen und Plagioklas. Schätzungen für Temperatur- und Druck-Maxima während der Granulitfazies-Metamorphose liegen bei ca. 800° C und 8 kbar. Wahrscheinlich repräsentieren die Migmatite eine niedrigere Metamorphosestufe (Andalusit/Sillimanit-Kfsp). Scapolit in den basischen Granuliten wurde während einer postgranulitischen Metamorphose-Phase gebildet. Die Lherzolithe sind intensiv brekziiert und serpentinisiert, was einen Entwicklungsvergleich mit anderen an der Leiza-Störung aufgeschlossenen Gesteinen schwierig macht. Die sauren und basischen Granulite, Migmatite und Lherzolithe entlang der Leiza-Störung sind vergleichbar mit ähnlichen Gesteinen, die in der Nordpyrenäen-Zone und entlang der Nordpyrenäen-Störung als tektonische Bruchstücke und Massive aufgeschlossen sind. Aufgrund der Analogie der Gesteine kann man die Granulitfazies-Metamorphose als herzynisch einstufen. Die Leiza-Störung stellt also die westliche Verlängerung der Nordpyrenäen-Störung dar. Die bearbeiteten Gesteine werden deshalb, bis auf die Lherzolithe, als Relikte eines metamorphen Massivs herzynischen Alters gedeutet, das aufgrund des Versatzes entlang der Störung am Ende der herzynischen Phase und während der alpidischen tektonischen und metamorphen Vorgängen zerrissen wurde.

Abstract

Acid and basic granulites, migmatites, and lherzolites outcrop along the Leiza Fault (Navarra, Spain) in the western extremity of the Pyrenean Belt. The protoliths of the acid granulites have granodioritic composition. Textural and mineralogical data suggest that the acid granulites evolved from a first, syn kinematic medium-pressure granulite-facies stage [garnet-biotite I-Kfsp] to a post-kinematic granulite-facies stage of lower pressure and higher temperature [garnet-biotite II-cordierite-Kfsp-(spinel?), kinzigites]. Basic granulites were formed from protoliths with composition of tholeiitic to alkaline basalts. Basic granulites exhibit millimeter size subidiomorphic garnets dispersed through the matrix and smaller coronitic garnets between opaques or orthopyroxenes and plagioclase. Thermo-barometric estimates for the peak of the

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granulite-facies metamorphism are c. 800°C and 8 kbar. The migmatites presumably represent a shallower level of metamorphism (andalusite/sillimanite-Kfsp). Scapolite in the basic granulites was formed during a post-granulitic metamorphic episode. The lherzolites have been intensely brecciated and serpentinized, which makes difficult the comparison of their evolution with that observed in the other rocks associated with the Leiza Fault. Acid and basic granulites, migmatites, and lherzolites along the Leiza Fault may be correlated with similar rocks outcropping elsewhere in the North-Pyrenean Zone and along the North-Pyrenean Fault as tectonic slices and massifs. By analogy with those rocks, the granulite-facies metamorphism observed in the rocks studied must be Hercynian in age. The Leiza Fault constitutes, therefore, the western continuation of the North-Pyrenean Fault, and the rocks studied (except perhaps the lherzolites) may be considered as remnants of an Hercynian metamorphic massif, dismembered as a consequence of the activity of the fault at the end of the Hercynian cycle and during the Alpine tectono-metamorphic events.

Résumé

Des granulites acides et basiques, des migmatites et des lherzolites affleurent le long de la faille de Leiza (Navarre, Espagne), à l'extrémité occidentale de la chaîne pyrénéenne. Les protolithes des granulites acides ont une composition granodioritique. Les données texturales et minéralogiques montrent que ces granulites acides ont évolué d'un premier stade syncinématique dans le facies des granulites à pression moyenne (grenat – biotite I – feldspath K) vers un second stade post-cinématique dans le faciès des granulites à basse pression et haute température (kinzigites à grenat – biotite II – cordiérite – feldspath K – (spinel?)). Les granulites basiques proviennent de protolithes à composition de basaltes tholéiitiques à alcalins. Les granulites basiques renferment des grenats millimétriques subidiomorphes dispersés à travers la matrice et des grenats coronitiques plus petits localisés entre des opaques ou des pyroxènes et le plagioclase. La thermo-barométrie donne une estimation de ± 800 °C et 8 Kb pour le pic du métamorphisme granulitique. Les migmatites représentent probablement un niveau de métamorphisme moins profond (andalousite/sillimanite-feldspath K). Dans les granulites basiques, de la scapolite s'est formée au cours d'un épisode post-granulitique. Les lherzolites ont été intensément bréchiées et serpentinisées, ce qui rend difficile la comparaison entre leur évolution et celle que l'on observe dans les autres roches associées à la faille de Leiza. Les granulites acides et basiques, les migmatites et les lherzolites de la faille de Leiza peuvent être corrélées avec des roches similaires qui se rencontrent en massifs et en écailles tectoniques, en d'autres endroits de la Zone nord-pyrénéenne et le long de la faille nord-pyrénéenne. Par analogie avec ces dernières, le métamorphisme granulitique des roches en question ici doit être d'âge hercynien. Dans ces conditions, la faille de Leiza représente le prolongement occidental de la faille nord-pyrénéenne et les roches étudiées ici (à l'exception peut-être des lherzolites) peuvent être considérées comme des restes d'un ancien massif métamorphique hercynien, démembré par l'action de la faille à la fin du cycle hercynien et au cours des événements tectono-métamorphiques alpins.

Краткое содержание

Кислые и базические гранулиты, мигматиты и лерцолиты являются типичными породами, залегающими вдоль нарушения Leiza (Наварра, Испания) на крайнем Западе Пиренейского пояса. Исходные породы для кислых гранулитов характеризуются гранодиоритным составом. Данные исследования текстуры и минералогического состава разрешают сделать вывод, что образование кислых гранулитов шло через син-кинематическую фазу гранулитного фация при условиях умеренного давления – гранит-биотит 1 – Kfsp – до пост-кинематической стадии гранулитной фации, характеризующейся условиями низкого давления и высокой температуры – гранит-биотит II – кордиерит – Kfsp – шпинель? –. Исходной породой базических гранулитов являются толеитные до алкалических базальты. Базические гранулиты содержат субидиоморфные гранаты размерами в мм., рассеянные в матрице, и среди непрозрачных минералов, или ортопироксенов и плагиоклазов более мелкие гранаты, окруженные каемкой. Считают, что максимум температуры и давления во время метаморфизма гранулитовой фации составляли, вероятно, 800°C и 8 кбар. Вероятно, мигматиты представляют собой низкую ступень метаморфизма – андалузит/силлиманит – Kfsp . Скаполит образуется в базических гранулитах во время пост-гранулитной фазы метаморфизма. Лерцолиты состоят гл. обр. из брекчий и сильно серпентизированы – что очень затрудняет их сравнение с другими породами, находящимися в зоне нарушения Lei-

za . Кислые и базические гранулиты, мигматиты и лерцолиты вдоль нарушения Leiza можно сравнивать с породами, которые установлены в зоне Северных Пиренеев и вдоль нарушения Северных Пиренеев в виде обломков и массивов. Этот метаморфизм гранулитовой фации можно отнести на основании сравнения названных пород в герцинскому времени. Т.о. зона тектонического нарушения Leiza представляет собой, как бы простирание на запад нарушений Северных Пиренеев. Исследованные породы до лерцолитов считают как бы реликтами метаморфного массива герцинского возраста, который в результате перемещения вдоль зон разрывов в конце герцинской фазы и во время альпийских тектонических и метаморфных событий оказался разорванным.

Introduction

The North-Pyrenean Fault constitutes an important late-Hercynian tectonic lineament reactivated during the Alpine orogeny (MATTAUER, 1968; SEGURET, 1972). Along the North-Pyrenean Fault and in the North-Pyrenean Zone situated north of it (Figure 1), a number of tectonic slices and metamorphic massifs with high-grade Hercynian metamorphism occur, showing, in some cases, high-temperature/low-pressure Alpine metamorphism overprint (CHOUKROUNE, 1970, 1974; MULLER & ROGER, 1977; ALBAREDE & MICHARD VITRAC, 1978; AZAMBRE & RAVIER, 1978; POSTAIRE, 1983; THUIZART et al., 1985; VIELZEUF, 1984). Low-pressure granulites and basic intrusives are a common feature of the North-Pyrenean Hercynian massifs. Associated with the North-Pyrenean Fault, lherzolites occur whose origin and significance is still a subject of debate.

The presence of granulites and lherzolites in the spanish portion of the Pyrenean Belt, along the Leiza Fault, had been indicated by LAMARE (1936), WALGENWITZ (1976), LLANOS (1980) and EGUILUZ et al. (1982). A detailed study of the localities mentioned by these authors has revealed the presence of different types of crystalline rocks forming outcrops of variable size, but rarely greater than some hundreds of meters. These rocks exhibit metamorphic features markedly different from the Mesozoic rocks outcropping in the surrounding area affected by the Alpine orogeny (»nappe des marbres«, LAMARE, 1936; WALGENWITZ, 1976). Hence, although their age is not known, by analogy with the rocks of the french sector their high-grade metamorphic features may, in principle, be considered as a result of the Hercynian orogeny. In this paper we present new data on the petrography, mineralogy, and metamorphic evolution of the high-grade rocks, including lherzolites, associated with the Leiza Fault, and review their relationships with the North-Pyrenean Fault and massifs.

2. Petrography

The main lithotypes found along the Leiza Fault (from Areso to Ziga, Figure 1) are: 1) acid granulites, 2) basic granulites, 3) metapelitic migmatites, 4) ultramafic rocks, mainly lherzolites, 5) phyllites and low grade schists, and 6) orthogneisses and quartzo-feldspathic metamorphic rocks. The two latter types are not considered in this study. The phyllites and schists are not very different from other phyllites and low grade Cretaceous rocks outcropping in the Fault area, hence it is doubtful whether they represent a pre-Alpine metamorphic basement. The orthogneises and quartzo-feldspathic metamorphic rocks are considered to be formed from late-Hercynian igneous acid rocks similar to the common Stephanian-Permian subvolcanic to volcanic materials that outcrop all along the Pyrenean Belt an that have only been affected by Alpine tectono-thermal events.

A c i d g r a n u l i t e s: These rocks occur c. 400 m to the northeast of Ziga (Figure 1) forming meter to decameter-size outcrops. An episode of ductile deformation produced mylonitic foliation in these rocks. The foliation is defined by bands rich in quartz and feldspar alternating with others rich in ferromagnesian minerals. There is a preferred orientation of biotite and elongated garnet grains. A period of brittle fracturing, without development of a new schistosity, took place later on. Microscopically these rocks are characterized by a strongly orientated granoblastic texture of blastomylonitic type.

Quartz generally shows undulatory extinction. Garnet and »primary« biotite (phlogopite, see below) are generally orientated following the foliation of the rock. The latter mineral quite often exhibits kink-bands and signs of post-crystalline deformation and recrystallization at a relatively low temperature (development of chlorite). »Secondary« biotite refers to the unoriented biotite which commonly fills fractures in garnet. Plagioclase (oligoclase) and perthitic K-feldspar may be partially transformed into sericite. Cordierite in symplectitic association with »secondary« biotite locally occurs surrounding garnet. Rutile is a common accessory phase and forms idiomorphic inclusions in quartz or biotite, or is

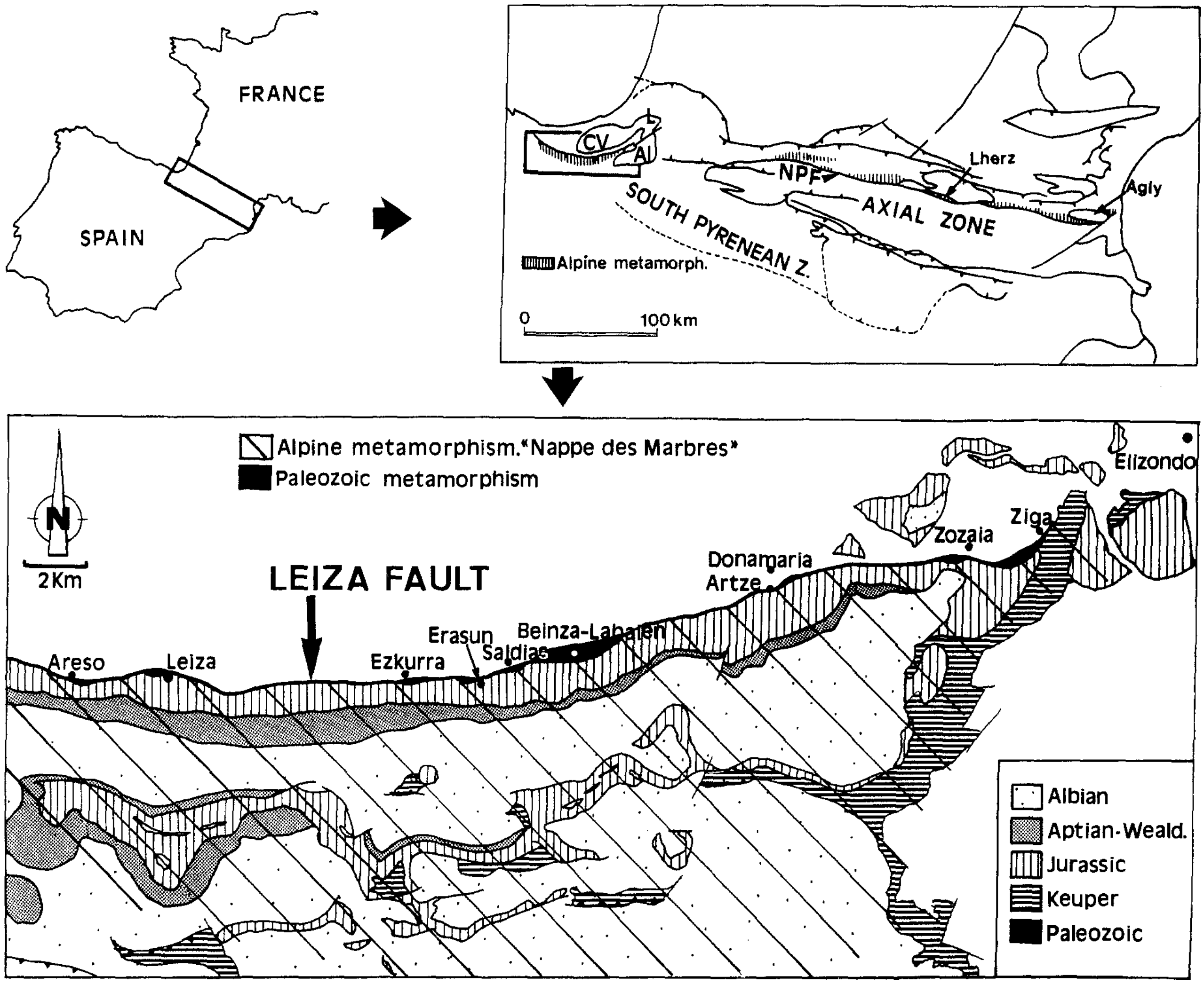

Fig. 1. Geological sketch map of the Leiza Fault area (Modified after MARTINEZ TORRES et al., in press). NPF: North Pyrenean Fault, CV: Cinco Villas, L: Labourd, Al: Aldudes.

dispersed through the matrix; it may appear as well as hypidiomorphic crystals or aggregates included in garnet. Spinel (pleonaste) is rare and generally occurs as inclusions in garnet.

A first metamorphic stage under dynamic conditions produced a paragenesis with quartz, plagioclase, K-feldspar, garnet, biotite-I and rutile. Destabilization of the garnet-K-feldspar pair caused, later on, the appearance of unoriented, lower-pressure granulite-facies associations with cordierite (kinzigitic association) through reactions such as: Garnet + K-feldspar + H_2O = Biotite-II + Cordierite + Quartz. Unoriented, Fe-richer (see below) biotite-II was presumably formed during this episode. It is doubtful whether spinel was already present prior to the destabilization of garnet. Although this mineral occurs as inclusions in garnet, the chemographic analysis (e. g. HENSEN, 1971; VIELZEUF, 1983) rather suggests that it presumably formed through the garnet breakdown. Retrogression under greenschists-facies conditions was accompanied by cataclastic deformation with development of secondary minerals such as chlorite and sericite.

Basic granulites: These rocks form meter-size outcrops near Ziga and Zozaia de Oronoz (Figure 1). They often exhibit a well developed foliation with preferred orientation of plagioclase and ferromagnesian phases. Microscopically they show granoblastic, polygonal texture with minor evidence of plastic deformation. Two main types of basic granulites may be distinguished: 1) those rich in orthopyroxene and plagioclase and, 2) those rich in garnet and biotite.

Plagioclase (An_{50-55} as average) is transformed along rims and, less often, at cores into scapolite. Garnet occurs as: i) idiomorphic crystals dispersed through the matrix of the rock, variably transformed into secondary biotite or into intergrowths of scapolite, biotite, green amphibole, and opaques (Garnet-I), or ii) as coronitic crystals between orthopyroxene or opaques and plagioclase (Garnet-II). Orthopyroxene mostly occurs transformed into cummingtonite being one of the rare minerals in these rocks to show evidence of plastic deformation. Clinopyroxene is often transformed into secondary amphibole. Brown amphibole is often replaced by blue-green secondary amphibole. Apparently primary biotite (phlogopite, see below) is abundant in the samples, whereas rare muscovite occurs intergrown with the biotite in the same sample (Z10C). Rutile is a rare accessory phase, but apatite can be abundant in some samples, specially in those rich in biotite. Ilmenite, presumedly of primary origin, appears dispersed through the matrix, whereas magnetite occurs forming smaller crystals than ilmenite and associated with secondary minerals. Secondary biotite was produced mainly along fractures in garnet. Other secondary minerals are prehnite, chlorite and epidote, the latter may show a coronitic disposition around pyroxene or between secondary amphibole and plagioclase.

Under granulite-facies conditions the stable association should be plagioclase, garnet-I, orthopyroxene, clinopyroxene with, eventually, brown amphibole and/or biotite. Coronitic garnets (Garnet-II) could be produced later on during recrystallization still under granulite-facies conditions or simultaneously with the formation of the first type of garnets. The textural and chemical evidence do not permit us to decide between the two possibilities. The retrograde evolution was responsible for the formation of different kinds of secondary amphibole and of prehnite, chlorite, epidote and magnetite. This suggests a decrease in pressure and temperature, with a progressive increase in μH_2O through the passage to amphibolite-facies and finally to greenschists-facies conditions.

Although scapolite may be stable under granulite-facies conditions (e.g. COOLEN, 1980; DEVARAJU & COOLEN, 1983), this mineral must have a secondary origin in the rocks studied. In effect, scapolite occurs replacing plagioclase and has a composition of chlorine-rich dipyre, with 35–47% of meionite component, i.e. less calcic than coexisting plagioclase (Table IV). In contrast to CO_2-rich meionitic scapolite, which is characteristic of high-grade, deep-seated rocks, compositions similar to the scapolite analysed may occur in a wide spectrum of low- to medium-grade metamorphics (cf. GOLDSMITH & NEWTON, 1977; KWAK, 1977; COOLEN, 1980). According to the compositional scheme proposed by HIETANEN (1967), the scapolites analysed here are typical of epidote amphibolite facies terrains. It is conceivable, therefore, that this mineral formed in the rocks studied at a lower temperature than that of the granulite-facies metamorphism, presumably under the relatively low-pressure and intermediate- to high-temperature conditions that characterize the Alpine metamorphism in the Pyrenean Belt (RAVIER, 1959; CHOUKROUNE, 1970).

Migmatites: The migmatites constitute the biggest outcrops of crystalline rocks associated with the Leiza Fault. The migmatites form decameter- to hectometer-size lenses near Labaien (Figure 1) with highly variable leucosome/total rock ratios. Mobilisates generally are concordant to the main foliation of the rock and occassionally they may be folded.

Leucosomes contain oligoclase and microcline which quite often form poikilitic crystals more or less altered to sericite and coarse-grained muscovite, respectively. Quartz in leucosomes is rich in inclusions of biotite, sillimanite and opaques, all presumably remnants of partially melted protoliths. Mesosomes consist of oriented biotite rich in inclusions of zircon and opaques, muscovite with the same habit as the biotite, sillimanite (mostly as fibrolite), and, less frequently, andalusite variably transformed into sericite. Crystals of graphite aligned parallel to the schistosity are a conspicuous feature of some of these rocks. Rutile may occur as discrete crystals or forming more or less elongated aggregates.

The assemblage of quartz, plagioclase, K-feldspar, muscovite, biotite, sillimanite/andalusite, graphite and rutile was formed under high-grade amphibolite-facies conditions at the maximum P,T conditions attained by these rocks. The retrograde evolution, as in the granulites, with a decrease in pressure and temperature and a progressive increase in μH_2O, gave rise to greenschists-facies associations.

Lherzolites: These rocks form decameter-size outcrops near Ziga (Figure 1). There are numerous veins and fractures filled with calcite which give these rocks a brecciated aspect. Microscopically they exhibit porphyroclastic texture with relics of clinopyroxene, orthopyroxene, olivine and spinel in a fine-grained matrix composed of serpentine and carbonates. The primary minerals show evidence of plastic deformation previous to the cataclastic events.

Diopsidic clinopyroxenes usually contain very small exsolutions below microprobe resolution. Enstatitic orthopyroxenes are often rich in exsolution lamellae of clinopyroxene. Olivines are rich in forsterite (see below) and, like the pyroxenes, are highly fractured and altered to serpentine and varying amounts of carbonates. The spinel is brown-green picotite becoming progressively darker (and richer in Fe and Cr, see below) towards the rims and along fractures. Besides these undoubtedly primary minerals, there is brown amphibole often replaced by pale green amphibole. Secondary pale green to colourless amphibole also occurs replacing clinopyroxene and orthopyroxene.

Sample	1a	1b	C10	Z10C	BL-12	2
SiO_2	64.23	59.33	45.44	45.75	70.67	33.35
Al_2O_3	16.32	16.81	21.46	13.16	15.56	2.49
Fe_2O_3	0.74	1.28	4.71	5.12	0.36	3.91
FeO	4.54	6.69	7.09	7.42	2.65	3.21
MgO	2.75	3.82	2.83	7.17	1.11	27.01
CaO	2.40	2.26	6.57	14.89	1.27	10.14
Na_2O	4.79	4.58	3.90	0.16	3.99	--
K_2O	1.59	1.80	2.94	0.41	2.07	0.04
TiO_2	1.02	1.23	1.65	1.03	0.41	0.17
MnO	0.11	0.19	0.29	0.11	0.02	0.08
P_2O_5	0.09	0.09	0.89	0.30	0.26	0.05
p.f.	1.27	0.78	1.54	2.67	1.83	18.11
TOTAL	99.85	98.86	99.31	98.19	100.20	98.56
Ba	453	518	102	133	331	19
Co	47	47	39	74	40	92
Cr	107	157	21	700	43	1919
Cu	11	10	<10	19	<10	<10
Ni	71	69	35	191	42	1524
Sr	281	265	306	536	267	332
V	160	217	137	214	72	97
Rb	35	47	49	<10	61	<10
La	39.47		32.87	5.08		
Ce	79.62		77.07	12.26		
Nd	40.23		45.64	8.55		
Sm	8.29		12.21	3.14		
Eu	1.74		2.95	1.64		
Gd	7.04		13.45	3.59		
Dy	6.96		16.95	3.88		
Er	3.99		10.04	2.10		
Yb	4.46		11.49	2.26		
Lu	0.64		1.68	0.33		
Y	47.01		120.43	24.67		
Nb	n.a.		19.14	17.24		
Zr	n.a.		287.39	59.55		

1a, 1b: acid granulites, C10, Z10c: basic granulites, BL-12: migmatite, 2: lherzolite; n.a.: not analysed.

Table 1. Major (wt%) and trace element (ppm) composition of high-grade metamorphic rocks and lherzolites outcropping along the Leiza Fault.

3. Bulk rock chemistry

Analyses of major and trace elements, including rare earths (REE), of selected samples have been carried out by ICP methods at the CRPG (Nancy, see GOVINDARAJU & MEVELLE, 1987, for analytical details). Measured abundances of rare earth and trace elements were normalized with reference to the ›best estimate‹ of unfractionated chondritic rare earth abundances provided by EVENSEN et al. (1978), and to the N-MORB composition reported by PEARCE (1983). The main results are described below.

A c i d g r a n u l i t e s : The mineralogy of these rocks suggests they might have formed through recrystallization of an igneous protolith of granodioritic composition. Their bulk rock chemistry (samples 1a, 1b, Table I) is consistent with this hypothesis. The high CaO and Na_2O contents (2.33 and 4.68 wt % respectively) reflect an important amount of feldspar in the protoliths. Transition element (Co, Cr, Ni and V) and barium contents are relatively high, while REE contents are normal for this kind of rocks with regard to the total amount of REE and Eu negative anomaly (Figure 2). The absence of fractionation of the HREE may reflect the presence of garnet in these rocks.

B a s i c g r a n u l i t e s : Two different types of basic granulites have been analyzed (Table I): one corresponds to the sample Z10C rich in orthopyroxene and plagioclase, the other to the sample C10 rich in garnet, amphibole and biotite. The first type is richer in Mg and Ca and has normative composition of quartz-tholeiite. The second type is richer in Al and alkalies and has normative composition of alkaline basalt. The latter sample, although having higher REE contents than Z10C, lacks the typical features of alkaline basalt spectra such as fractionation and LREE enrichment (Figure 2). These features could reflect some kind of contamination with crustal host rocks during the emplacement of the basic magma. On the other hand, sample Z10C, with much lower REE contents, is characterized by a flat pattern with positive Eu anomaly (Figure 2). This suggests an origin for the protolith through a cumulative process as a result of early olivine and pyroxene fractionation from a tholeiitic magma.

M i g m a t i t e s : The leucosomes of the migmatitic rocks have a composition of peraluminous, sodium-rich granites (sample BL12, Table I). The composition corresponds to near minimum melts (q = 34, or = 12, ab = 35) formed at relatively low pressures (less than 5 kb P_{H_2O}, cf. WINKLER, 1979) which is consistent with their probable origin as in situ partial melts from an essentially metasedimentary source material (abundant quartz, micas, Al-silicates and graphite in mesosomes).

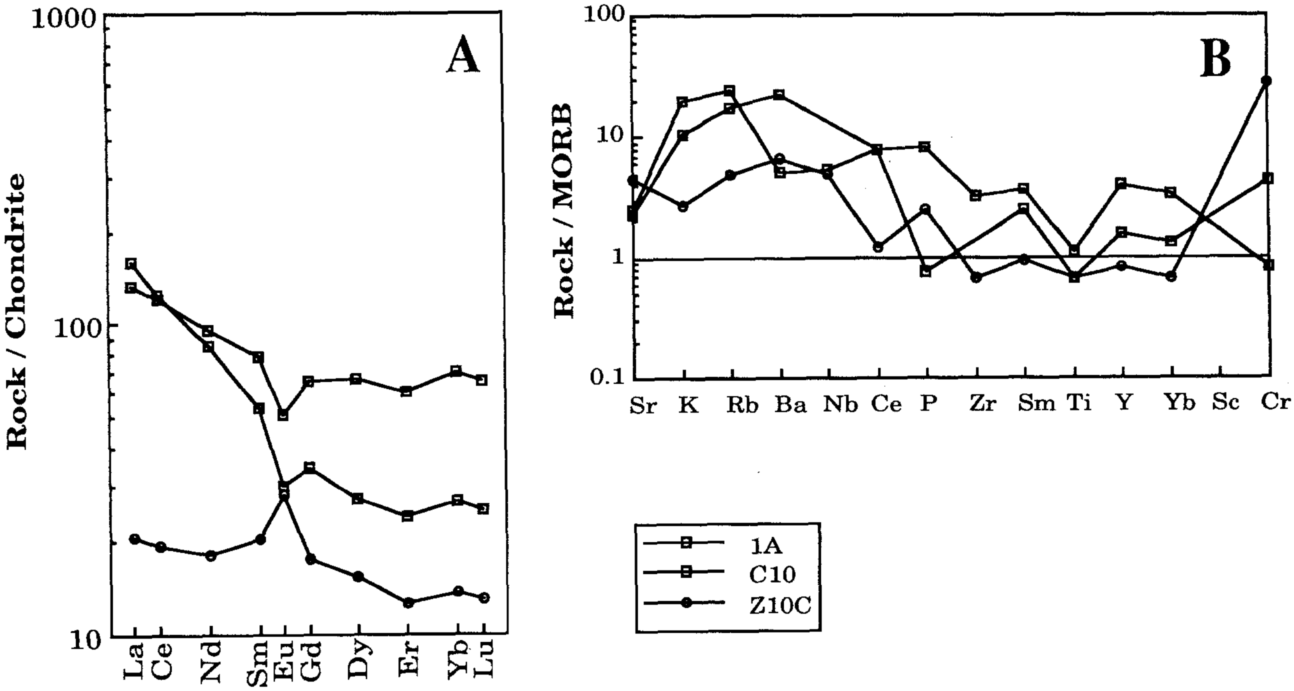

Fig. 2. A: chondrite normalized rare earth distribution for acid (1A) and basic granulites (C10, Z10C). B: MORB normalized REE and trace element patterns for acid (1A) and basic granulites (C10, Z10C).

4. Mineral chemistry

Minerals from selected samples were analyzed using a Camebax MICRO automatic microprobe at the University of Clermont-Ferrand (France). Working conditions were: 10 s counting time, c. 10 nA beam current and 15 kV accelerating voltage. Calibration was against BRGM (French Geological Survey) standard oxides and silicates, an a ZAF correction procedure was used. Ferric iron contents in garnets, pyroxenes and amphiboles were estimated by charge balance criteria following the procedures suggested by LAIRD & ALBEE (1981), MORIMOTO et al. (1988) and LEAKE (1978), respectively.

Garnet: The garnets from acid granulites are rich in almandine and pyrope end-members (53–64 and 30–42 mol %, respectively, Table II). The contents in grossular and spessartine end-members range 2–4.5 and 0.5–2 mol %, respectively. The garnets are slightly zoned, with Mg and less pronounced Ca decreasing and Fe and Mn increasing from core to rim which may be related, in principle, to a retrograde evolution (cf. HOLLISTER, 1966; ATHERTON, 1968; GRANT & WEIBLEN, 1971).

Garnets-I from the basic granulites are rich in almandine, pyrope and grossular end-members (ranges are 52–67, 15–28, and 12–18 mol %, respectively, Table II). These garnets are distinctly richer in Ca and Mn than the garnets from the acid granulites, but have approximately the same contents in Fe and are poorer in Mg (Table II). These garnets

Sample	1a/r	1a/c	2-4/r.I	2-4/c.I	SN/r.I	SN/c.I	2-4/c.II	2-4/c.II
SiO_2	38.66	39.00	38.62	39.20	37.85	38.03	37.91	37.78
Al_2O_3	22.89	23.37	22.09	22.53	22.15	21.71	21.80	22.65
TiO_2	bd	0.15	0.21	0.03	bd	0.09	0.09	0.08
Cr_2O_3	bd	0.06	0.13	0.07	bd	bd	0.27	bd
FeO	28.79	24.82	25.01	24.02	28.98	30.11	26.07	25.75
MnO	0.81	0.31	1.10	1.11	1.84	1.46	1.46	1.33
MgO	7.71	10.87	6.44	7.10	4.54	3.90	4.93	4.92
CaO	1.21	1.69	6.54	6.39	4.79	4.86	7.42	7.37
NiO	bd	bd	0.04	bd	0.06	bd	bd	0.05
TOTAL	100.07	100.27	100.18	100.45	100.21	100.16	99.95	99.93
Cations on the basis of 0:12								
Si	2.997	2.951	2.988	3.007	2.977	3.008	2.967	2.949
Al^{IV}	0.003	0.049	0.012	0.000	0.023	--	0.033	0.051
Al^{Vi}	2.089	2.035	2.002	2.037	2.031	2.025	1.978	2.034
Ti	bd	0.009	0.012	0.002	bd	0.005	0.005	0.005
Cr	bd	0.004	0.008	0.004	bd	bd	0.017	bd
Fe^{2+}	1.867	1.570	1.618	1.541	1.906	1.992	1.706	1.681
Mn	0.053	0.020	0.072	0.072	0.123	0.098	0.097	0.088
Mg	0.891	1.226	0.743	0.812	0.532	0.460	0.575	0.572
Ni	bd	bd	0.002	bd	0.004	bd	bd	0.003
Ca	0.101	0.137	0.542	0.525	0.404	0.412	0.622	0.617
Gros	3.45	4.46	17.83	17.59	13.62	13.91	19.90	20.84
Spes	1.83	0.67	2.42	2.44	4.13	3.30	3.23	2.97
Pyr	30.60	41.51	24.96	27.51	17.95	15.52	19.17	19.35
Alm	64.12	53.18	54.39	52.24	64.30	67.26	56.87	56.83

1a: acid granulite; 2-4, SN: basic granulites; r: rims; c: cores; I: Garnet-I; II: Garnet-II (coronitic garnet); bd: below detection limit of 0.01 wt %

Table 2. Representative chemical compositions of analyzed garnets.

Sample	11b/o	11c/o	2-4/o	2-4/o	11b/c	2B/c	2-4/c	2-4/c
SiO_2	54.98	54.81	50.29	50.47	51.85	51.17	50.24	49.70
Al_2O_3	4.37	5.02	3.06	3.18	6.83	6.75	4.45	4.15
TiO_2	0.15	bd	0.18	0.13	0.57	0.47	0.85	0.79
Cr_2O_3	0.27	0.47	0.20	0.13	0.76	0.96	0.15	0.12
Fe_2O_3	0.41	--	--	0.47	0.61	1.21	--	1.86
FeO	6.05	6.08	25.96	25.76	1.68	0.98	9.55	8.72
MnO	0.09	0.14	0.55	0.54	0.14	0.11	0.23	0.30
MgO	32.89	31.42	18.23	18.46	14.34	13.90	11.16	11.38
NiO	0.13	bd	0.04	bd	bd	bd	0.05	0.01
CaO	0.54	1.03	0.68	0.78	22.14	22.17	21.30	21.84
Na_2O	0.06	0.05	bd	0.03	1.46	1.57	0.70	0.60
K_2O	0.01	bd	bd	0.04	bd	0.02	0.03	0.02
TOTAL	99.94	99.02	99.19	99.99	100.38	99.31	98.71	99.49
FeO (t)	6.41	6.08	25.96	26.18	2.23	2.07	9.55	10.39
Cation proportions on the basis of O: 6								
Si	1.900	1.918	1.929	1.918	1.871	1.867	1.906	1.879
Al^{IV}	0.100	0.082	0.071	0.082	0.129	0.133	0.092	0.121
Al^{VI}	0.078	0.125	0.067	0.061	0.162	0.158	0.107	0.064
Ti	0.004	bd	0.005	0.004	0.015	0.013	0.024	0.022
Cr	0.007	0.013	0.006	0.004	0.022	0.028	0.005	0.004
Fe^{3+}	0.010	bd	bd	0.013	0.017	0.033	bd	0.053
Fe^{2+}	0.175	0.178	0.833	0.819	0.051	0.030	0.303	0.276
Mn	0.003	0.004	0.018	0.017	0.004	0.003	0.007	0.010
Mg	1.694	1.638	1.042	1.046	0.771	0.756	0.632	0.641
Ni	0.004	bd	0.001	bd	bd	bd	0.002	bd
Ca	0.020	0.039	0.028	0.032	0.856	0.867	0.866	0.885
Na	0.004	0.003	bd	0.002	0.102	0.111	0.051	0.044
K	bd	bd	bd	0.002	bd	0.001	0.001	0.001

11b, 11c, 2B: lherzolites, 2-4: basic granulite, o: orthopyroxenes, c: clinopyroxenes; bd: below detection limit of 0.01 wt %

Table 3. Representative chemical compositions of analyzed pyroxenes.

are slightly zoned, becoming richer in Fe and Mg and poorer in Ca towards the cores. Some garnets, however, preserve › normal ‹ zoning with an increase in Mg and a decrease in Mn contents from core to rim (e. g. sample SN). In the latter case, a slight enrichment in Mn in the outermost part is occasionally observed, which could be due to some late retrograde event (e. g. sample C2a).

Garnets-II (coronitic garnets) from the basic granulites (e. g. sample 2–4) have compositions slightly richer in Ca and poorer in Fe than the Garnet-I from the same rocks. Their average composition (cores) is $Alm_{57}Pyr_{19}Gros_{20}Spes_3$ (Table II).

Orthopyroxene: Unzoned orthopyroxenes from the basic granulites have an average composition $En_{55}Fs_{43}Wo_2$ (Table III). VIELZEUF (1984) has shown that granulitic orthopyroxenes from various outcrops along the North-Pyrenean Zone display considerable compositional scatter. The orthopyroxenes analyzed here have compositions similar to those from the granulites of Treilles and Lherz-Saleix (Eastern Pyrenees), and exhibit higher Ca and Ti contents than most orthopyroxenes analyzed by VIELZEUF (1984), which could be related to a higher temperature of metamorphism in the area studied.

Orthopyroxenes from the lherzolites are rich in enstatit end-member: $En_{89}Fs_{10}Wo_1$ as average (Table III). The relics which are not serpentinized do not show appreciable differences in composition from core to rim. The average Mg/(Mg+Fe) ratio, 90, is similar to that of coexisting olivines (90). These orthopyroxenes are rich in Al (both Al^{IV} and Al^{VI}) and Cr with moderate contents in Ca (0.04–0.03 f.u.), which suggests an origin at a relatively high pressure and temperature. Our results are comparable to those reported by MONCHOUX (1970) and CONQUERE & FABRIES (1984) for orthopyroxenes in lherzolites from Lherz and Frechinède (Eastern Pyrenees); the lower Al contents reported here may indicate a shallower origin for the lherzolites westwards along the North-Pyrenean Fault.

Clinopyroxene: Cinopyroxenes from the basic granulites are Al-rich diopside, with average composition $En_{23}Fs_{19}Wo_{58}$ (Table III). The clinopyroxenes analyzed are richer in Al, Ti and Mg (average X_{Mg} = 0.68) than those reported by VIELZEUF (1984) from basic granulites elsewhere in the Pyrenees. As in the case of orthopyroxenes, this fact might be related to a higher-temperature gradient of metamorphism towards the western part of the Pyrenean belt.

The clinopyroxenes from lherzolites are unzoned diopsides, with an average composition $En_{46}Fs_3Wo_{51}$ (Table III). These clinopyroxenes are relatively rich in Cr (>0.02 f.u.) and Al and have Ti contents and Cr/Al ratios similar to those of clinopyroxenes from the lherzolites in Lherz and Frechinède (MONCHOUX, 1970; CONQUERE & FABRIES, 1984). As in orthopyroxenes and olivines, X_{Mg} values are relatively high (>0.94), but there is no correlation between X_{Mg} values of clinopyroxenes and olivines as seems to be the case of the lherzolites from the Eastern Pyrenees (CONQUERE & FABRIES, 1984). According to the Cr and Na contents of the clinopyroxenes, the lherzolites from the area studied should represent fragments of subcontinental mantle (spinel-bearing lherzolites of subcontinental type, cf. classification of KORNPROBST, 1981).

Olivine: Unzoned olivines from the lherzolites have fairly Mg- and Ni-rich compositions (X_{Mg} = 0.9, NiO = 0.28 wt %, Table IV), which together with the low Ca and Cr contents may indicate that these minerals preserve compositions that have not been reequilibrated during the lower temperature recrystallization episodes.

Biotite: Biotite is relatively common in acid and basic granulites and in the migmatites. Primary biotites from the acid granulites have Ti-rich phlogopitic composition, whereas the secondary biotites are Mg-rich biotites s. str. There is in both types a certain amount of Al substituting for Fe and Na for K. Ca and Mn contents are very low and Ti

Sample	2B/o	2a/o	1b/b-I	1b/b-II	2-4/b-I	C10/b-II	BL-12a/b-I	2-4sc
SiO_2	41.24	40.34	38.36	39.16	36.46	36.20	36.47	52.87
Al_2O_3	bd	bd	16.02	15.08	19.37	14.42	20.62	25.66
TiO_2	bd	0.04	4.98	2.38	1.32	4.33	1.94	0.02
Cr_2O_3	bd	0.04	0.10	0.11	0.08	bd	0.05	bd
FeO_t	9.75	9.58	9.71	15.08	11.36	18.11	12.29	0.07
MnO	0.17	0.80	bd	bd	0.08	0.07	0.06	0.01
MgO	48.51	48.24	17.45	15.05	16.26	11.90	14.55	0.01
NiO	0.28	0.29	bd	0.05	0.74	bd	0.03	bd
CaO	0.02	0.02	0.03	bd	bd	0.01	bd	10.77
Na_2O	bd	bd	0.09	bd	0.28	0.14	0.14	7.90
$K2_2O$	bd	bd	10.51	9.81	9.90	9.99	10.70	0.31
TOTAL	100.04	99.86	97.21	95.61	95.85	95.17	96.85	97.61
Number of cations on the basis of O:4 for olivines, O:11 for biotites and Si+Al : 12 for scapolite								
Si	1.010	0.997	2.822	2.961	2.694	2.835	2.707	7.633
Al^{IV}	bd	bd	1.178	1.039	1.306	1.165	1.293	4.367
Al^{VI}	bd	bd	0.212	0.206	0.381	0.166	0.511	--
Ti	bd	0.001	0.276	0.135	0.073	0.255	0.108	0.002
Cr	bd	bd	0.006	0.007	0.005	bd	0.003	bd
Fe_t	0.200	0.197	0.598	0.953	0.702	1.186	0.763	0.008
Mn	0.003	0.016	bd	bd	0.005	0.005	0.004	0.001
Mg	1.770	1.775	1.909	1.696	1.790	1.389	1.609	0.002
Ni	0.006	0.006	bd	0.003	0.044	bd	0.002	bd
Ca	bd	bd	0.002	bd	bd	bd	bd	1.666
Na	0.003	0.015	0.013	bd	0.040	0.021	0.020	2.211
K	bd	0.006	0.987	0.946	0.933	0.998	1.013	0.057
X_{Mg}	0.90	0.90	0.762	0.640	0.718	0.539	0.678	

2B, 2a: lherzolites, 1b: acid granulite, 2-4, C10: basic granulites, BL-12a: migmatite, 2-4sc:scapolite from basic granulite, o : olivine, b-I: primary biotite, b-II: secondary biotite; bd: below detection limit of 0.01 wt %

Table 4. Representative chemical compositions of analyzed olivines, biotites and scapolites.

and Al^{IV} contents are higher in the primary biotites (Table IV). The biotites from basic granulites also have phlogopitic compositions and generally high Ti contents, but are distinctly richer in Na than the biotites from acid granulites (Table IV). The biotites from migmatites have phlogopitic composition too, with high Al^{IV} and K contents and, although relatively high, distinctly lower Ti contents than the biotites from granulites (Table IV).

A m p h i b o l e s : Primary, brown amphiboles in basic granulites have compositions of ferroan pargasite to magnesio-hastingsite (Figures 3–5, Table V); X_{Mg} values of these amphiboles vary between 0.79 and 0.3, whereas Si contents are relatively constant. Secondary amphiboles replacing clinopyroxene and brown amphibole have compositions of actinolitic hornblende, ferroactinolitic hornblende, ferro-hornblende or actinolite, whereas secondary amphiboles replacing orthopyroxene are cummingtonite (Table V). The main substitution in primary amphiboles is edenitic: (A) + $Si^{(IV)}$ = $Na^{(A)}$ + $Al^{(IV)}$, with a certain amount of tschermakitic component. In secondary amphiboles the pargasitic substitution predominates (Figure 3).

Brown amphiboles in lherzolites have a composition of magnesian hastingsite to magnesio-hastingsitic hornblende and relatively high X_{Mg} values (> 0.9, Table V). Pale green idiomorphic amphiboles are edenitic hornblende with Si ranging from 6.5 to 6.7, and relatively constant X_{Mg} values of c. 0.9 (Table V), whereas the undoubted secondary amphiboles replacing clinopyroxene and ›primary‹ amphibole may be tremolitic hornblende to tremolite (Table V). The secondary amphiboles that replace orthopyroxene are cummingtonite (Table V). Ti, Na, K, Al_t and Al^{IV} contents are generally higher in the ›primary‹ hastingsitic amphiboles than in the clearly secondary edenitic ones. The latter amphiboles are in turn richer in these elements than the also secondary tremolitic amphiboles. As a whole, the Si contents increase as the Ti, Na, K and Al contents decrease. This suggests formation under progressively lower temperature conditions from hastingsitic to tremolitic types (cf. SPEAR, 1980, 1981a, 1981b). The main substitution operating in these amphiboles is one of pargasitic type: (A) + $Mg^{(VI)}$ + $Si^{(IV)}$ = $Na^{(A)}$ + $Al^{(VI)}$ + $2Al^{(IV)}$ (Figure 3).

5. P-T conditions of metamorphism

A c i d g r a n u l i t e s : Quantitative estimates of temperature conditions of metamorphism in acid granulites have been obtained applying the garnet-biotite geothermometer as formulated by HODGES & ROYDEN (1984). Other geothermometric formu-

Sample	2B	2a	11c	12b	2-4 I	Z10c	SN	2-4 II
SiO_2	44.62	47.69	52.66	56.72	55.24	49.03	37.93	41.26
Al_2O_3	13.16	9.68	5.34	0.06	1.86	5.41	17.96	14.25
TiO_2	0.18	0.36	0.30	bd	0.03	0.31	0.31	4.23
Cr_2O_3	0.26	0.88	0.66	0.04	0.05	bd	0.10	0.13
Fe_2O_3	--	5.38	3.43	--	--	4.25	6.65	--
FeO_t	5.13	--	--	15.80	12.83	16.35	12.86	11.43
MnO	0.66	0.11	0.01	0.38	0.37	0.18	0.07	0.12
MgO	18.51	19.71	21.44	23.40	21.14	10.03	6.88	11.04
NiO	0.18	0.02	0.04	bd	bd	0.09	bd	0.09
CaO	12.19	12.30	12.45	0.59	5.66	11.44	10.42	11.85
Na_2O	3.17	2.37	1.07	bd	0.34	1.02	2.64	1.67
K_2O	0.46	0.23	0.05	bd	0.01	0.23	1.15	2.08
TOTAL	98.52	98.73	97.45	96.99	97.53	98.35	96.98	98.15
FeO(t)	5.13	4.84	3.09	15.80	12.83	20.18	18.85	11.43
Cation proportions on the basis of O: 23								
Si	6.331	6.637	7.284	8.021	7.803	7.269	5.768	6.128
Al^{IV}	1.669	1.363	0.716	--	0.197	0.731	2.232	1.872
Al^{VI}	0.532	0.225	0.155	0.010	0.113	0.214	0.987	0.623
Ti	0.019	0.038	0.031	bd	0.003	0.035	0.035	0.472
Cr	0.029	0.097	0.072	0.004	0.006	bd	0.012	0.015
Fe^{3+}	--	0.563	0.357	--	--	0.475	0.761	--
Fe^{2+}	0.609	--	--	1.869	1.516	2.027	1.636	1.420
Mn	0.079	0.013	0.001	0.046	0.044	0.023	0.009	0.015
Mg	3.914	4.088	4.420	4.932	4.450	2.216	1.559	2.444
Ni	0.021	0.002	0.004	bd	bd	0.011	bd	0.011
Ca	1.853	1.834	1.845	0.089	0.857	1.817	1.698	1.886
Na	0.872	0.640	0.287	bd	0.093	0.293	0.525	0.481
K	0.083	0.041	0.009	bd	0.002	0.044	0.223	0.394

2B,2a,11c,12b: amphiboles from lherzolites; 2B: hastingsitic amphibole around spinel; 2a: idiomorphic edenitic hornblende; 11c: secondary tremolite; 12b: secondary cummingtonitic. 2-4 I,Z10c, SN,2-4 II: amphiboles from basic granulites; 2-4 I: 'primary' brown amphibole; Z10c, SN: 'secondary' blue-green amphiboles; 2-4 II: secondary cummingtonite; b.d.: below detection limit of 0.01 wt %

Table 5. Representative chemical compositions of analyzed amphiboles.

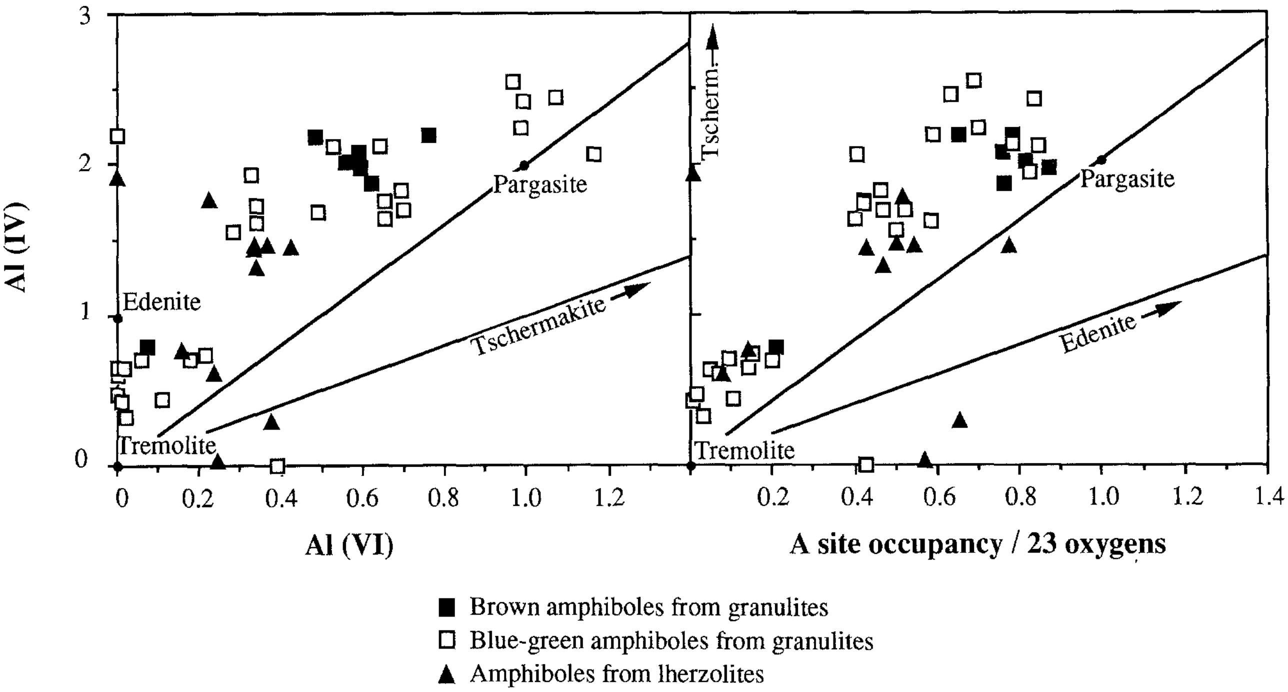

Fig. 3. Cationic substitutions in amphiboles from granulites (squares) and lherzolites (triangles). A: Al (IV) vs. Al (VI); B: Al (IV) vs. A site occupancy.

lations for the same mineral pair (cf. HOLDAWAY & LEE, 1977; INDARES & MARTIGNOLE, 1985, etc.) have been discarded since they give greater scatter of the results or unrealistic too low temperatures. It may be noted that although ›primary‹ biotites (cf. petrography) of acid granulites are richer in Ti, Al^{IV} and Mg/Mg + Fe ratios than ›secondary‹ biotites, temperature estimates using garnet-primary biotite compositions are distinctly lower (by c. 100 °C) than those calculated using secondary biotites. Using maximum X_{Mg} values for garnet and maximum X_{Fe} for biotite, the temperature estimates for the late stages of the granulite-facies metamorphism (kinzigitic stage) are 800 ± 40°C at 1 bar and 840 ± 40°C at 10 kbar. The maximum pressure conditions (since sillimanite is absent from the equilibrium mineral assemblage) can be approximated using the garnet-cordierite geothermometer/geobarometer. Problems arising from the use of the experimental determinations and the theoretical reconstructions of the garnet-cordierite equilibrium have been reviewed by NEWTON (1983) and ESSENE (1989) among others. A pressure estimate of c. 7 ± 0.5 kbars at 800–850°C is obtained by comparison with the diagrams of NEWTON & WOOD (1979) and assuming $P_{H2O} = P_t$. Higher pressure estimates – c. 10.5 kbar at the same temperatures – are obtained using the calculation methods proposed by POWELL & HOLLAND (1988, THERMOCALC program) with their extended dataset (HOLLAND & POWELL, 1990).

Basic granulites: Quantitative pressure and temperature estimates for the metamorphic peak in the metabasites have been obtained applying the garnet-clinopyroxene geothermometer (KROGH, 1988; PATTISON & NEWTON, 1989), and the garnet-orthopyroxene-plagioclase-quartz and garnet-clinopyroxene-plagioclase-quartz geobarometers (cf. review of the geobarometers in ESSENE, 1989). The results obtained, using maximum X_{Mg} values of garnet and maximum X_{Fe} of clinopyroxene, are in good agreement with those obtained for acid granulites: 790 ± 30°C and 6–7 kbar for the clinopyroxene equilibrium, and 7–8 kbar for the orthopyroxene equilibrium. The preferred results are those obtained using calibrations of the garnet-orthopyroxene-plagioclase-quartz barometer, considered to yield more reliable pressure estimates (cf., LAMB et al., 1986; POWELL & HOLLAND, 1988) and which are similar to those obtained for the garnet-cordierite equilibrium in the acid granulites. Note that the ilmenite-pyroxene geothermometer (BISHOP, 1980) reflects re-equilibration under distinctly lower temperatures (350–400°C)

Temperature estimates for the pairs garnet-brown hornblende (GRAHAM & POWELL, 1984), and garnet-biotite (HODGES & ROYDEN, 1984) from basic granulites containing garnet and two pyroxenes are slightly lower: c. 745 and 725°C respectively (at 8 kbar), which suggests that these hydrated minerals in these rocks equilibrated near the granulite-facies peak of the metamorphism. In rocks rich in garnet and biotite but lacking the two pyroxenes, only the formulation of HOINKES (1986) yields consistent temperatures higher than 700°C. Temperature estimates for the equilibrium muscovite-plagioclase (GREEN & USDANSKY, 1986) in sample Z10C also suggest equilibration of this mineral pair near the peak of granulite-facies metamorphism: c. 730°C at 8 kbar.

The Ti contents of primary amphiboles from the basic granulites are similar to those reported by RAASE (1974) for rocks formed under high-grade amphibolite- or granulite-facies conditions, whereas secondary amphiboles have Ti contents similar to those formed under low-grade amphibolite- to greenschist-facies conditions. According to their Si and Al^{VI} contents, most amphiboles of both types plot, however, in the field of pressures below 5 kbar (graphic method of RAASE, 1974, Figure 4). This may imply that the primary amphiboles, in part, re-equilibrated during the retrograde evolution of the granulites that produced secondary amphiboles during amphibolite-facies and lower grade conditions.

According to the fields defined by LAIRD & ALBEE (1981) for the prograde metamorphism of basic rocks, both the primary and secondary amphiboles were formed under conditions of low to intermediate pressure and relatively high temperature (Figure 5), which is consistent with the previous results. Secondary amphiboles show a great dispersion in the diagram of Figure 5, which suggests considerable disequilibrium of the system during retrogression.

L h e r z o l i t e s : The orthopyroxene-clinopyroxene geothermometer (WOOD & BANNO, 1973; WELLS, 1977) based on the Fe-Mg partition between these phases, and the olivine-orthopyroxene geothermometer (BERGER & VANNIER, 1977) based on the distribution of Ni and Mg yield temperatures of c. 1300 °C. Lower temperatures, ranging between 1000 and 600 °C, have been obtained using the formulations of MERCIER (1980) and SAXENA et al. (1986) for the two- pyroxene equilibrium. The latter results may reflect the re-equilibration which resulted in the growth of amphibole in these rocks. Temperature estimates using the composition of spinel, e.g., olivine-spinel (FABRIES, 1979), orthopyroxene-spinel (TABIT et al. 1986), and Si content of spinel (BERGER et al. 1984) yield in all cases unrealistic too high values: 1600–1900 °C.

The only acceptable value for the pressure conditions was obtained using MERCIER's (1980) single-pyroxene geobarometer: 19 kbar for a temperature of 900 °C. However, this estimate must be considered as a limiting value since in the temperature range of 800–1000 °C at this pressure, the limit of the spinel-peridotite stability field is reached (LANE & GANGULY, 1980).

The amphiboles of the lherzolites plot in the fields of low- to intermediate-pressure metamorphism defined by LAIRD & ALBEE (1981) for the prograde metamorphism of basic rocks, and most of them below the garnet isograd (Figure 5), whereas according to their Si and Al^{VI} contents, the analyzed amphiboles were formed at less than 5 kbar (cf. Figure 4).

6. Conclusions

The petrological and mineralogical data indicate that a number of rocks associated with the Leiza Fault have presumably been affected by pre-Alpine metamorphism at conditions of intermediate- to high-temperature (biotite stable) granulite-facies. Retrograde metamorphism took place under amphibolite- to greenschist-facies conditions.

The granulite-facies metamorphism was of intermediate-pressure type, the maximum P-T conditions recorded by the rocks with granulitic mineral assemblages were around 800 °C and 7–8 kbar. These results are comparable to those reported for granulitic massifs and tectonic slices elsewhere in the Pyrenees (Lherz, Saleix, Agly, Bessède de Sault, etc., cf. ANDRIEUX, 1982; VIELZEUF, 1984),

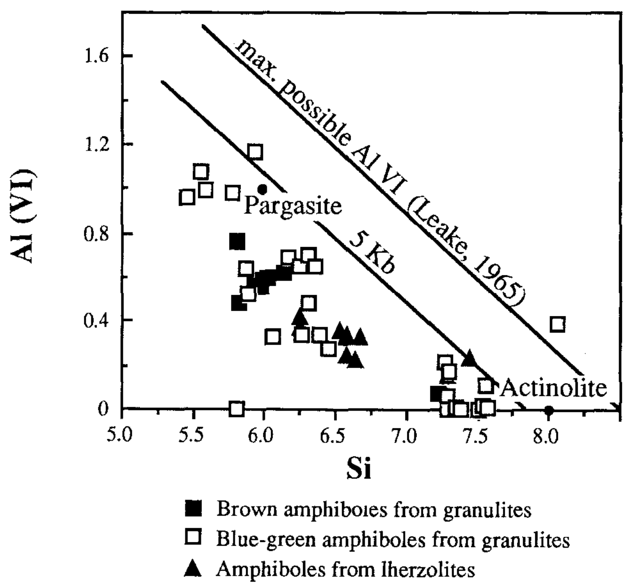

Fig. 4. Al^{VI} vs. Si for amphiboles from granulites (squares) and lherzolites (triangles). Pressure field divide after RAASE (1974).

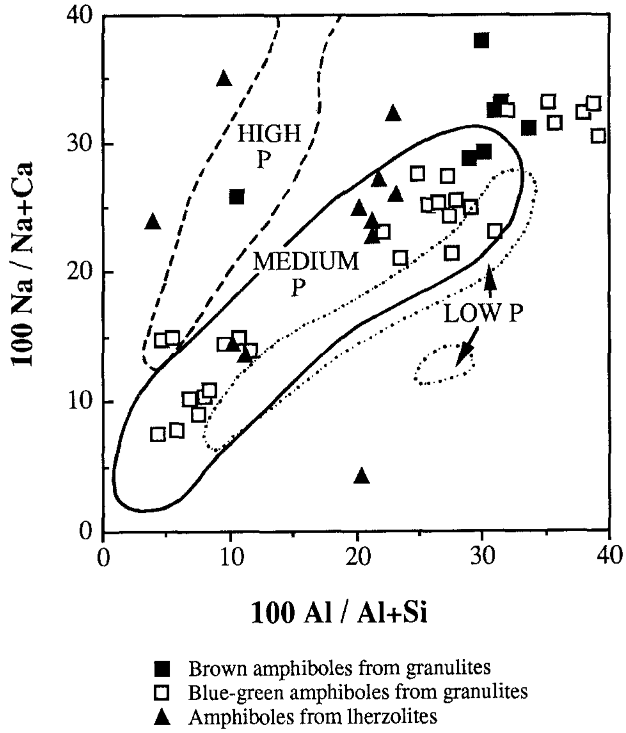

Fig. 5. 100Na/Na+Ca vs. 100Al/Al+Si for amphiboles from granulites (squares) and lherzolites (triangles). Metamorphic fields for low-, medium- and high-pressure metamorphism according to LAIRD & ALBEE (1981).

acid granulites (re)crystallization might be a two-stage process: a first stage under intermediate-pressure/low- temperature granulite-facies conditions (garnet, biotite, K-feldspar parageneses) and a second stage under lower pressure and likely higher temperatures with the development of cordierite and perhaps spinel. The first stage was probably related to the development of regional fabrics (elongated garnets, blastomylonitic foliation), whereas the second one apparently took place under static conditions. It cannot be ascertained with the available data whether the origin of these granulites is to be related to a period of uplift and crustal extension or to a compressive orogenic episode.

Basic magmas formed the igneous protoliths of the associated basic granulites. Whether the basic magmas were generated in connection with the referred uplift/distensive period is not yet clear. Their tholeiitic to alkaline composition with evidence, in some cases, of contamination with crustal materials supports this hypothesis. These rocks underwent a period of dynamic recrystallization under intermediate-pressure/high-temperature, granulite-facies conditions and then retrogression under decreasing pressure and temperature.

The migmatitic rocks represent a stage of partial melting at a shallower crustal level. Granitic melts

although the pressure estimates for the Leiza area suggest slightly deeper conditions of metamorphism (Figure 6). By analogy with those massifs, this metamorphic event may be related to the Hercynian cycle (cf. POSTAIRE, 1983). The great scatter of temperature estimates for lherzolites reflects a lack of metamorphic equilibration among the mineral phases in these rocks. The estimates of c. 1300 °C and 19 kbar are, in any case, sensibly different from those reported by CONQUERE & FABRIES (1984) for the ultramafic rocks at Lherz and Frechinède (950 °C and 13–15 kbar).

The Alpine metamorphism gave rise to the formation of scapolite (dipyre with 35–47% of meionite component, Table IV) in the basic granulites under conditions of low-pressure and intermediate- to high-temperature: c. 500 °C, < 5 kbar (cf. HIETANEN, 1967; KWAK, 1977).

Acid granulites were presumably formed from igneous protoliths of granodioritic composition. The granodioritic magmas possibly were generated by partial melting of crustal material with an important metasedimentary component as deduced from the richness of the granulites in garnet, biotite and cordierite. On the basis of the paragenetic evolution of

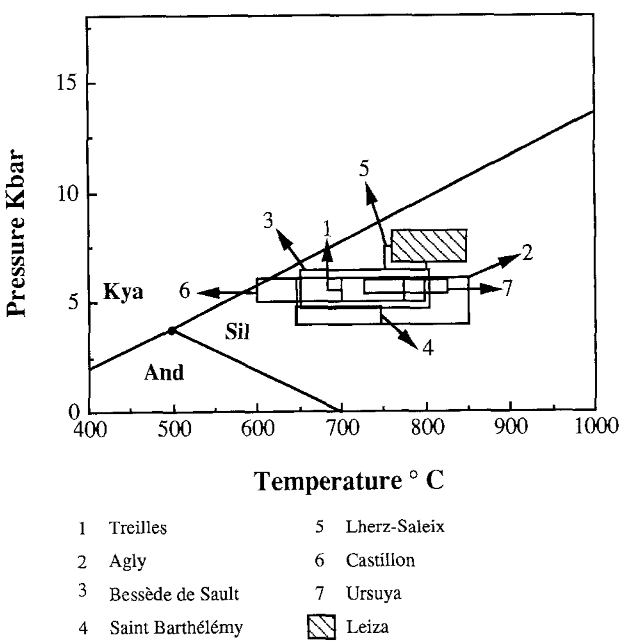

Fig. 6. P-T estimates for granulite terrains in the Pyrenees. Shaded area represents the Leiza region (present study). Other fields (Treilles, Agly, Bessède de Sault, Saint Barthélémy, Lherz-Saleix, Castillon and Ursuya) are from VIELZEUF (1984). Equilibrium curves for phase relations among the Al-silicate minerals, after (HOLDAWAY, 1971).

instead of granodioritic ones were generated and andalusite/sillimanite-K feldspar parageneses developed in the mesosomes instead of the garnet/cordierite-K feldspar parageneses of acid granulites. The presence of two-mica granites, leucogranites and pegmatites associated with the migmatitic rocks suggests the existence of an intermediate, deeper level, with a higher degree of partial melting than that presently observed in the migmatitic outcrops.

The lherzolites from the area studied appear to be similar to the lherzolites from North-Pyrenean sectors (Lherz, Saleix, etc.). These rocks are intensely brecciated and serpentinized and the data available do not permit an accurate statement of their evolution. It appears that they recrystallized at conditions of the granulite or high-grade amphibolite-facies during a first metamorphic event.

It seems clear from the data presented in this paper that the Leiza Fault is an extension of the North-Pyrenean Fault. The metamorphic rocks of presumably Hercynian metamorphic age outcropping along the Leiza Fault closely correspond to those appearing in scattered outcrops along the North-Pyrenean Fault and in the North-Pyrenean massifs. In the area studied these rocks represent different metamorphic depth-levels. They may constitute remnants of a metamorphic massif of Hercynian age which was dismembered after the main metamorphic event as a result of the tectonic activity in the Fault zone.

The granulites from the area studied are very different from the granulites of allochthonous, high-grade complexes elsewhere in the Hercynian Foldbelt (Cabo Ortegal and others in NW Spain and N Portugal). The latter granulites occur associated with eclogites and are characterized by high-pressure parageneses with garnet and sodic clinopyroxene in metabasites (VOGEL, 1967; GIL IBARGUCHI et al., in press). The granulites studied here are, on the contrary, rather similar to those dredged to the West of the Study area along the northern continental margin of the Iberian Peninsula (CAPDEVILA & MOUGENOT, 1988). However, although the dredged granulites are considered to have been brought to surface by tectonic activity in westwards extension of the North-Pyrenean Fault (CAPDEVILA et al., 1974, 1980), they are apparently much older than those from the Pyrenees (Precambrian after CAPDEVILA & VIDAL, 1975; POSTAIRE, 1983), which may indicate that the North-Pyrenean Fault activates different kinds of basement from East to West.

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