Geologie en Mijnbouw **73:** 53–61, 1994.

Timing of Variscan mid-crustal shearing and batholith intrusion in the Central Pyrenees (Ariège, France)

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Received 19 March 1993; accepted in revised form 18 January 1994

Key words: Aston massif, Hospitalet massif, shear zone, Variscan orogeny

Abstract

A gneiss body in the Variscan Aston massif is overlain by Cambro-Ordovician metasediments that have been intruded by a granite batholith. At the gneiss-cover contact a 1.2 km-thick zone of highly strained medium-grade metasediments occurs. The batholith is surrounded by a zone where metasediments are strained and metamorphosed due to intrusion of the pluton. This contact aureole overprints the shear zone at the gneiss-cover contact, showing deformation and retrogression of the medium-grade metasediments. This relationship reveals a younger age for batholith intrusion with respect to the formation of the shear zone at the gneiss-cover contact. This observation together with regional correlation indicates that formation of the shear zone occurred between 292 and 280 Ma ago.

Introduction

The Axial Zone of the Pyrenees is a large outcrop of Variscan rocks comprising three major structural units (Fig. 1). A flat-lying mid-crustal shear belt mainly consisting of LP-HT schists and gneisses is situated structurally beneath a fold-and-slate belt which was formed earlier in Variscan times. This fold-and-slate-belt, which consists of low-grade siliciclastics and carbonates, envelopes granodiorite batholiths which are classically considered to be of late or post-Variscan age because they cut the folds and because their erosional debris is found in lower Triassic redbeds. The mid-crustal shear belt is referred to by some authors as infrastructure, while the fold-and-slate belt is called suprastructure. In Fig. 2 a schematic cross-section shows the general stratigraphy (after Guitard 1970, Zwart 1979, Laumonier 1988, Den Brok 1989, Pouget et al. 1989), and structural elements and their relationships (after Verhoef et al. 1984, Van den Eeckhout 1986, 1990, Gibson 1989, Kriegsman 1989, Kriegsman et al. 1989, Pouget 1991,).

We wish to identify the temporal relationship between batholith intrusion and formation of the shear belt, in particular in the area within the shear belt where more than one generation of shear zones has been mapped, the Aston-Hospitalet massif. The evidence at present leaves room for scenarios such as (a) intrusion taking place between periods of shearing, and (b) intrusion post-dating shearing. Knowledge of the exact time relationship is required to understand the tectonics of the region and for this purpose we have investigated an area in the eastern Aston massif (Fig. 1).

Deformation, metamorphism, magmatism and time in the Aston and Hospitalet massifs of the Central Pyrenees

A remarkable feature of the mid-crustal shear belt in the Aston and Hospitalet massifs is a two-stage structural evolution (Verhoef et al. 1984; Van den Eeckhout 1986, Fig. 2). Initially, a wide shear zone (S_3) formed, exceeding 4 km in structural thickness. It encompasses

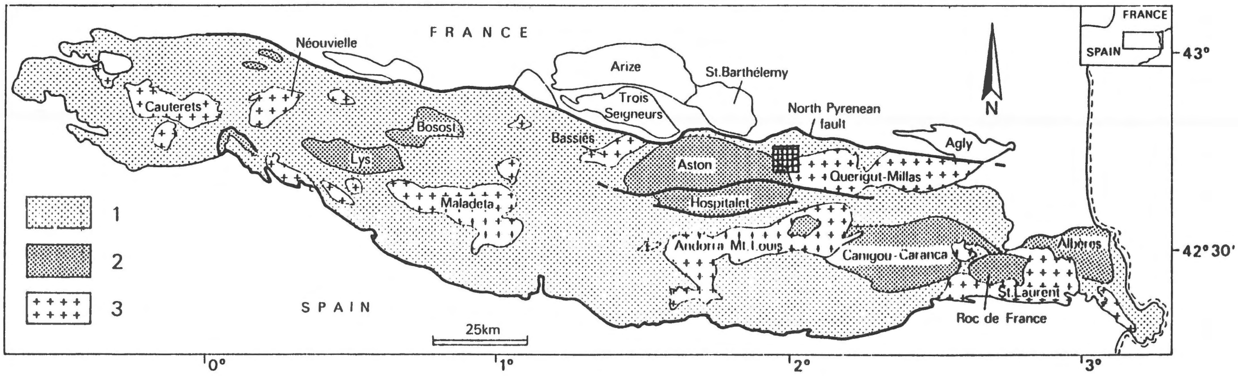

Fig. 1. Structural units in the Axial Zone of the Pyrenees (after Van den Eeckhout 1986, Zwart 1986). 1. Fold-and-slate belt. 2. Flat-lying mid-crustal shear belt, mainly consisting of schists and gneisses. 3. Late Variscan batholiths. Cross-hatched rectangle indicates study area.

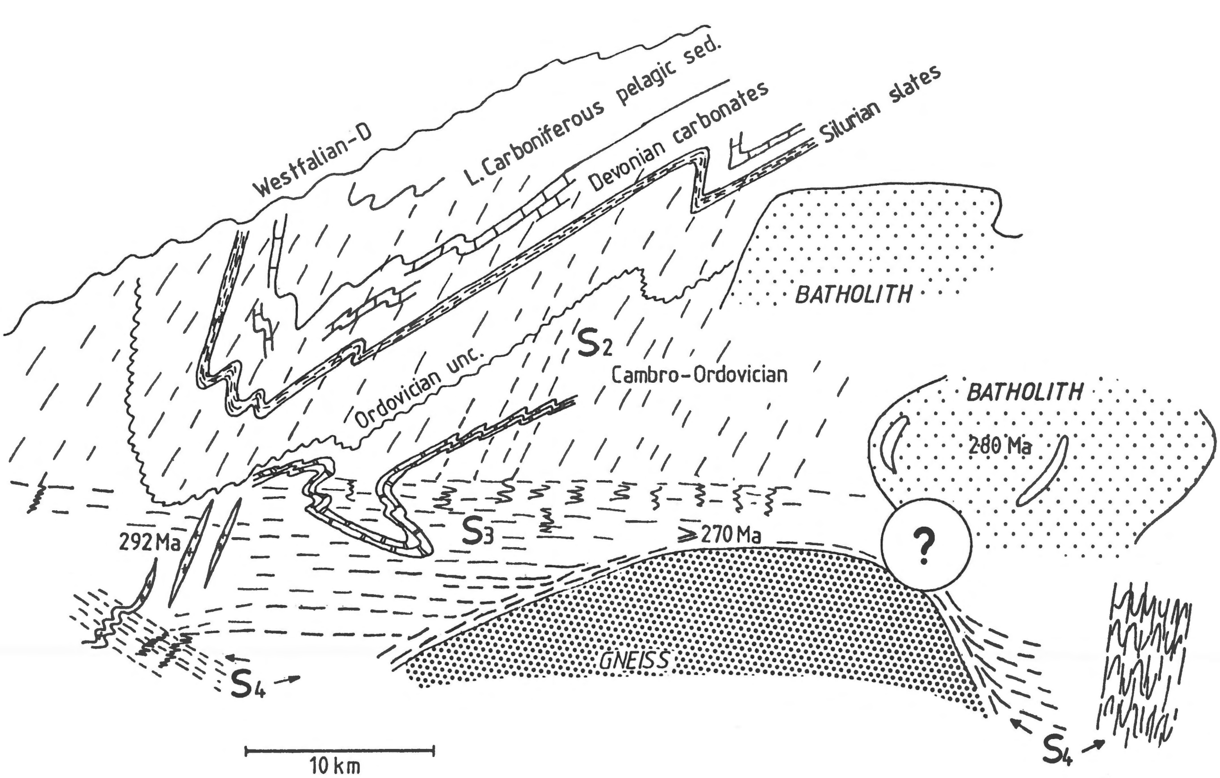

Fig. 2. Schematic cross-section showing general stratigraphy, structural elements, their attitude and detailed structural relationships in the Axial Zone. S_2: foliation in the fold-and-slate belt. S_3: main foliation in the mid-crustal shear belt. S_4: narrow shear zones (< 1.5 km) that deform S_3, only recognized as such in the Aston and Hospitalet massifs (Verhoef et al. 1984, Van den Eeckhout 1986). Question mark indicates schematic position of study area. Total thickness of structural stack is about 10 km.

both the Aston massif and the Hospitalet massif. This zone was subsequently deformed by relatively narrow zones of shearing (S_4). These latter zones include (1) an impressive (up to 1 km thick) extensional shear zone at the gneiss-cover contact in the Hospitalet massif (the contact high-strain zone of Van den Eeckhout, 1986), which, as we will show in this paper, has an equivalent in the Aston massif, (2) a steep dextral transcurrent 1.5 km-wide shear zone in the western Hospitalet massif, (3) flat-lying structures of the western Aston massif (Soulcem area, Verhoef et al. 1984), and (4) a steep zone of strongly deformed schists at the gneiss-cover contact in the north of the Aston massif. All four structural elements have in common that (a) they post-date structures of the wide shear zone, (b) they post-date the pattern of regional metamorphic isograds which formed post-kinematically with respect to the wide shear zone, and (c) they are cut by arrays of NW-SE (Aston) or NE-SW (Hospitalet) trending small-scale shear zones of Alpine age. In particular, with respect to (b) the metasediments and metamorphic mineral zones existing within them have been wrapped around the relatively rigid gneiss, yielding a map pattern in the Aston and Hospitalet massifs that should not be mistaken for a contact aureole of the gneiss (Van den Eeckhout 1986).

Absolute age relationships have been studied by Jäger & Zwart (1968), Majoor & Priem (1987) and Majoor (1988), who carried out Rb-Sr whole-rock analyses on metamorphic metasediments and gneiss of the Aston massif. Their work may be summarized as follows. The regional metamorphic culmination is 315 Ma (Majoor & Priem 1987, Majoor 1988: 78) and possibly younger at depth. The Ax granite, which has intruded the Aston gneiss and which is cut by the shear zone north of the Aston gneiss, is 301 ± 15 Ma. Pegmatite veins in the western Aston massif, which are folded by the Soulcem structural element, intruded 292 ± 13 Ma ago. These dates constrain the absolute age of the narrow shear zones in the Aston massif to about 292 ± 13 Ma or younger, if we assume all of them to have the same absolute age (this point will be elaborated further). The younger age limit is less well defined. White-mica cooling ages within the narrow shear zones in the Aston and Hospitalet massifs vary from 270 to 294 Ma according to Jäger & Zwart (1968), Majoor & Priem (1987) and Majoor (1988).

In summary, the wide shear zone is about 315 Ma or older and the narrow shear zones formed roughly between 290 and 270 Ma ago. Now, if we look at the absolute ages of batholiths around the massif we note that the Bassies batholith to the northwest has an intrusion age of 290 ± 17 Ma (Majoor & Priem 1987, Majoor 1988) and the Quérigut complex to the east is 280 Ma (references cited in Ben Othman et al. 1984). Given these radiometric age determinations and their uncertainties compared to those for formation of the narrow shear zones, a time span of at least 20 Ma (290-270) exists wherein the batholiths intruded and the narrow shear zones formed. The rates of geological processes such as these have recently been evaluated by Kukal (1990) and Paterson & Tobisch (1992). In particular, Paterson & Tobisch discussed rates in magmatic arcs, and they indicate that most plutons probably intrude within a few hundred thousand years and subsequently cool to ambient wallrock temperatures in 1-3 Ma up to 10 Ma. Furthermore, deformation zones such as the narrow shear zones described here could form in less than 1 Ma. Given the relatively high rates of these processes there is clearly room from various age relationships between batholith intrusion and formation of narrow shear zones in the Aston and Hospitalet massifs.

Therefore, to determine the exact age relationship between these features we have chosen to map and study lithology, structures and their relationship with metamorphic porphyroblast growth in the Orlu-Quérigut area in the eastern Aston massif, where granite, gneiss and metasediments meet (Fig. 3).

Geology of the study area

Three main rock units occur in the Orlu-Quérigut area: (a) gneiss of the Aston massif in the west, (b) granite of the Quérigut batholith in the east and (c) a wedge of metasediment in between (Fig. 3).

Gneiss and gneiss-metasediment contact

The Aston gneiss body is enveloped by metasediment. Field evidence allows two different interpretations of the gneiss-metasediment contact: either the precursor of the gneiss intruded the sediments as a batholith or it served as a basement to the sediments (Van den Eeckhout 1987). Majoor (1988) established an Ordovician age for the precursor of the gneiss.

In the study area the gneiss is a leucocratic amphibolite-facies augengneiss. Feldspar augen reaching 5 cm in diameter are wrapped by biotite seams and a medium to coarse-grained quartz-feldspar matrix with a granitic texture. The gneiss is lithologically similar to the augengneiss of the Hospitalet massif described by Van den Eeckhout (1986). Deformation is moderate, as indicated by platy foliations and neatly aligned porphyroclasts within those foliations. The gneiss-metasediment contact is abrupt. The foliation in the gneiss is parallel to this contact, a phenomenon which is best exposed in the Dent d'Orlu, where it dips steeply to the northeast. Gneiss and metasediment

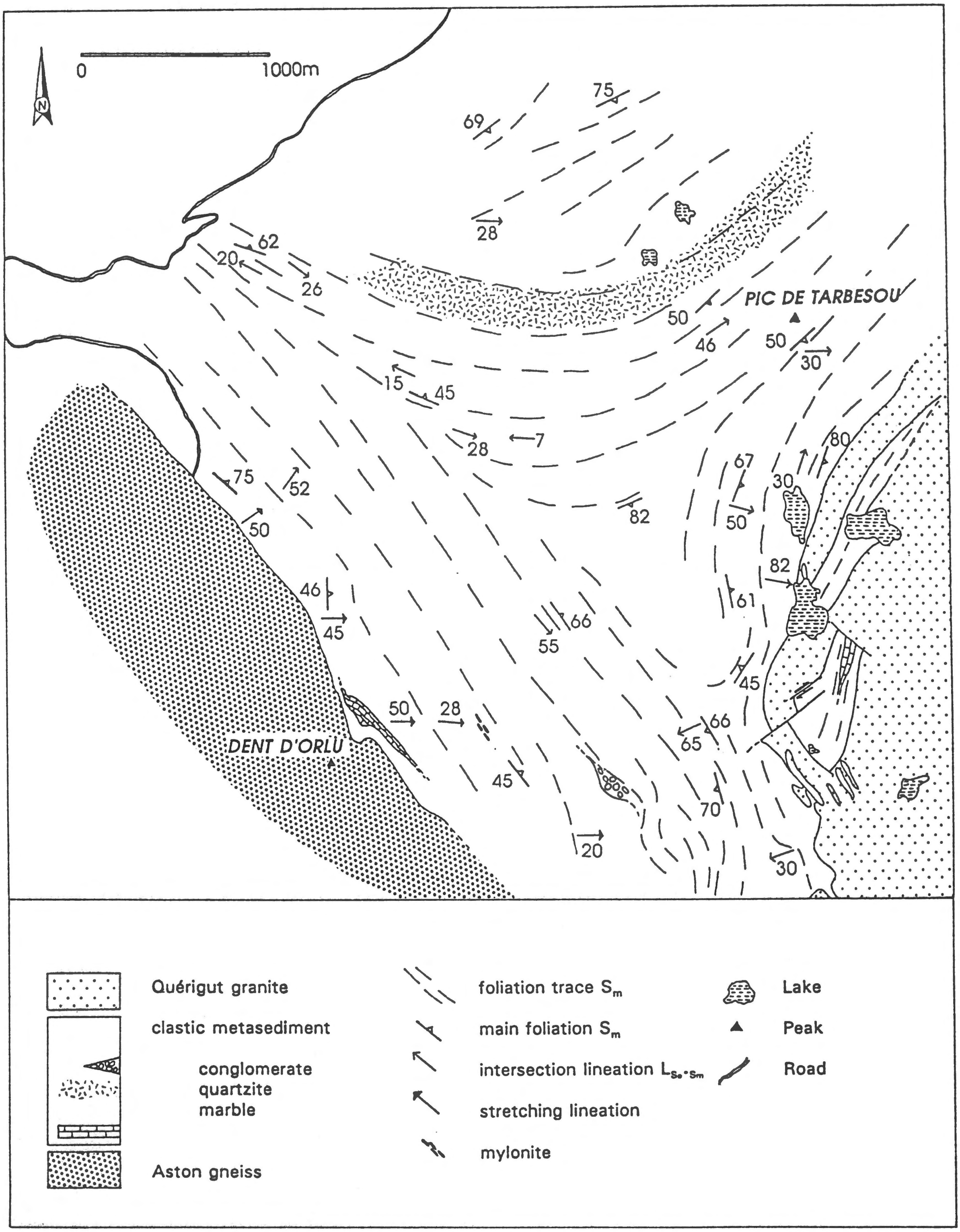

Fig. 3. Structural map of the Orlu-Quérigut area.

near the contact have been cut by white aplite dykes that reach 1 m in thickness. The dykes show no ductile deformation. The entire succession is cut by faults that terminate in kink folds of 10 m in amplitude within the metasediments.

Granite and granite-metasediment contact

The Quérigut batholith (Marre 1982, 1973) has been described as a zoned pluton comprising biotite granite and monzogranite. Minor amounts of gabbro and diorite occur in stock-like bodies. The shape of the pluton resembles an inverted onion (Soula 1982). Marble and garnetiferous quartzite xenoliths reaching 1 km in length occur in the outer zone of the batholith and broadly follow its outline. Marre (1973) suggests that these xenoliths represent a collapsed roof. The batholith has been the subject of thorough petrological and isotopic study (Albarède & Michard-Vitrac 1978, Fourcade & Allègre 1981, Ben Othman et al. 1984). According to Ben Othman and co-workers the batholith formed by anatexis of Precambrian basement which had been reworked between around 600 and 550 Ma ago.

In the study area the contact between granite and metasediment is abrupt and locally reworked by small-scale shear zones. Near the granite the main foliation in the metasediments is parallel to the contact. A faint grain-shape fabric parallel to the contact is present in the granite. This general parallelism is also observed in and near metasediments included in the batholith. The granite-metasediment contact dips steeply to the east in our area of investigation. On the map it is slightly curved, marking the western termination of the batholith.

Metasediments

The metasediments of the area are typical of the Pyrenean Cambro-Ordovician succession, which mainly comprises low-grade pale grey metapelites and metapsammites (Laumonier 1988). However, four remarkable rock types occur in the metasedimentary mass. The entire sedimentary succession bears a strong resemblance to the sediments on top of the gneiss in the eastern Hospitalet massif. From north to south and towards the gneiss-cover contact the four rock types are as follows:

(1) A 200 m-thick white quartzite horizon constituted by beds of 5 cm to 1 m in thickness. A lithologically similar horizon has been mapped in the eastern Hospitalet massif (Van den Eeckhout 1987, 1990) and there may be a correlation between the two horizons.
(2) Conglomeratic quartzites with bed thicknesses of up to 30 cm and containing pebbles usually of less than 0.5 cm in size ('microconglomerates'). The true thickness of this unit, observed over a distance of about 230 m, cannot be given because it has been disrupted by faults.
(3) Quartz-feldspar mylonite in a distinctive white layer of about 4 m thickness, observed over a distance of 100 m, within the schists. A similar layer is present in the eastern Hospitalet massif at similar distance from the gneiss-cover contact.
(4) A light grey marble-quartzite alternation near the gneiss-cover contact. This is lens-shaped, about 20 m thick, and separated from the gneisses by approximately 50 m of schist. It is not clear whether there is a correlation between these rocks and the marble xenoliths within the granite.

Porphyroblasts are abundant in two distinct zones within the metasediments. One of these zones (Fig. 4, zone a) is parallel to the gneiss-cover contact, the other (Fig. 4, zone b) is parallel to the granite-metasediment contact. A low-grade slaty domain (Fig. 4: c) exists in the north of the area between these two zones. In the south of the area the two zones meet (Fig. 4: d).

Measured perpendicularly to the contact, the metamorphic zone (a) at the gneiss-cover contact is about 1.2 km thick. Biotite schists with scattered porphyroblasts of cordierite and elongate andalusites reaching 7 cm in length occur in this zone. A few aplite veins of about 1 m in length are also present in these schists. This metamorphic zone is part of the envelope of regionally metamorphosed rocks around the Aston and Hospitalet gneisses.

The metamorphic zone (b) at the granite-metasediment contact is about 1.1 km thick. This zone is characterized by phyllites and knotenschiefer with evenly distributed porphyroblasts of andalusite that reach 1 cm across. Close to the granite, biotite is a common porphyroblast in both rock types. This zone is part of the contact metamorphic aureole of the Quérigut granite.

In the south of the area (d), where zones a and b overlap, schists have been mapped with the same texture, grain size and porphyroblast distribution as the regional metamorphic rocks. However, these rocks contain abundant chlorite, as shown by their greenish hue, which is due to the conversion of the biotite porphyorblasts to chlorite-rich aggregates. We inter-

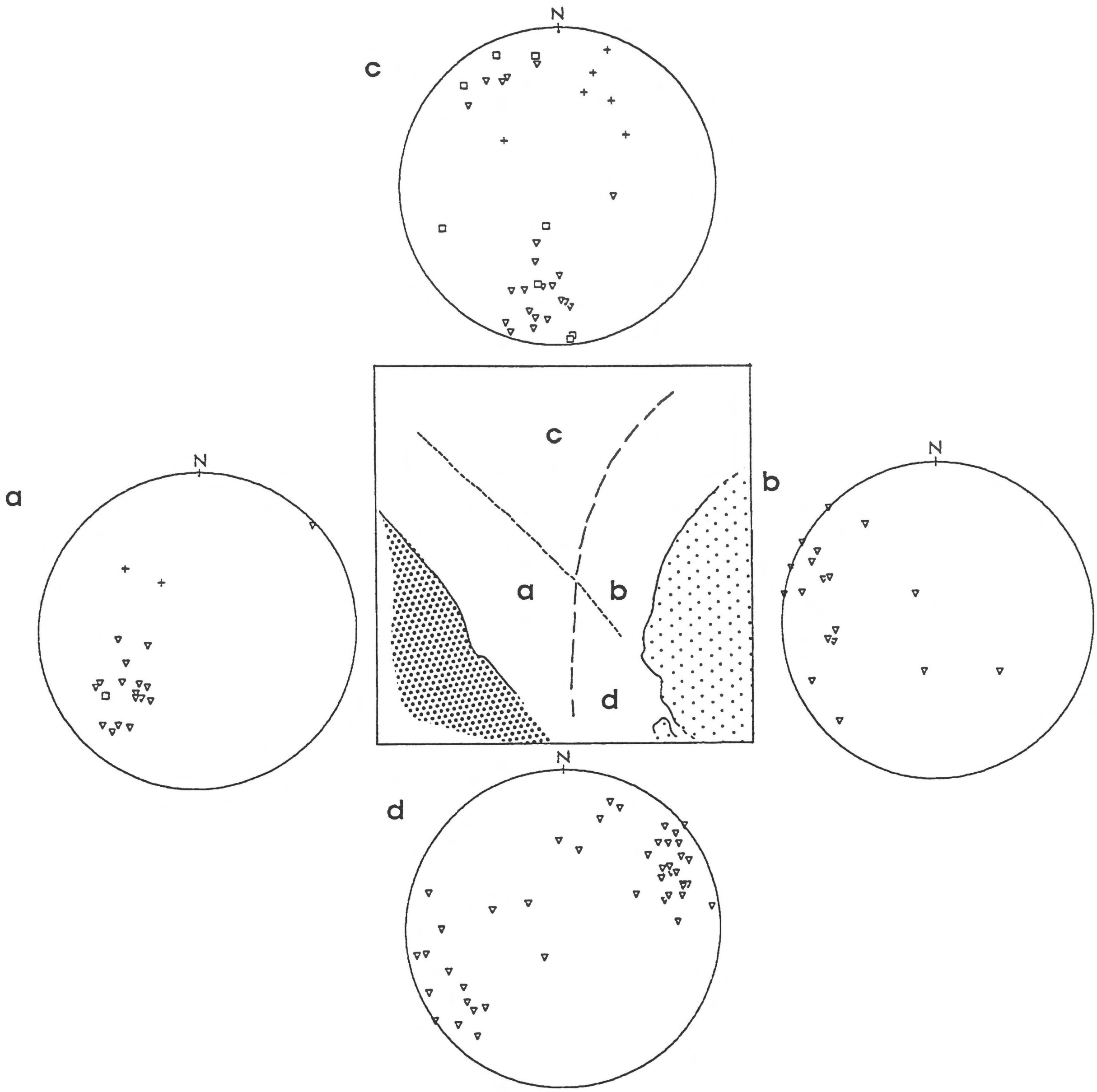

Fig. 4. Subdivision of the Orlu-Quérigut area, as shown in Fig. 3, into four structural and metamorphic zones. For each of these zones a stereogram of poles of bedding (□ S_o), main foliation (∇ S_m) and crenulation cleavage (+ S_{cren}) is shown. (a) Andalusite-cordierite-biotite zone at gneiss-cover contact; the shear zone forming the western limb of the megascopic fold. (b) Contact metamorphic andalusite-biotite zone aureole of the Quérigut granite; the granite-metasediment contact, forming the eastern limb. (c) Low-grade chlorite zone metasediments of the fold-and-slate belt; the hinge area of the megascopic fold. (d) Overlap area of a and b.

pret this as retrogression of the regional metamorphic rocks due to intrusion of the batholith and subsequent development of its contact aureole.

Structures in the metasediments

All metasediments have a foliation, called the main foliation (S_m), which in most outcrops is parallel to the bedding plane. The traces of the main foliation reveal a kilometre-scale fold which closes to the south (Fig. 3). There is distinct overlap between the metamorphic zones and the structural elements of the fold. Firstly, the metamorphic zone at the gneiss-cover contact and the western limb of the fold coincide, secondly, the metamorphic zone at the granite-metasediment contact matches the eastern limb, and thirdly, the low-grade domain coincides with the hinge region. The western limb, hinge zone and eastern limb differ not only in metamorphic grade, but also in structural features at all scales.

The andalusite-biotite schists of the western limb show structures that identify the entire limb as a zone of high strain. The small-scale structures include a platy biotite foliation that wraps around elongated and flattened porphyroblasts, extensional crenulations, foliation boudinage and isoclinal intrafolial folds. A fine quartz-biotite grain-shape lineation is observed in most rocks; this is often best seen at phase boundaries of quartz lenses. This lineation, which plunges roughly east, is interpreted as a stretching fabric. Fold axes are parallel to this mineral lineation. The quartz-feldspar mylonite in this zone emphasises its high-strain character. The generally straight trace of the foliation S_m of the western limb (Fig. 4 stereogram a) is locally disturbed by steep faults with small offsets and associated folds. However, in the south of the area, where it is overlapped by the contact aureole zone of the Quérigut batholith, the foliation has been disrupted by phyllonitic shear zones and faults with offsets of up to 100 m. Open folds of 100-200 m in amplitude accompany this feature and have refolded the main foliation to flat-lying attitudes. The main foliation in general dips steeply northeast or southwest (Fig. 4 stereogram d).

The small-scale structures, the relationship of metamorphic mineral growth relative to these structures and the thickness of this zone at the gneiss-cover contact are identical to those in the zone of high strain at the gneiss-cover contact in the Hospitalet massif (Van den Eeckhout 1986, 1990). Therefore we suggest that both zones represent the same structure.

The hinge zone of the megascopic fold in the area refolds steep foliations (Fig. 4 stereogram c). This foliation (S_m) here is a slaty cleavage, axial planar to small-scale folds and to megascopic folds that are situated to the north-east, just outside the study area (Zwart 1979). Foliation and bedding are nearly parallel and cleavage-bedding relationships are rarely observed. Cleavage-bedding intersection lineations plunge gently east or west. Crenulations of the slaty foliation and locally developed crenulation cleavages are quite common. These structures are axial planar to open folds of 5 cm to 6 m in amplitude. At least two differently oriented sets of crenulation cleavage exist, but no clear-cut age relationship between them has been deduced. There is no evidence of megascopic folds related to the slaty foliation within the study area. We therefore suggest that the lithological succession is a single pile that youngs to the north into Silurian black slates and Devonian carbonates, outside the area. The same lithological succession has been observed in the Hospitalet massif (Van den Eeckhout 1986).

In the eastern limb of the fold, the cleavage (S_m) and bedding dip steeply east to south-east (Fig. 4 stereogram b), the planar structures follow the granite-metasediment contact. The cleavage is the same structure as that of the hinge zone of the fold. Cleavage-bedding intersection lineations plunge east, down-dip in the foliation. Porphyroblasts have grown over the foliation. Rotation of porphyroblasts and associated small-scale flexure of the foliation are thought to be related to the formation of crenulations. These are the same sets which were found in the hinge zone of the fold, and they curve around the porphyroblasts, indicating their post-porphyroblast nature.

Discussion

The relationship between structure, metamorphism and kinematic indicators allows an interpretation of the large-scale fold in the Orlu-Quérigut area in terms of successive deformation events. We suggest a three-stage development (Fig. 5). The oldest deformation event in the area was the formation of the low-grade slate domain (Fig. 5A). This is the oldest event because metamorphism is of low grade and its structures have been overprinted (in the limb areas). The second event was the formation of the western limb (Fig. 5B). On the basis of the reorientation of foliations towards it and the asymmetric kinematic indicators within it we interpret this zone of high strain as one that underwent a large degree of simple shear. Rotation of foliations from the low-grade domain into the shear zone suggests a normal sense of shear, the metasediments moving eastward relative to the underlying gneiss, parallel to the stretching lineation. The third event was the formation of the eastern limb (Fig. 5C). Parallelism between planar structures in metasediments and granite indicates reorientation and neoformation of foliations at the granite-metasediment contact; a significant amount of strain is required to cause this. In addition, given the reorientation of the cleavage-bedding inter-

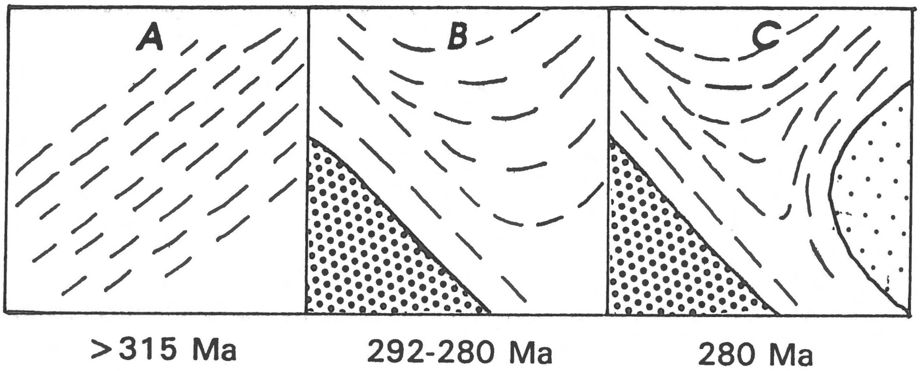

Fig. 5. Three-stage tectonic evolution of the Orlu-Quérigut area shown in Fig. 3: (A) formation of low-grade slate domain; (B) formation of high strain zone at gneiss-cover contact; (C) intrusion of batholith and associated deformation and metamorphism.

section lineations into a down-dip orientation a large component of simple shear has again to be taken into account. We interpret the eastern limb as a reverse shear zone which has brought up the granite relative to the metasediments.

Arguments for the younger age of the eastern limb relative to the western limb are firstly retrogression and secondly deformation of the western limb in the area where the two limbs overlap. In our opinion this relationship between the shear zone at the gneiss-cover contact and the contact metamorphic aureole of the Quérigut granite unequivocally shows that the granite intruded after formation of the shear zone. This is important because it shows that the shear zone at this particular location is older than 280 Ma.

An important item with respect to the entire Aston-Hospitalet massif is that the zone of highly strained metasediment and the gneiss that constitute the Hospitalet massif have their equivalents and continuations in the eastern Aston massif. This implies that the gneisses in the Aston and Hospitalet massifs represent one body overlain by one shear zone. In our interpretation this shear zone is older than 280 Ma and at least younger than about 301 Ma (the age of the Ax granite). If we further assume that the shear zone of the western Aston massif (the Soulcem area) is part of the large shear zone, its date of formation must lie between 292 and 280 Ma. It is a reasonable assumption that these shear zones formed simultaneously or even that the shear zone that overlies the gneiss in the eastern part of the massif is younger than that in the Soulcem area. The argument is that the Soulcem shear zone pre-dates a metamorphic culmination in that particular area while the shear zone overlying the gneisses formed on the retrograde path.

In summary, the formation of 1-2 km-wide shear zones at mid-crustal level in the Aston-Hospitalet massif (Fig. 2) can be assigned to the 292-280 Ma period. These zones deformed a mid-crustal flat-lying shear-zone system which exceeds 4 km in thickness and which developed in an extensional setting (Van den Eeckhout & Zwart 1988, Vissers 1992) before about 315 Ma (Majoor 1988). There hence exists a time gap of at least 25 Ma between the two shearing events. It is therefore uncertain whether the two events formed as a response to the same dynamic conditions. Following this line of thought a picture emerges of an older Variscan (> 315 Ma) history of shortening (fold-and-slate belt) followed by extension (mid-crustal shear belt) and metamorphic culmination, and a younger Variscan (292-280 Ma) history of extensional shearing accompanied by batholith intrusion.

Conclusions

- A medium-grade shear zone exists at the gneiss-cover contact in the eastern Aston massif. This zone has its equivalent in the Hospitalet massif and also continues into the zone of highly strained metasediments at the gneiss-cover contact to the north of the Aston gneiss. This implies that the entire Aston-Hospitalet gneiss body is overlain by a 1.2 km-thick zone of highly strained metasediment and gneiss.
- This shear zone has been deformed and metamorphosed by the intrusion of the Quérigut complex

in the Orlu-Quérigut area. This provides a younger age limit of 280 Ma for this zone.

- The shear zone overprints the earlier mid-crustal extensional shear zone system in the Aston-Hospitalet massif. Correlation with the western Aston massif indicates formation of the shear zone between 292-280 Ma.

Acknowledgements

We thank Mr. Timothy Horscroft and Mr. Bernard Laumonier for reviewing this article. Their constructive comments helped us improve and clarify the manuscript. We are grateful for funding by the Vakgroepfonds Structurele Geologie of the University of Amsterdam.

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