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Shear deformation and emplacement of the gneissic Canigou thrust nappe *(Eastern Pyrenees)*

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Abstract

The Canigou gneiss nappe is one of the most striking features developed during Variscan convergent tectonics in the Pyrenean chain. The Canigou structure is classically interpreted as a recumbent fold nappe. New data concerned with kinematic analysis of the deformation argue for the importance of thrusting tectonic imprints. Shear criteria analysis indicates that the main transport direction was towards the SW. The mylonitic shear zone described from the bottom of the Canigou gneiss is assumed to represent a main ductile thrust zone, with a magnitude of transport in excess of 30 km.

Introduction

The Canigou massif, located in the axial zone of the Pyrenees appears as a Variscan antiformal structure, which mainly consists of gneisses and micaschists (Figs. 1 and 2). Guitard (1970) interpreted the Canigou gneisses as a recumbent fold. The following assumptions were essential in his interpretation:

1. the augen orthogneisses (Cadi gneisses) were interpreted as a Precambrian basement underneath a Paleozoic transgressive sequence;
2. the 'Balatg' micaschists, wich crop out in a window underneath the gneisses, were attributed to the Paleozoic. The Canigou gneisses were interpreted as the core of a huge recumbent fold with an inverted and a normal limb. The entire structure was refolded in a large-scale E-W trending post-nappe anticline.

The presence of a tectonic repetition has generally been admitted, but the sense of transport and the kinematics of the associated deformation have remained disputed questions. Autran & Guitard (1969) proposed that the sense of nappe emplacement is towards the NE; other authors have described a southward sense (Mattauer et al., 1967; Santanach, 1972; Lagarde, 1978). Another crucial point concerns the evidence for the existence of a recumbent fold, as the abnormal superposition could equally be explained by a thrust. The nappe structure of the Canigou massif has recently been questioned (Soula et al., 1986), nevertheless the 580 M.a. (U/Pb/Zircon) age obtained on Canigou gneisses confirms the presence of a Precambrian basement, and suggests the existence of a major nappe (Vitrac & Allègre, 1975).

Regional mapping of the intensely developed stretching lineations associated with ductile shear deformation and an analysis of the deformational structures in the gneisses allow us to clarify the kinematics of the deformation, and to demonstrate the presence of a major thrusting contact at the bottom of the gneiss slab.

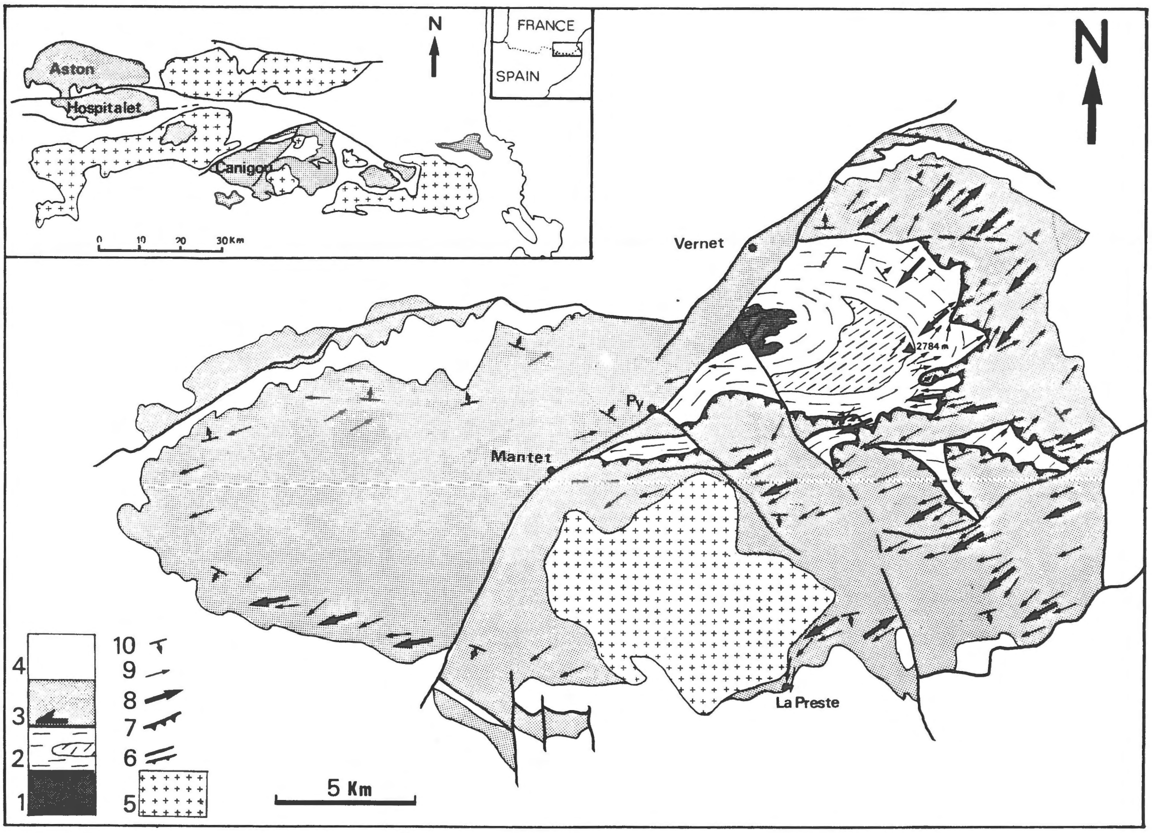


Fig. 1. Structural sketch map of the Canigou Massif, and its location in the eastern Variscan Pyrenees (inset), modified after Autran et al., (1963). 1, Cadi gneiss (Precambrian); 2, Balatg micaschists (Paleozoïc); 2a, Casemi gneiss; 3, Canigou gneiss (Precambrian); 4, marbles (Cambrian) and schists (Ordovician); 5, Costabonne granite; 6, Late faults; 7, Main basal Canigou thrust; 8, shear sense; 9, lineation; 10, Foliation.

Geological setting

Lithostratigraphic components of the Canigou massif

From top to bottom, the massif is made up of the following succession of rocks (Fig. 2):

1. A sequence of alternating schists and metasandstones with a basal layer of marbles classically considered as Cambrian (Cavet, 1957). This sequence is commonly referred to as the 'Canaveilles' and 'Jujols' series.
2. A thick sheet of granitic orthogneiss of the Canigou, essentially represented by augen gneisses, and interpreted as a Precambrian basement (Plate I), (Vitrac & Allègre, 1971).
3. The 'Balatg' micaschists, similar to Paleozoic cover series crop out underneath the gneisses. A homogeneous leucocratic gneiss called the 'Casemi gneiss' and possibly of volcanic origin (Gibson 1987) occurs intercalated within the micaschists.
4. The 'Cadi' gneisses, which are thought to be analogous to the Canigou gneisses. These rocks are intensely affected by migmatisation/partial anatexis.

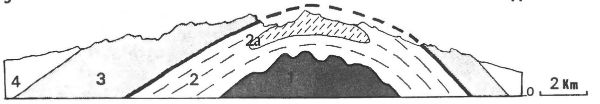


Fig. 2. Diagrammatic cross-section of the main structural units of the Canigou massif. 1, Cadi gneiss; 2, Balatg micaschists; 3, Canigou gneiss; 4, Paleozoïc cover.

In addition, two types of igneous intrusives occur within the above sequence of rocks. These are the 'Granite Profond du Canigou' of 330 M.a. old (Vitrac & Allègre, 1973), a two-mica granite which intrudes the sequence, from 'Cadi' gneisses up to the 'Casemi' gneisses, and the clearly post-tectonic 'Costabonne' and 'Batère' granites with sharp contacts with the surrounding rocks.

Sequence of deformational events
The Canigou massif has been affected by Variscan deformation and metamorphism. Several phases have been recognized:

Phase 1: the major thrusting phase is characterized by a flat-lying S1 foliation (generally parallel to bedding) displaying a mineral stretching lineation (L1) parallel to minor F1 recumbent isoclinal folds (see below).

Phase 2: F2 folds, oriented NE-ENE, refold the S1 foliation. A steeply oriented spaced cleavage S2 is developed in pelites parallel to the axial planes of F2 folds. In addition, 'late' folding phases have been described from the Balatg' window (Gibson, 1988, oral comm.) and from the sedimentary Paleozoic cover (Guitard et al., 1984; Laumonier et al., 1984). In particular, in the 'Balatg area', a third phase resulted in a flat-lying foliation (S3).

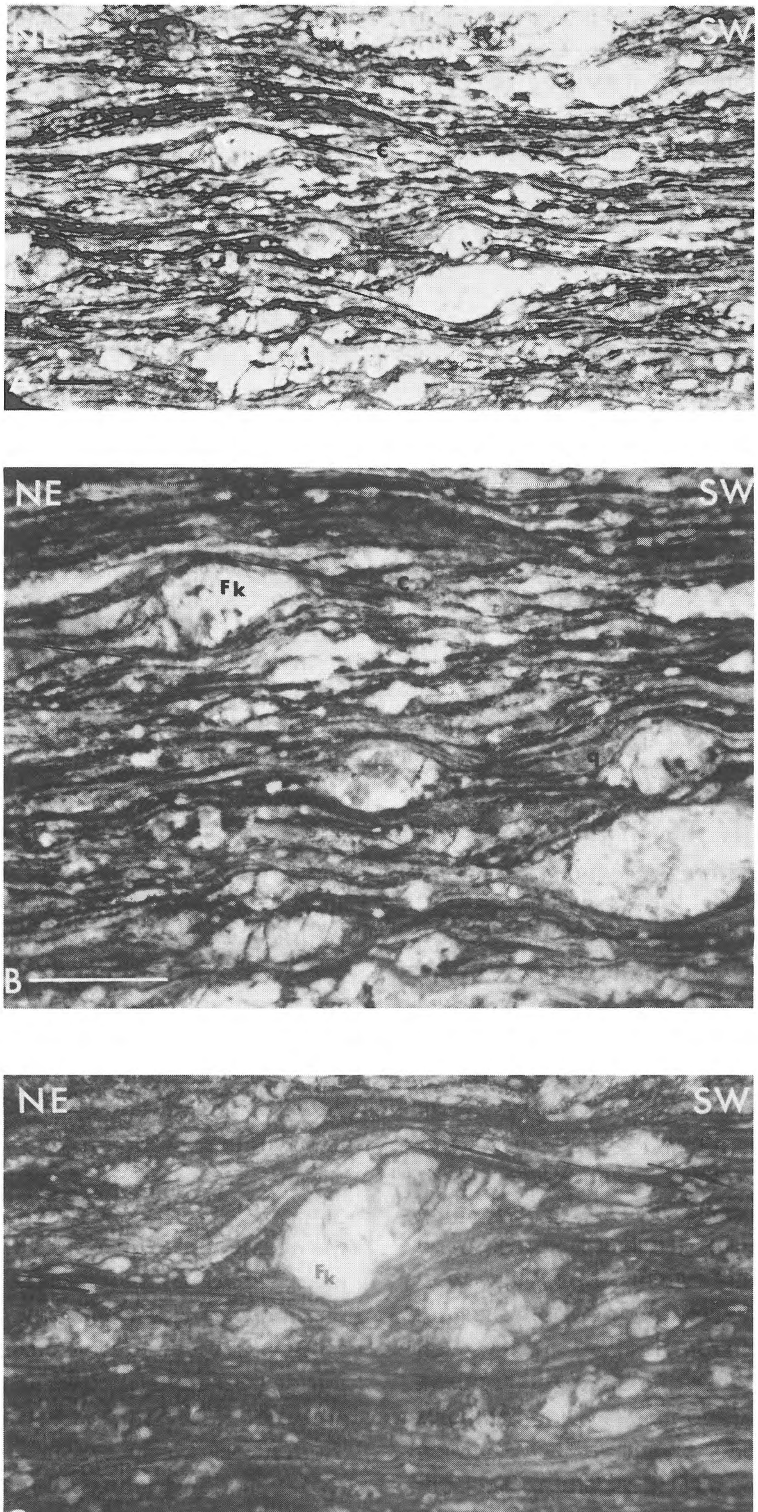
The Canigou metamorphism is a HT-LP metamorphism with a biotite-andalusite-sillimanite facies series. The sillimanite assemblages are spatially related to the occurrence of anatectic melts (Autran & Guitard, 1957). The S1 foliation and shear bands associated with the main phase are defined by oriented synmetamorphic biotite grains, andalusite and cordierite are present as porphyroblasts, their growth post-dates S1 and would, according to Gibson (1988, oral comm.), approximately be contemporaneous with the development of a flat-lying (S3) foliation in metapelites during the third deformation phase. The structural and metamorphic evolution ends with late granite emplacement.

Analysis of the main phase ductile shear deformation in the Canigou gneiss

Augen gneisses, mylonitic gneisses and even almost undeformed gneisses as in 'La Preste' in the upper part of the Canigou sequence (Fig. 1) constitute the main Canigou gneiss body. However, a major part of the gneiss unit consists of augen gneisses which display a plano-linear structure defined by slightly pronounced S1 foliation bearing a NE-SW trending L1 mineral stretching lineation. These microstructures are refolded by a large WNW-ESE trending antiform (Fig. 4) contemporaneous with D2 small scale folds. The foliation is defined by the orientation of synkinematic biotites around not very elongated K-feldspar porphyroclasts. These rocks may contain old polycrystalline aggregates of quartz and 'rapakivi' feldspars. Their X/Z ratio ($X > Y > Z$) is less than 3.

Strain increases downwards in the section and reaches high values within the 100 to 200 m thick basal mylonitic zone (Lagarde, 1978) at the contact with the 'Balatg' micaschists (Figs. 5 and 6). Here, a very pervasive NE-SW stretching lineation is developed. These mylonitics rocks are light-coloured and have small grain sizes. The alternation of fine-grained layers and levels rich in augen feldspar results in a banded aspect of this mylonite. The mylonitic zone is mainly composed of small grain size neoblasts, old porphyroclastic structures occur but are uncommon. Crystals of K-feldspar are broken and elongated, biotite is delaminated, and quartz occurs as elongated ribbons (up to 2 cm long) parallel to L1. Shear bands and pressure shadows attest the heterogeneous character of the deformation; as mentioned above, the intensity of the deformation decreases upwards within the Canigou gneisses slab, but other less thick mylonitic zones (up to 10 m wide) exist within the gneiss pile.

Underneath the gneisses, in the micaschists of the 'Balatg window' synkinematically recrystallized biotites and ribbons of quartz define the S1 foliation. The NE-SW trending L1 lineation is defined by elongated biotite patches and quartz lenses. This prominent mineral stretching lineation is well developed in a quartz-rich horizon where it is parallel to long axes of sheath microfolds (Mat-


NE
SW
c
A
NE
SW
Fk
c
q
B
NE
SW
Fk
C

←
Plate I

A and B – Main facies of the Canigou augen gneiss. Typical S/C structure and retorted K-feldspar (Fk) are indicative of the shear sense towards SW. Sample originates from the middle part of the gneiss slab, southern limb of the Canigou anticline (Estagnol lake). Scale bar left bottom side is 1 cm, q: quartz.

C – Typical monoclinic 'porphyroclast system'. The geometry of the tail and deflected foliation indicate a shear sense towards the SW. Shear bands which become parallel to the S_1 foliation are responsible of inhomogeneous layering. Sample collected in the northern side of the Canigou anticline (Roc Mousquit). Note K-feldspar cataclasis and quartz-fill in tension gashes.

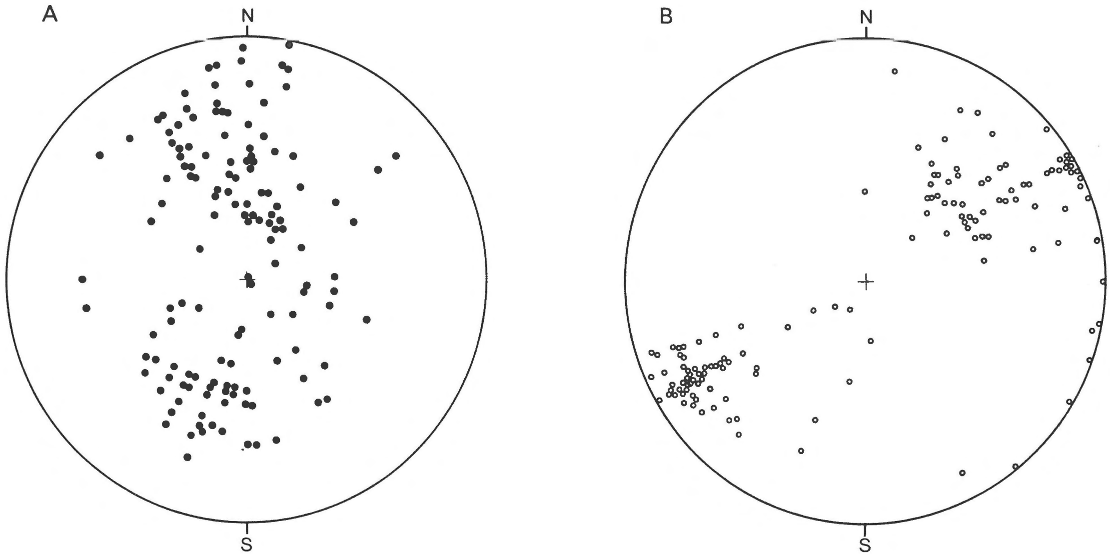


Fig. 3. Orientation diagrams (Schmidt projection, lower hemisphere), showing poles to foliation (black circles), and lineations (white circles).

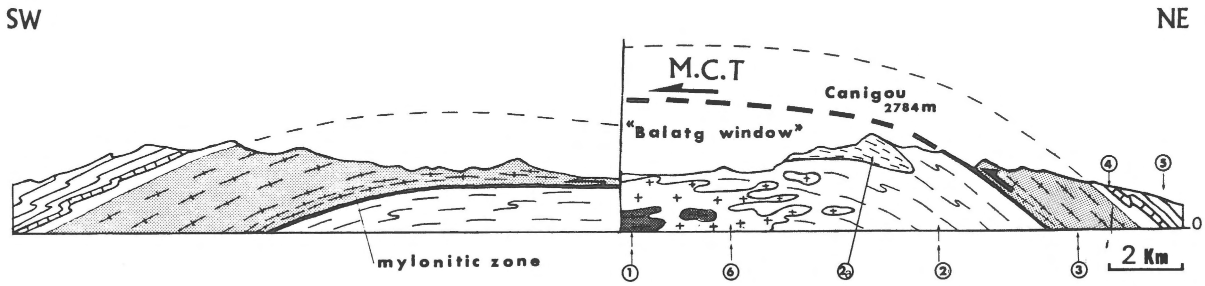


Fig. 4. Geological cross-section through the Mont Canigou. 1, Cadi gneiss; 2, Balatg micaschists; 2a, Casemi gneiss; 3, Canigou ortho-gneiss; 4, Cambrian marble; 5, Ordovician schists; 6, Granite Profond.

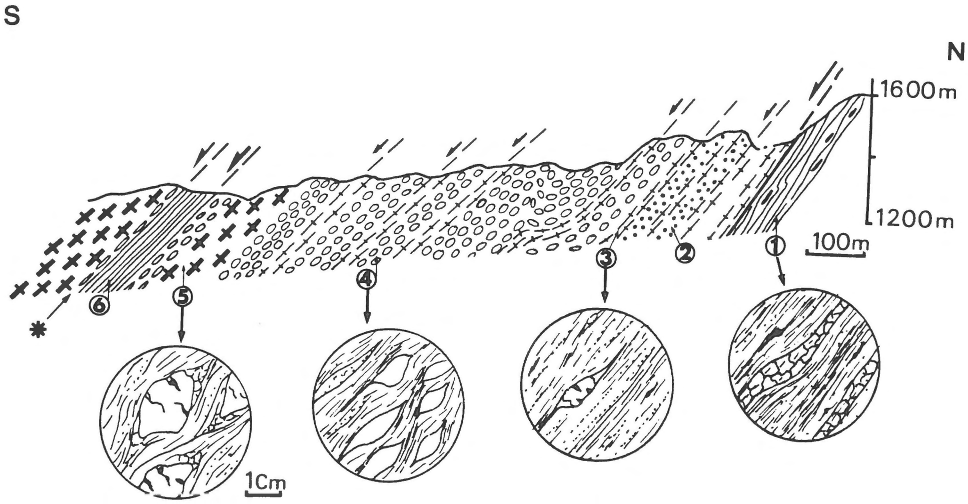


Fig. 5. Detailed cross-section and main tectonic facies of the main Canigou thrust, at St Guillem, in Coumelade valley. 1, Balatg micaschists; 2, quartzites; 3, mylonitic gneiss; 4, strong deformed gneisses; 5, augen gneiss; 6, Phyllonitic micaschists; Star indicates the location of Fig. 6.

tauer et al., 1977; Cobbold & Quinquis, 1980) (Plate IIA).

Above the Canigou gneisses, in the 'Canaveilles' sequence, S1 consists of a chlorite schistosity oblique to bedding planes. These rocks, and the lower Paleozoic schists in particular, are strongly folded during later deformations. It is likely that the rheological contrast between the basement gneisses and the Paleozoïc rocks, led to localization of the deformation along a décollement level to accomodate the intense folding of the sedimentary cover.

Shear criteria

The augen gneisses display a strong shape-preferred orientation of K-feldspar and pressure shadows filled with recrystallized quartz are well developed. For the most strongly lineated tectonites, the X/Z ratio (estimated in sections normal to S1 and parallel to L1) is about 5. The feldspars comprise twinned plagioclase and K-feldspar with microcline twinning. The micas are either large muscovites and porphyroclastic biotites (with undulose extinction) or neoblastic biotite crystals (Plate IIB). Quartz grain boundaries are lobate and their extinction is slightly undulose (Plate IIC). Asymetric recrystallized pressure shadows 'δ' and 'σ' types (Passchier & Simpson, 1986), dragfolds, micafish and shear bands characterize a non-coaxial deformation type. Systematic analysis of these shear criteria allow us to determine a SW directed shearing sense (Van den Driessche, 1986; Van den Driessche & Brun, 1987). Similar microstructures do occur in the mylonites, but sense of shear cannot be macroscopically determinable in these rocks because of the small grain sizes and intense deformation. In the 'Llec' gneiss, which is located in the northern limb of the massif, S/C structures are related to later northward shearing deformation.

Quartz fabrics

Quartz fabrics have been measured in quartz-rich rocks of the Canigou gneisses. Three samples were collected, two from a mylonitic zone of the north limb (Fig. 7a, b) and one from the basal mylonitic zone to the south (Fig. 7c). All samples display a quartz ribbon type structure with an isodiametric recrystallized quartz grain texture. The foliation is outlined by oriented mica grains. Subgrains are developed, and the grains generally show indented boundaries and undulose extinction. The quartz <c> axes diagrams show a clearly monoclinic fab-

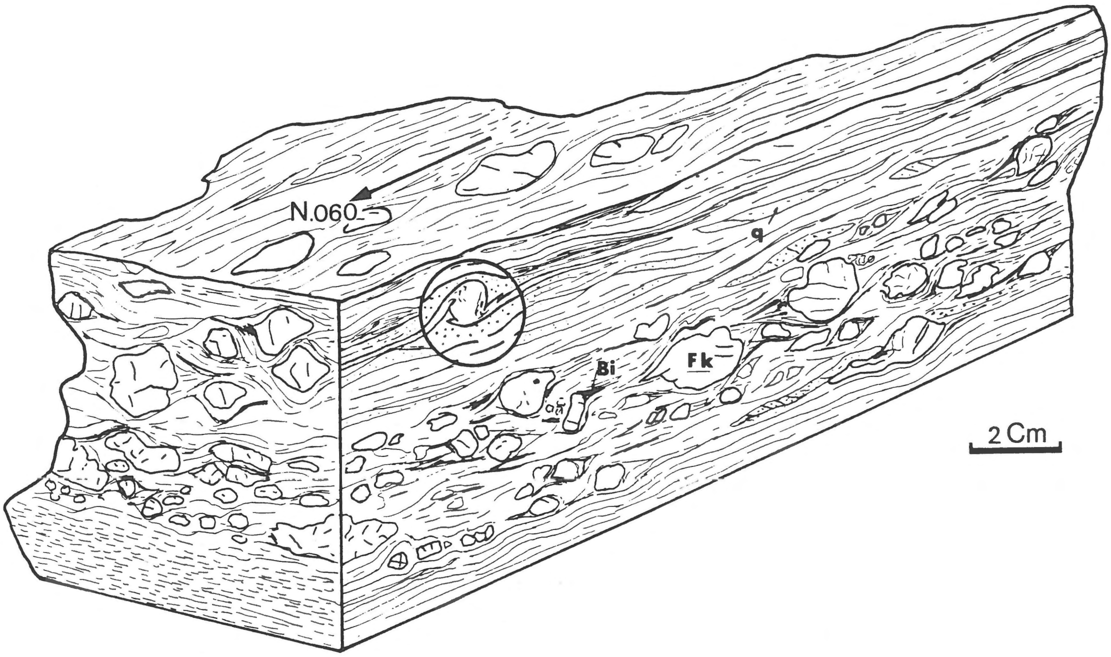


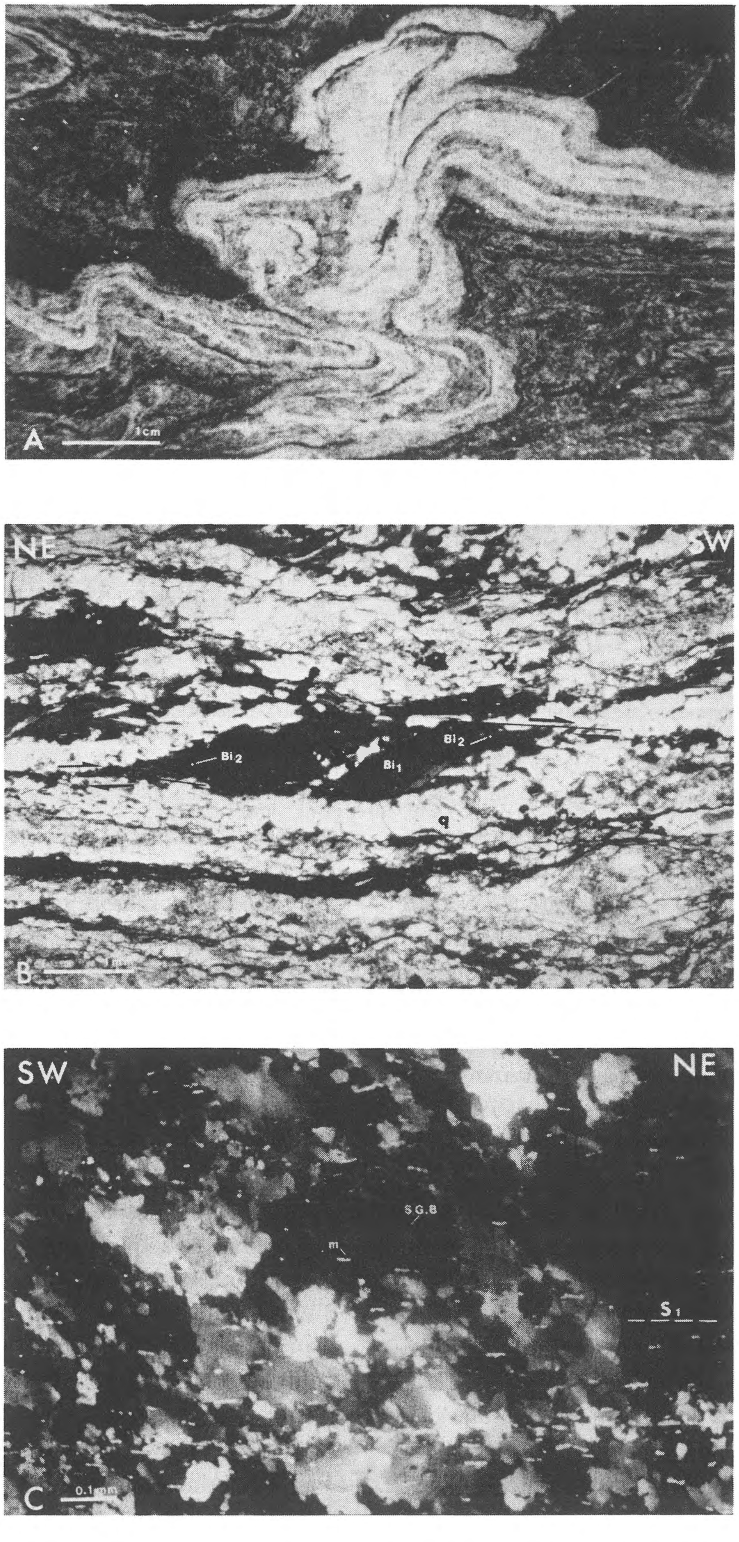
Fig. 6. Inhomogeneous deformation at the sample scale. Fk: potassic felspar; q: quartz; Bi: biotite.

ric with a girdle obliquely oriented at an angle α to the foliation plane, suggesting a shear sense of the upper block towards the South-West. The <c> axes concentration in maxima near the X/Z plane suggests that intra-crystalline deformation in quartz was dominated by basal glide on <a> planes (Fig. 7), which points to relatively low grade synkinematic metamorphic conditions during mylonitic deformation (Lister & Williams, 1979; Bouchez & Pecher, 1981). In some samples (Plate IIC) where migration recrystallization took place after development of S1, the shear sense deduced from the quartz fabrics could be interpreted to be the result of a late thrusting event (Brunel, 1980; 1986).

Discussion and conclusion

Various shear criteria indicate that the Canigou gneisses are affected by major ductile non-coaxial progressive deformation event (D_1), the associated NE-SW trending stretching lineation strongly suggests a relationship with the direction of nappe transport (Burg et al., 1987). The shear sense criteria, related to this ductile deformation affecting the entire Canigou massif, points to south-west directed nappe emplacement. The shear strains appear to be inhomogeneously dispersed, and high-strain mylonitic zones are mainly concentrated near the bottom of the gneiss pile. This deformation gradient near the base of the slab lead us to propose the existence of a main basal thrust zone. Such a thrust alone could explain the tectonic repetition in the pile, and allows to dispense with a recumbent fold interpretation as proposed by Guitard (1970).

As emphasized by Casas (1986), the repetition of the different gneiss types (G1, G2, G3) within the Canigou massif is not clearly demonstrated. In addition, the stratigraphic correlation between the 'Balatg' marbles and Cambrian basal marble is not an unquestionable fact. The 'Balatg' marble for instance could equally be related to another level, higher in the sequence. In the 'Py' area (Fig. 1), within the 'Balatg' window, the presence of a major fold is difficult to confirm because of complexities due to later faulting and intrusive granitic bod-


A
1cm
NE
SW
Bi2
Bi1
Bi2
q
B
1mm
SW
NE
SG.8
m
S1
C
0.1mm

←
Plate II

A – Typical sheath fold in a quartzitic horizon in the upper part of the Balatg schist formation. Section normal to the main stretching lineation. (Scale bar is 1 cm).

B – Microphotograph of the mylonitic augen gneiss, common facies type of the Canigou Massif, collected 200 m above the basal contact north limb of the Canigou anticline A. Note micafish biotite made up by a clastic biotite (Bi1) core and neorecrystallized biotites (Bi2) within the tails. Monoclinic symmetry of the system indicates a southwards shear sense. Quartz aggregates display a ribbon structure. (Scale bar is 1 mm). q: quartz ribbon.

C – Recrystallized texture in quartzitic level at the main Canigou thrust sole (Pic des trois vents, Southern side of the Canigou anticline). Quartz grain size varies from 50 μm to 300 μm, smaller grains accentuate shear bands parallel to S_1 cleavage, marked by muscovite (m). Note lobate grain contours and muscovite included inside quartz grain. These observations demonstrate late quartz grain growth by migration recrystallization. S.G.B.: subgrain boundaries are pinned at included muscovites. The monoclinic symmetry of the system characterizes a sinistral shear sense towards the SW. (Scale bar is 0.1 mm).

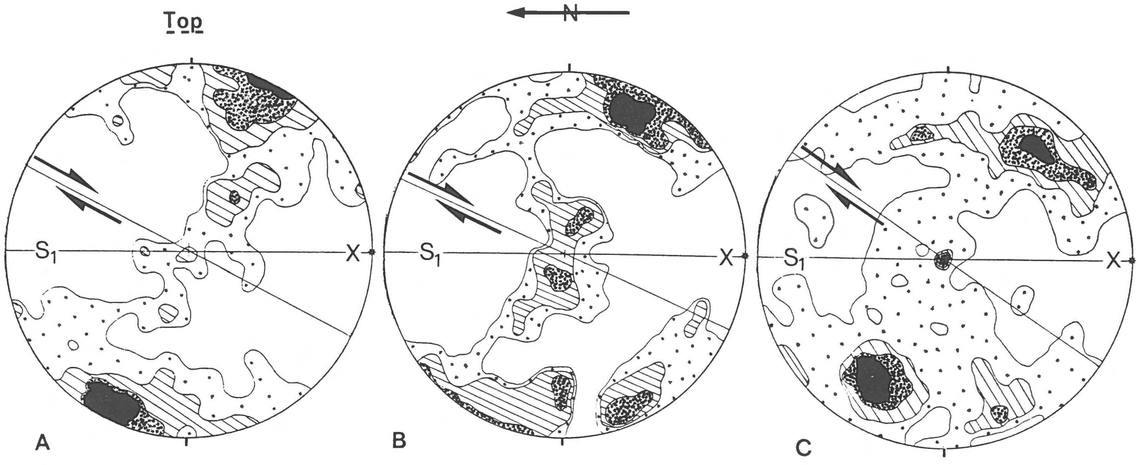


Fig. 7. P.O.A. <c>. quartz <c> axes fabrics within quartz rich rocks (Schmidt projection, lower hemisphere). A) 200 measurements, contours at 0.5,2,3.5,5% per 1% area. B) 200 measurements, contours at 1,2,3,5% per 1% area. C) 200 measurements, contours at 1,2,4,7% per 1% area.

ies. In that case, we do not have evidence for large scale recumbent folding tectonics.

We assume that the thick mylonitic zone (200 m) developed at the bottom of the Canigou gneiss slab represents a main ductile thrust ('Main Canigou Thrust!') comparable (on a small scale) with the Himalayan Main Central Thrust. We suggest that the Canigou nappe may be interpreted as a monoclinal Precambrian gneiss slab thrust over the Paleozoic series towards the south-west. The transport distance exceeds 30 km when measured in a direction N 060° parallel to the stretching lineation. The Canigou thrust is probably continuous into the Roc de France Massif (Lagarde, 1978), and may persist towards the west below the other gneissic domes of the axial zone (Aston, Hospitalet). In this context, a huge crustal-scale ductile shear zone doubling the Variscan crust could be a viable hypothesis.

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