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Metamorphic evolution of the palaeozoic series of the Betic Cordilleras (Nevado-Filabride complex, SE Spain) and its relationship with the alpine orogeny

By M. T. Gomez-Pugnaire, Granada and G. Franz, Berlin*)

With 14 figures and 1 table

Zusammenfassung

Die paläozoischen Gesteinsserien der Veletadecke im Nevado-Filábride Komplex (Betische Kordillere, Südspanien) bestehen aus Graphitglimmerschiefern mit Oxichlorit — Chloritoid — Albit — Granat — Porphyroblasten. Die Kristallchemie der Minerale, ihre Phasenbeziehungen und Mikrogefüge sind konsistent mit einer normalen prograden Metamorphoseentwicklung und leichter retrograder Überprägung. Die Basis der darüberliegenden Mulhacendecke besteht ebenfalls aus paläozoischen Graphitglimmerschiefern, die jedoch deutliche Anzeichen für polymetamorphe Entwicklung zeigen: Eine frühe Niedrigdruckmetamorphose mit Andalusit und Chloritoid wird überprägt von einer Hochdruckmetamorphose mit Disthen und Mg-reichem Chloritoid. Diese spätere Entwicklung ist, wie die Metamorphosebedingungen der im Hangenden folgenden permotriadischen Gesteine der Mulhacendecke zeigen, frühalpin und schließt Eklogitbildung mit ein, gefolgt von einer amphibolitfaziellen Überprägung. Die Metamorphose der Veletadecke wird als präalpine Metamorphose angesehen: Eine mögliche alpine Überprägung hat keinen Temperaturanstieg verursacht. Zwischen Mulhacendecke und Veletadecke besteht kein inverser Metamorphosegradient, sondern ein Sprung in den Metamorphosealtern.

Abstract

The Palaeozoic rocks of the Veleta nappe (Nevado-Filábride complex, Betic Cordilleras, Southern Spain) consist of graphite-mica schists with oxychlorite — chloritoid — albite — garnet porphyroblasts. Crystal chemistry of the minerals, their phase relations and microfabrics are consistent with a normal prograde metamorphic evolution and a slight retrograde overprint. The basis of the overlying Mulhacén nappe consists also of Palaeozoic graphite-mica schists, but with clear signs of polymetamorphic development. An early low-pressure metamorphism with andalusite and chloritoid is overprinted by high-pressure metamorphism with kyanite and Mg-rich chloritoid. This later development is of Alpine age, which is demonstrated by the metamorphic conditions of Permo-Triassic rocks in the upper part of the Mulhacén nappe, included formation of eclogites, followed by an amphibolite facies overprint. The metamorphism of the Veleta nappe is regarded as pre-Alpine: a possible Alpine overprint did not cause an increase in temperatures. No inverse metamorphic gradient exists between Veleta and Mulhacén nappes, because of the different ages of metamorphism.

Resumen

El Paleozoico del Manto del Veleta (complejo Nevado-Filábride, Cordilleras Béticas, suroeste de España) está formado por micasquistos grafitosos con porfiroblastos de oxicloritas — chloritoide — albita — granate. La cristalquímica de los minerales, sus relaciones de fase y microfábrica son coherentes con una evolución metamórfica progresiva normal y con un ligero retrometamorfismo. La base del suprayacente Manto del Mulhacén está también formado por micasquistos grafitosos paleozoicos, pero muestran signos evidentes de un desarrollo polimetamórfico. El metamorfismo más antiguo tiene unas caracteristicas de baja presión con la formación de andalucita y cloritoide. Estas rocas sufren los efectos de un nuevo proceso metamorfico de edad alpina, lo que puede ser demostrado por comparación con las rocas Permo-Triásicas de la parte superior del Manto del Mulhacén, en las cuales las eclogitas formadas en la primera fase son afectadas por otra en la facies de las anfibolitas. El metamorfismo del Manto del Veleta puede ser probablemente considerado como pre-Alpino: si está afectado por el metamorfismo alpino, éste no ha causado un incremento de temperatura. No existe, por tanto, inversión del gradiente metamórfico entre los Mantos del Veleta y del Mulhacén puesto que la edad del metamorfismo en ambos es diferente.

Краткое содержание

Палеозойские серии пород покрова Велета в комплексе Невадо-Филябрид / бетские кордильеры, южная Испания / состоят гл. обр. из сланцев графитослюдяного типа с включениями оксихлорита, хлоритоида, альбита, граната и порфиробластов. На основании кристаллохимических исследований этих минералов, соотношения их фаз и их микротекстуры установили обычное прогессирующее развитие процессов

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*) Authors' addresses: M. T. Gomes-Pugnaire, Departamento de Mineralogia y Petrologia, Instituto Andaluz de Geologia Mediterranea, Facultad de Ciencias, Granada, Spain and G. Franz, Institut für Angewandte Geophysik, Petrologie und Lagerstättenforschung, Technische Universität, 1000 Berlin 12, Federal Republic of Germany.

метаморфизма с незначительными ретро-градными преобразованиями. Основание покрывающих горизонтов Mulhacen также содержит палеозойские графито-слюдяные сланцы, проявляющие явные черты полиметаморфического развития : ранний метаморфизм при низком давлении, при котором появляются андалузит и хлоритоид, оказался преобразованным процессами метаморфизма высокого давления с образованием таких минералов, как дистен и богатые магнием хлоритоиды. Это более позднее развитие, как и условия процессов метаморфизма пермо-триассовых пород кровли Mulhacen, по своему возрасту относятся к раннему периоду альпийского горообразовательного процесса и заканчиваются появлением эклогитов, дальнейшее развитие которых шло до амфиболитовой фации. Метаморфизм покрова Велета рассматривают, как до-альпийский метаморфизм : возможные преобразования в альпийское время не вызывали значительного повышения температуры. Однако, обратный градиент метаморфизма между покровами Mulhacen и Veleta установлен не был; они оба отличаются друг от друга только по возрасту их метаморфизма.

1. Introduction

The Internal Zone of the Betic Cordilleras has been subdivided into three complexes (Fig. 1): 1) the Maláguide complex at the top, 2) the Alpujárride complex and 3) the Nevado-Filábride complex (NFC in the following) at the base. Each of these complexes is composed of several tectonic units or nappes. The NFC, from a stratigraphic point of view, consists of two series: a) the Lower Series, a thick formation (>4000 m) characterized by a monotonous succession of graphite-bearing metamorphic rocks (metapelites, quartzites and occasionally marbles); b) the Upper Series, a thinner sequence (<400 m) composed of metapelites, quartzites, marbles (all of them essentially without organic matter) and metamorphosed mafic and ultramafic rocks (Fig. 1,2). The occurrence (or its absence) of graphite is the most obvious characteristic in distinguishing between the Lower and the Upper series in the field.

Most authors (FALLOT et al., 1961, NIJHUIS, 1964, EGELER & SIMON, 1969, PUGA et al., 1974, GOMEZ-PUGNAIRE, 1979a) agree with the hypothesis that the graphite-bearing rocks (or Lower Series) are Palaeozoic in age, and paleontological data also demonstrates the Precambrian age of part of these rocks (GOMEZ-PUGNAIRE et al., 1982). A Permo-Triassic age can be attributed to the Upper Series on the basis of the correlation with the Maláguide complex (the least metamorphosed of the Internal Zone), e. g. the occurrence of abundant gypsum in the marbles.

This simplistic stratigraphic subdivision is more complicated from a tectonic point of view. Both, Upper and Lower Series consist of several tectonic units, and the number of recognized tectonic units varies in different areas and according to the different authors. The tectonic situation is one of the most important problems in the interpretation of the NFC structure.

All the rocks of the NFC have been affected by metamorphism which, in the Upper Series (Permo-Triassic rocks), is undoubtedly Alpine. It has also been accepted that the Palaeozoic and older rocks have been affected by Alpine metamorphism, but there is no general agreement about the existence of pre-Alpine metamorphism. It is evident at least in parts of the Lower Series (PUGA & DIAZ DE FEDERICO, 1976a in the Sierra Nevada; GOMEZ-PUGNAIRE & SASSI, 1983 and MARTINEZ-MARTINEZ, 1984 in the Sierra de los Filabres), and this evidence is the basis for the distinction of two types of Lower Series:

1) The first (Palaeozoic I in Figs. 2 and 3) occurs locally and represents the upper part of the Lower Series. The rocks contain generations of minerals interpreted (see references above) as being relics of pre-Alpine metamorphism followed by an Alpine metamorphic overprint. This is the lower part of the Mulhacén nappe (*sensu* PUGA et al., 1974, see Figs. 2 & 3).

2) The second (Palaeozoic II) ist the Veleta nappe (*sensu* PUGA et al., 1974) and consists of monotonous graphite-micaschists and quartzites and shows no obvious signs of polyphase development. The rocks of the Palaeozoic II (in the following Veleta nappe) occupy the greater part of the NFC and form the highest peaks of the Iberian Peninsula.

The polyphase character and the Alpine age of the metamorphism attributed to the Veleta nappe are questionable. There are no clear indications (like age data) and we therefore investigated the following aspects of the Palaeozoic graphite-bearing schists:

1) The metamorphic evolution of the rocks.
2) A comparison between the metamorphic character of the Veleta nappe and the polymetamorphic rocks of the Palaeozoic I (the lower part of the Mulhacén nappe, see Fig. 2).
3) A comparison between the Alpine metamorphism of the Upper Series (Permo-Triassic rocks and the upper part of the Mulhacén nappe).
4) The interpretation of the tectonic relationships between the different series.

The results of the investigations demonstrate that the metamorphism of the Veleta nappe is different from that of the Palaeozoic I and Permo-Triassic rocks of the Mulhacén nappe. Two possible interpretations are discussed in the final chapters of this paper.

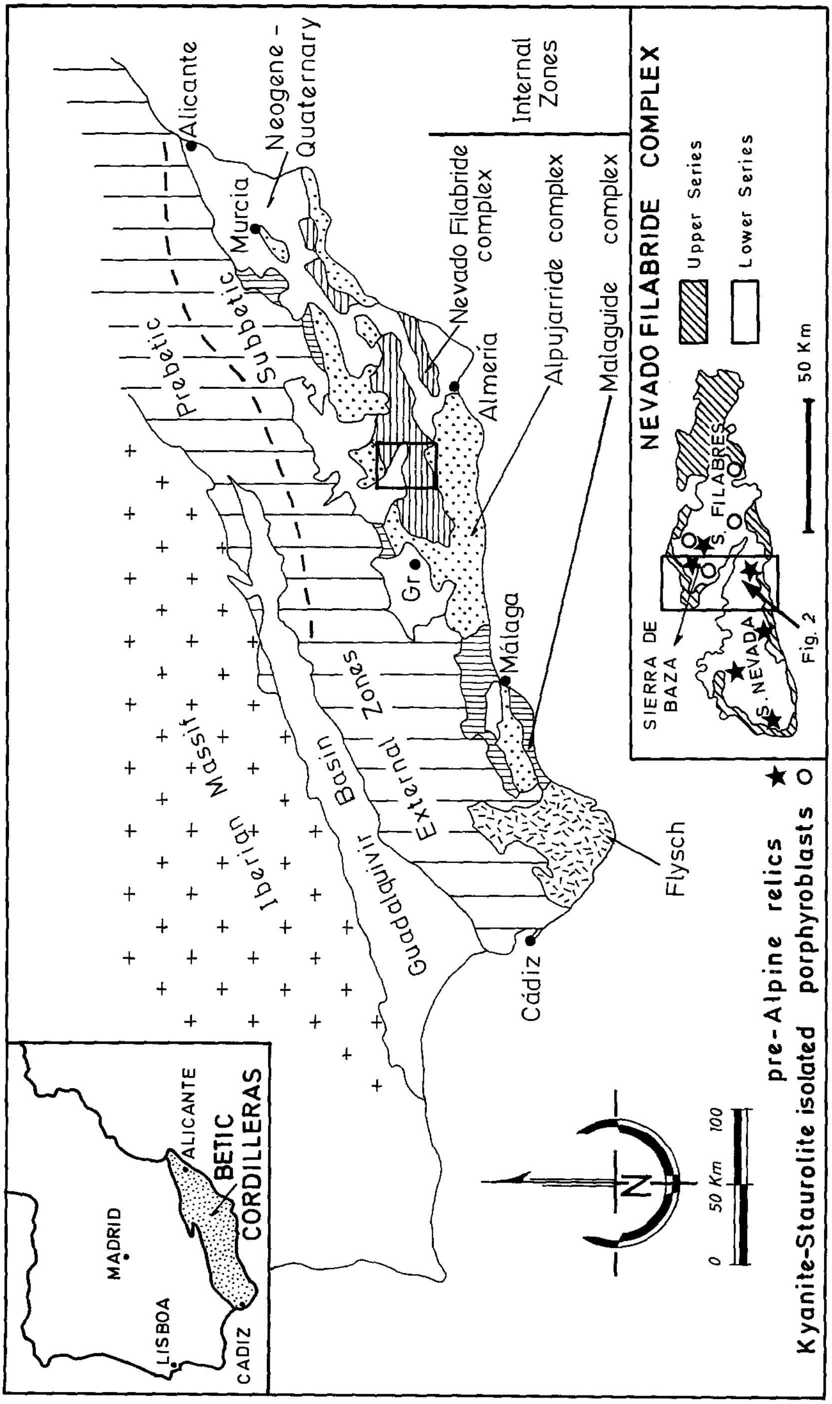

Fig. 1. Tectonic sketch of the Betic Cordilleras, Spain. The Nevado-Filábride complex as a part of the Internal Zones is shown in the insert in the lower right (Gr = Granada).

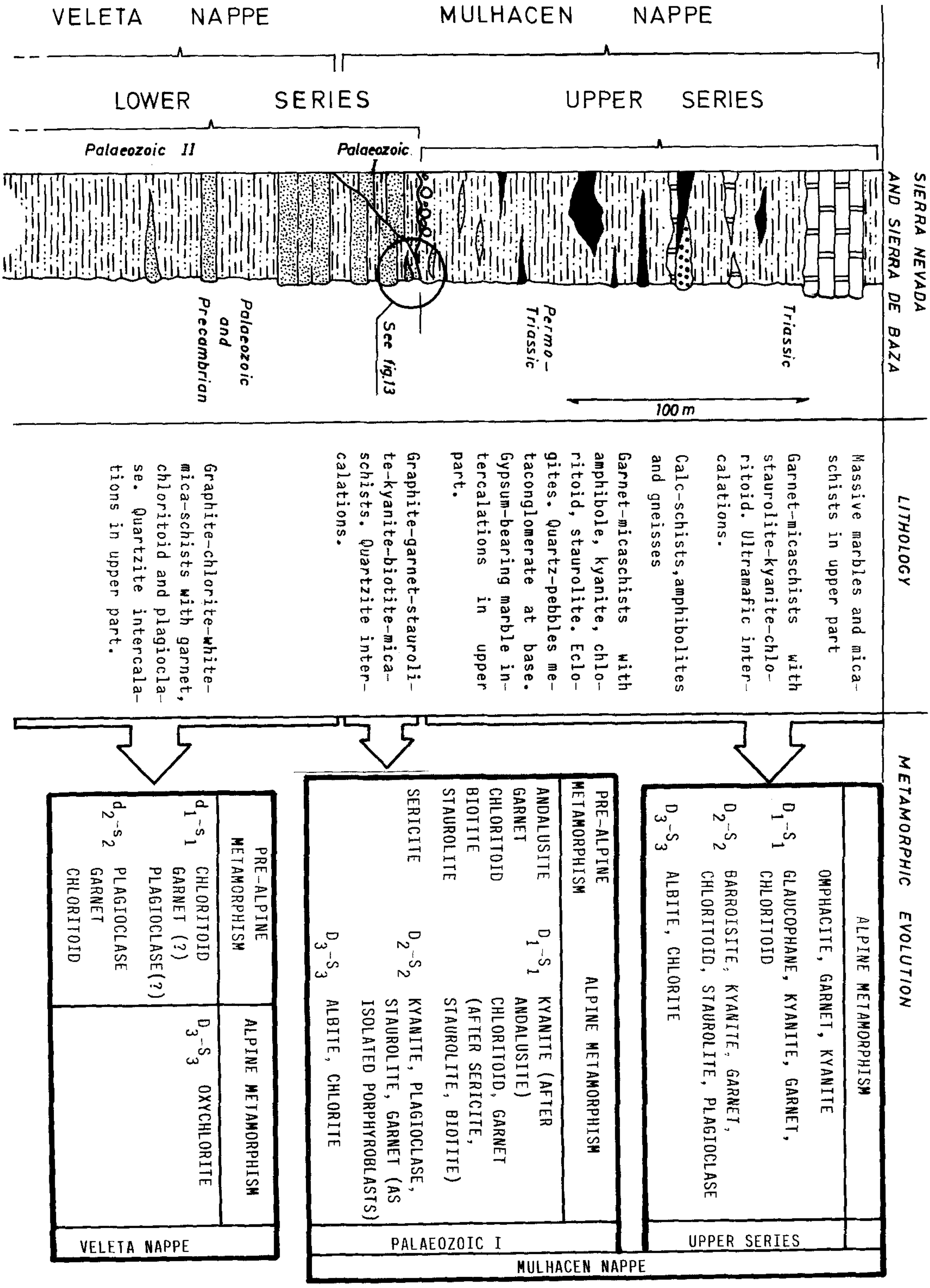

Fig. 2. Tectonic and stratigraphic relationships and metamorphic evolution of the central part of the Nevado Filábride complex.

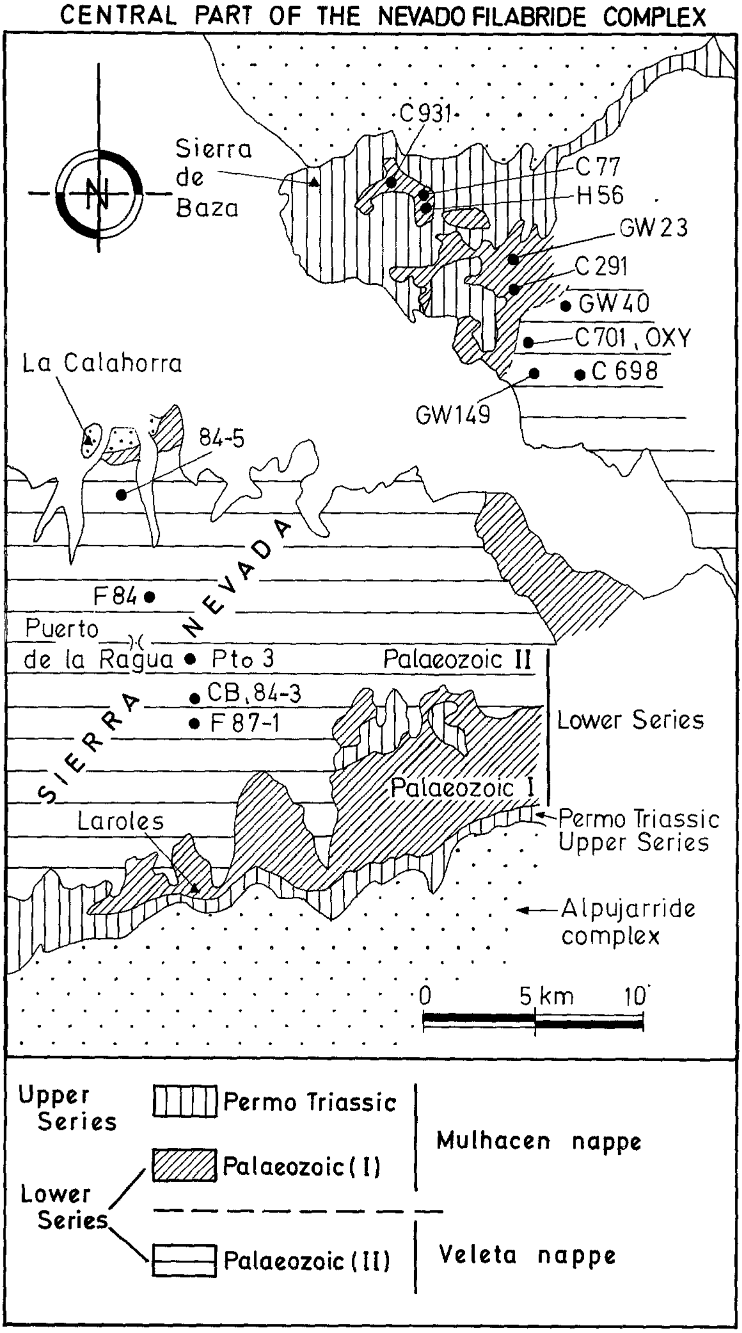

Fig. 3. Samples localities and tectonic subdivision in the central part of the Nevado-Filábride complex.

2. Sample areas and methods

The observations on which the conclusions are based were made in several traverses across the NFC, in the Sierra Nevada, the Sierra de los Filabres and also in the Sierra Alhamilla (SE of the Sierra de los Filabres, see Fig. 1). The similarities among the rocks of the Veleta nappe from different traverses is remarkable, but the best outcrops and development of different lithologies and microstructures occur in the area shown in Fig. 3; the analyzed samples were selected in this area.

Fig. 3 shows the sample localities in a simplified geological map of the central part of the NFC with the Lower Series (Palaeozoic I and Veleta nappe) and the Upper Series (Permo-Triassic rocks) compiled from Geological Maps of Instituto Geológico y Minero de España and GOMEZ-PUGNAIRE (1979a).

Samples C77, C295, C698, C701, C931, Oxy, H56, GW23, GW40 and GW149 come from a sequence of quartzites with a few thin layers of carbonates and metapelites from the Sierra de Baza. Samples 84-3, 84-5, CB, F84, F87-1 and Pto3 come from the Sierra Nevada from a thicker sequence of similar characteristics. Locally the rocks are highly tectonized. Mylonitic rocks are very abundant and different fault systems and shear zones oblique to the main schistosity are frequent.

Minerals were analyzed for Si, Ti, Al, Mg, Mn, Ca, K, Na, F by electron microprobe with the Camebax WDS system at TU Berlin and an electronic microscope (Atospec/SEM) with a spectrometer ORTEC EDS at Istituto di Mineralogia at Padua using natural minerals as standards. In addition, wet chemical analyses on a mineral concentrate of chlorite from one sample were carried out. X-ray data were obtained with a Philips diffractometer (Cu Kα-radiation, graphite monochromator).

3. Petrography and chemical data

The investigated rocks from the Veleta nappe are dark, fine-grained micaschists, with black crystals of either chloritoid or plagioclase and mm-size brown-red cross-cutting chlorites. The mineral assemblage of the analyzed rocks is: quartz, white mica, green and brown chlorites, chloritoid, garnet, plagioclase, graphite, ilmenite, zircon, tourmaline, apatite. Garnet coexists with either plagioclase or chloritoid but plagioclase rarely occurs in the same chloritoid-bearing rocks. Plagioclase, garnet and chloritoid normally occur concentrated in different layers.

Deformational history

At least three generations of microstructures can be distinguished in the Lower Series. The main deformational event (D_2) produced isoclinal folds and a penetrative schistosity (S_2) subparallel to the axial planes of these folds and to the lithological contact. This fabric is developed on previously deformed rocks (D_1), and the older schistosity (S_1) is only visible very locally and generally within the large porphyroblasts. The third deformational phase (D_3) produces asymmetrical folds and, locally, crenulation foliation (S_3), developed with different intensity.

The relationship between blastesis and deformation.

Garnet

Garnet porphyroblasts in the Veleta nappe show an undeformed, folded or sigmoidal helicitic inclusion pattern of graphite and quartz (Fig. 4a), sometimes with an inclusion-free rim. Other garnets have no distinct inclusion pattern or occur as small euhedral crystals included also in plagioclase (Fig. 4e). S_1 and S_2 are mostly continuous. Therefore the garnet must have formed during or after S_2. Some of the garnet crystals have also a S_1, apparently rotated with deformational pressure shadows and flattening of the main schistosity. They were interpreted by GOMEZ-PUGNAIRE (1979a) and VELILLA (1983) as syn- to post-S_1, but could be syn-D_2 (see BELL et al. 1986 for a reinterpretation of the timing of the porphyroblast growth) and we conclude that the most important stage of porphyroblast growth is syn- to post-S_2.

The chemical data of the garnets are given in the section »Metamorphic evolution«.

Plagioclase

Albite occurs as rounded or almond-like crystals and also of irregular shape where they grow mimetically over the main schistosity S_2 (Fig. 4d). Undeformed, sigmoidal (Fig. 4e) or folded graphite and quartz inclusion patterns (S_1, Fig. 4d) appear within plagioclase porphyroblasts. In many cases S_1 and S_2 are continuous, but in the crystals which grew in the early stage of the development of S_2 or which show S_3 crenulation (Fig. 4f) they are discontinuous. These fabrics indicate a fast growth rate for the syntectonic porphyroblasts with respect to the schistosity, as described by EECKHOUT & KONERT (1983).

In many cases the albite crystals show one (or several) inclusion-free rim(s) around a graphite-rich core (Fig. 5a, b); the zones, however, have the same optical orientation and identical composition (albite). Oligoclase rims are occasionally developed around the albite cores but this chemical zonation does not necessarily coincide with that defined by the inclusions. The oligoclase rims do not seem to be related to any tectonic process, as previously interpreted at other sites in the NFC (in the Sierra Alhamilla, EECKHOUT & KONERT 1983).

The plagioclase growth was more or less continuous during the development of the S_2 schistosity and after the D_2-phase ended.

Chloritoid

This mineral is present as large (2 – 3 mm) euhedral porphyroblasts (Fig. 4b, c) and in smaller crystals in the matrix (Fig. 4b). All the crystals (large and small ones) are rich in inclusions of graphite and ilmenite, and the

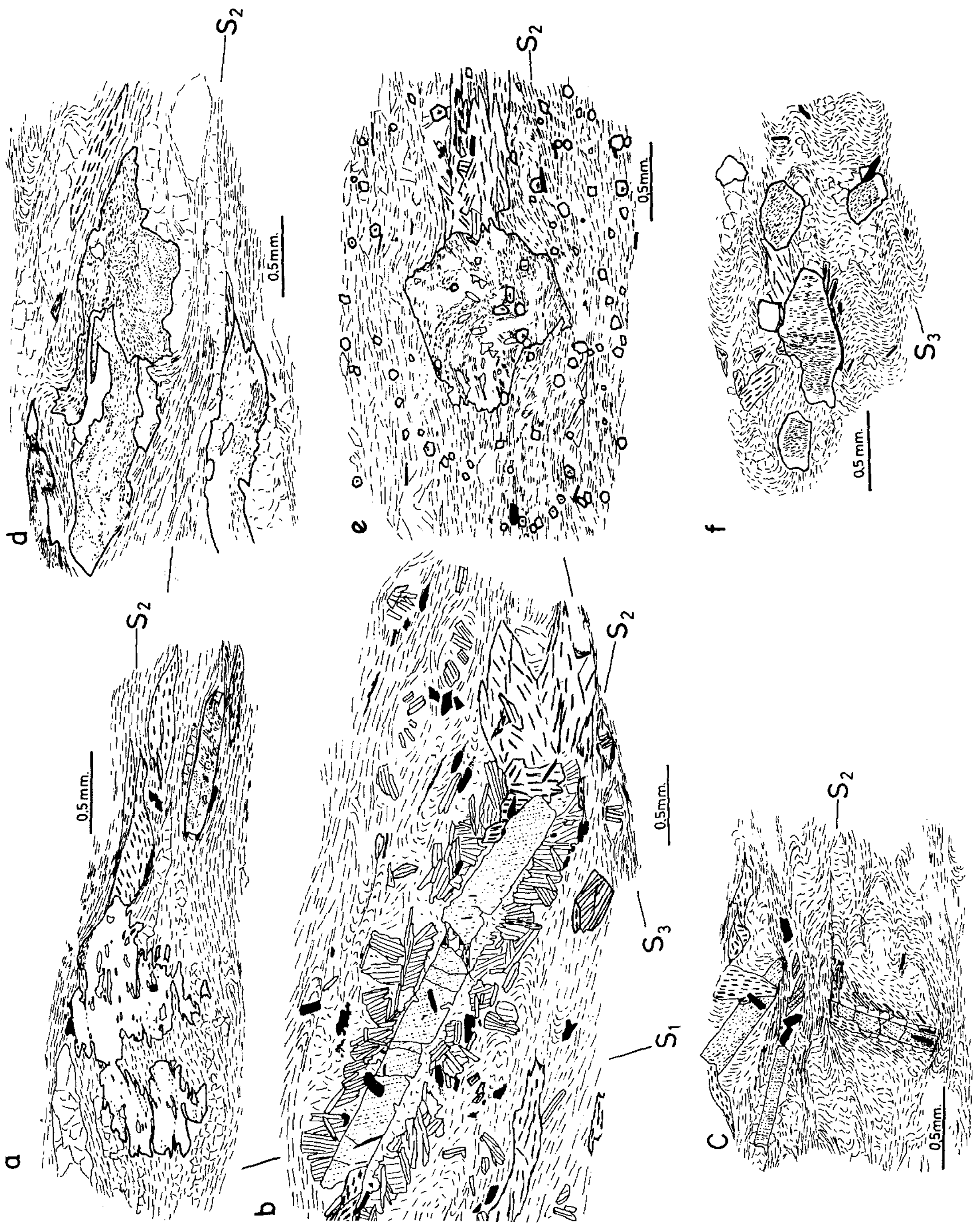

Fig. 4 (a–f). Drawing of porphyroblasts from graphite-quartz-white mica-ilmenite-schists, Veleta nappe. a) Garnet (left) with S-inclusion pattern, chlorite (thick dashed) and chloritoid (slightly folded and irregular inclusion pattern), quartz and white mica (sample F87 – 1). b) Cracked chloritoid with undeformed inclusion pattern, surrounded by small chloritoid crystals (thin dashed) and partly replaced by oxychlorite (thick dashed) (sample Pto3B). c) Irregular distribution of chloritoid porphyroblasts, internal inclusion pattern partly continuous, partly discontinuous (sample Pto 3A). d) Albite blast with irregular shape growing parallel to S_2. Inclusion pattern of an early crenulation is mostly continuous (sample GW23). e) S-shaped inclusion pattern in albite with small garnets, right of the blast is chlorite (sample GW149). f) Albite blasts in a mica rich matrix, affected by S_3 crenulation (sample C698).

large porphyroblasts have an undeformed or folded inclusion pattern (S_1) and occasionally a narrow inclusion-free rim. Sometimes the matrix chloritoid is concentrated in the pressure shadows around them (Fig. 4b), oriented at an angle of about 40° to the main axis of the porphyroblast. The long axes of the porphyroblasts are randomly oriented, but often at a high angle to the main schistosity S_2 (Fig. 4c). The matrix chloritoid is also randomly oriented, sometimes perpendicular to S_2. Fig. 6 shows that there is no difference in the chemical composition of these chloritoids, either between different samples or between core and rim, or between large and small crystals (MgO = 1.6 to 1.8 wt%; FeO = 24.0 to 25 wt%: MnO = 0.5 wt%).

The porphyroblasts show a rigid behaviour in the last D_3 deformational event, which produced fractures filled by quartz and chlorite (Fig. 4b). Chlorite/oxychlorite also forms as a decomposition product of chloritoid (e. g. at the end of the large crystal in Fig. 4b, c).

Inclusion trails are almost always discontinuous, in contrast to plagioclase. Nevertheless, all the chloritoid textures in these rocks can be interpreted as being syn- to post-S_2. PRIOR (1987) and BELL et al. (1986) have shown that a discontinuous inclusion pattern is no proof of a pre-S_2 growth, but that it indicates an overgrown early crenulation. PUGA & DIAZ DE FEDERICO (1976a) and VISSERS (1981) have argued that the chloritoid textures are an indication of the polymetamorphic history of the Veleta nappe. They have attributed an Alpine age to the main deformational event and assumed a pre-D_1, character for the chloritoid with pre-Alpine inclusion patterns.

We conclude that the chloritoid in the Veleta nappe grew in the early stage of the pre-Alpine deformation D_2, overgrowing a S_1 schistosity, which is occasionally crenulated, and continued to grow until the end of D_2 (for a comparison of the different interpretations of porphyroblast textures see Figs. 5, 6, 7 and 8 in PUGA & DIAZ DE FEDERICO, 1976a, Fig. 53 in VISSERS, 1981 and Fig. 5a in PRIOR, 1987). We attribute more or less the same age to both, the matrix and the porphyroblastic chloritoid (though the matrix chloritoid may have formed slightly later), as both show inclusions of graphite and ilmenite, have similar textures with regard to S_2 and also identical composition (Fig. 6). This is at least a good indication, that metamorphic conditions were similar for D_1 to D_2 deformational phases.

Chlorites

Both green and brown chlorite types occur in the same crystals, either as parallel intergrowths or, in the case of yellow-brown chlorite, forming the external part of the grains (Fig. 7a). Both minerals are always in optical continuity. In some cases, the green variety predominates whereas in others only the brown is present, sometimes with a few relics of the former mineral, with all intermediate stages. The optical properties (birefringence, pleochroism and mottled extinction) of the brown chlorite are similar to those of biotite, which is typical for oxychlorite (as described e.g. by CHATTERJEE, 1966 in the schistes lustrés of the Italian Alps and FRANCESCHELLI et al., 1986 in Sardinia).

Both varieties occur in aggregates as well as in isolated crystals growing across the main foliation (S_2, see Fig. 7b). They rarely occur in the mica-quartz matrix. The aggregates are sometimes orientated along the schistosity S_2 with a decussate texture and/or cleavage of the crystals oblique to it. Whenever later microfolding is observed, consequently, they are older than the last deformation (D_3). The two chlorites are also found in aggregates resulting from the alteration of chloritoid (Fig. 7b) and sometimes garnet. These textural characteristics of the chlorites indicate post-S_2 growth.

X-ray diffraction powder data demonstrate that the brown chlorite has a 14 Å structure. Additional diffuse reflections were observed at 16 Å and 8 Å. Representative microprobe analyses are listed in Table I. In Fig. 8 (a, b, c) and Fig. 9 all data are shown. The total of the microprobe analyses varies around 88 wt%. SiO_2 contents are highly variable (Fig. 8a), between 22 and 32 wt% for brown and 23.5 to 29.5 wt% for green chlorite. Al_2O_3 is less variable (8 – 14 wt%) with a slight negative correlation for SiO_2 in the green chlorite.

Similarly there is only a slight negative correlation between the total FeO and MgO contents (Fig. 8b). Almost all the analyses show a rather high K_2O and CaO content (Fig. 8c). These impurities are explained by the presence of small amounts of other layer silicates, interstratified with the chlorite mineral. These may be muscovite as described by FRANCESCHELLI et al. (1986), or vermiculite/smectite minerals as indicated by the X-ray data.

The green chlorites are more restricted in their chemical composition than the brown ones, but there are no systematic differences in their chemical composition. There is a slight tendency that in coexisting green-brown chlorites the amount of Al_2O_3 and the Mg/(Mg+Fe) ratio are a little lower in the brown chlorite than in the green one, but the overall variation is much larger and does not allow distinction between the two types. A wet chemical analysis of a mineral concentrate of the brown chlorite is similar to the microprobe analyses; the H_2O-content is 12.6 wt%

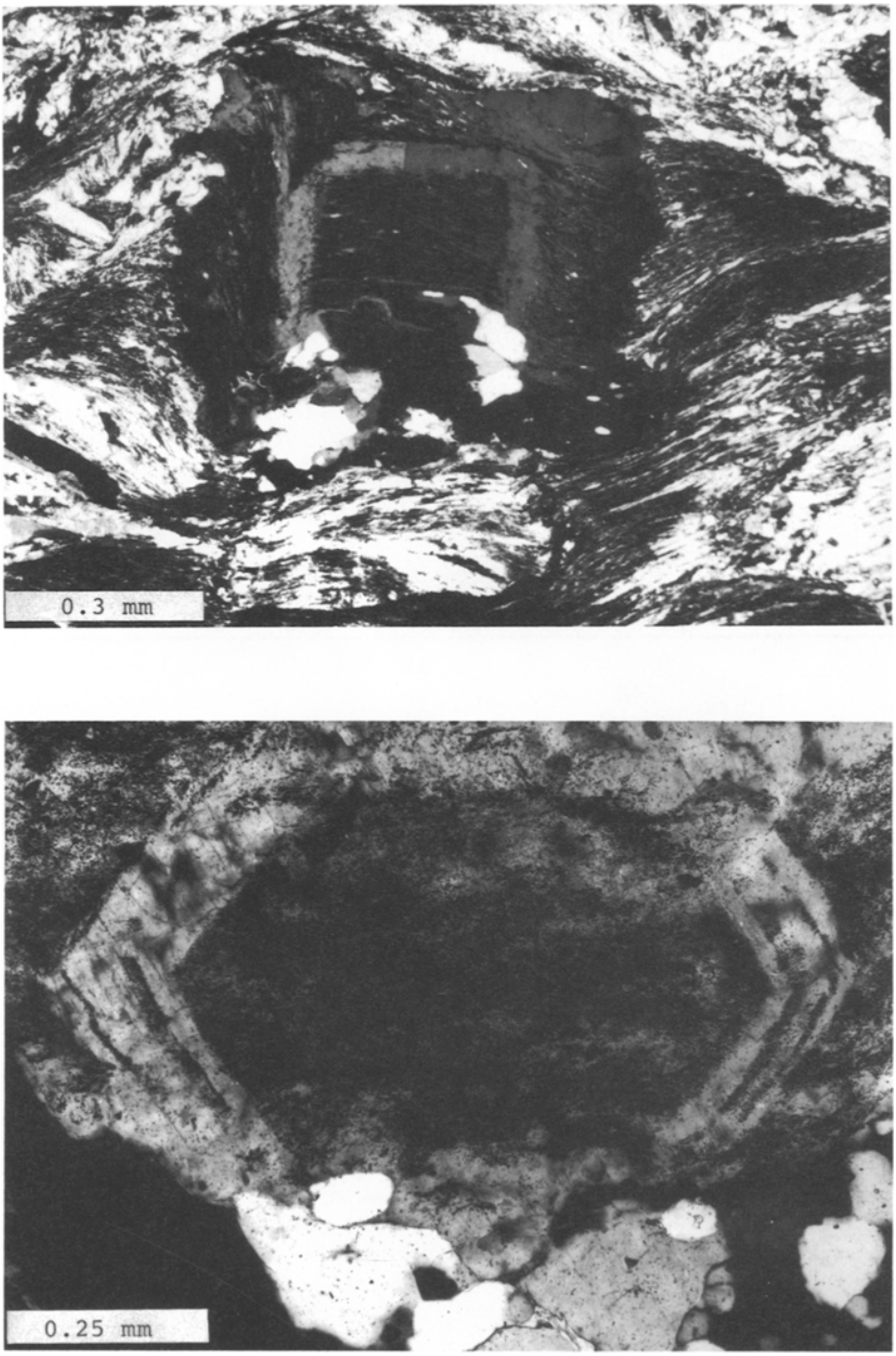

Fig. 5 (a, b). Photomicrographs (crossed nicols) of albite porphyroblasts with interrupted inclusion patterns of graphite and white mica (5a, sample GW 40) and graphite (5b, sample GW 67) in a matrix of quartz — white mica — chlorite — graphite.

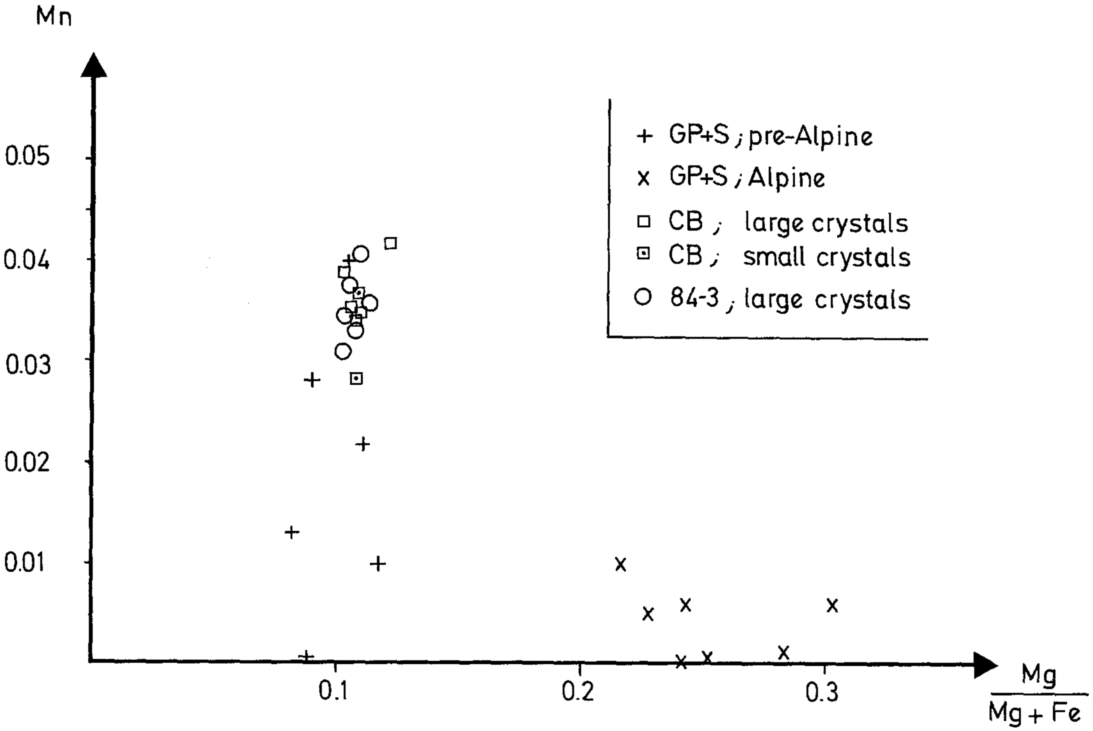

Fig. 6. Chemical composition of chloritoid (cation coefficients), compared with the data given by GOMEZ-PUGNAIRE & SASSI (1983; GP + S).

and Fe_2O_3 (19.7 wt%) is higher than FeO (12.8 wt%), see Table I.

In order to compare the cation proportions of the minerals, the formulae (assuming a chlorite structure and all Fe as Fe^{2+}) were first calculated on the basis of 20 cations and then also separately on the basis of 28 oxygens. The results of both calculations are essentially similar and are represented (for 20 cations) in Table I and in a triangular diagram Si-Al-(Fe+Mg) in Fig. 9, which shows the deviations from the pure chlorite endmember composition. In addition to the presence of K_2O and CaO, elements which are not compatible with a chlorite structure, the calculated formulae on the basis of 28 oxygens have significantly less than 12 octahedral cations per formula unit; e.g. the formula calculated from the wet chemical analysis has only 9.9 octahedral cations.

Scanning electron microscopy investigations on crystals from the mineral concentrate (analysis 9 in Table I) did not show any structures which could be interpreted as mixtures of minerals (resolution 0.25 μm), only a few prismatic crystals of Fe-rich minerals were identified.

It is concluded that the analyses represent mixed analyses of mainly chlorite with small amounts of other layer silicates, on a scale below the resolution of the microprobe beam. The high birefingence and brown colour of the chlorite results from the high amount of Fe^{3+}, and the mineral may be classified as oxydized chlorite (CHATTERJEE, 1966; thuringite according to HEY, 1954).

White micas are very fine grained and the microprobe analyses indicate potassic mica with substitution of (Mg, Fe) + Si for Al and a silicon content of 6.5 per formula unit. X-ray data of mineral separates indicate small amounts of paragonite together with phengite.

Ilmenite occurs in the matrix as tabular crystals (frequently altered into Fe-oxides/hydroxides) and as inclusions in chloritoid. The two types show no difference in composition, are homogeneous and essentially pure $FeTiO_3$ with up to 1.2 wt% MnO and 0.1 wt% MgO.

4. Metamorphic evolution

In order to compare the metamorphic evolution among the different series of the NFC we describe the Alpine metamorphic evolution in the Upper Series (Permo-Triassic rocks) and the pre-Alpine metamorphism in the Palaeozoic I.

	1	2	3	4	5	6	7	8		9		9A	9B
Sample	C77	OXY	931	F84	C77	OXY	931	F84		SF1			
SiO_2	27.76	25.14	23.99	23.50	27.60	25.52	25.94	22.68	SiO_2	27.33	Si	5.646	6.368
TiO_2	0.05	0.11	0.08	0.08	0.12	0.13	-	0.10	TiO_2	0.44	Al^{IV}	2.354	1.632
Al_2O_3	19.33	20.37	22.64	23.31	28.81	19.96	19.37	20.17	Al_2O_3	19.34			
FeO_{tot}	30.69	29.76	29.37	31.69	29.95	29.31	31.61	38.17	Fe_2O_3	19.72	Al^{VI}	2.355	3.679
MgO	9.50	12.29	12.02	9.90	10.61	13.03	10.12	6.42	FeO	12.77	Fe^{3+}	3.065	3.458
MnO	0.04	0.01	0.08	0.18	0.22	0.04	-	0.07	MgO	6.51	Fe^{2+}	2.206	2.488
CaO	0.29	0.22	0.03	0.02	0.26	-	0.30	0.39	MnO	0.19	Mg	2.003	2.260
K_2O	0.35	0.20	0.02	0.01	0.51	0.02	0.78	0.31	CaO	0.33	Mn	0.211	0.037
									Na_2O	0.13	Ti	0.068	0.077
Total	88.10	88.10	88.10	88.69	88.08	88.21	88.12	88.31	K_2O	0.45	Σoct	9.908	11.999
									H_2O	12.57			
Si	6.088	5.410	5.139	5.082	6.011	5.481	5.663	5.103			H	17.336	
Al^{IV}	1.912	2.590	2.861	2.918	1.989	2.519	2.337	2.897	Total	99.78			
Al^{VI}	3.082	2.577	2.856	3.024	2.839	2.534	2.648	2.452					
Ti	0.008	0.018	0.013	0.130	0.020	0.021	-	0.017					
Fe	5.629	5.356	5.262	5.732	5.455	5.265	5.772	7.182					
Mg	3.105	3.942	3.838	3.191	3.444	4.168	3.293	2.153					
Mn	0.007	0.002	0.015	0.033	0.041	0.007	-	0.013					
Ca	0.068	0.051	0.007	0.005	0.061	-	0.070	0.094					
K	0.098	0.055	0.005	0.003	0.142	0.005	0.217	0.089					

Table 1. Chemical analyses of chlorites, (1) to (4): green chlorite, microprobe analyses; (5) to (8): brown chlorites, microprobe analyses, structural formulae calculated concentrate; (9A): structural formula calculated on the basis of 36 oxygens; (9B): structural formula calculated on the basis of 20 cations; ignoring the alkalies and CaO.

Alpine metamorphism

The Alpine metamorphism developed in three main events (Fig. 2):

1) The first metamorphic event at high pressure and relatively low temperature is pre- and syntectonic to the first deformational event (D_1). The metamorphic conditions can be deduced from the assemblages developed fundamentally in the metamorphosed basic rocks. Glaucophane-kyanite-bearing eclogites developed, indicating at least 12.5 kb and 500 °C for the P-peak of the metamorphism (see GOMEZ-PUGNAIRE & FERNANDEZ-SOLER, 1987). Pyrope-rich garnet, kyanite and chloritoid grew in metapelites during this event (NIJHUIS 1964, PUGA & DIAZ DE FEDERICO, 1976b, GOMEZ-PUGNAIRE, 1979a; VISSERS, 1981; MARTINEZ-MARTINEZ, 1984).

2) The second Alpine metamorphic event, syn- to postectonic with respect to the second deformational phase (D_2), is characterized by an intermediate pressure regime. Blue-green amphibole, albite and almandine-rich garnet occur in metabasites, and kyanite, chloritoid, staurolite, garnet, albite and oligoclase in metapelites. The peak of this event (GOMEZ-PUGNAIRE, 1979b) attained 6.5 kb and 610 °C.

3) The last metamorphic event (D_3) is related to the uplift and led to the development of (oxy)chlorite, quartz, albite and white micas under greenschist facies conditions.

Pre-Alpine metamorphism

Fig. 2 shows that the Upper Series (Permo-Triassic rocks) lies either on the Palaeozoic I or on the Veleta nappe of the Lower Series. The rocks attributed to the Palaeozoic I show in many cases relics of a metamorphic process prior to the formation of the main mineral assemblage. These polymetamorphic rocks were studied in the Sierra Nevada (PUGA & DIAZ DE FEDERICO, 1976a) and in the Sierra de los Filabres (GOMEZ-PUGNAIRE & SASSI, 1983; MARTINEZ-MARTINEZ, 1984).

The assemblage of the early metamorphism (andalusite, staurolite, almandine-rich garnet, Fe-rich chloritoid and biotite) is typical for low-pressure conditions, very different from those recorded in the Upper Series (Permo-Triassic rocks) during the Alpine metamorphism. These rocks have also been metamorphosed under Alpine metamorphism (see references above). This overprint produced an identical assemblage to that of the Upper Series: kyanite (from andalusite), pyrope-rich garnet (from biotite, staurolite and as rims around older almandine-rich garnet porphyroblasts) and Mg-rich small crystals of chloritoid (GOMEZ-PUGNAIRE & SASSI, 1983). In the rocks of the Palaeozoic I, which do not show the low pressure metamorphic relics, the Alpine metamorphism produced kyanite, chloritoid, staurolite and pyrope-rich garnet in isolated porphyroblasts (and not as pseudomorphs), which grew during the first and second Alpine metamorphic events (NIJHUIS, 1964, GOMEZ-PUGNAIRE, 1979a).

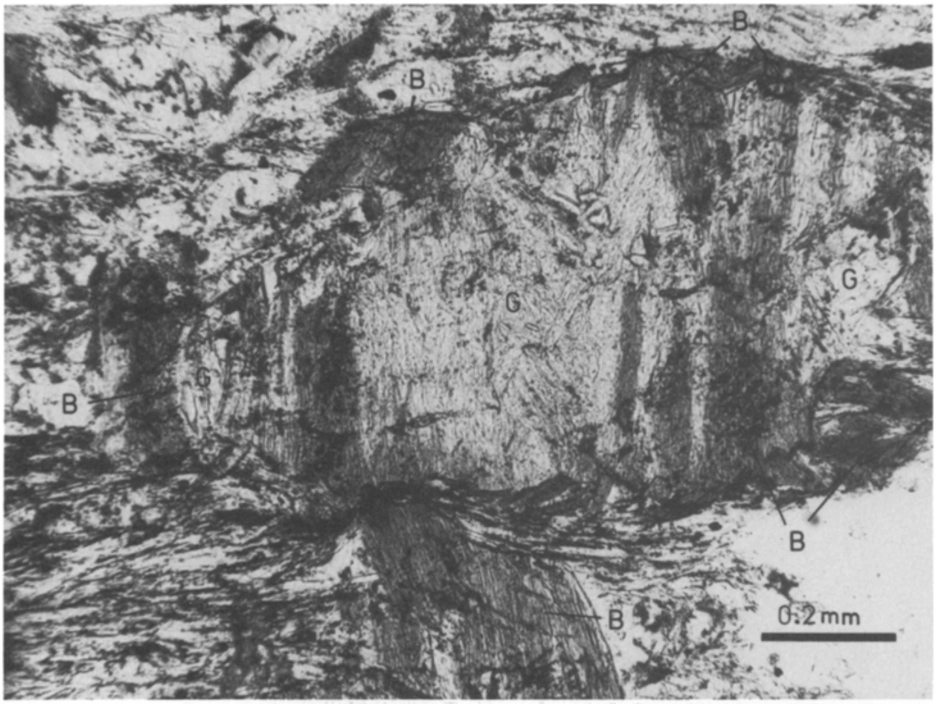

Fig. 7a. Photomicrograph of cross-cutting chlorite in a matrix of fine-grained white mica, graphite and quartz. The green chlorite (G) is partly altered into brown oxychlorite (B); plane polarized light.

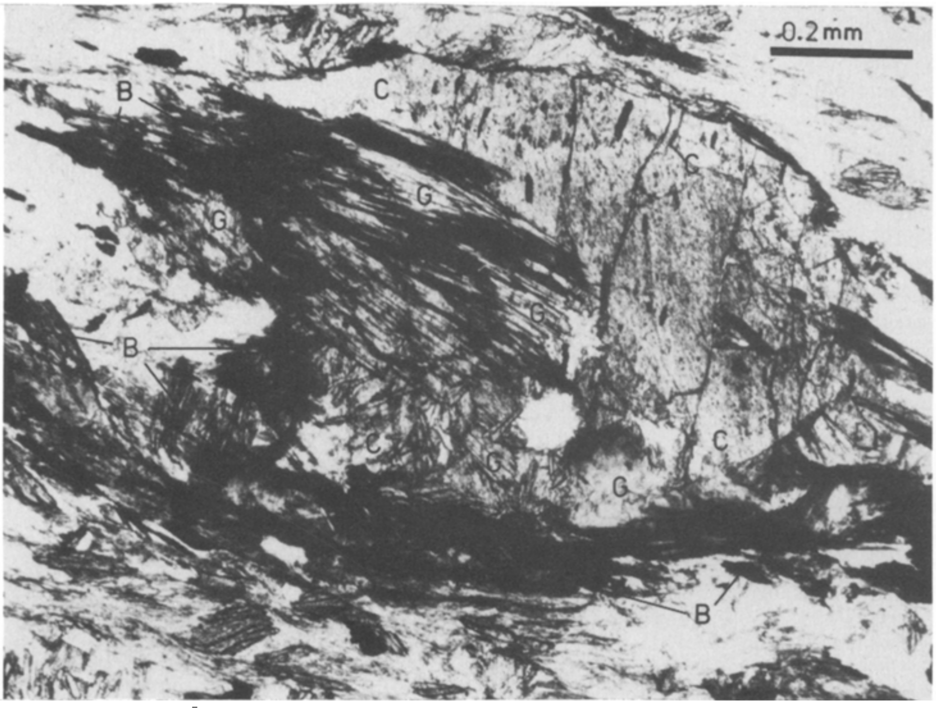

Fig. 7b. Photomicrograph of the chloritoid (C)-chlorite assemblage, in a matrix of white mica, quartz, graphite. The brown chlorite (B) intergrown with green chlorite (G) appears black. Opaque inclusions in chloritoid are ilmenite; plane polarized light.

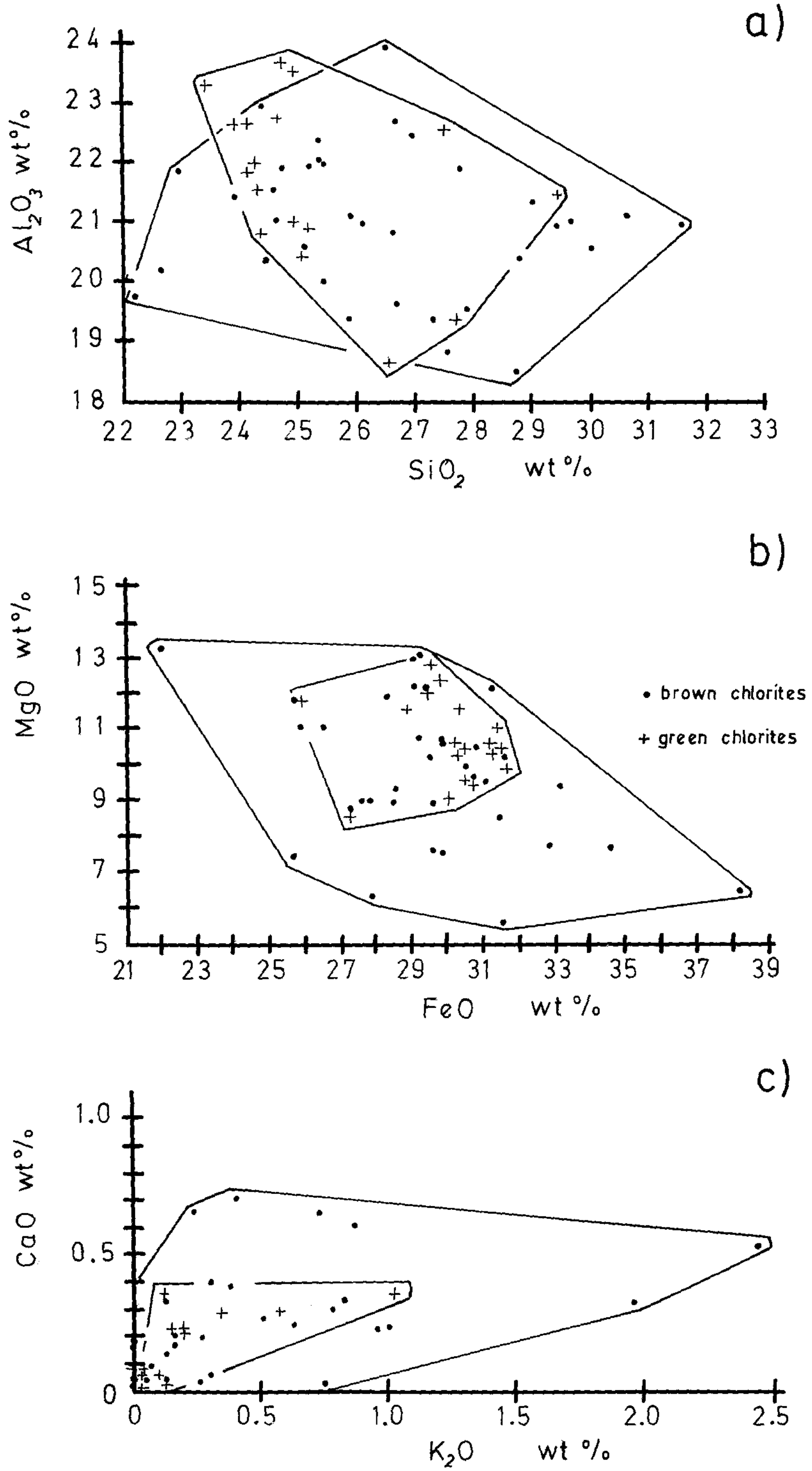

Fig. 8 (a, b, c). Chemical composition of green (+) and brown chlorite (O) minerals; note that the compositional field of green chlorite is more restricted than that of the brown chlorite.

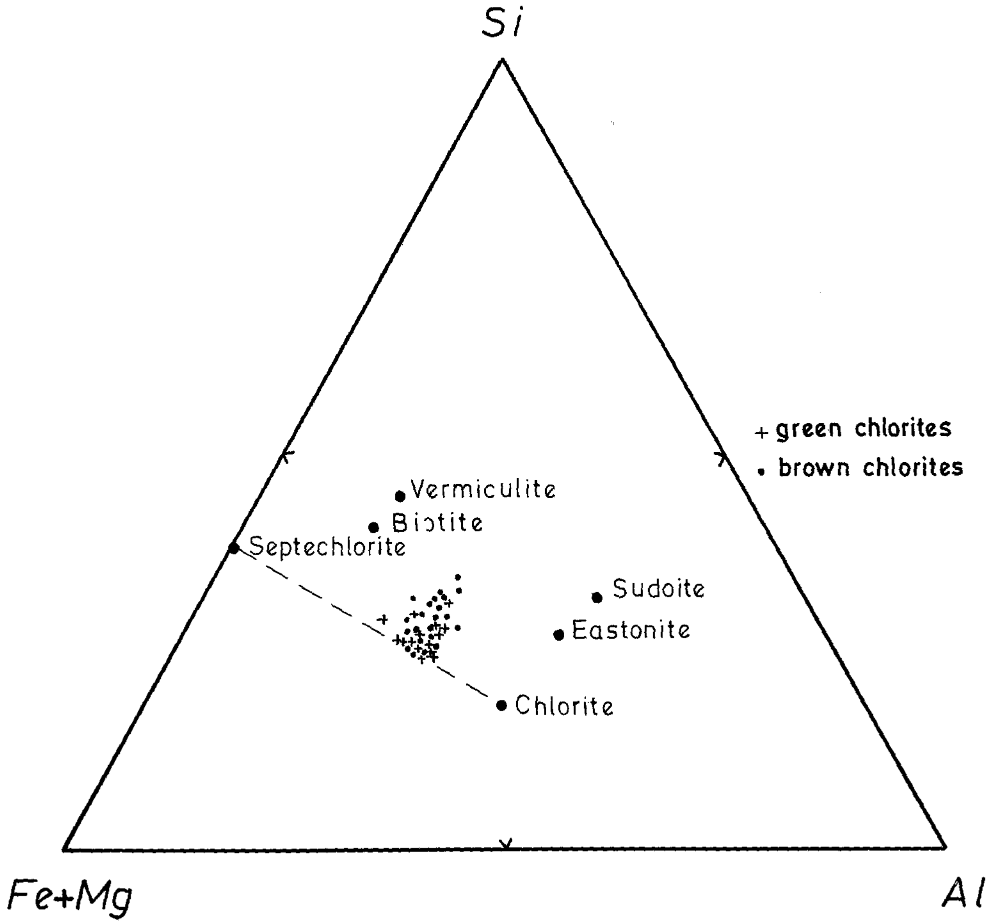

Fig. 9. Chemical composition of green (+) and brown (●) chlorite minerals in terms of cations Si-(Fe+Mg)-Al, calculated on the basis of 20 cations per formula unit, compared with the ideal composition of various layer silicates.

Metamorphic evolution of the Veleta nappe

In this section we describe the metamorphic evolution of the Veleta nappe and compare it to both, Alpine and pre-Alpine metamorphism in the Palaeozoic I.

The graphite schists from the Veleta nappe in the NFC show a monotonous mineralogical composition. The phase relations are represented in a conventional AFM-diagram in Fig. 10a. It is a high-variance assemblage which permits only an estimation of temperatures between 400 °C and 500 °C. The pressures are also uncertain, but in the whole Veleta nappe there are no indications of high-pressure conditions as in the eclogitized metabasites in the Upper Series.

Biotite is generally absent, as well as staurolite and kyanite, and the typical Fe-Mg-mineral is chlorite, which is widespread. NIJHUIS (1964), VISSERS (1981) and MARTINEZ-MARTINEZ (1984) additionally noted that biotite and stilpnomelane might be present but only in small amounts (probably in rocks of suitable bulk chemistry).

Phase relations of graphite schists from Palaeozoic I are shown in Fig. 10b. Their pre-Alpine assemblages are characterized by the presence of biotite, staurolite and andalusite, and their alpine assemblages by Mg-rich chloritoid and kyanite.

VELILLA (1983) investigated the graphite schists of the Lower Series in the NFC in the Sierra Nevada with regard to their major chemical composition (Fig. 11) and the data show that they are very similar. It is therefore possible to compare mineral chemistry and especially zoning in minerals from the Lower Series.

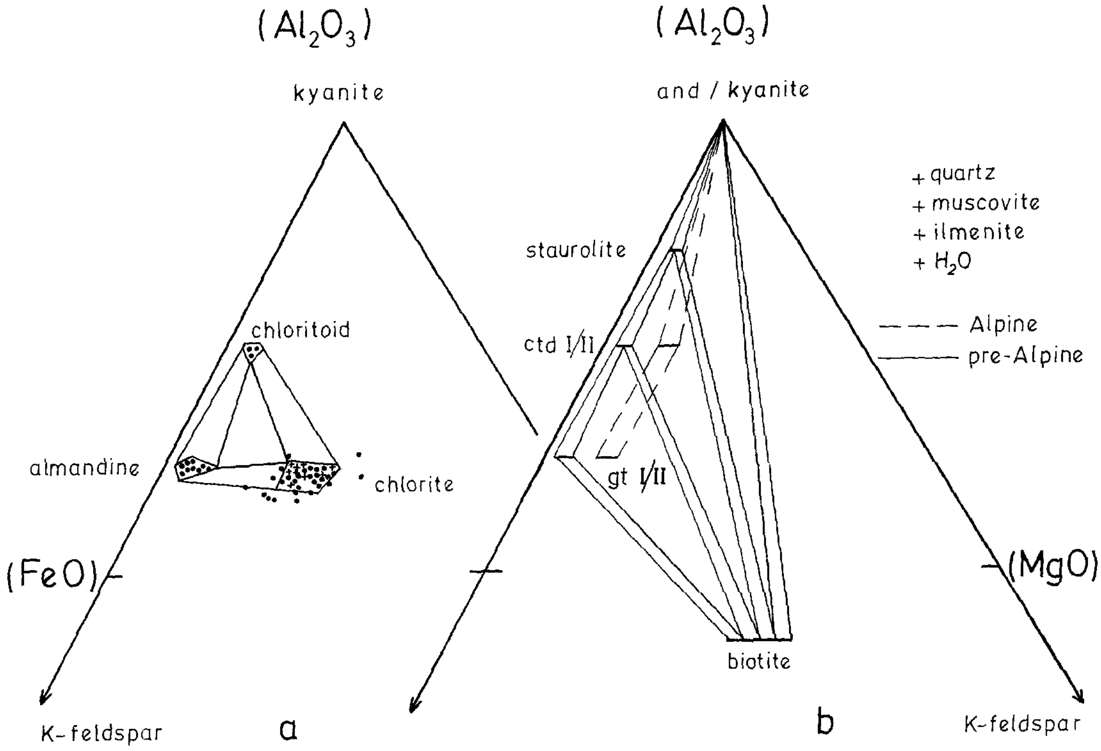

Fig. 10 (a, b). Conventional A-F-M diagram with a) assemblages of the Veleta nappe. b) Palaeozoic I (data from GOMEZ-PUGNAIRE & SASSI, 1983). Polymetamorphism for Palaeozoic I is documented by different generations of minerals, whereas polymetamorphism of the Veleta nappe is not proven (see text).

Fig. 12 shows the zoning of garnets from the Veleta nappe in terms of cations Ca-Fe^{2+}-Mg (12a) and Mn-Fe^{2+}-Mg (12b). Their zoning is continuous, with high Ca- and Mn-contents in the core and increasing Mg in the rim. Pre-Alpine garnets from Palaeozoic I (data from GOMEZ-PUGNAIRE & SASSI, 1983, shown as dashed areas) have a Ca-poor core and Ca-poor alpine rims (stippled areas). The inclusions of garnets in pre-Alpine chloritoid are similar in composition as the garnet cores from the Veleta nappe.

Garnets analyzed by VELILLA (1983) from rocks of Palaeozoic I have the same composition as those described in this paper from the Veleta nappe (Palaeozoic II), but they also have the Ca-poor rim, typical for the polymetamorphic garnets.

Fig. 13 shows an example for the zoning pattern in a profile of a garnet from the Veleta nappe. Retrograde alteration into chlorite, phengite and quartz influences the garnet chemistry, and there is no clear indication for a break in the development of the zoning. It is compatible with a single metamorphic event, and all irregularities can be explained by discontinuous reactions during growth, by different adjacent minerals and by different retrograde reequilibration.

The textural features of the chloritoid (see above) prove that this mineral is a product of the same metamorphism which produced the S$_1$ and S$_2$ schistosities. In this sense we agree with EECKHOUT & KONERT (1983) and not with PUGA & DIAZ DE FEDERICO (1976a) and VISSERS (1981), who interpreted chloritoid as older than the other minerals or structures in these rocks and, therefore, as an indication of the polymetamorphic character. The chemical composition of the chloritoid shows that both large (post-S$_1$ and syn-S$_2$) porphyroblasts and small (syn- and post-S$_2$) crystals are identical in composition (see Fig. 6). Therefore, a polymetamorphic evolution cannot be proven. Also a comparison between these chloritoids and those occurring in the polymetamorphic rocks of the Palaeozoic I indicates that the chloritoid in the Veleta nappe is similar to that produced during the pre-Alpine metamorphism (GOMEZ-PUGNAIRE & SASSI, 1983, Figs. 6 & 11b). On the other hand, they are very different from those crystallized later during the

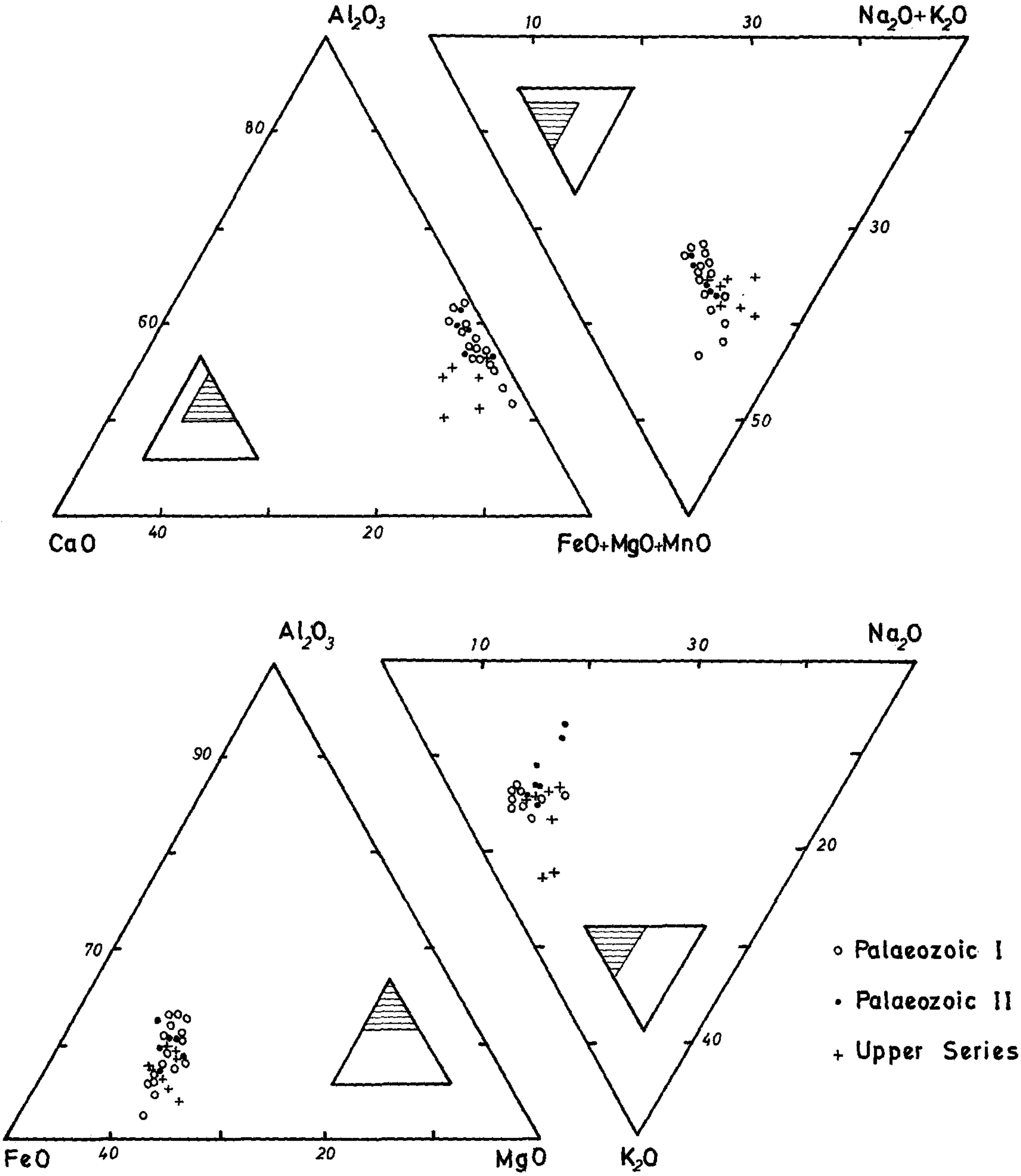

Fig. 11. Bulk-rock chemical composition of metapelites from the Sierra Nevada. Data taken from VELILLA (1983).

Alpine metamorphism. They are very rich in Mg, indicating high pressure conditions (CHOPIN & SCHREYER, 1983).

The metamorphic textures of the plagioclase indicate simultaneous growth with the chloritoid and garnet, mostly during and post-D_2. The occurrence of post-S_2 rims of oligoclase around cores of albite indicates an increase in temperature. Nevertheless, this increase is not necessarily related to a specific tectonic environment such as a ductile shear zone as described by EECKHOUT & KONERT (1983). In the whole of the NFC, rims of oligoclase occur in rocks not obviously affected by shear zones.

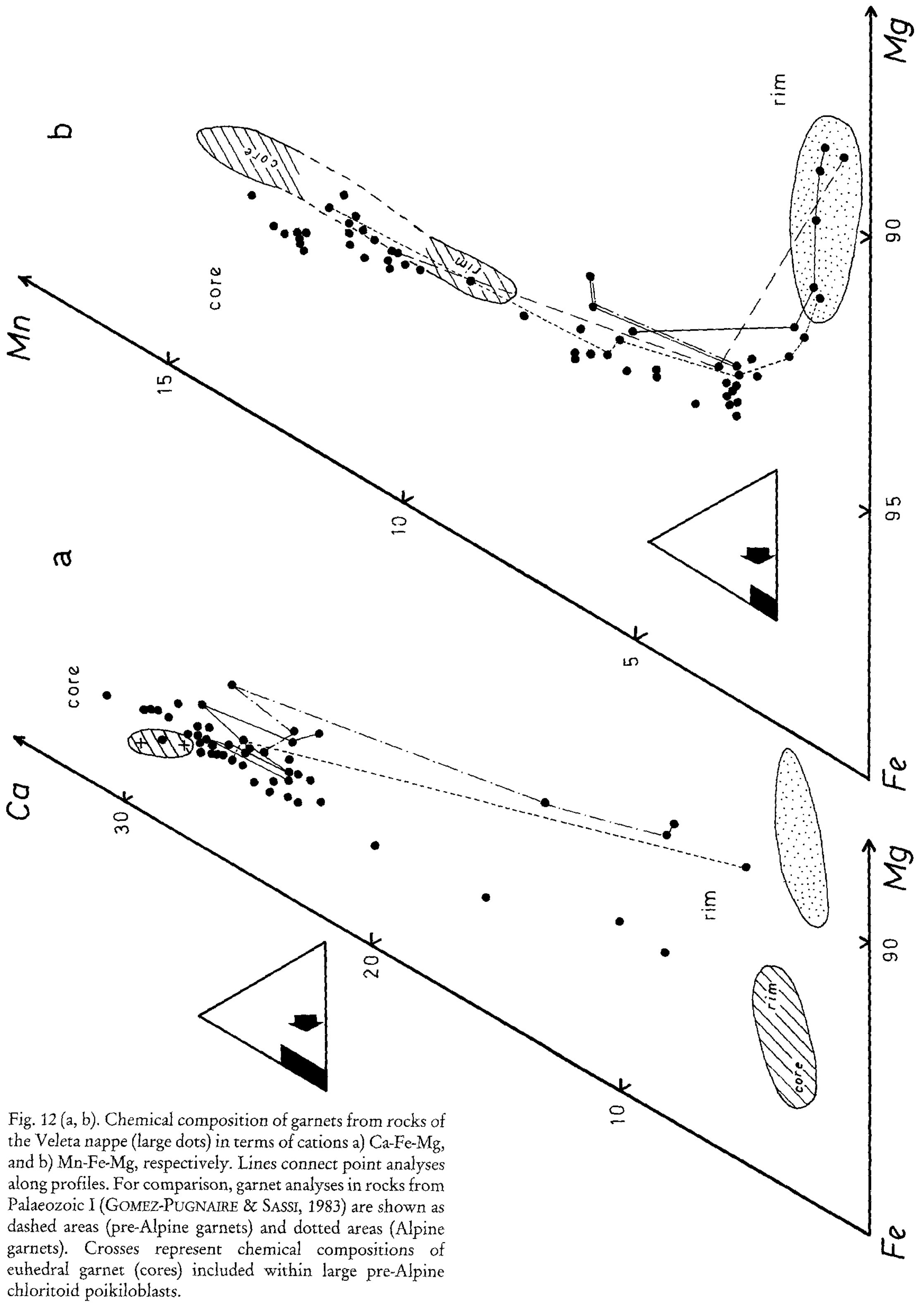

Fig. 12 (a, b). Chemical composition of garnets from rocks of the Veleta nappe (large dots) in terms of cations a) Ca-Fe-Mg, and b) Mn-Fe-Mg, respectively. Lines connect point analyses along profiles. For comparison, garnet analyses in rocks from Palaeozoic I (GOMEZ-PUGNAIRE & SASSI, 1983) are shown as dashed areas (pre-Alpine garnets) and dotted areas (Alpine garnets). Crosses represent chemical compositions of euhedral garnet (cores) included within large pre-Alpine chloritoid poikiloblasts.

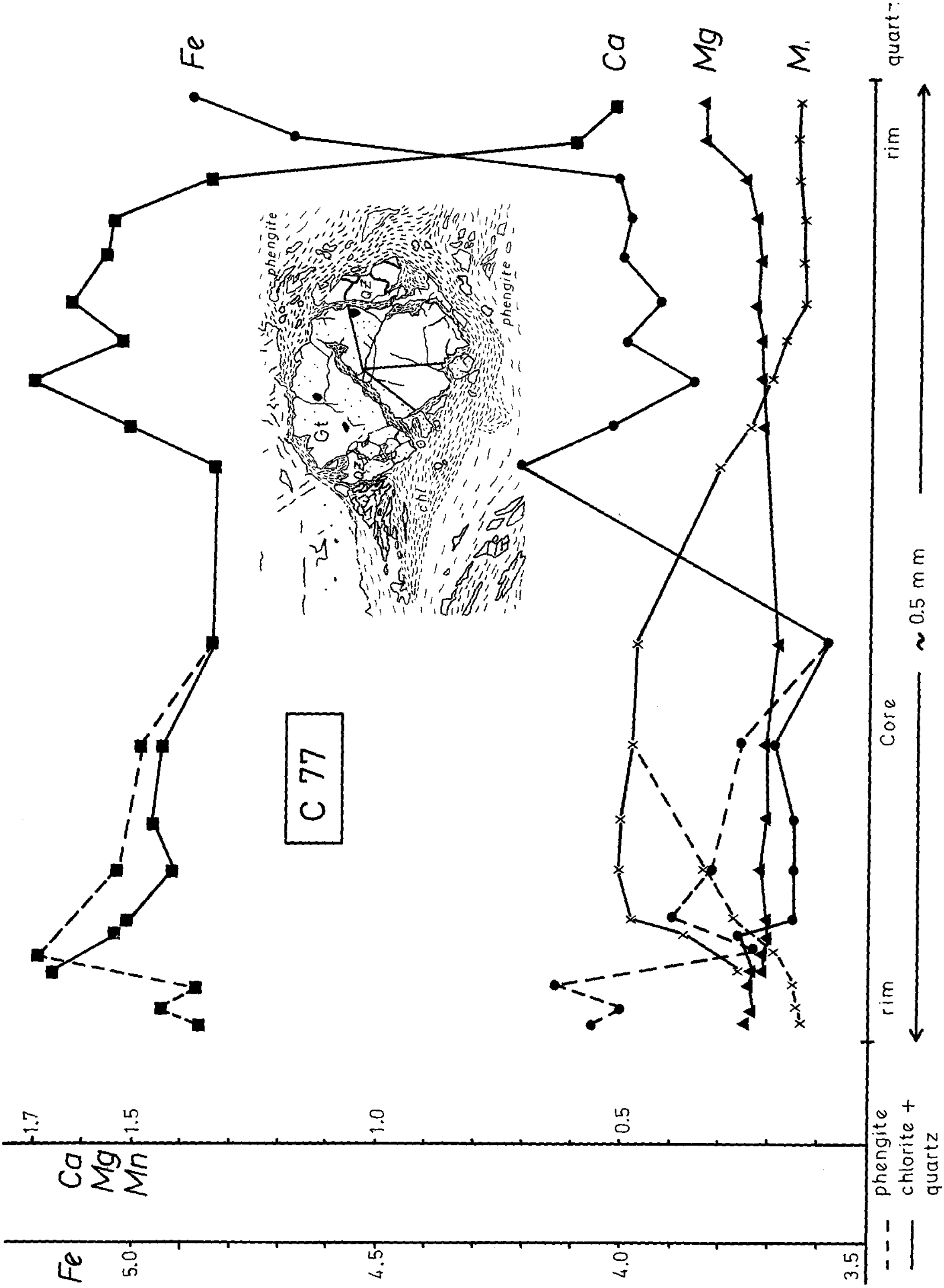

Fig. 13. Typical profile across garnet in terms of cations Fe, Ca, Mg, and Mn. To the right, the garnet has a small rim with increased Fe and Mg-contents, and a decreasing Ca-content. To the left, this rim is completely missing where the garnet is altered by coarse grained chlorite + quartz (solid lines of the profile), and is partly present where the garnet is bordered by phengite (dashed lines of the profile).

Earlier studies of the Palaeozoic Series of the NFC described biotite as a very abundant mineral (WESTERVELD, 1929, FALLOT et al., 1961). Additionally, PUGA & DIAZ DE FEDERICO (1976b) interpreted this mineral as being a pseudomorph of previous chlorites thus implying an increase in temperature after the growth of chlorites. They related the chlorite to a post-D_1 retrograde metamorphism due to the uplift of the rocks. A new metamorphic event with increasing temperatures simultaneous to D_2, altered the chlorite into biotite.

This interpretation is impossible because, as shown in this paper, firstly, the so-called biotite is actually oxychlorite and therefore does not call for any increase in temperature, and secondly, textural evidence indicates that both, chlorites and oxychlorites grew post-S_2 and not post-S_1.

In conclusion, the metamorphic evolution of the Veleta nappe is significantly different from that of the Upper Series (Permo-Triassic rocks) and Palaeozoic I during the Alpine metamorphism. On the contrary, the chemical composition of the minerals from the Veleta nappe is very similar to the mineral generation in the rocks of the Palaeozoic I, which can be clearly attributed to pre-Alpine metamorphism. There are no textural or mineralogical indications in the Veleta nappe which can unequivocally be interpreted as products of polymetamorphism, as in the rocks of the Palaeozoic I.

Geological interpretation

The present distribution of the metamorphism in the Palaeozoic sequences

Fig. 1 shows the location of the relics of pre-Alpine metamorphism and of the alpine porphyroblasts. The relics of pre-Alpine metamorphism are more evident in the westernmost part of the NFC (e.g. in the Mulhacén area); the pseudomorphs of pre-Alpine metamorphism in the Palaeozoic I are less frequent in the Sierra de los Filabres (GOMEZ-PUGNAIRE, 1979a; MARTINEZ-MARTINEZ, 1984, 1985; JABALOY, 1985). In contrast to this, the typically Alpine, isolated porphyroblasts, such as kyanite and staurolite, are frequently found in the Palaeozoic I of the Sierra de los Filabres and have never been mentioned in the Sierra Nevada. These differences show that the intensity of the Alpine overprint (at least the most evident effects related to the second event) is higher towards the E of the NFC.

Is the Alpine metamorphic inversion true or only apparent?

The gradient in temperature in the NFC decreases abruptly at the limit between the Upper Series + Palaeozoic I and the Veleta nappe. The metamorphic grade is less in the deepest rocks (Veleta nappe, see Fig. 2 and above). For the interpretation of this inverted temperature gradient we have to bear in mind the following facts:

1) The metamorphic evolution in the Veleta nappe is different from that of the Upper Series and the Palaeozoic I: no high pressure conditions are recorded and no distinct change in the grade during the metamorphic evolution exists.
2) There are no indications of a polymetamorphic evolution and, therefore, all the metamorphic features can be explained by a single metamorphic process.
3) The results of our chemical and textural investigations show the similarities between the metamorphism of the Veleta nappe and the pre-Alpine metamorphic relics of the Palaeozoic I.

The most consistent interpretation according, to the above points is to attribute a pre-Alpine age to the metamorphism of the Veleta nappe. Therefore, the change of the metamorphic grade does not correspond to a metamorphic inversion during the Alpine metamorphism, because the metamorphic process that affected the materials above and below the contact are of different ages.

The regional distribution of metamorphism in the Veleta nappe also confirms this hypothesis. It shows a variation in metamorphic grade opposite to that of the Alpine metamorphism in the Palaeozoic I. In the Sierra Nevada the Veleta nappe is more intensely metamorphosed than in the Sierra de los Filabres. In the eastern part of the NFC less deformed and recrystallized rocks, which preserve even the original sedimentary features, have been found (own observation and JABALOY per. comm.). This fact suggests that the metamorphic grade of the Veleta nappe decreases eastwards, in an opposite sense to the Alpine metamorphism.

All these observations are much more difficult to explain if the metamorphism in the whole NFC is Alpine. None of the proposed interpretations has satisfactorily explained the different evolution during the Alpine metamorphism in the different tectonic units of the NFC.

Relationship between the Veleta nappe and the Alpine orogeny

The arguments used to demonstrate the Alpine age of the metamorphism in the Veleta nappe are based on the assumption that the maximum temperature of the metamorphism (which produced staurolite and oligoclase-andesine porphyroblasts in the Upper series) is largely synchronous with the development of the S_2 schistosity. This structure is related to an extensive ductile deformation developed during the emplacement of the Upper Series and Palaeozoic I onto the Veleta nappe. For this reason several authors (EECKHOUT & KONERT, 1983; GONZALEZ-LODEIRO et al. 1984; MARTINEZ-MARTINEZ, 1985) have concluded that the higher temperature metamorphism in the Upper Series and Palaeozoic I was produced by this process and is, therefore of Alpine age in the Whole NFC. Nevertheless, the Veleta nappe does not show the same increase in temperature as the Upper Series. Obviously, if the emplacement predates or is synchronous to this metamorphism the deepest buried rocks should have been formed, at least, under the same metamorphic conditions.

The S_2 structure in both Veleta nappe and Upper Series out of the shear zones, is not mylonitic and not related to the tectonic supperposition. In consequence, we think that the S_2 schistosity in rocks unaffected by ductile shearing is not the same in the Upper Series (and the Palaeozoic I) as in the Veleta nappe. Both structures (S_2) have been obliterated by a third mylonitic schistosity (apparently S_2) in the areas affected by ductile shear deformation related to the supperposition of Upper Series (and Palaeozoic I) onto the Veleta nappe, which took place after the second metamorphic phase in both nappes (D_3 in the Upper Series and D_1 Alpine in the Veleta nappe). Fig. 14 illustrates this relationship.

The most important argument against the syn-shearing, amphibolite-facies metamorphism nevertheless is based on the nature of the metamorphic process itself. The second Alpine metamorphic event (developed under amphibolite-facies conditions) is a response to a combination of the rate of erosion and the time required for the thermal equilibration of the rapidly buried rocks (see GOMEZ-PUGNAIRE, 1979, VISSERS, 1981). These rocks underwent a rapid increase in pressure without a corresponding great increase in temperature (the first metamorphic high-pressure

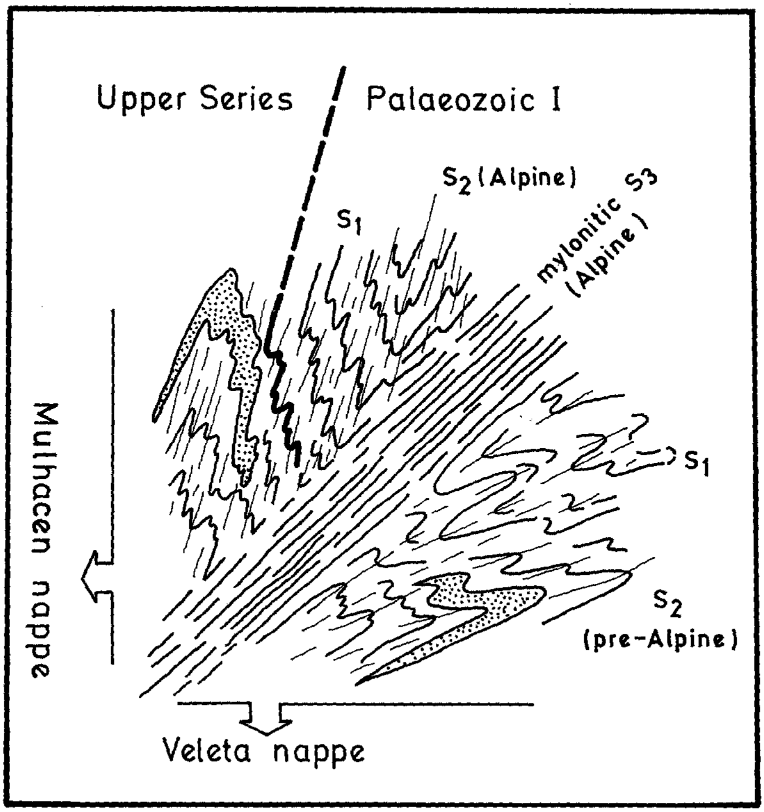

Fig. 14. Tectonic scketch showing the supperposition of the Mulhacén nappe on the Veleta nappe which developed under ductile shear conditions, and the formation of a mylonitic schistosity (S_3) which affected both nappes.

event) followed by a relatively long phase of heating with little uplift although not long enough to obliterate all the high pressure relics (the second metamorphic intermediate-pressure event). The rocks reached their maximum temperature in a decompressional stage and not at the maximum burial depths. The increase in temperature is therefore a product of a regional metamorphic process and not a localized phenomenon in more or less thin areas affected by ductile shearing. In fact, shear zones similar to that developed by the folding and thrusting of the Upper Series and Palaeozoic I onto the Veleta nappe are also found within the NFC and they have not developed the typical effects of the higher temperature metamorphism.

In conclusion, we believe that there are no consistent arguments to prove that the metamorphism in the Veleta nappe is Alpine in age. All the data presented here indicate that the most consistent interpretation is to consider the Veleta nappe as being a portion of an original pre-Alpine basement not affected by the main events of the Alpine metamorphism and being involved in the Alpine orogeny only at a relatively late stage.

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