Crystalline Provence: Structure and Variscan Evolution

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1 Introduction

Crystalline Provence, located in southeastern France and located along the Mediterranean Sea, constitutes one of the basement inliers which belong to the southern branch of the internal zone of the western European Variscan fold belt (Arthaud and Matte 1974; Autran and Cogné 1980; Matte 1986 a, b). Its relationships with the French Massif Central, the External Crystalline Massifs of the Alps, and the Axial Zone of the Pyrenees are not yet well understood. However, numerous data indicate that together with the Corso-Sardinian block it formed the continuous "Thyrrenian block" in Variscan times. This block was subsequently disrupted as a result of the Tertiary opening of the north-Balearic basin (Vellutini 1977; Orsini et al. 1980).

Crystalline Provence stretches for nearly 110 km from Toulon in the SW to Cannes in the NE. It is composed of three main geographical and geological units (Fig. 1):

1. The Maures Massif, to which the small massifs of the Toulon area and the Hyeres islands are attached.
2. The Tanneron Massif, which constitutes the northern continuation of the Maures Massif.
3. The Permian basin which surrounds the Maures Massif and, together with the Esterel Permian volcanic massif, separates the Maures Massif from the Tanneron Massif.

The Maures and Tanneron Massifs consist of Variscan metamorphic formations intruded by Carboniferous granitoids. These massifs, in which major structures display a submeridian trend, expose an 80-km transect. The western half of the transect exhibits epi- to mesozonal formations and the eastern half is primarily composed of migmatitic formations.

The Maures and Tanneron Massifs, Permian basin, and Esterel Massif are cut by N-S and E-W sets of extensional faults which have been active at different points during the region's evolution. The N-S faulting led to the development of northerly-trending Stephanian coal basins (Plan-de-la-Tour in the Maures Massif, Pennafort and Reyran in the Tanneron Massif). The E-W faulting active throughout the Permian formed grabens and controlled their sedimentary and volcanic evolution. On the eastern and northern edges of Crystalline Provence, detrital basal Triassic formations rest unconformably on deeply eroded metamorphic basement and Permian formations.

2 Stratigraphy and Paleontology

2.1 Major Lithologic Sequences

2.1.1 Introduction

The first lithostratigraphic and structural schemes for the Provencal basement were developed in the 1950s and 1960s by Bordet (1951, 1957, 1961, 1966) and Gueirard (1957). The works of Bordet, on which are based the regional geological maps (seven 1:50000 maps published between 1966 and 1976) highlight two fundamental points:

1. The continuity between the Maures and Tanneron Massifs as evidenced by similarities between their post-metamorphic features; consequently, the continuity of their metamorphic formations appears probable.
2. In the Maures and Tanneron Massifs the metamorphic series appears continuous from West to East. Isoclinal folding is responsible for repeating the lithologic formations. Among them, an amphibolite formation is regarded as an important stratigraphic reference.

In the 1970s and early 1980s, detailed field studies (Maluski 1968; Orsini 1968; Giraud et al. 1975; Seyler 1975; Le Marrec 1976; Crevola 1977; Olives Baños 1979; de Groulard 1982; Seyler 1983) resulted in many local modifications of Bordet's scheme. New attempts were also made to erect improved general lithostrati-

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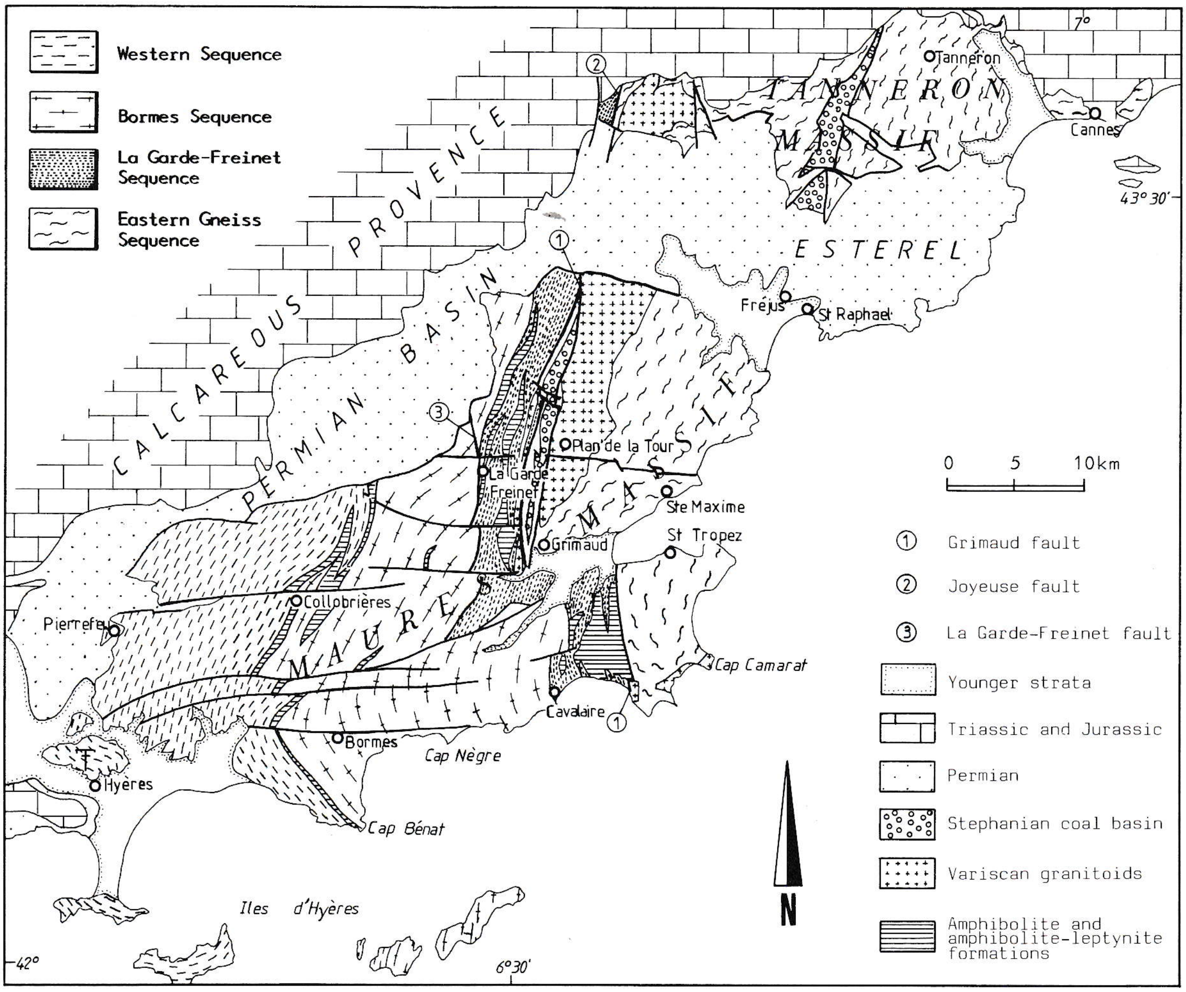

Fig. 1. General sketch map of crystalline Provence

graphies (Caruba and Turco 1976; Seyler and Boucarut 1978; Seyler 1983).

However, in recent years, the continuity of the metamorphic series has been questioned due to the recognition of the importance of the Grimaud-Joyeuse fault, which separates two sequences regarded as structurally contrasting (Caruba 1983; Vauchez and Bufalo 1985, 1988).

In the lithostratigraphical scheme adopted in this chapter, four major lithologic and/or lithotectonic sequences can be distinguished from west to east (Figs. 1, 2, and 4) on the basis of lithology, degree of metamorphism, and tectonic discontinuities (Tempier 1978; Crevola 1985). The first and second sequences are restricted to the Maures Massif, whereas the third and fourth ones extend over the Maures and Tanneron Massifs. The significance of major discontinuities will be discussed later.

2.1.2 The 4.2Sequence (WS)

This essentially epizonal sequence, 15 to 18 km wide, (Bordet 1966; Maluski 1968; Seyler 1975; Olives Baños 1979; de Groulard 1982) extends over the westernmost part of the Maures Massif (Figs. 1, 2). Its base is located at the structural top of the Bormes orthogneisses. The WS consists predominantly of thick and monotonous phyllite and quartzphyllite formations with frequent flysch-like facies. Some particular layers are intercalated in this series: (1) massive quartzites which form conspicuous ridges in the landscape, (2) amphibolites and leptynites (Collobrières formation), and (3) locally (Mont Fenouillet) rare lenses of crinoidal limestone and a fossiliferous black schist layer of middle Silurian age.

Thick Cambrian limestone formations characteristic of other Variscan regions (Montagne Noire,

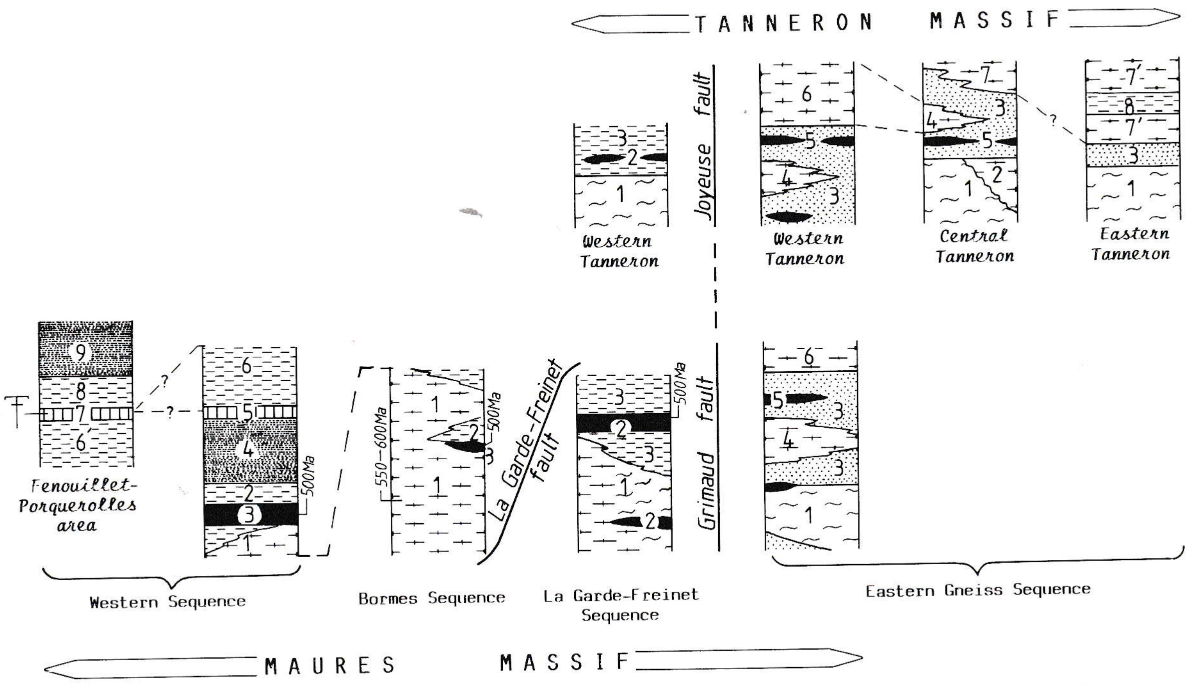

Fig. 2. Tentative general lithostratigraphy of Provencal basement metamorphic formations. Western sequence: *1* Bormes orthogneisses; *2* mica schists; *3* Collobrières amphibolites; *4* Loli flysch-like formation; *5* Temple quartzite; *6* and *6'* Maurettes phyllites; *7* Fenouillet quartzite; *8* Les Salins phyllites; *9* Porquerolles flysch-like formation. Bormes sequence: *1* Bormes orthogneisses; *2* mica schists; *3* amphibolites. La Garde-Freinet sequence: *1* Orthogneisses grading up to migmatites; *2* amphibolites; *3* sillimanite mica schists. Eastern gneisses sequence: *1* Auribeau and Peygros migmatites; *2, 4, 6,* orthogneisses; *3* plagioclasic and sillimanite micaceous gneisses; *5* amphibolites; *7* Les Adrets leptynites; *7'* Cannes leptynitic migmatites; *8* mica schists

Cévennes, Sardinia) do not outcrop in this sequence, and formations of Devonian age have not been recognized in its upper part.

2.1.3 The Bormes Sequence (BS)

The BS, which is overlain by the WS, (Gueirard 1957; Maluski 1968; Seyler 1975; Crevola 1985) is 10 to 20 km wide and has an apparent thickness of about 10 km (Figs. 1, 2). A narrow band of BS occurs along the Grimaud fault separated from the main outcrop area.

The BS consists mainly of augen to flaser gneisses (Bormes gneisses) intimately associated with micaceous gneisses or garnet-staurolite-kyanite mica schists (the micaschistes à minéraux). These two formations are locally (Vaucaude) intercalated with thin leptynite and amphibolite layers.

The Bormes gneisses, previously divided into ortho- and paragneisses (Maluski 1968; Seyler and Boucarut 1978; Seyler 1983), are now considered totally orthogneisses (Gueirard 1982; Crevola 1985). They originated through intense blastomylonitization of previous aluminous porphyritic monzogranites of which some remnants (Barral, Aire du Lac, Route des Crêtes metagranites) are exposed over restricted areas (m^2 to km^2). The mica schists are considered as metasediments originally constituting either the cover (Seyler 1983) or the country rock (Caruba, 1983) of the older granites. However, they may also originate through blastomylonitization with mass transfer of the older granites (ortho-mica schist, Crevola 1985).

2.1.4 The La Garde-Freinet Sequence (LGFS)

The LGFS is structurally overlain by the BS, the contact being normal or marked by faults of La Garde-Freinet fault system (Figs. 1, 2). This sequence is slightly more metamorphic than the BS, as kyanite is replaced by sillimanite and anatexis is reached.

In the Maures Massif (Gueirard 1957; Bordet 1957; Seyler 1975; Crevola 1985), the LGFS is 3 to 6 km wide and is bounded to the east by the Grimaud fault. Four main lithologic types can be distinguished: (1) prominent aluminous orthogneisses, (2) sillimanite mica schists, (3) cordierite migmatites, and (4) amphibolites associated with leptynites, subordinate metagabbros and serpentinites (the leptynitic-amphibolitic complex). The aluminous orthogneisses (La Garde-Freinet orthogneisses, Crevola 1985) contain huge masses of metagranite (the Moure-Jaumet metagranite: Seyler 1975; Crevola 1985) which outcrops over about 15 km from north to south. The orthogneisses and mica schists of this sequence are distinct from those of the BS: nonporphyritic orthogneisses vs. porphyritic orthogneisses, sillimanite mica schists vs. kyanite mica schists. The establishment of a lithostratigraphy is problematic in this sequence, which contains many orthogneisses grading up to mica schists and migmatites.

In the Tanneron Massif the LGFS is restricted to a narrow band extending to the west of the Joyeuse fault which is the northern continuation of the Grimaud fault (Bordet 1957, 1961; Crevola 1994). It consists of sillimanite mica schists and cordierite migmatites with subordinate amphibolite layers. These formations are in the same structural position as their equivalents of the Forêt des Arcs at the northern edge of the Maures Massif.

2.1.5 *The Eastern Gneisses Sequence (EGS)*

This sequence, extending to the east of the Grimaud-Joyeuse fault for nearly 40 km, consists mainly of migmatitic gneisses (Bordet 1961; Orsini 1968; Giraud et al. 1975; Le Marrec 1976; Crevola 1977, 1994). Its continuity is not affected by the La Moure fault which forms the eastern limit of the Reyran coal basin. A tentative lithostratigraphy can be established in the Tanneron and northeastern Maures Massifs in which the folded structures are fairly well-defined (Crevola 1994).

In the Tanneron Massif (Fig. 2), the structurally lower part of the series is made up of fairly homogeneous, banded and augen migmatites, which outcrop in the Tanneron and Auribeau areas (Auribeau migmatites, Crevola 1977). Of possibly granitic origin, they are themselves cross-cut by granitic orthogneisses (Tanneron orthogneisses). They are overlain by a complex of plagioclasic and micaceous sillimanite gneisses of sedimentary origin, with subordinate marble and calc-silicate gneiss lenses. This complex contains huge orthogneiss masses (Rioutard and Bois de Bagnols orthogneisses, Adrets leptynites) as early premetamorphic intrusions and/or tectonic repetitions. The Mandelieu and Cannes leptynitic migmatites, which are exposed at the eastern edge of the Tanneron Massif over tens of kilometers, are structurally situated under the lower migmatites. Nevertheless, their lithological analogies with the Adrets leptynites and their staurolite-kyanite-sillimanite mica schists suggest that they may be regarded as part of the upper complex which has been tectonically repeated. Mafic formations consisting of lensoidal masses of amphibolite with eclogitic relicts are intercalated at various levels of the series.

In the northeastern Maures Massif (Fig. 2), banded and augen migmatites similar to Auribeau migmatites outcrop near the Plan-de-la-Tour granite (Peygros migmatites, Le Marrec 1976), being intercalated near the base of the series. They are overlain by a thick sillimanite micaceous gneiss formation in which several huge masses of orthogneiss are intercalated (Fournel and Les Issambres orthogneisses). As in the Tanneron Massif, lensoidal masses of amphibolite with eclogitic relicts occur at various levels of the series. The upper part of this lithostratigraphic column is quite similar to the western Tanneron Massif, but banded migmatites are missing in the Tanneron Massif due to present-day different levels of erosion (Crevola 1994).

2.2 The Metamorphic Series: General View

2.2.1 *Age of the Metamorphic Series: Paleontological and Radiometric Data*

The original age of the metamorphic series from the Provencal basement can be estimated based on scarce paleontological and radiometric data which were acquired only in the western and central part of the Maures Massif. In the WS, the occurrence within the Mont Fenouillet quartzite of a thin black schist layer which yielded graptolites of Middle Silurian age (Upper Llandovery to Lower Tarannonian) allows dating of the uppermost part of the WS (Schoeller 1938; Gueirard et al. 1970). The Bormes orthogneisses were formed from ancient Cadomian granites which were emplaced at about 550-600 Ma (Rb-Sr dating[1]: Maluski, 1971; ^{39}Ar–^{40}Ar dating: Maluski and Gueirard 1978). Leptynites, which belong to the bimodal metamagmatic formations of the WS, BS, and LGFS in the Maures Massif, were formed from felsic volcanics emplaced at about 500 Ma (U-Pb zircon dating: Lancelot et al. 1992).

Thus, these data, at least for the WS and BS, enable the establishment of a loose stratigraphical framework. These two sequences, taken together, appear to comprise ancient Cadomian granites and Lower Paleozoic formations. The age of the formations of the LGFS and EGS is still unresolved due to the lack of reliable radiometric data.

[1] All Rb-Sr ages are calculated using the constant $\lambda_{^{87}Rb} = 1.42 \times 10^{-11}$/year.

2.2.2 Occurrence of a Basement-to-Cover Relationship

The occurrence, prior to metamorphism and deformation of a pre-paleozoic basement intruded by Cadomian granites and a Paleozoic cover, suggests the potential of local cartographic unconformities (Crevola 1977; Seyler and Boucarut 1978; Bourrouilh et al. 1980; Seyler 1983). This scheme, though criticized (Bard and Caruba 1983), might apply to the two more westerly sequences (WS and BS) for which a suitable geochronological framework exists (Seyler 1983). However, the age and significance of the mica schists intimately associated with the Bormes orthogneisses remain poorly known. In the LGFS and the EGS, the occurrence of several orthogneiss masses at various levels of the series and the scarcity of geochronological markers hampers the correlation with western formations and does not enable the definition of a basement-to-cover relationship.

2.2.3 Importance of Granite-Derived Gneisses

The granitic origin of numerous masses of augen to flaser gneisses and augen migmatites has been progressively recognized over the two last decades, in three (BS, LGFS, and EGS) of the four lithologic sequences (Maluski 1968; Seyler 1975; Crevola 1977, 1994; Gueirard 1982). Because they appear at various levels in different sequences, it is not clear that they were emplaced contemporaneously. Some of these orthogneissic formations (Bormes, Moure-Jaumet, Bois de Bagnols, Fournel, and Tanneron orthogneisses) contain slightly deformed metagranitic remnants of various sizes (m^2 to km^2) displaying mafic microgranular enclaves. Petrographical (magmatic cordierite and sometimes garnet), zircon typology, and geochemical features indicate that they belong to an aluminous granitic suite of crustal origin.

3 Structure

3.1 Succession of Phases of Deformation

Three main phases of deformation have been recognized in various areas of the Provencal basement (Arthaud and Matte 1966; Maluski 1968; Seyler 1975; Le Marrec 1976; Crevola 1977). The two first are synmetamorphic and characterized by isoclinal, subhomoaxial F1 and F2 folds with S1 and S2 axial-planar foliations. The F1 folds are scarce and small (cm to m). In contrast, the F2 folds are more frequent and developed on all scales (cm to km). These two phases are clearly distinguished in the WS by the superposition of their folds and foliations (Arthaud and Matte 1966; Maluski 1968). In the more deformed and metamorphosed sequences to the east (BS, LGFS, and EGS), only F2 folds are clearly visible. Some sheath folds (cm to m) related to F1 or F2 folding have also been locally described (BS: Goldberg 1983; LGFS: Seyler 1983; EGS: Vauchez and Bufalo 1988). They trend E-W to NW-SE in the BS and LGFS and N-S to N 30 in the EGS.

A pervasive blastomylonitization or mylonitization is related to these two first phases of deformation and affects the whole metamorphic pile of the BS, LGFS and EGS (Le Marrec 1976; Crevola 1977; Seyler 1983; Vauchez and Bufalo 1988). As a result, the S1 foliation is progressively transposed into a composite S1-S2 foliation with blastomylonitic or mylonitic character in orthogneisses, banded migmatites, late-migmatitic granites, and bimodal metavolcanics. Stretching lineations are well developed in the orthogneisses as well as in the late-migmatitic granites. They are regarded as mainly related either to the first phase of deformation (Vauchez and Bufalo 1985, 1988) or to the second phase (Le Marrec 1976; Crevola 1977; Seyler 1983; Caruba 1983). In the EGS, they exhibit a submeridian trend, being broadly parallel to regional trends, in particular to axes of large F2 folds. To the west of the Grimaud-Joyeuse fault (i.e., in the WS, BS, and LGFS) the pattern of the stretching lineations is poorly known. E-W to N 130-trending stretching lineations have been locally described (Goldberg 1983; Seyler 1983; Vauchez and Bufalo 1988) as well as N-S-trending stretching lineations (Crevola 1994) and relationships between the two sets of lineations are unknown (Fig. 3).

The third phase (F3), developed on all scales, is post-metamorphic and clearly post-dates the extensive blatomylonitic or mylonitic episode (Crevola 1977). It is characterized at outcrop scale, in the eastern Maures and Tanneron Massifs, by concentric F3 folds which grade to chevron folds or kink-bands in the western Maures Massif.

3.2 Large-Scale Folds

In the Maures and Tanneron Massifs, the general trend of cartographic bands, fold axes, and foliation is broadly N-S. However, in some areas it is diverted to an E-W direction. These trends are not modified by late E-W and N-S trending major faults.

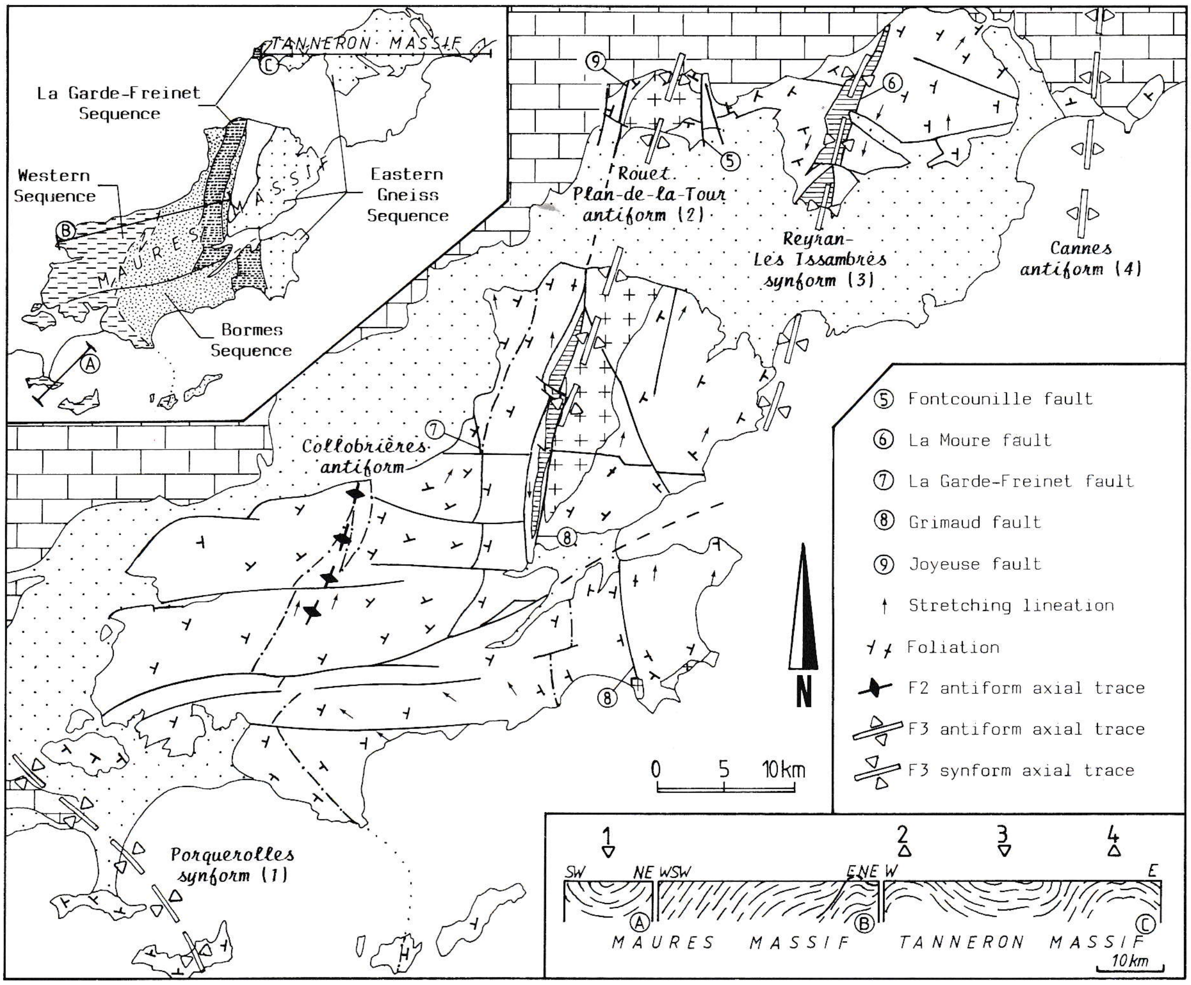

Fig. 3. Synthetic map of the Provencal basement and synthetic cross-section showing major F3 structures shown by foliation attitudes

To date, regional mapping has not identified any large recumbent fold related to the first phase (F1), as suggested by microstructural markers found in the WS (Maluski 1968). In fact, the only conspicuous map-scale structures are F2 and F3 folds, which affect the metamorphic banding and S1 foliation. By their superposition these large-scale structures can account for the overall observed geometry.

The large-scale F2 structures are hectometric to kilometric subisoclinal folds with thinned limbs and thickened hinges, displaying a fairly good axial continuity. By their close spacing, they define an "isoclinal style" (Bordet 1957; Gueirard 1957). However, only a few of these large F2 folds have been thoroughly mapped in suitable areas such as the "Chaîne de la Sauvette" (between Collobrières and La Garde-Freinet in the Maures Massif), and the central part of the Tanneron Massif. Among these large F2 folds the "Collobrières anticline" and the "Sauvette syncline" (Bordet 1957; de Groulard 1982), with an amplitude nearing 10 km, appear as major structures of the Provencal basement.

The third phase plays a major part, long unrecognized, in the structure of the Provencal basement (Crevola 1977). The large-scale F3 structures are hectometric to decakilometric open or box folds, with NS trending axes (Figs. 3, 4). They constitute an overall "dome and basin" structure. This kind of structure is shown by large arcuate outcrop patterns and by alternating areas of N-S-trending steep foliation and E-W-trending flat-lying foliation. F3 major folds are well developed in the Tanneron and the northeastern Maures Massifs. Three large decakilometric structures can be distinguished from east to west: the Cannes antiform, the Reyran-Les Issambres synform, the Rouet/Plan-de-la-Tour antiform (Figs. 3, 4). In the rest of the Maures Massif this pattern is less clear. However, various map-scale structures can be related

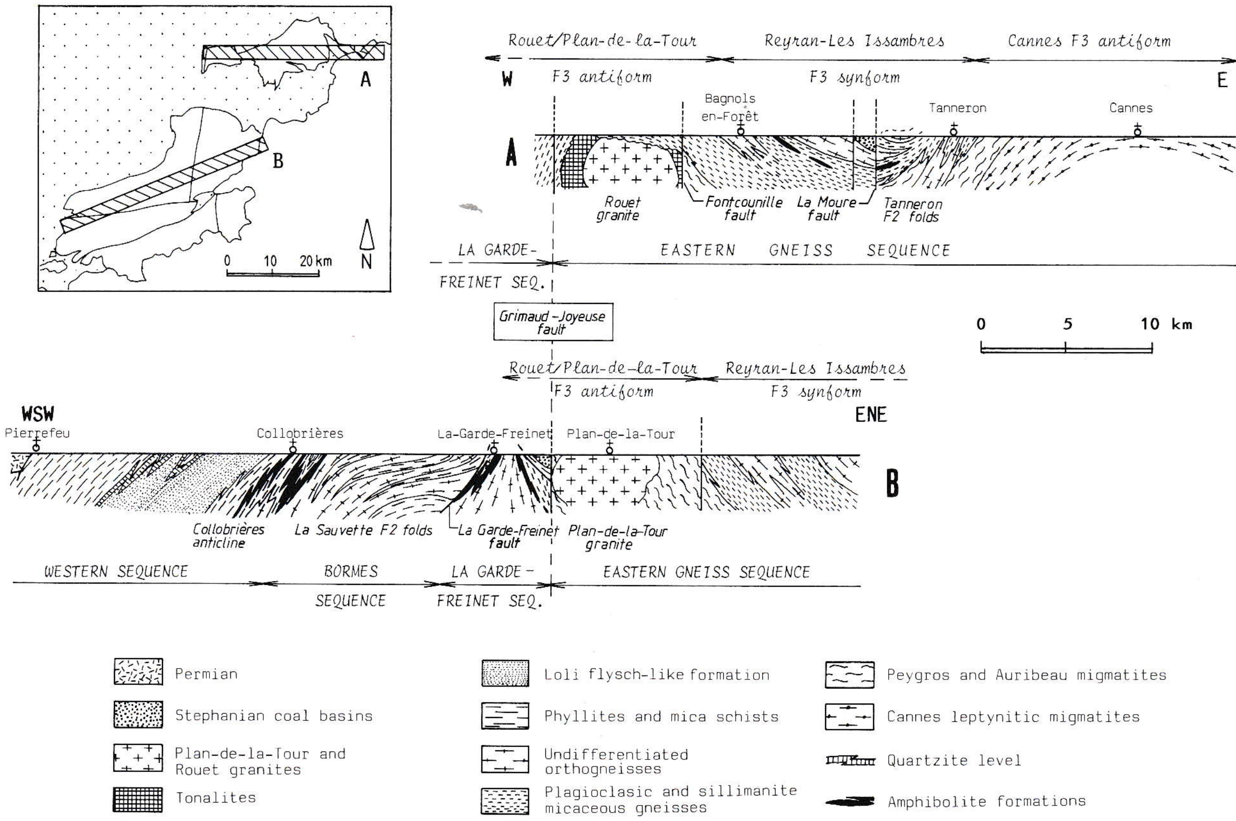

Fig. 4. A, B. Synthetic cross-sections. **A** Tanneron Massif. **B** Northern Maures Massif.

to this phase of folding: the regional arcuate outcrop pattern around the Saint-Tropez peninsula, the Porquerolles synform (Bronner et al. 1971) and the so-called La Garde-Freinet virgation, which corresponds to a giant bend in the western limb of the Rouet/Plan-de-la-Tour antiform.

3.3 Major Faults

The metamorphic formations are cut by sets of E-W- and N-S-trending faults. The E-W faults, of Permian age, may have significant vertical displacement (1 or 2 km). In the Maures Massif, some of them also have sinistral strike-slip motion, with increasing lateral displacement toward the south of the massif (i. e., the Saint-Tropez Gulf fault, whose main movement is probably Permian). In contrast, the N-S faults may have been active earlier in the structural evolution. Two groups of N-S faults are of particular importance.

The La Garde-Freinet fault (Figs. 1, 3, 4) and the faults which bound to the west the narrow band of the BS stretching along the Grimaud fault are steeply dipping, although they can locally display moderate dips. They can be interpreted as thrust faults (Crevola 1985) or more likely as extensional faults (Crevola 1994). They appear as late metamorphic, as they induced local low-grade retromorphic crystallization, and possibly predated the third phase of folding.

The Grimaud-Joyeuse fault (Figs. 1, 3, 4) belongs to a system of N-S mylonitic faults closely related to the development of the coal basins and the emplacement of the Plan-de-la-Tour and Rouet granitic line. Unlike the Fontcounille and the La Moure faults, which in the Tanneron Massif do not affect the continuity of the EGS, the Grimaud-Joyeuse fault separates two blocks regarded as lithologically and structurally contrasting. Owing to its structural position and to repeated episodes of mylonitization it has been widely studied.

The identity of the Grimaud fault, in the Maures Massif, and the Joyeuse fault, in the Tanneron Massif, has been established by Bordet (1951, 1961) and subsequently confirmed by geophysical data (Debeglia, 1977) and recent mapping (Crevola 1994). In the Maures Massif, classical studies (Demay 1927; Gueirard 1957; Bordet 1951, 1957, 1961; Triat 1964) have shown that cataclastic rocks developed along the fault were locally intruded by the Plan-de-la-Tour granite and were found in the Stephanian conglomerate, demonstrating a pre-Stephanian movement. Subsequently modern studies have shown that the Grimaud fault may correspond to a synmetamorphic and/or post-tectonic strike-slip fault of major importance (Caruba 1983; Vauchez and Bufalo 1985, 1988). Based on detailed microstructural studies, Vauchez and Bufalo have indentified three stages of evolution:

- a sinistral ductile strike-slip movement under epi- to mesozonal metamorphic conditions contemporaneous with F2 folding. This stage corresponds to the mylonitization of a 2 km wide zone of the EGS adjacent to the fault, particularly developed in late-migmatitic granites;
- a moderate cataclastic reactivation of the fault with a dextral sense of shear which predated the emplacement of the Plan-de-la-Tour granite;
- a late post-Stephanian and pre-Triassic brittle movement.

3.4 Problems with the Structural Interpretation of the Provencal Basement

3.4.1 Tectonic Significance of the Leptynitic-Amphibolitic Complex of the LGFS

This complex, which consists of bimodal metavolcanics associated with subordinate mafic metaplutonics, has undergone an early high pressure metamorphism and a subsequent blastomylonitization under lower grade metamorphic conditions. The geochemical features of its rock types (Sect. 5.1, below) suggest a pre-Silurian extensional magmatism related to a phase of crustal thinning (Bard and Caruba 1981; Caruba 1983; Seyler 1986).

However, the tectonic setting of this complex remains a debated question. Based on general considerations about the allochthonous setting of many leptynitic-amphibolitic complexes within the western European Variscan fold belt, Bard and Caruba (1981) and Caruba (1983) have regarded this complex a allochtonous. They have suggested that it may represent the sole of a nappe emplaced by westward ductile thrusting over the Bormes gneisses, during the first phase of deformation. Other authors (Seyler and Crevola 1982; Seyler 1983; Crevola 1994) have considered this complex to be autochtonous as no cartographic evidence has been found for a major overthrust, and as a pervasive blastomylonitization affected all the metamorphic pile of the central and eastern Maures Massif, being not restricted to the narrow zone of the complex.

3.4.2 Significance of the Grimaud-Joyeuse Fault

The Grimaud-Joyeuse fault has been regarded either as a post-tectonic normal fault (Gueirard 1957; Bordet 1951, 1957, 1961; Triat 1964; Seyler and Crevola 1982; Seyler 1983) or as a strike-slip fault of major importance (Caruba 1983; Vauchez and Bufalo 1985, 1988). The significance of the Grimaud-Joyeuse fault appears as a key problem for the understanding of the structure of Crystalline Provence and even of the southern part of the European Variscan fold belt. The most recent contributions to this problem are based on different kinds of arguments and develop contrasting points of view.

For Caruba (1983), in the Maures Massif the two blocks separated by the Grimaud fault exhibit contrasting lithologies, lithostratigraphies, and structures (opposite dips and plastic flow directions). Moreover, general considerations about late-Variscan wrench tectonics suggest that the Grimaud fault may correspond to a late-Variscan strike-slip fault with a dextral strike-slip movement. For Vauchez and Bufalo (1985, 1988) microstructural markers indicate distinct plastic flow directions for the two blocks and repeated transcurrent displacement along the Grimaud fault even as early as the second phase of deformation.

For Seyler and Crevola (1982), Seyler (1983) and Crevola (1994), the two blocks are similar in lithology and metamorphic grade and are both involved in F3 megastructures. Indeed recent mapping (Crevola 1994) has shown common foliation attitudes when the two blocks are in contact without the interposition of the Plan-de-la-Tour granite, i. e., in three main areas along the Grimaud-Joyeuse fault: western Tanneron, north of Grimaud, and Saint-Tropez Peninsula. These data appear consistent only with a minor strike-slip movement.

3.4.3 Structural Vergences

1. Structural Vergences Inferred from Stretching Lineations. Stretching lineations are well developed in the BS, LGFS, and EGS. In the Maures Massif, Vauchez and Bufalo (1985, 1988) have regarded these lineations as tectonic transport markers of the first phase of deformation indicating an overall ductile thrusting towards the north in the eastern Maures Massif and towards the west in the central Maures Massif.

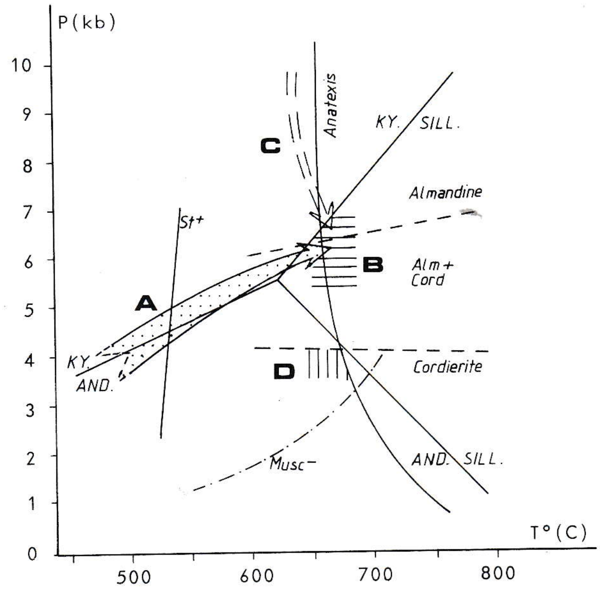

Fig. 5. Temperature-pressure conditions of crystalline Provence metamorphism. *A* Metamorphic path of western, Bormes, and La-Garde-Freinet sequences (Seyler 1975; Caruba 1983; Goldberg 1983); *B* field of eastern gneisses sequence metamorphism (Le Marrec 1976; Crevola 1977); *C* hypothetic retromorphic path of eclogitic rocks (after Maquil 1976); *D* field for late-migmatitic granites (after Maquil 1976) and retrograde assemblages (after Seyler 1975)

2. Structural Vergences Inferred from Fold Trends. A general westerly fold vergence has frequently been proposed, due to local microstructural observations of F1 microfolds in the WS (Arthaud and Matte 1966; Maluski 1968). In fact, early major F1 folds coeval with the development of S1 foliation have not been recognized. On the other hand, the large F2 folds display an apparent easterly vergence that has been observed in some areas: Chaîne de la Sauvette in the Maures Massif and central part of the Tanneron Massif (Crevola 1977, 1985, 1994). It should be stressed that, in the EGS where the pattern of stretching lineations is clear, the vergence inferred from fold trends appears orthogonal to the one inferred from stretching lineations.

4 Metamorphism

4.1 Tectonometamorphic Evolution (Fig. 5)

Numerous studies carried out over the two last decades in various areas of Maures and Tanneron Massifs have resulted in the establishment of a coherent tectonometamorphic scheme (Maluski 1968; Seyler 1975; Le Marrec 1976; Maquil 1976; Crevola 1977; Caruba 1983; Goldberg 1983). Three successive metamorphic stages with decreasing pressure conditions may be distinguished. The second stage which is the most extensive and the best known can be correlated with the two first deformation phases (F1 and F2) recognized.

The metamorphic evolution began with a high pressure stage of unknown age, which predated the two first phases of deformation. This high pressure event is particularly visible in relict meta-igneous rocks found in two metamorphic sequences (GFS and EGS). Metagabbros from amphibolite formations of the LGFS display a coronitic stage of granulite facies grade (Lasnier 1970). Amphibolite formations of the EGS contain widespread eclogitic relict lenses displaying various stages of amphibolitization (Le Marrec 1976; Maquil 1976; Crevola 1977; Caruba 1983). Among these eclogitic rocks a kyanite-sapphirine-hypersthene eclogite, which displays a retromorphic stage of granulite facies grade (P: 8–10 kbar, T: 750–850 °C), has been found (Les Cavalières eclogite: Le Marrec 1976; Bard and Caruba 1982). In the BS, LGFS, and EGS, metagranites showing coronas of garnet around magmatic biotite and pseudomorphs of garnet and sillimanite after magmatic cordierite might also record this high pressure event (Crevola 1977; Maluski and Gueirard 1978).

The main metamorphic event corresponds to the second stage of intermediate pressure type. Accompanying the first two isoclinal phases of deformation, it grades from epizone in the west up to catazone in the east. The metamorphic suite displays a complete Barrovian succession with a characteristic staurolite-kyanite zone, well-exposed in the BS (Gueirard 1957; Seyler 1975; Caruba 1983; Goldberg 1983). Locally andalusite, which occurs alone or associated with kyanite, appears as a typomorphic mineral (Seyler 1975; Goldberg 1983). Anatexis is reached just to the west of the Grimaud-Joyeuse fault in the sillimanite-muscovite zone and affects the entire EGS. Anatexis is partial, mainly developed in quartzo-feldspathic lithologies, particularly in orthogneisses, and rarely produces homogeneous migmatites. In the epizone and mesozone, the crystallization-deformation relationships show that the metamorphic mineral growth began before the first deformation phase and continued until the end of the second deformation phase, when the metamorphic peak was reached. In the anatectic domain the development of migmatitic banding was broadly contemporaneous with the F1 tectonic phase (Le Marrec 1976; Crevola 1977). Pegmatites or biotite-muscovite-(cordierite) leucogranites were emplaced between the two first tectonic phases, as dikes and stocks cross-cutting the metamorphic foliation. Migmatitic gneisses, late-migmatitic granites and pegmatites were reworked during the F2 tectonic phase sometimes with sillimanite development. However, locally in the EGS, thin leucocratic mobilizates were emplaced along shear planes affecting small F2 folds (Le Marrec 1976).

The third metamorphic stage is ill-defined and not clearly related to the second or the third deformation phase. It is characterized by a widespread but slight retrogression of earlier metamorphic minerals. Locally, cordierite or andalusite crystallized during this stage (Seyler 1975). Retrograde assemblages are also associated with some major faults: the La Garde-Freinet thrust fault and the Grimaud fault. In two Tanneron areas numerous dikes and veinlets of tourmaline granite were emplaced along a predominantly E-W direction, cross-cutting concentric folds of the F3 phase.

4.2 Age and Significance of Tectonometamorphic Events

The chronology of the tectonometamorphic evolution is poorly constrained due to scarce paleontological and radiometric data. The basic framework is as follows:

1. The epizonal formations of the BS, which contain the Mont Fenouillet fossiliferous layer of Silurian age, exhibit the same sequence of structures as more highly metamorphic formations. The lacustrine coal deposits of Westphalian D to Stephanian B age represent the first sedimentary formations overlying a deeply eroded metamorphic basement.
2. The post-tectonic Plan-de-la-Tour granite was emplaced at about 313 Ma (Rb-Sr dating: Maluski 1972) and the post-tectonic Camarat granite at about 300 Ma (Rb-Sr dating: Roubault et al. 1970 a; Amenzou 1988).
3. The age of the metamorphism itself can be only broadly estimated due to paucity of radiometric dates. The metamorphism of the Barral metagranite took place between 340 and 310 Ma (^{39}Ar–^{40}Ar dating: Maluski and Gueirard 1978), like that of some gneisses of the EGS (about 336 Ma, Rb-Sr dating: Roubault et al. 1970 a). However, some gneisses from the Tanneron Massif yield older ages, at about 400 Ma (Rb-Sr dating: Roubault et al. 1970 a).

Finally, owing to the scarcity of radiometric data, it is difficult to know precisely whether the tectonometamorphic evolution is Devonian to Carboniferous or confined solely to the Carboniferous. However, no radiometric evidence has been found for the existence of remnants of an older metamorphic basement displaying Cadomian or Precambrian metamorphism and deformation.

The tectonometamorphic evolution of the Provencal basement is similar to that of other regions belonging to the southern branch of the internal zone of the western European Variscan fold belt, e. g., the French Massif Central (Santallier 1983; Ledru et al. 1989). As in these regions, the tectonometamorphic evolution should be interpreted as the result of collision tectonics during Devonian and/or lower to middle Carboniferous: first, high pressure stage related to subduction of continental crust, then continent-continent collision with Barrovian metamorphism, anatexis, and major folding, finally crustal reactivation and late granite emplacement.

5 Igneous Activity

5.1 Lower Paleozoic Mafic and Felsic Magmatism

Amphibolite or amphibolite-leptynite formations, occur within the four lithologic sequences. In recent years detailed petrographical and geochemical studies have been carried out in order to define their original magmatic affinities and evolutions and their original tectonic settings (Ricci and Sabatini 1978; Seyler and Boucarut 1979; Caruba 1983; Seyler 1986). Owing to their different locations, these formations exhibit varied original magmatic features:

1. The Collobrières formation, part of the WS, corresponds to a moderately alkaline differentiated suite in which basaltic and acid products (trachyte, rhyolite) have a co-magmatic origin (Caruba 1983; Seyler 1986).
2. The so-called leptynitic-amphibolitic complex of LGFS (Forêt des Arcs and Gassin formations) represents bimodal magmatism. It consisted originally of tholeiitic basic rocks (basalts, gabbros) with continental affinities associated with alkali rhyolites, which originated either by differentiation or crustal anatexis (Seyler 1986).
3. The amphibolitic formations of the EGS were derived from a tholeiitic protolith of oceanic or continental affinities (Caruba 1983; Seyler 1986).

All these original rock types can account for an intracontinental magmatism related to the development of extensional basins or even of an incipient oceanic rifting. In the western and central Maures Massif, this event took place at the Cambrian-Ordovician boundary, as shown by recent radiometric datings of some felsic occurrences (Lancelot et al. 1992). Such an event is now recognized throughout the West European Variscan fold belt (Ricci and Sabatini 1978; Matte 1986b).

5.2 Variscan Granitoids

(J. P. Pupin)

The Variscan granitoids appear as numerous small intrusions mainly confined to a N-S-trending belt in the Maures and Tanneron Massifs (Fig. 6).

5.2.1 *Typology*

Two main groups can be distinguished from a genetic standpoint, using classical data (field mapping, petrography, geochemistry) along with typologic studies of zircons (Pupin 1980, 1985; Chèvremont et al. 1988). The granitoids are of either crustal or mantle-crustal origin.

The first group of entirely or mainly crustal origin includes:

1. Late-migmatitic syn-tectonic granites and pegmatites (Saint-Pons-les-Mures and Moulin Blanc deformed leucogranites, the latter with cordierite-andalusite; Ramatuelle biotite granite) or late anatectic dikes of tourmaline Grime-type leucogranite from the Tanneron Massif.
2. Aluminous cordierite-aluminium silicate granites (some of which contain mafic microgranular enclaves) resulting from melting at various crustal levels (Rouet and Plan-de-la-Tour monzogranites, Gigaro granodiorite, Plan-de-la-Tour and Camarat micromonzogranites, various dikes of biotite-cordierite or two-mica-cordierite-andalusite leucogranites, dikes of granophyric microgranite from the Tanneron Massif).

The second group is calc-alkaline, resulting from a mantle-crust hybridization. It includes varied biotite and biotite-amphibole granitoids (Fontcounille quartz-gabbro; Prignonet, Reverdi and Bagarède tonalites; Figarets granodiorite; L'Hermitan, Colle Dure, La Mente monzogranites; Vignon and Minuti microgranite dikes) and the Camarat biotite-muscovite granite.

5.2.2 *Age of Emplacement and Structure*

Structural relationships and radiometric data (Roubault et al. 1970a) indicate multiple episodes of emplacement.

Apart from the late-migmatitic granites, the oldest Variscan intrusions have a tonalite mean composition (Boucarut 1963; Orsini 1968; Pupin 1976; Amenzou 1988) similar to those of older intrusions in the western French Massif Central. They are unfoliated or slightly foliated, small intrusions of assumed pre-upper Visean age (Rb-Sr dating: Roubault et al. 1970a) emplaced along a N-S-trending "tonalitic line" which extends from the Tanneron Massif to the Saint-Tropez Peninsula. The Figaret granodiorite and the Hermitan-type monzogranite, which have varying degrees of deformation, exhibit petrographical and mineralogical characteristics indicating genetic links with the tonalitic formations (Amenzou 1988).

At about 315–335 Ma, in upper Visean-Namurian times (Rb-Sr dating: Roubault et al. 1970 a; Maluski 1972), a 45-km-long belt of cordierite porphyritic granites was emplaced (Rouet: Boucarut 1963; Plan-de-la-Tour: Triat 1964; Serment 1965; Serment and Triat 1967; Pupin 1976; Amenzou 1988; Gigaro: Amenzou and Pupin 1986; Amenzou 1988) along the Grimaud-Joyeuse fault. This linear intrusion cross-cuts the "Provencal tonalitic line" in the Tanneron Massif. It is interrupted to the north by the Permian trough and offset to the south by the Saint-Tropez Gulf fault. As a general rule, the outcrops are, from north to south, increasingly more basic and have less cordierite. The main bodies are cross-cut by dikes of cordierite-biotite leucogranites, dikes, and stocks of cordierite-andalusite submiarolitic leucogranite (Plan-de-la-Tour: Triat 1964; Pupin 1976; Amenzou 1988) and granophyre dikes (Rouet: Boucarut 1963), all of essentially anatectic origin (Pupin 1976; Amenzou 1988). In the eastern Tanneron Massif, K-feldspar megacryst-bearing microgranites, which have been emplaced as dikes, belong to this aluminous group (Crevola 1977).

During the Stephanian (Rb-Sr dating: Roubault et al. 1970 a; Amenzou 1988) the magmatism was mainly marked by the Camarat granitic intrusion dated at 300 Ma, where detailed mapping has been recently carried out (Amenzou and Pupin 1986). Zircon typology indicates the calc-alkaline affinities of this two-mica granite (Pupin 1976; Amenzou 1988), suggesting that this southerly Provencal area may represent a transition zone between the Provencal plutonism and the wholly calc-alkaline Corsican orogenic plutonism developed to the SSE (Pupin 1985, 1988).

Anatectic magmatism resumed in the upper Stephanian. During this episode a subvolcanic stock and microgranular to felsitic dikes were emplaced in the Plan-de-la-Tour coal basin (Bordet 1951; Pupin and Turco 1973). Ash layers were deposited in the Reyran coal basin (Basso 1985; Begassat 1985) and

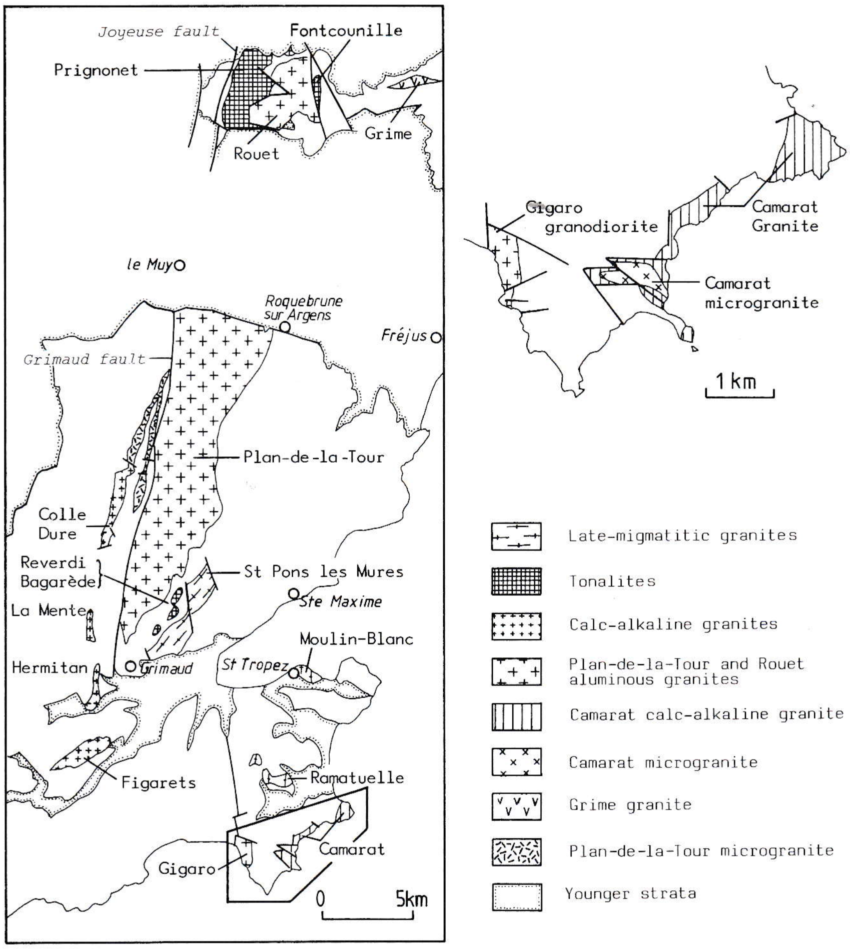

Fig. 6. The granitoid belt of crystalline Provence

the Camarat cordierite-andalusite-dumortierite microgranite was emplaced in older Camarat two-mica granite (Amenzou and Pupin 1986; Amenzou 1988).

The orogenic magmatism (the first Permian magmatic cycle of calc-alkaline type; Vellutini 1977) appears to have continued until the Autunian, as revealed by volcanic markers which occur within the detrital fill of Permian basins. In particular, calc-alkaline rhyolite pebbles derived from a more southerly volcanic source are widespread in Permian deposits of southern Esterel and Toulon areas (Pupin 1987).

5.2.3 Geodynamic Significance

In agreement with current plate tectonic models proposed for the West European Variscan orogenesis (Bard et al. 1980), the late emplacement of granitoids of either hybrid calc-alkaline or crustal anatectic type appears to be the result of a subduction-collision coupling (Pupin 1985; Amenzou 1988). The major suture would be situated to the west of Crystalline Provence. It may be the extension of the proposed suture located to the west of the Massif Central (Lameyre and Autran 1980). The waning stages of this long-lived magmatic event would be related to the slow resorption of thermal anomalies generated during the subduction-collision stage.

On the other hand, the comparison between Provencal and Corsican granitoids based on zircon typology reveals a magmatic complimentarity between the two domains (Amenzou 1988; Pupin 1988): crustal anatectic and calc-alkaline granitoids in Provence, calc-alkaline and K-calc-alkaline granitoids in Corsica. Thus, Provence and Corsica, when placed in their Variscan time positions, display an overall magmatic zoning: from crustal anatectic granites to the west, to increasingly hybrid calc-alkaline granitoids towards the east (Amenzou 1988; Pupin 1988).

5.3 Middle and Upper Permian Alkaline Magmatism

The Saalian phase at the Autunian-Saxonian boundary resulted in a tilting of previous Autunian formations of the small Avellan graben (Esterel Massif), deposition of widespread sedimentary breccias and local outpourings of alkali-basalts. These eruptions marked the onset of extensive alkaline volcanism (the second Permian magmatic cycle of alkaline type; Vellutini 1977) in downthrown E-W elongated basins (Toutin 1980; Baudemont 1985), particularly in the Esterel massif at the eastern edge of crystalline Provence (Bordet 1951; Boucarut 1971). The volcanic products are felsic (ignimbritic rhyolites, flow-banded rhyolites), mafic (basalts, hawaites, mugearites) and intermediate (trachytes). The volcanic activity occurred between 278 and 228 Ma (K-Ar dating: Roubault et al. 1970 b) with a peak in activity at about 270 Ma, corresponding to the A7 ignimbritic flow. This volcanism was marked by three main stages (Boucarut 1971): initial outpouring of several voluminous ignimbritic rhyolite flows along E-W-trending faults which form the northern border of the Permian basin; secondary emplacement of small rhyolitic domes accompanying or post-dating caldera collapses (Vellutini et al. 1976; Gondolo 1989); and ultimate emplacement of basaltic or weakly differentiated basaltic flows and sills.

Thus in Provence as well as in Corsica, after the waning of orogenic magmatism, the second alkaline magmatism occurred in an extensional regime related to an incipient rifting already heralding the Alpine orogenesis (Vellutini 1977; Bonin 1987; Toutin-Morin 1987).

6 Metallogeny

In crystalline Provence, aside from a few isolated mineralizations related to the metamorphic evolution, the main metallogenic epoch was Permian to Triassic in age. In particular, it should be stressed that the well-developed Variscan granitoids are not accompanied by any mineralization.

6.1 Metallogeny Related to Metamorphic Evolution

Two mineralizations are clearly related to metamorphic evolution:

1. In the Tanneron Massif near les Adrets de l'Estérel, scattered scheelite mineralizations with economic concentrations (5 to 6% wt.% $W0_2$ at La Favière Mine) occur within calc-silicate gneiss lenses intercalated in a plagioclasic gneiss formation. A "peri-anatectic" model has been proposed to explain these mineralizations: tungsten-bearing anatectic fluids induced chemical changes as they crossed calc-silicate gneiss lenses (Sonnet et al. 1985).
2. Near the boundary between WS and BS the so-called Collobriérite (i.e., an iron ore consisting of magnetite, almandine garnet, and fayalite) occurs as thin lensoidal bodies within garnet-staurolite mica schists. This mineralization is classically regarded as a metamorphosed sedimentary iron ore which was intercalated in a sedimentary pelitic formation (Gueirard 1957; de Groulard 1982).

6.2 Metallogeny Related to Post-Variscan Evolution

Two types of mineralization are related to this stage of development of fault-bounded basins with detrital infill and bimodal volcanism:

1. In crystalline Provence, numerous Qz-Pb-Zn-F Ba vein-type deposits occur near major E-W or N-S faults either in the basement or in the Permian cover (Solety 1965; Vervialle 1975; Rostand and Turco 1982). Most of them have been extensively mined until recent times. They can be divided in two groups distinguished by their principal metal content, morphology, and relative age: a Qz-Pb-Zn group occurring in the western Maures Massif, and an F-Ba group occurring in the eastern Maures, Tanneron, and Esterel Massifs. The first group could be of end-Stephanian age while the second could be of Permian to lower Triassic age (Baudemont 1985).

Three kinds of metallogenic hypothesis have been successively proposed to explain these mineralizations (review in Begassat 1985).

- A magmatic hypothesis: mineralization is related to Permian late volcanic fluids.
- A "per descensum" hypothesis: mineralization originates through filling of previous fractures by surface brines.
- A paleothermal hypothesis: fluids are related to an extensive geothermal event during Permian and lower Triassic times which accompanied the break up of the Variscan basement.

2. Several small uranium deposits occur in the Permian trough, either as stratiform lenses hosted in sandstones or as veins cross-cutting the volcanics or the metamorphic basement. Among them, the Le Capellan stratiform deposit, near Vidauban, is the

only one to reach an economic size. Up to now, only scarce information about these deposits was available.

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