Comparison of the western Aston-Hospitalet and the Bossòst domes: Evidence for polymetamorphism and its implications for the Variscan tectonic evolution of the Axial Zone of the Pyrenees

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Abstract: The Bossòst and the western Aston-Hospitalet structural and metamorphic domes have similar metamorphic characteristics. Textural observations show garnet and staurolite as earlier phases, andalusite, cordierite and sillimanite as later phases. Metastable staurolite–cordierite–biotite–muscovite assemblages found in both domes indicate a decompressional path from medium pressure–medium temperature regional metamorphism producing garnet and staurolite to a low pressure–higher temperature contact metamorphism resulting in the growth of andalusite, cordierite and sillimanite. In the Bossòst dome these two metamorphic events are separated by a phase of strong non-coaxial deformation which is preserved in a prominent shear zone. The shear zone is inferred to have facilitated decompression as an extensional shear zone. In the Aston-Hospitalet domes, the similarity of the metamorphic characteristics with the Bossòst dome is not matched with the mircostructural evidence. This may be due to the lack of a suitable lithology which prevented subsequent metamorphic phases to form, so that earlier fabrics had been completely obliterated by later thermal and tectonic events. The presence of large migmatite zone along the western Aston gneiss may record such an event. The tectonic conclusions derived from the Bossòst dome can not readily be applied to the Aston-Hospitalet domes.

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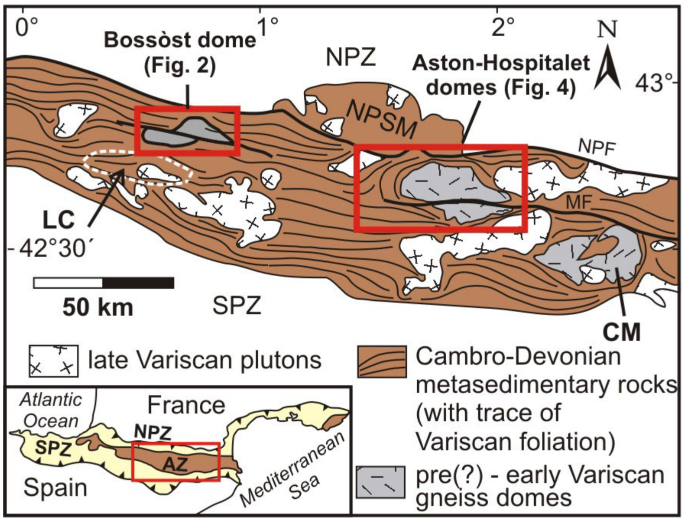
Introduction

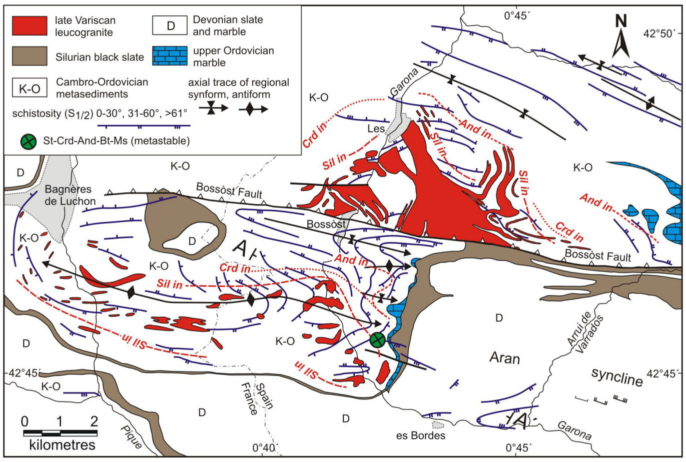
The Variscan core of the Pyrenees, the Axial Zone, consists of three major tectonic elements: Cambrian to Devonian metasedimentary rocks, pre- or early-Variscan orthogneisses, seated in Cambro-Ordovician strata, and Late Carboniferous granitic plutons. The Axial Zone is separated from the Alpine fold and thrust belts of the Pyrenees by the steep North Pyrenean fault zone and south-dipping thrusts (Nogueras Zone) to the south. Within the Axial Zone gradually deeper structural levels are exposed towards the east (Majeste-Menjoulas & Debat 1994). The most striking structural features are elongated structural-metamorphic domes aligned parallel to the E-W trend of the Axial Zone (Figure 1). They are composed of cores of orthogneiss gneiss or granitic intrusions mantled by greenschist to amphibolite facies Cambro-Ordovician schists. The metasedimentary rocks in the proximity of the dome cores are of medium to high metamorphic grade and possess a distinct flat-lying schistosity, termed infrastructure. Away from the core zone metasedimentary cover rocks are gradually less metamorphosed and display a steeper, subvertical main foliation, termed suprastructure. While the infrastructure is thought to represent deeper structural levels, the suprastructure is inferred to be developed into shallower levels (Carreras & Capella 1994). The temporal relationship of infra- and suprastructure is reflected in the various tectonometamorphic models evoked for the evolution of the Axial zone:

Figure 1. Sketch map of the Axial Zone



Sketch map of the Axial Zone (AZ) of the central and eastern Pyrenees with the three major tectonic elements and the trace of Variscan foliation. CM - Canigou massif; LC - Lys-Caillaouas massif; MF - Merens fault; NPF - North Pyrenean fault; NPZ - North Pyrenean Zone; NPSM - North Pyrenean satellite massifs; SPZ - South Pyrenean Zone. Modified after van den Eeckhout & Zwart (1988) and Gleizes et al. (1997).

Figure 2. Tectonometamorphic map of the Bossòst



Tectonometamorphic map of the Bossòst structural and metamorphic dome showing mineral isograds and the trend of the S1/2 foliation. The location of the crucial metastable assemblage staurolite-cordierite-andalusite-biotite-muscovite is indicated. Modified after Mezger & Passchier (2004) with lithology from de Sitter & Zwart (1960a).

1. coeval development of infra- and suprastructure during compression (de Sitter & Zwart 1960b);
2. later steepening of an initial flat lying foliation (Matte 1969);
3. initial extension followed by compression leading to diapiric uprise of gneiss domes (Pouget 1991, Soula 1982);
4. transpression with earlier development of the deeper seated infrastructure overprinted by later steep crenulation cleavage at shallower levels (Carreras & Capella 1994); transpression (Gleizes et al. 1998);
5. a combination of compression followed by extension or doming (Aerden 1994, 1998, Gibson 1989, 1991, van den Eeckhout & Zwart 1988, Zwart 1986). Most recently Mezger and Passchier (2003) and Olivier et al. (2004) suggested local extension due to strain partitioning in an overall compressive or transpressive setting.

A recent study of the Bossòst or Garonne dome in the central Pyrenees, incidently the original location where the important interaction of metamorphism and deformation was first postulated in the landmark paper by Zwart (1962), has shown that polymetamorphism, inferred from preserved metastable phases, plays a crucial role in distinguishing individual metamorphic and deformation events and developing pressure-temperature (P-T) paths (Mezger & Passchier 2003, Mezger et al. 2004). An important metastable assemblage comprises staurolite, cordierite, muscovite and biotite (García-Casco & Torres-Roldán 1999, Holdaway et al. 1982, Pattison et al. 1999). The current study focusses on the tectonometamorphic evolution of the Aston-Hospitalet massifs, tectonic and metamorphic domes in a similar tectonic setting in the eastern Axial Zone. The objective of this paper is to outline similarities and differences of the metamorphic character of both regions, and present first conclusions of petrographic studies of an ongoing study.

Summary of the metamorphic and tectonic evolution of the Bossòst dome

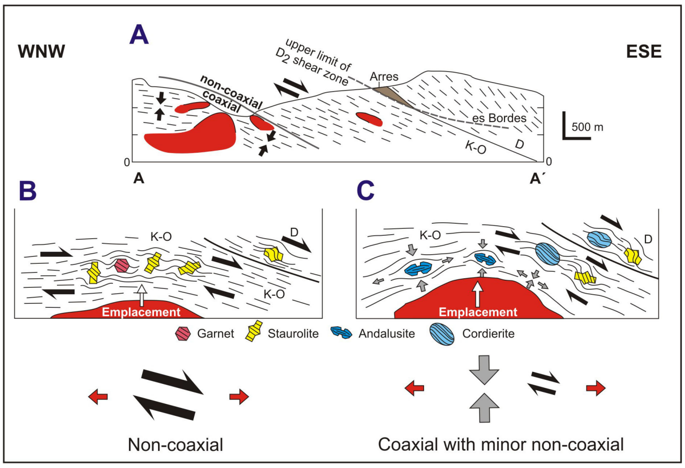
The Bossòst dome is a 35 km long and 15 km wide structural and metamorphic dome, located in the central Axial Zone, bound by the Northern Pyrenean Fault and by the Aran Valley synclinorium. The E-W-trending Bossòst Fault, part of orogen-parallel mylonite zones of latest Variscan or Alpine age (Carreras & Cirés 1986, McCaig & Miller 1986), divides the Bossòst dome into a northern half dome with an exhumed core of leucocratic muscovite-hornblende granites and two-mica granites, and a southern doubly plunging antiform with smaller, elongated, E-W-aligned bodies of granitic intrusions. The contact between granite and the mantling metasedimentary rocks is intrusive, generally crosscutting a pre-existing schistosity. Absence of internal deformation and ductile fabrics indicates that Bossòst granites are of Late Carboniferous age, similar to the Bassiès (312 Ma) and Mont Louis-Andorra (305 Ma) plutons (Gleizes et al. 1997).

Mantling the granites are mica-quartz schists and minor micaceous quartzites and quartzites of Cambro-Ordovician age (Zwart, 1963; Garcia-Sansegundo, 1996), which grade into phyllites towards the margins of the dome. They are overlain by Ordovician marble, carbonaceous Silurian slate and Devonian slate and marble (de Sitter & Zwart, 1960).

The main foliation within the Bossòst dome is a flat-lying schistosity in the core zone and a steeper foliation along the marginal areas and in the overlying post-Ordovician rocks. While the main schistosity in the northern section forms a half dome, south of the Bossòst fault it outlines a doubly plunging ESE-trending antiform. Mineral lineations are obliquely oriented to the antiformal fold axis and trend NW-SE (Mezger & Passchier, 2003). The tightly folded Devonian cover units have moved southward over a décollement located at the base of the Silurian black slates (Zwart, 1962; Matte & Xu Zhi, 1988; Garcia-Sansegundo, 1996).

Mezger & Passchier (2003) have shown that two distinct metamorphic events occurred after formation of the main S1 foliation (Figure 3). Medium pressure-medium temperature regional M1 metamorphism was followed by low pressure-high temperature M2 contact metamorphism, related to granitic intrusion. The two metamorphic events are divided by a period of strong non-coaxial D2a deformation in an extensional setting and distinguished by polymetamorphic assemblages. M2 is coeval with coaxial deformation within the contact aureole and doming during continuing emplacement of the granitic core. The final domal shape resulted from later NNE-SSW compression that formed local to regional folds.

Figure 3. Summary of the main tectonic phases in the Bossòst dome



A. Sketch of present day observed shear zone in the eastern part of the southern antiform. Location indicated in Figure 2 . B. Early non-coaxial phase of the shear zone. C. Continuous rising of Bossòst granite causes predominant coaxial deformation within the contact aureole, while non-coaxial shearing continued further away in the overlying rocks. Modified after Mezger & Passchier (2003).

M1 is characterized by successive growth of biotite, spessartine garnet and staurolite. Staurolite inclusion trails are straight, and random orientation of crystallographic length axis indicate that it nucleated in a period of deformational quiescence. Staurolite porphyroblasts experienced rotation with a uniform top-to-the-SE sense of shear, within a 1.5 km thick zone in the eastern part of the southern antiform. This is best preserved in staurolite-garnet schist, whose bulk rock composition did not favour growth of staurolite-consuming cordierite. Almandine garnets nucleated after staurolite. (Mezger & Passchier, 2003; Mezger et al., 2004).

M2 is indicated by overgrowth of staurolite by andalusite and cordierite. Centimetre-sized poikiloblastic andalusite porphyroblasts commonly possess inclusion trails have a convex geometry, indicating growth during coaxial deformation, flattening. Cordierite appears proximal to granitic intrusions in various parageneses with staurolite, garnet, andalusite and sillimanite, all of which are commonly found as inclusions within centimetre sized cordierite. Staurolite and andalusite inclusions in cordierite show strongly corroded rims, suggesting consumption of both phases to form cordierite. The presence of coexisting cordierite, andalusite and staurolite, and evidence for corrosion of andalusite suggest that the andalusite-producing reaction had not been completed, when cordierite-producing reaction began to consume andalusite. The presence of cordierite- and aluminosilicate-bearing assemblages within the proximity (< 1 km) to granitic intrusions suggests that M2 is related to contact metamorphism. In the northern part of the Bossòst dome a contact aureole is prominently developed and had almost completely annealed the M1 paragenesis, where only staurolite relics remain. Cordierite shows with few exceptions no indication of synkinematic growth. Fibrolitic sillimanite occurs close to granitic intrusions, commonly observed grow epitaxial on biotite and to form millimetre-long lenses, but rarely observed replacing andalusite.

M1 regional metamorphic conditions are best preserved in garnet-staurolite-biotite assemblages. Pressure conditions of this assemblage are poorly constrained by traditional geobarometry. By using computer software, THERMOCALC (v. 3.2.1) of Powell et al. (1998), P-T pseudosections and AFM diagrams can be calculated with known bulk rock chemistry. In this case pressures of 5.5 kbar and 580°C were calculated for M1 (Mezger et al. 2004). Pseudosection also show, that in the garnet-staurolite-andalusite-cordierite schist staurolite is not stable within the cordierite-andalusite-biotite stability field. Calculated pressures of 2 kbar and temperatures of 525°C indicate decompression and cooling during M2. Actual temperatures during peak-contact metamorphism were probably generally higher in the sillimanite-bearing assemblages closer to the granite intrusions.

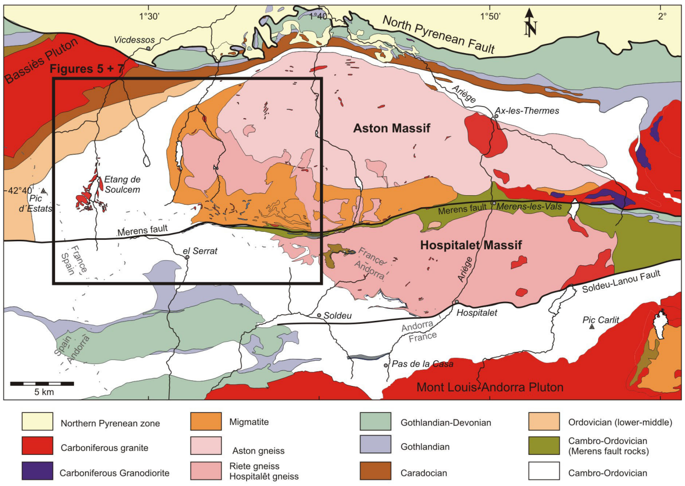
The presence of a 1,5 km thick shear zone with hanging wall down sense of shear preserved in earlier medium pressure assemblages, the strong non-coaxial deformation that separates earlier medium pressure from a later low pressure metamorphism suggests that the D2a shear zone facilitated uplift of the core of the Bossòst dome in a regional extensional setting, similar to that of a metamorphic core complex. The difference of 3,5 kbar equals approximately 10-11 km of exhumation. The time frame for activity of the shear zone can only be guessed due to the lack of geochronological data, but can be constrained if a mid-Westphalian (c. 310 Ma) age for the formation of S1 (Matte & Xu Zhi 1988) and an approximate intrusion age of the granite of 300 Ma is assumed. Mezger & Passchier (2003) conclude that the Bossòst dome can be interpreted as the result of two compressional events separated by a temporally and probably spatially restricted dome-subparallel extension due to strain partitioning caused by rheological heterogeneities in an overall bulk compressional setting. Rheological heterogeneities could be found in orthogneiss cores of the structural-metamorphic domes. Such a core is not obvious in the Bossòst dome, but foliated diorite crosscut by granite has been observed in the core of the northern part of the dome. Geochronological dating of this diorite is planned by the author.

Structural and metamorphic characteristics of the Aston-Hospitalet domes

Geological setting

The Aston and Hospitalet massifs form the largest domal structures in the Axial Zone and consist of large orthogneiss cores mantled by Cambro-Ordovician metasedimentary rocks. The two domes are separated by a narrow E-trending mylonite zone, the Merens Fault, which was active during the latest Variscan or the Alpine deformation (Figure 4 , Carreras & Cirés 1986). Cambro-Ordovician rocks are overlain by Silurian and Devonian slate, separated from the Northern Pyrenean Zone by the steeply dipping North Pyrenean Fault. To the south, Cambro-Ordovician rocks are intruded by the late Variscan Mont Louis-Andorra pluton, and locally overlain by Silurian and Devonian slate in the southwest. The Soldeu-Lanous fault, a mylonite zone considered to be of the same age as the Merens fault, marks the southern boundary of the Hospitalet orthogneiss (van den Eeckhout 1986).

Figure 4. Geological overview



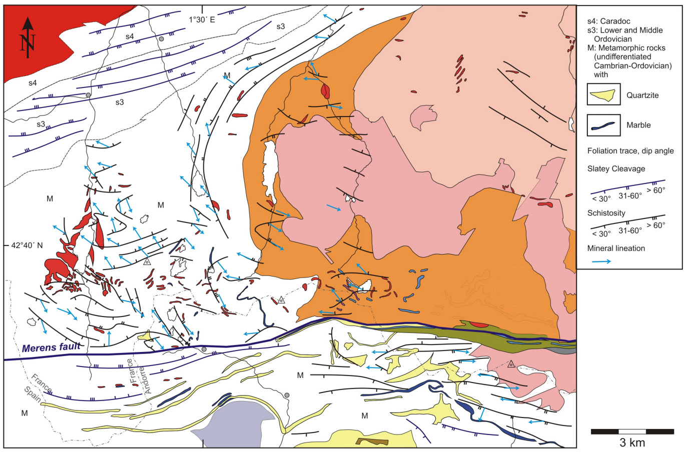
Geological overview of the Aston and the Hospitalet domes with location of Figures 5 and 7. Modified after Casteras et al. (1969), van den Eeckhout (1986) and Besson (1991).

The Cambro-Ordovician metasedimentary rocks are commonly graphite-bearing pelitic rocks composed of, depending on metamorphic grade, quartz, chlorite, mica, garnet, staurolite, andalusite, sillimanite, cordierite. Common accessory phases are zircon, apatite and ilmenite. Plagioclase occurs locally where it can be a major component. Epidote and tourmaline are locally occurring trace minerals. Horizons of marble and quartzite up to 100 m thickness, and mapable conglomerate and mafic lenses are intercalated with the metapelitic schist (Besson 1991, Casteras et al. 1969, van den Eeckhout 1986). Aplitic and granite pegmatite dikes intrude the metasedimentary rocks.

The orthogneisses are commonly garnet-bearing two mica granite gneisses, subdivided further based on appearance (Besson 1991, Casteras et al. 1969). A penetrative gneissic foliation is present throughout the domes, and development of augengneiss can be observed (van den Eeckhout 1986). The protolith age of the orthogneisses is not known.

A broad zone mapped as pelitic migmatites mantles the western and southern margin of the Aston gneiss (Besson 1991, Casteras et al. 1969). However, field work for this study has shown that in the western part the migmatites resemble a coarse paragneiss with a well preserved gneissic foliation. Actual migmatites, rocks that display signs of partial melting (leucosomes) or schlieren fabrics, have been observed closer to the contact with the gneiss. They are labelled as "M" on the map (Figure 5). The orthogneiss also experienced migmatization.

Figure 5. Foliation trend and mineral lineation

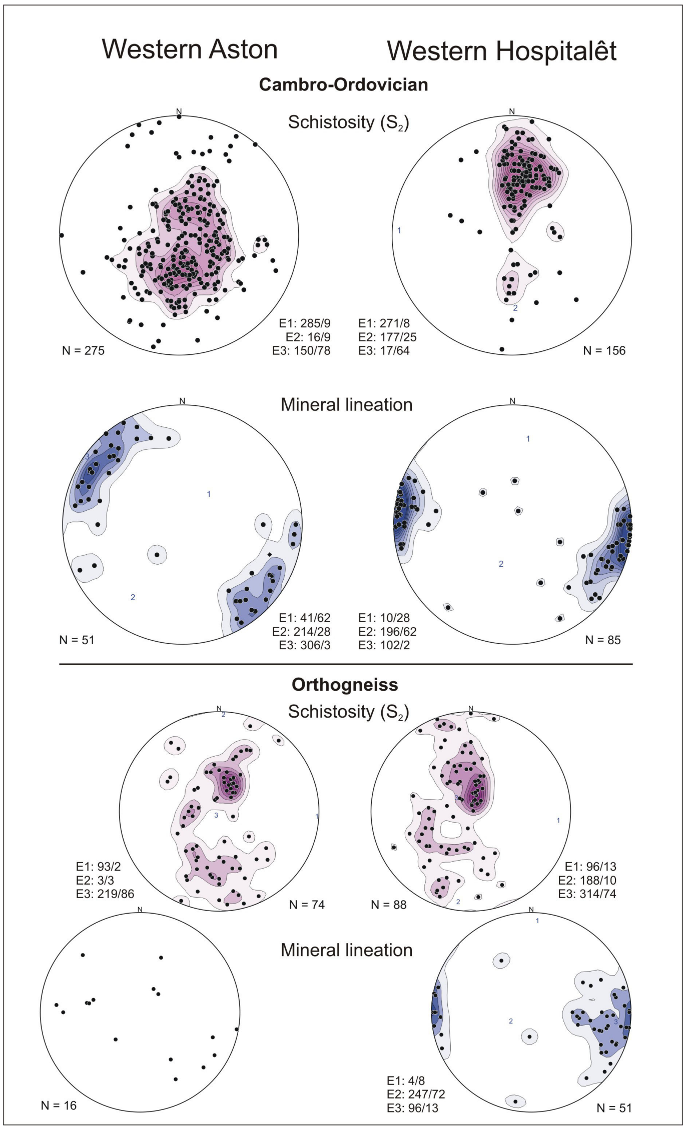


Foliation trend and mineral lineation of the western Aston and Hospitalet domes. Same geological symbols as in Figure 4. For clarification the colours of the Caradoc and Lower to Middle Ordovician units were replaced by signatures.

Structural character of the Hospitalet dome

The orientation of original bedding of the Cambro-Ordovician metasedimentary rocks can still be recognized in the Hospitalet dome. In the eastern part of the dome, bedding is steeply northerly dipping, while in the western part bedding is folded by southwesterly dipping folds with easterly vergence (van den Eeckhout 1986). The major foliation, referred to as S2, is steeply northerly to northeasterly dipping in the eastern part. In the western part the main schistosity is E-W striking with predominantly moderate to steep southerly dips that grade to steep northerly dipping slaty cleavage further west, towards the border with France and Spain (Figs. 5, 6). A younger, generally steeper dipping crenulation cleavage of similar orientation locally overprints S2. A well developed mineral lineation, defined by mica on S2, is shallowly plunging with easterly trends (Figure 6). A foliation and lineation developed in the orthogneiss have orientations similar to those in the mantling metasedimentary rocks (Figure 6). van den Eeckhout (1986) traces the main schistosity of the metasedimentary rocks into the gneiss, but also notes an angle between the foliation along the contact, which is interpreted as the result of later mylonitic deformation.

Figure 6. Stereographic projection



Stereographic projection of the major foliation and lineation in Cambro-Ordovician schist and orthogneiss. Data of the slaty cleavage, outlined in blue in Figure 5, is not included. Equal area, lower hemisphere projection with Schmidt net.

Structural character of the Aston dome

North of the Merens fault the orientation of foliation is more varied (Figure 5). Original bedding can be observed, though difficult to measure, in the lower grade slates along the northern flank of the Aston dome. The slaty cleavage is steeply dipping to subvertical with easterly strike orientation in the eastern and northern part of the dome grading into an east-northeasterly strike direction in the western part. The dip direction is generally northerly, but easterly dips prevail along the contact with the Bassiès pluton (Figure 5). If this is due to folding or represents dip fanning related to the intrusion of the Bassiès pluton remains to a conjecture. In the higher grade schistose rocks, isoclinally folded, sheared quartz layers are indicative of an older foliation. The main schistosity, which is referred to as S2, is a spaced schistosity which grades into a continuous schistosity with increasing metamorphic grade towards the contact with the orthogneiss. At the eastern termination of the Aston gneiss the schistosity wraps around the gneiss, dipping moderately to steeply east to southeast (Bon et al. 1994). In the western Aston dome near the gneiss core S2, strikes southwesterly with moderate northwesterly dip angles, and gradually shifts to northerly and southeasterly strikes with shallow westerly dip angles. Six kilometres west of the orthogneiss margin, orientation of S2 varies considerably. This can be attributed to late Variscan granites that are centred around the Etang de Soulcem, which deflected the schistosity during intrusion (Verhoef et al. 1984). The Merens fault, which is difficult to localize in the field, nevertheless results in a marked structural break. The slates to the south have a steeply northerly orientation, while the schist to the north vary in dip direction, but maintain a shallow attitude. This strongly suggests that the Merens fault postdates development of S2. As a result, S2 yields a wide clustering on stereographic projection, a distinct different appearance than the semi-girdle of the S2 in the western Hospitalet dome (Figure 6). Orientation of mineral lineation is also wider dispersed and with an average trend of 126° slightly oblique (24°) to lineation in the Hospitalet dome, although with similar shallow plunge angles.

The foliation and lineation in the Aston orthogneiss display a similar dispersion as those of the mantling schist, and are very similar to that of the Hospitalet gneiss (Figure 6). This suggests that development of S2 in the schists of the Aston dome is coeval with that of the foliation in the Aston gneiss, although this could not yet be supported by direct field observation.

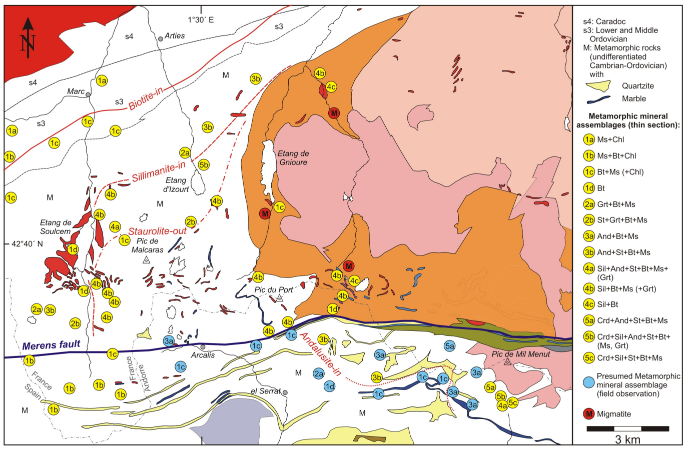
Mylonitic zones are observed in the proximity of the Merens fault (Carreras & Cirés 1986) and as steep discrete metre-scale mylonitic bands throughout the Cambro-Ordovician schist (Soula et al. 1986).

Shear sense indicators in the mica schist are not very common, and are mostly c'-type shear bands (Figure 13). The inferred sense of shear is generally top-to-the-ESE or hanging wall up. Most of the shear sense indicators observed are located close to the contact with the orthogneiss. Other kinematic indicators such as boudinaged and/or rotated quartz veins are disregarded because of ambiguous interpretation.

Metamorphic characteristics of the western Aston dome

Characterization of the metamorphic grade is established by means of metamorphic mineral assemblages and textural relationships observed in thin sections, which are listed on Tables 1 and 2. This method is preferred over mapping mineral or reaction isograds or metamorphic mineral zones. These methods all require very detailed sampling and knowledge of chemical equilibrium and bulk rock composition, which are very difficult to establish in this terrain. As a compromise, the first or last appearance of suitable major phases is projected as a line on the map (Figure 7). Important equilibria reactions which are inferred from the observed assemblages and textural relationships are listed on Table 2. It should be noted that there are no mineral analyses by electron microprobe or whole rock chemistry yet available in this stage of the study.

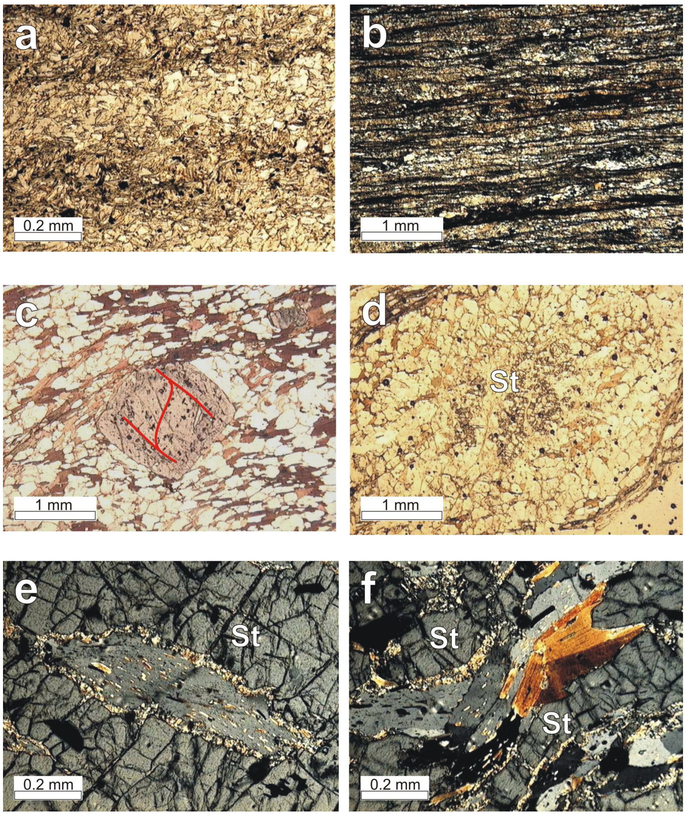
Figure 7. Metamorphic mineral assemblages



Metamorphic mineral assemblages and selected mineral isograds for the Cambro-Ordovician metasedimentary rocks of the western Aston and Hospitalet domes.

Outside the narrow contact aureole of the Bassiès pluton, near the villages of Marc and Arties, the lowest grade rocks are fine grained Ordovician slates. The slates possess a spaced cleavage and have average grain sizes of 50 µm. They are composed of quartz, muscovite and chlorite (assemblage 1a). Towards the southeast the grain size increases to approximately 100 µm, coinciding with the appearance of biotite (assemblage 1b, Figure 8 a). With increasing biotite abundance, the amount of chlorite diminishes (assemblage 1c, Figure 8 b). The local occurrence of biotite-quartz schist (assemblage 1d) appears not to be correlated to metamorphic grade and is most likely the result of bulk rock composition.

Figure 8. Thin section photographs from the western Aston dome



a. Fine grained muscovite-chlorite slate (assemblage 1b, sample 98-97). Plane polarized light (PPL).
b. Spaced cleavage developed in a muscovite-chlorite- biotite schist (assemblage 1c, sample 98-101). Crossed polarized light (XPL).
c. Garnet with graphite inclusion trails preserving an earlier crenulation cleavage. PPL.
d. Xenoblastic staurolite in a biotite-quartz matrix, partially altered to sericite (assemblage 2b). PPL.
e. Quartz lens in staurolite with parallel white mica and opaque inclusions.
f. Quartz lenses with folded inclusions overgrown by staurolite. XPL.

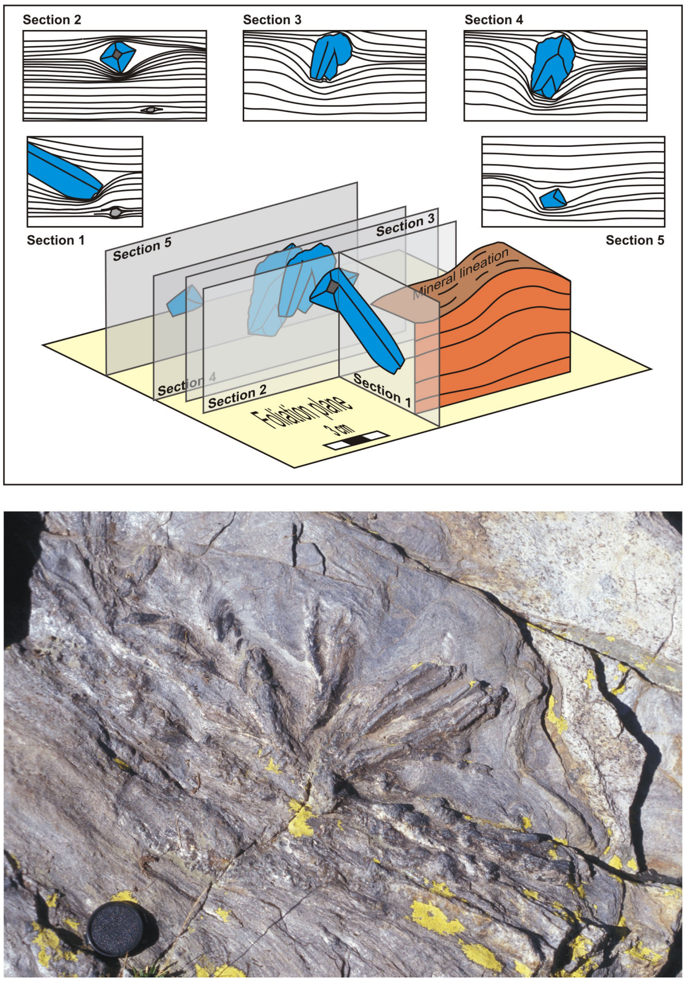
The next minerals to appear are garnet and staurolite (assemblages 2a and 2b). Garnets are commonly subhedral and contain inclusion trails of quartz and graphite. In some samples garnets display straight inclusion trails that are commonly obliquely oriented to the external foliation. In some localities inclusion trails in garnet preserve an older crenulation cleavage (Figure 8 c). Periodical garnet growth can be inferred in some cases from zonation evident from a dusty core and a clear rim. Garnets commonly occur as an accessory phase, seldom amounting up to several weight percent, with sizes up to 1.5 mm. Large, centimetre sized poikiloblastic staurolite occur in garnet-bearing schist (assemblage 2b). Staurolite can form subhedral to anhedral, often twinned, porphyroblasts or have an irregular xenoblastic shape (Figure 8 d). Alteration at the rims to fine grained white mica (sericite) is very common. Inclusions of opaque phases and quartz can form trails that are straight, often oriented obliquely to the external foliation, suggesting a relative rotation of the staurolite porphyroblast. At some localities, the inclusion trails trace a crenulation cleavage, which is absent in the matrix, indicating that the staurolite porphyroblast nucleated prior to the development of the present schistosity (Figure 8 e, f). Smaller grain size of quartz found as inclusions than those in the matrix also suggest that staurolite grew at a time when the rock was finer grained. Due to the lack of textural relationships the sequence of appearance of garnet and staurolite can not be determined. Both phases can be viewed as the result of the breakdown of muscovite and chlorite:

1. muscovite + chlorite + quartz = almandine + annite + H2O
2. muscovite + chlorite = staurolite + biotite + quartz

The staurolite-forming reaction (2) also produces biotite, which appear as large biotite porphyroblasts truncated by the present schistosity.

The most prominent metamorphic phase to observe in the field is andalusite. It can form decimetre-sized porphyroblasts that are easily distinguished on the schistosity plane (Figure 9). Notable exposures are at the Etangs de la Gardelle, 1.5 km southwest of the Etang de Soulcem, and south of l'Estany Primer northwest of the Arcalis ski station in Andorre. The length axes of the andalusite blasts are randomly oriented, indicating absence of significant simple shear component during growth. Some twinned blasts also display significant growth across the foliation plane (Figure 9), suggesting that compressional strain was also negligible. Thin sections show that most andalusite porphyroblasts are subhedral and poikiloblastic with inclusions of biotite and quartz, and in places complete quartz layers. The inclusions commonly form trails that are either straight or concave, indicating interkinematic or synkinematic growth under coaxial deformation. Generally, the internal foliation continues into the external (Figure 10 a). Oblique orientation of the internal foliation with respect to the external schistosity indicates postkinematic rotation of the blast. Centimetre-sized blasts can display curved inclusions that are the result of bending of the andalusite grain, evident in the continuous, fan-like extinction under crossed polarized light. Large broken blasts are also common. Alteration at the rims to fine grained white mica (sericite) is not uncommon. Two distinct generations of andalusite in one sample as proclaimed by Verhoef et al. (1984) were not seen. Along with andalusite, large biotite porphyroblasts also occur in the matrix (Figure 10 b), suggesting the following reaction:

Figure 9. Block diagram of andalusite twins



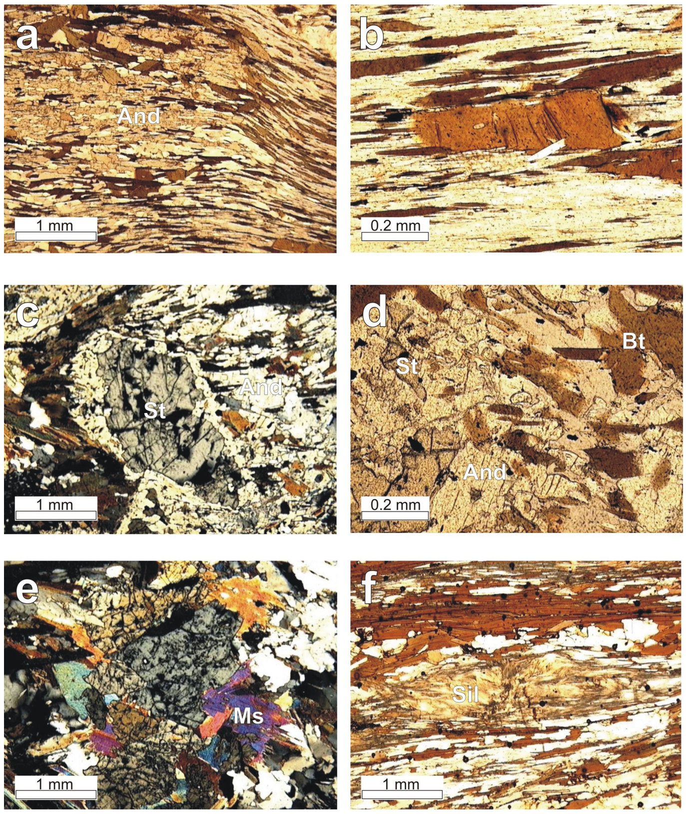
Block diagram of andalusite twins in a fine grained mica quartz schist from a locality southeast of the Soulcem granites. Section 1 is cut perpendicular to the mineral lineation, defined by muscovite grains, sections 2 to 5 are oriented parallel to the lineation. The twins are not aligned within the foliation plane, but describe an up side down "V". Also note that the andalusite twin in the foreground is tilted in opposite direction with respect to the mineral lineation than the twin in the background. Photograph shows radiating andalusite megablasts apparently growing in random orientation on foliation plane.

3. chlorite + muscovite = aluminosilicate + biotite + quartz + H2O

Coexistence of staurolite and andalusite (assemblage 3b) without any indication of resorption of any phase is seen as indication that both phases are part of the same assemblage. In that case reactions (2) and (3) take place simultaneously.

With the first appearance of fibrolitic sillimanite (assemblage 4a) staurolite displays signs of resorption. Staurolite can be found as relic, with embayed grain boundaries or completely xenomorph (Figure 10 c), within andalusite. Large biotite inclusions in the surrounding andalusite (Figure 10 d) indicate a staurolite-consuming reaction to form andalusite and biotite:

Figure 10. Thin section photographs from the western Aston dome



(a) Poikiloblastic andalusite with inclusion trails that continue straight into the external foliation and

(b) older biotite grain truncated by new schistosity (assemblage 3a, sample 98-114). PPL.

(c) Staurolite inclusion within andalusite displaying corroded rims (assemblage 4a, sample 98-73). XPL.

(d) Same sample showing new biotite growing within andalusite near a relic staurolite. PPL.

(e) Staurolite from the same sample rimmed by large muscovite, interpreted as retrograde reaction. XPL.

(f) Fibrolite lens completely replacing biotite in a sillimanite-biotite schist (assemblage 4b, sample 98-127). PPL.

4. staurolite + chlorite + muscovite + quartz = aluminosilicate + biotite + H2O

Staurolite that is not a relic in andalusite is rimmed by large muscovite porphyroblasts that overgrow the main foliation (Figure 10 e). In places the original staurolite crystal is reduced to relic or has disappeared completely, so that muscovite porphyroblasts pseudomorph after staurolite. In theses rocks chlorite is also abundant as an alteration product. The textural relationships suggest that staurolite replacement in this case is not a prograde, but a retrograde metamorphic reaction, a reversal of the staurolite-forming reaction (2) (Guidotti & Johnson 2002).

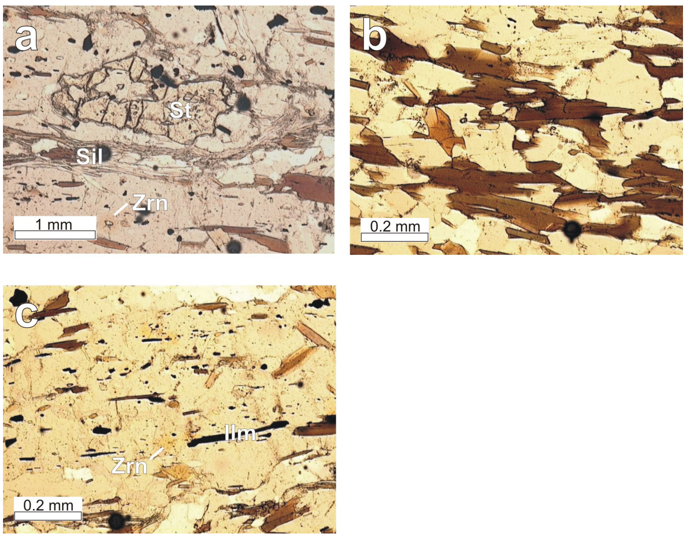
A very common assemblage (4b) consists of sillimanite, biotite, muscovite and quartz, which is found east of the Soulcem plutons and close to the migmatitic zone of the western Aston gneiss. Fibrolitic sillimanite is first seen (assemblage 4a) nucleating in quartz. With increasing abundance the fibrolite needles grow epitaxial in biotite. No evidence for replacement of andalusite is found. Although primary muscovite is decreasing with increasing fibrolite abundance, fibrolite most likely did not form by reaction (3). First, there is not enough primary chlorite left. Second, nucleation of fibrolite on biotite suggests that fibrolite replaced biotite. Large, millimetre-sized muscovite grains overgrowing cleavage domains are observed near fibrolitic lenses. Kerrick (1987) and Kerrick & Woodsworth (1989) proposed that fibrolite had formed the decomposition of biotite, due to removal of K, Mg and Fe caused by acidic fluids emanating from adjacent magmatic intrusions. Contemporaneous muscovite would act as a local K sink. Fibrolite can amount up to 20 vol. %, completely replacing individual biotite grains, and form millimetre-long fibrolite lenses, which are characterized by foliation-parallel needles at the margin and irregularly oriented needles in the centre (Figure 10 f). Spry (1969) referred to this process as irregular growth following seeded nucleation. In schists with a high abundance of sillimanite, prismatic sillimanite grains can be observed in the central part of the fibrolite lenses.

Coinciding with increasing sillimanite abundance the rocks become coarser grained and possess a continuous schistosity, attaining a gneissic appearance. Although some of the samples of the assemblage (4b) lie within the zone mapped as migmatitic by Casteras et al. (1969), the rocks generally have a well developed gneissic foliation as outlined in section 3 a., and should better be referred to as paragneiss. True migmatites have been observed closer to the actual contact with the orthogneiss.

In the southern migmatite zone, sillimanite-biotite schist (00-104) contain large centimeter-sized poikiloblastic garnets with inclusions of plagioclase, quartz, biotite and opaques that form distinct parallel layers. The shapes of the inclusions are irregular and the plagioclase grain boundaries are rounded. These garnets are most likely newly grown, overprinting the existing continuous foliation.

Cordierite is rare and only observed in the western Aston dome north of the Etang d'Izourt (assemblage 5b, 98-124). There it forms centimeter-sized porphyroblasts with several inclusions of relic staurolite, fibrolite lenses, biotite, muscovite and ilmenite (Figure 11 a). Abundant fibrolite and biotite is present in the matrix. Poikiloblastic, millimeter-seized anhedral andalusite is found at the rim of cordierite. A thin section from the same sample without cordierite shows abundant andalusite, fibrolite lenses replacing biotite, abundant biotite, but no muscovite or illmenite (Figure 11 b). Regarding the growth of cordierite the following can be concluded from these observations. Cordierite and andalusite can be produced from the breakdown of staurolite:

Figure 11. Thin section photographs from a cordierite-bearing schist



Thin section photographs from a cordierite-bearing schist (assemblage 5b, sample 98-124) of the western Aston dome.

a. Staurolite relic within cordierite, which covers the whole figure and contains inclusions of ilmenite (opaque phase). Embayed rims indicate that staurolite is being consumed. Note fibrolite needles nucleate in cordierite.

b. Section of the matrix at the same scale. Note the abundance of biotite and the absence of ilmenite.
c. Abundant ilmenite needles within cordierite result from released TiO_2 during replacement of biotite by cordierite. PPL.

4. staurolite + quartz = cordierite + aluminosilicate + H_2O

The presence of ilmenite as inclusions in cordierite, the small amount of biotite as inclusions compared to the matrix, suggests that biotite was consumed to produce cordierite (Figure 11 c). TiO_2 which is abundant in biotite, but is not incorporated into cordierite, nucleates as illmenite. A possible reaction is:

5. cordierite + muscovite = aluminosilicate + biotite + quartz + H_2O

This reaction also produces muscovite, which occurs as inclusions in cordierite, but is missing in the cordierite-absent thin section. Though there is no direct textural evidence this reaction also involves the breakdown of andalusite.

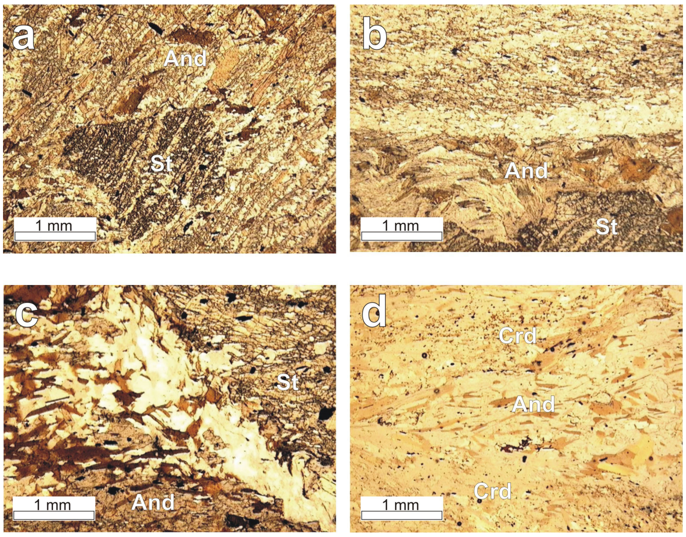
The distribution of the metamorphic assemblages of the western Aston massif outlines a distinct increase of metamorphic grade towards the southeast. The three isograds that can be drawn with some reliability are the biotite-in, the sillimanite-in, and the cordierite-out isograds. Due to the paucity of data east and south of the Pic de Malcaras area, and west of Etang d'Izourt, the course of the sillimanite-in and staurolite-out isograds in these parts is presumptive. Verhoef et al. (1984) postulated a separate sillimanite isograd mantling the plutons in the Soulcem area, terming it the Soulcem thermal high. In contrast to their claims, this study has not recorded any sillimanite in the western Soulcem valley. Likewise, sillimanite-bearing rocks occur further to the southeast as shown by Verhoef et al. (1984). Future work will show if sillimanite extends east into northern Andorra up to the Aston gneiss, as it is implied in this study. The presently mapped metamorphic assemblages and the presence of pegmatite intrusions indicate the presence of heat source in that region.

Metamorphic characteristics of the western Hospitalet dome

The western Hospitalet dome is characterized by low grade muscovite-chlorite-biotite slate (assemblages 1b, 1c) from the French-Spanish border to el Serrat. The contrast is most evident at the Portella de Rialb, one kilometre south of the Pic du Port, where coarse grained sillimanite-biotite schist (assemblage 4b) is juxtaposed against fine grained slate along a steeply dipping shear zone, presumed to be the Merens fault. The grain sizes of the slates range from 50-200 μm, and a spaced cleavage is developed.

One kilometre further east andalusite and staurolite appear (samples 00-85, 00-99, assemblage 3b). This staurolite-andalusite zone forms a band approximately two kilometres wide and is bounded to the south, along the valley that extends eastward from el Serrat, by slate. It is not clear if the boundary is a structural break, i.e. shear zone. There is evident that it may be a metamorphic gradient. Sample 00-85, close to the mapped boundary, displays millimetre-sized staurolite and centimetre-sized andalusite porphyroblasts. Both phases contain quartz inclusions that preserve a crenulation folding and associated cleavage (Figure 12 a). Andalusite also contain up to one millimetre-sized biotite porphyroblasts that overgrow the crenulation. The appearance and width of the crenulation is the same in staurolite and andalusite. Staurolite is also found as inclusion in andalusite, without any evidence for resorption. It is interesting to note that the matrix is a rather fine grained (50-200 μm) muscovite-chlorite-biotite schist (Figure 12 b). These observations suggest that both staurolite and andalusite are part of the same paragenesis, being the result of the break down of chlorite and muscovite (reactions (2) and (3)), which also produced large biotite in the andalusite. Both phases statically overgrew an older crenulation cleavage, which since has been obliterated in the matrix. The matrix grain size, however, remained relatively fine. This changes further to the north in sample 00-99 (Figure 12 c), which is a coarser grained andalusite-staurolite schist, similar in appearance to those in the western Aston dome. In this sample, staurolite and andalusite porphyroblasts are anhedral and poikiloblastic with straight inclusion trails, that are oriented parallel to the main schistosity in andalusite, and obliquely oriented in the staurolite. An older generation of biotite porphyroblasts, truncated by the main schistosity is present. Lacking any textural evidence for resorption, andalusite and staurolite appear to be of the same paragenesis, as in the previous sample.

Figure 12. Thin section photographs from the western Hospitalet dome



a. Subhedral staurolite porphyroblast found as inclusion in andalusite without signs of corrosion. Both phases overgrow the same crenulation cleavage, suggesting that both phases are part of the same paragenesis.
b. At the margin of the large andalusite blast the grain size difference to the matrix becomes evident. New biotite that formed along with andalusite is significantly larger than younger biotite in the matrix (assemblage 3b, sample 00-85).
c. A sample from the same assemblage approximately one kilometre further north displays a larger grain size of the matrix (sample 00-99). (d) Andalusite with embayed rims completely surrounded by cordierite. Note the presence of biotite in the andalusite, while cordierite contains abundant ilmenite inclusions. (assemblage 5a, sample 98-193). PPL.

The major difference compared to the western Aston dome is the negligible abundance of sillimanite. Cordierite on the other hand is more common, and occurs with staurolite, andalusite, sillimanite, biotite, muscovite, and garnet (assemblages 5a, 5b, 5c). The appearance is similar to the cordierite schist of the western Aston dome. Staurolite porphyroblasts are several millimetre in size, commonly rimmed by coarse new muscovite, cordierite forms large centimetre-sized porphyroblasts with abundant inclusions of ilmenite, and in places muscovite. Here, andalusite is found as an inclusion with embayed rim within cordierite, suggesting that andalusite was consumed to form cordierite (reaction 7), as postulated in section 4 c (Figure 12 d).

Metamorphic evolution of the western Aston and Hospitalet domes

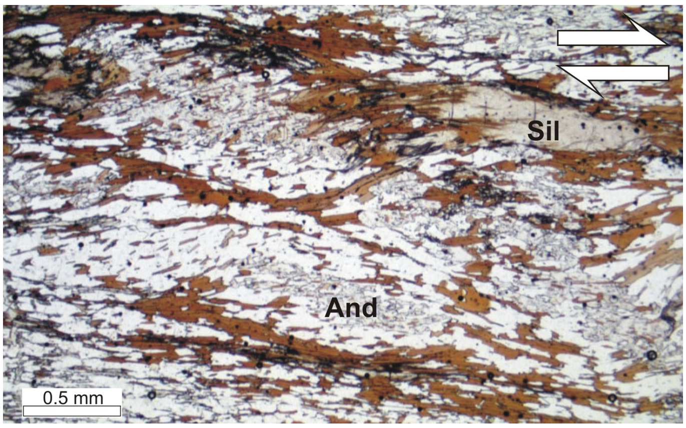
Description of metamorphic and tectonic events in the Cambro-Ordovician metasedimentary rocks of the western Aston and Hospitalet domes is best accomplished by comparison with the evolution of the Bossòst dome (Table 3; Mezger & Passchier 2003; Mezger et al. 2004).

In the Bossòst dome nucleation of the earliest spessartine garnets occurred during early regional metamorphism M1. Crenulation folds are preserved as garnet inclusion trails. Next, staurolite and almandine garnet grew during periods of deformational quiescence. A phase of intense non-coaxial shearing, evident in rotated staurolite porphyroblasts, separates earlier staurolite growth from nucleation of andalusite. There is clear textural evidence that andalusite consumes staurolite (reaction 4) and andalusite grew during coaxial deformation. In the Aston and Hospitalet domes crenulation folding is preserved in garnet, staurolite and andalusite. In other localities coexisting garnet, staurolite and andalusite overgrew an already existing foliation. The main difference to the Bossòst dome is that staurolite and andalusite belong to the same paragenesis, since there is no evidence in these rocks of growth of one phase on the expense of the other. Also, there is no distinct deformational event that would separate metamorphic phases. Preservation of crenulation folding in one case and a well developed foliation in another could be interpreted as development of the assemblages during different times, or a different structural environment during metamorphism. At the moment there is no definite answer to that problem.

In the Bossòst dome simultaneous breakdown of staurolite to andalusite and cordierite, and contemporaneous consumption of andalusite by cordierite is evident. This can be linked to the intrusion of the late Variscan (?) Bossòst granodiorite. In the Aston and Hospitalet domes, consumption of staurolite by andalusite, staurolite and andalusite by cordierite can also be inferred from textural relationships. Peak metamorphic temperatures are reached in the sillimanite-biotite schist, which are found within the migmatite zone, close to the contact with Aston orthogneiss. The important question is, which thermal event is responsible for peak metamorphism? The intrusion of the protolith of the Aston and Hospitalet orthogneisses would create a contact aureole of considerable width, if intrusion occurred in midcrustal depth. However, the foliation that was imparted on the orthogneiss and the mantling metasedimentary rocks predates development of andalusite and cordierite, with the exception of some staurolite assemblages. The next possible event, the migmatization of the mantling metapelitic rocks obviously effects already foliated rocks, and contains the rocks of the highest metamorphic grade. Lacking any geochronological data, timing of migmatization is still unclear. It may well be related to an earlier phase of late Variscan plutonism, that resulted in the intrusion of the Bassiès pluton to the northwest of the Aston dome, and emplacement of the Soulcem plutons. Alternatively, cordierite and sillimanite growth of the Soulcem thermal dome is of younger age than metamorphism along the western margin of the Aston migmatite zone (Verhoef et al. 1984).

In the Bossòst dome no significant non-coaxial deformation occurred after peak metamorphism. In the Aston dome top-to-the-ESE shear is recorded in c'-type shear bands indicating hanging-wall up motion that clearly postdate peak-metamorphism (Figure 13). At the top of the Hospitalet gneiss further east van den Eeckhout (1986) postulated an extensional shear zone, the Contact High Strain Zone, was developed following peak-metamorphism, agreeing with observations in the western Aston dome.

Figure 13. Well developed c'-type shear bands



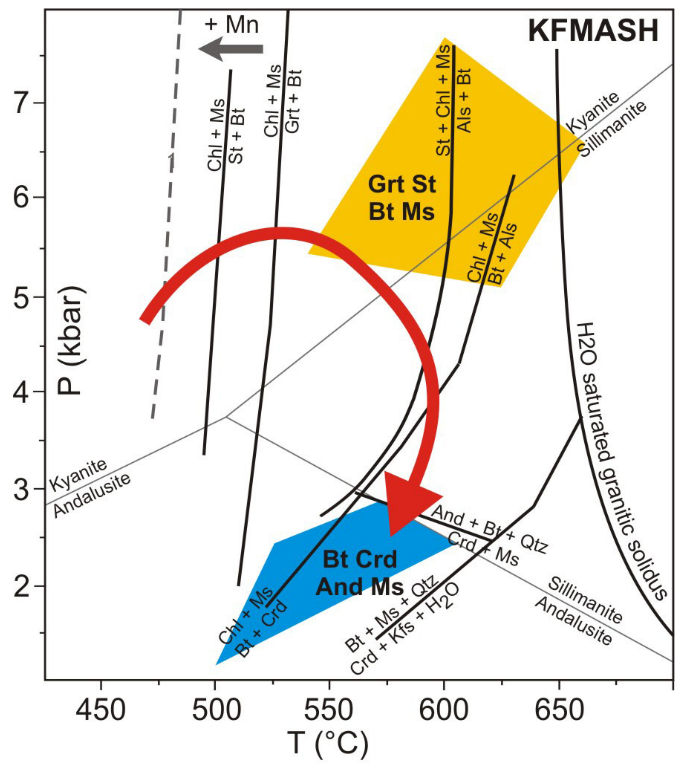
Well developed c'-type shear bands in an andalusite-sillimanite schist from south of Etang d'Izourt, close to the western migmatites. Note that the shear bands deflect the fibrolite, indicating post-peak metamorphic non-coaxial deformation, with a top-to-the-SE sense of shear.

Both the Bossòst and the Aston-Hospitalet domes are divided into two parts by a late fault or mylonite zone. While in the Bossòst dome the faulted zone is narrow, the mylonite zone separating the Aston and Hospitalet gneiss in the central part can be up to one kilometre wide (Besson 1991). In both regions, the northern block records higher metamorphism. This suggests that the Bossòst and the Merens faults accompanied significant vertical motion, prior to their development into latest Variscan or Alpine mylonite zones (Mezger & Passchier 2003).

P-T path for the Aston-Hospitalet domes

A pressure-temperature path was established for the Bossòst dome which can be used as a guide for the Aston and Hospitalet domes (Figure 14 , Mezger et al. 2004). However, lacking additional mineral compositional data and whole rock geochemistry to calculate pseudosections, a quantitative P-T path can not yet be established. Nevertheless, the similarities between both regions outlined above allow for qualitative comparison. The crucial assemblages are 5a-c, with coexisting cordierite, staurolite, biotite and muscovite, which are considered metastable and the result of polymetamorphism (Holdaway et al. 1982; Garcia-Casco & Torres-Roldán 1999; Pattison et al. 1999). For the Bossòst dome this is supported by geochemical data (Mezger et al. 2004), and need yet to be done for the Aston-Hospitalet domes.

Figure 14. Reconstructed P-T path



Reconstructed P-T path for the Bossòst dome using petrogenetic grids and pseudosections calculated with

THERMOCALC. A similar path may be envisioned for the Aston and Hospitalet domes.

Consumption of andalusite by cordierite (reaction 7) is a retrograde reaction with a negative slope. The location of that reaction is dependent on the Mg/Fe ratio of biotite and the graphite content (Pattison et al. 2002). For the Bossòst dome it could be shown that it lies close to the sillimanite-andalusite equilibrium.

Conclusions

The Aston and Hospitalet domes display a complex metamorphic and tectonic evolution, involving early Variscan main deformation and medium pressure metamorphism which was overprinted by one or more thermal events of later or late Variscan age. The sequence of metamorphic phases is similar, though not exactly the same as in the smaller Bossòst structural and metamorphic dome in the Central Pyrenees. Results of recent studies of the Bossòst dome are helpful in providing a framework to the reconstruction of the Aston and Hospitalet metamorphic evolution. Notably, the presence of metastable assemblages which hint at polymetamorphism: an early medium pressure event followed by a higher temperature-lower pressure event along a clockwise P-T path. To further quantify these conclusions, additional fieldwork, individual mineral composition and calculations of pseudosections are planned.

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