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SYN- TO POST-KINEMATIC FIBROLITE-BIOTITE INTERGROWTHS IN THE ARDARA AUREOLE, NW IRELAND

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Abstract

The relations of fibrolite-biotite are discussed by presenting data from the Ardara aureole, NW Ireland. Biotite-fibrolite intergrowths are developed in all three aureole zones including: the outer kyanite-bearing andalusite zone, the middle kyanite-free andalusite zone and the inner prismatic sillimanite zone. A strain-assisted mechanism is proposed for the fibrolitisation of biotite in the Ardara aureole. The concentration of fibrolite in zones of high non-coaxial strain, which wrap around zones of low co-axial strain, now occupied by minerals such as plagioclase (in the outer kyanite-bearing andalusite zone), andalusite (in the middle kyanite-free andalusite zone) and pods rich in biotite, quartz and plagioclase (in the inner sillimanite zone) provides strong evidence that fibrolite growth was syn-kinematic. Some textural evidence, especially from the inner sillimanite zone is consistent with continuation of fibrolite growth after ductile deformation.

Keywords: Fibrolite; Aureole; Non-coaxial strain

1. Introduction

Fibrolite-biotite intergrowths have long been recognised in a variety of both contact and regional metamorphic environments. Their nature has been an enigma. Some workers [22] have invoked a large-scale metasomatic process, such as base cation leaching due to acid volatiles. Others have favoured deformation-induced fibrolitisation of biotite [16,24], and Foster has suggested that biotite may have acted as a mineral catalyst [7]. In this study, we address the problem of fibrolite-biotite relations by presenting data from the Ardara aureole. Biotite-fibrolite intergrowths are developed in the Ardara aureole, thus making it an excellent place to study the factors involved in their development.

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2. Geological Setting

The Donegal region is located in the north west of the Republic of Ireland. The geology of the Donegal region has been comprehensively reviewed by Pitcher and Berger [17]. The country rocks of Donegal granites consist of Dalradian metasedimentary and meta-igneous rocks that range in age from Late Precambrian to Middle Cambrian. This group of rocks subsequently underwent major deformation (the Caledonian orogeny) during Late Cambrian to Late Ordovician. The granites of Donegal have been divided into six units having different ages, composition and modes of emplacement.

The northern Ardara aureole, which is the focus of the present study, consists of a pelitic horizon (locally referred to as the Clooney Pelitic Group) and an adjacent limestone unit (the Portnoo Limestone). Pitcher and Berger correlated these units respectively with the Upper Falcarragh Pelites and the Falcarragh Limestone which are members of the Creeslough Succession [17]. The Upper Falcarragh Pelite and the Falcarragh Limestone were correlated by Harris and co workers with the Appin Group (Lower Dalradian) of Dalradian rocks of Mainland, Scotland [10]. In detail, the pelitic horizon of the northern Ardara aureole consists of interlayered aluminous pelites and semipelites. Lenses and pods of metadolerite are also common in a zone extending about 200 metres from the contact with the Ardara pluton [1].

The Ardara pluton, which is the southernmost of the Donegal granites, has a tear-drop shape and is about 8 kilometres in diameter. It consists of two units, an outer ring of quartz-monzodiorite and an inner core, with the composition varying from quartz-monzodiorite to granodiorite. The Ardara aureole represents a forcibly emplaced, diapiric intrusion [2].

The contact metamorphism of the Ardara pluton has been studied in detail by many previous workers [1,12,15,18]. In brief, the metamorphic effects of the Ardara pluton extend nearly 1.5 km from the intrusion contact. The rocks of the aureole show a strong foliation. The regional structures, S_1, S_2-S_3, are steepened and intensified in the aureole [17]. The steepening of regional structures can be seen from 800 metres to 1 kilometre from the contact [23]. Akaad, Pitcher and Berger and Holder attributed the squeezing and reinforcing of regional structures in the contact aureole to the emplacement of the granite pluton [1,2,11,17]. However, Vernon and Paterson suggested the possibility of syn- or post-emplacement regional deformation [23].

The Ardara aureole has been divided into two units [2]:

(a) an outer unit which is made up of the non-porphyroblastic rocks showing minor contact effects and characterised by new thermal biotite flakes crosscutting the regional schistosity;

(b) an inner unit which comprises three zones (Fig. 1) on the basis of prismatic Al_2SiO_5 polymorphs found [15];

I. an outer kyanite-bearing andalusite zone,
II. a middle kyanite-free andalusite zone,
III. an inner prismatic sillimanite zone.

Naggar and Atherton demonstrated that kyanite in the Ardara aureole is restricted to rocks with MgO/(MgO+FeO) values higher than 0.50 and lower bulk-rock MgO/(MgO+FeO) ratios precluded kyanite as a phase in the assemblage [15].

3. The Petrography of the Metapelitic Rocks from the Ardara Aureole

The details of textural and mineralogical characteristics of aluminium silicate-bearing rocks from the contact aureole of the Ardara pluton are given elsewhere [12]. In brief, dark porphyroblastic schists with conspicuous andalusite on most surfaces characterise the outer kyanite-bearing andalusite zone. In thin section, typical rocks consist of quartz + plagioclase + biotite + muscovite ± chlorite ± staurolite ± garnet ± kyanite ± andalusite ± fibrolite. Graphite and ilmenite are also present. Kyanite takes place as small idioblastic to subidioblastic prisms (0.15-0.35 mm in length). Crosscuted by kyanite, biotite is usually not disturbed along the kyanite boundaries. Idioblastic kyanite occurs as inclusions within andalusite porphyroblasts. Kyanite is also found included in plagioclase poikiloblasts. Staurolite commonly takes place as small (0.12-0.35 mm in diameter) subidioblastic generally inclusion free grains. In some slides staurolite can be seen as irregular grains, or clusters of grains, disseminated throughout the rock. Staurolite is also found as relatively large porphyroblasts (0.4-0.9 mm in diameter) containing continuous curved trails of quartz inclusions. Staurolite, with good crystal faces, is commonly included in andalusite and plagioclase porphyroblasts. Garnet occurs only in kyanite-free rocks i.e., kyanite and garnet never occur together in the same rock. It develops as tiny (0.09-0.13 mm in diameter) idioblastic crystals in the groundmass. It also occurs as inclusions in andalusite, plagioclase and staurolite suggesting garnet was formed earlier than these minerals. Andalusite comes as large porphyroblasts (1-5 mm in diameter) and include quartz, staurolite, kyanite, garnet and ore minerals. Plagioclase always takes place as porphyroblasts (0.5-4 mm in diameter). It generally shows "S"-shaped inclusion trails of quartz. The textures exhibited by plagioclase could easily be mistaken as textures evolving from rotated porphyroblasts. However, these textures are clearly formed by overprinting regional microfolds (S_2-S_3) in the groundmass.

Within the kyanite-free andalusite schists, andalusite can be seen to consist of an inclusion-free pink pleochroic core with the mantle of colourless poikilitic andalusite. A common feature in idioblastic andalusites is the development of textural sector-zoning and matrix displacement [12]. Other common minerals are garnet, staurolite and fibrolite. Staurolite and garnet display similar textural features to those in the kyanite-bearing andalusite zone.

The inner sillimanite zone is characterised by dark brown hornfelses with biotite, garnet and occasionally sillimanite visible in hand specimens. Under the microscope the overall textures of the rock suggest that the transformation from the kyanite-free andalusite zone to the sillimanite zone was accompanied by a wholesale textural reconstitution [13]. Sillimanite appears as long prisms, growing from the groundmass as well as large grains to show symplectic intergrowth with quartz in the groundmass. In some of the specimens, sillimanite is formed by the coarsening of fibrolite groundmass. In one slide, square areas about 4 millimetres in diameter may be presumed from the resemblance of the morphology to be andalusite, pseudomorphed by sillimanite. Staurolite occurs as tiny subhedral grains throughout the groundmass. Garnet in most of the samples from the sillimanite zone displays two different habits. Away from the contact it occurs as small idioblastic to subhedral crystals in biotite clusters after regional garnet. At the immediate contact with the pluton, garnet is present as large porphyroblasts (1-1.5 mm in diameter) which contain inclusions of biotite, quartz and fibrolite. Cordierite can be seen as xenoblastic grains throughout the groundmass. It also occurs as large porphyroblasts (4-8 mm in diameter) which contain inclusions of fibrolite and biotite.

4. The Occurrence of Fibrolite in the Ardara Aureole

In contrast to sillimanite, which is limited to the rocks adjacent to the contact with the Ardara pluton, fibrous sillimanite in the contact aureole of the Ardara extends to a distance of about 400 metres from the intrusion contact (Fig. 1). It occurs as light-brown, 0.1 to 0.5 millimetre length bundles and can be seen in the outer kyanite-bearing andalusite zone, the middle kyanite-free andalusite zone and the inner sillimanite zone. Fibrolite increases in modal amount towards the contact with the pluton. The modal per cent of fibrolite varies from 0.1% to 0.3% in the outer kyanite-bearing andalusite zone, 0.5% to 3.5% in the middle kyanite-free andalusite zone and 5% to 12% in the inner sillimanite zone. In the Ardara aureole, fibrolite is dominantly intergrown with the biotite. With rare exceptions, fibrolite does not present any textural evidence for nucleating on or within andalusite. Of 53 samples containing fibrolite, in 4 samples, fibrolite occurs in rocks lacking other Al_2SiO_5 polymorphs (Fig. 1), indicating fibrolite formation in the Ardara aureole can neither be considered as a polymorphic reaction nor as a local closed-system ionic equilibria linking two aluminum silicate phases, as suggested by Carmichael [5].

4-1. Evidence for Syn-Kinematic Growth of Fibrolite

Previous studies on fibrolite from Ardara aureole emphasised the late stage, metasomatic nature of fibrolite production [13,18]. This may well be right, however, textural evidence in this study suggests deformation-induced fibrolitisation of biotite.

fibrolite in many rocks of the outer kyanite-bearing andalusite zone is found anastomosing around plagioclase porphyroblasts (Fig. 2). It also occurs as discontinuous folia anastomosing between lenticular grains of quartz in the matrix (Fig. 3).

In the kyanite-free andalusite zone, many fibrolite folia are concentrated in narrow high strain zones between andalusite porphyroblasts (Fig. 4). In such cases, the presence of tight crenulations in the fibrolite folia is evident (Fig. 4). Fibrolite in the kyanite-free andalusite zone is also found anastomosing around andalusite porphyroblasts (Fig. 5). In the sillimanite zone, fibrolite is commonly concentrated in folia that anastomose between pods rich in biotite, quartz and plagioclase (Fig. 6).

In some instances from the kyanite-bearing andalusite zone, andalusite porphyroblasts enclose the fibrolite or part of the fibrolitised biotite (Fig. 7). Naggar considered the occurrence of fibrolite enclosed in andalusite, as an early phase of fibrolite formation [14]. He attributed the presence of fibrolite inclusions in the andalusite porphyroblasts to a sharp rise in temperature at the early stage of the Ardara pluton emplacement. However, Atherton considered it as a late nucleation of fibrolite in andalusite [15].

A careful examination of fibrolite and andalusite textural relationship reveals that andalusite statically

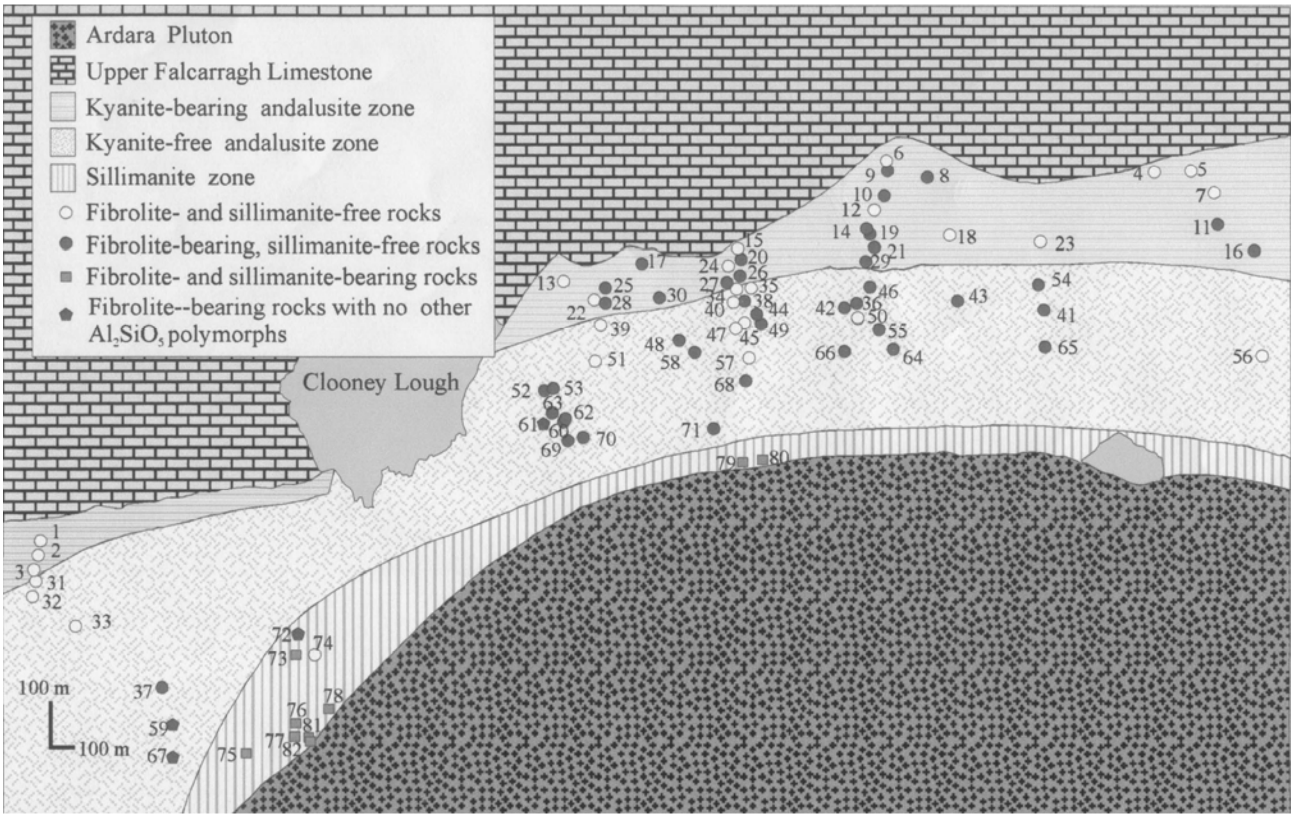

Figure 1. Sample localities in the inner aureole of the Ardara pluton, showing fibrolite- and sillimanite-free rocks, fibrolite-bearing, sillimanite-free rocks and fibrolite- and sillimanite-bearing rocks.

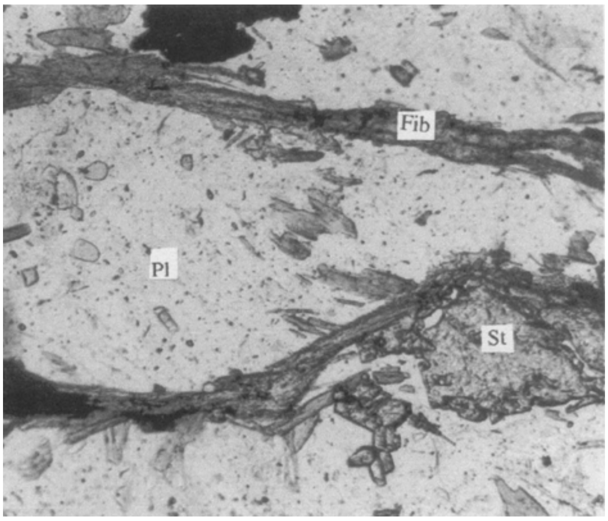

Figure 2. Folia of fibrolite (Fib) anastomosing around plagioclase (Pl) porphyroblasts. Other minerals are staurolite (St), biotite and opaque ilmenite. Base of photo 0.6 mm. (PPL. slide 12, the outer kyanite-bearing andalusite zone)

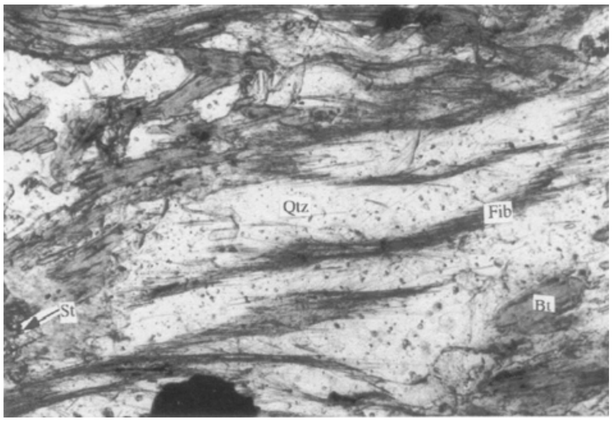

Figure 3. Discontinuous folia of fibrolite (Fib) anastomosing between lenticular grain of quartz (Qtz). Other minerals are staurolite (St), biotite (Bt) and opaque ilmenite. Base of photo 0.8 mm. (PPL. slide 12, the outer kyanite-bearing andalusite zone)

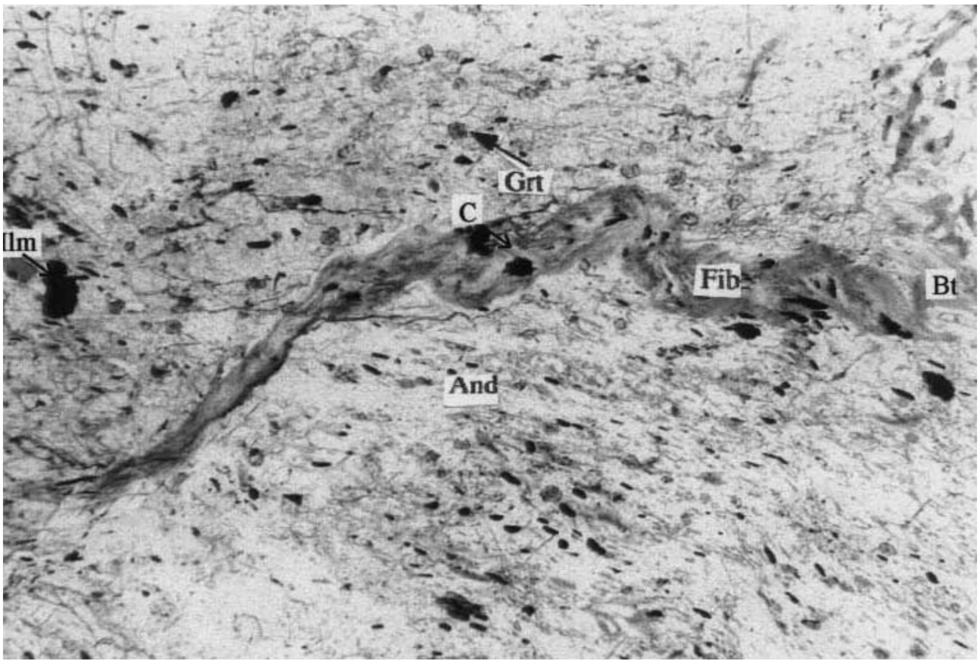

Figure 4. Fibrolite (Fib) folia is concentrated in narrow high strain zone adjacent to the andalusite (And) porphyroblasts. Note the presence of the crenulation © foliation in the fibrolite folia. Other minerals are biotite (Bt), garnet (Grt) and ilmenite (Ilm). Base of photo 3.8 mm. (PPL. slide 63, the kyanite-free andalusite zone)

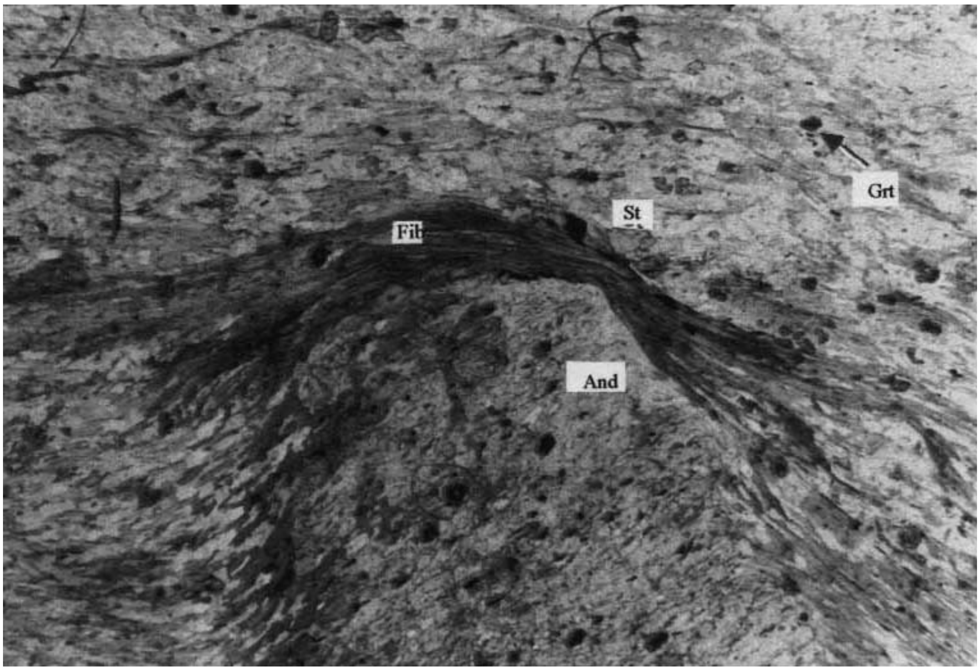

Figure 5. Folia of fibrolite (Fib) anastomosing around the andalusite (And) porphyroblasts. Other minerals are staurolite (St), biotite and garnet (Grt). Base of photo 6.8 mm. (PPL. slide 53, the kyanite-free andalusite zone)

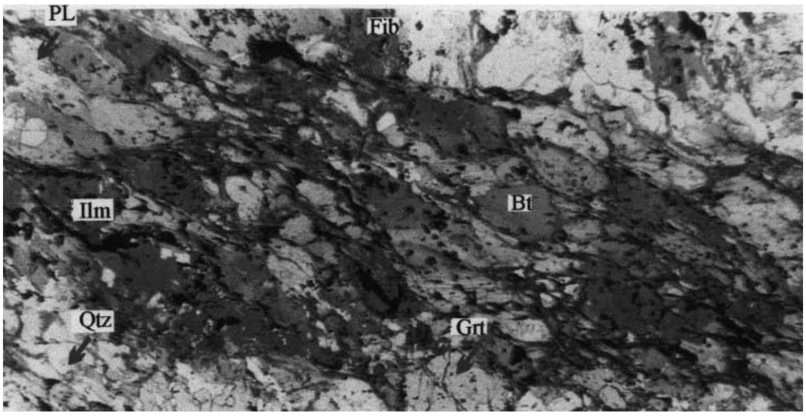

Figure 6. Fibrolite (Fib) is concentrated in folia that anastomosing between pods rich in biotite (Bt), quartz (Qtz) and plagioclase (PL). Other minerals are garnet (Grt) and ilmenite (Ilm). Base of photo 8.5 mm. (PPL. slide 81, the sillimanite zone)

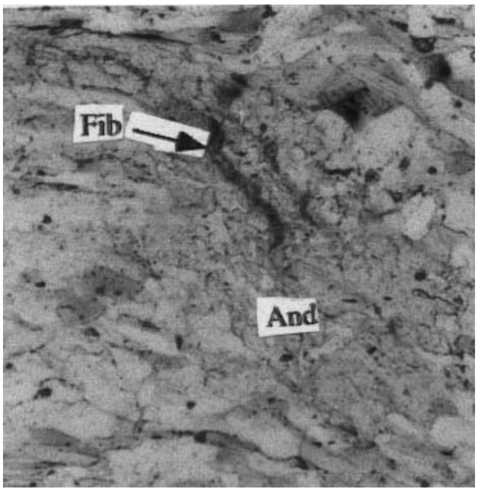

Figure 7. Fibrolite (Fib) included in andalusite (And). Base of photo 2.1 mm. (PPL. slide 27, the outer kyanite-bearing andalusite zone)

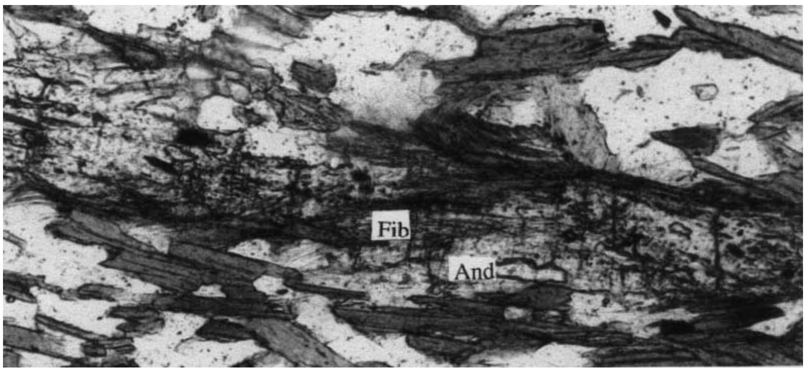

Figure 8. Andalusite (And) enclosed fibrolite (Fib) from formerly high strain zones. Base of photo 3 mm. (PPL. slide 19, the outer kyanite-bearing andalusite zone)

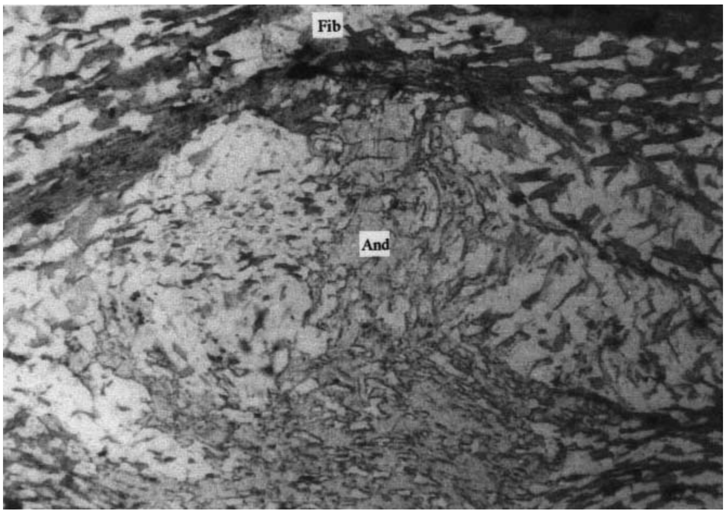

Figure 9. Fibrolite (Fib) preserved as inclusions in the andalusite (And) porphyroblast, has curved or folded shapes. Base of photo 0.8 mm. (PPL. slide 27, the outer kyanite-bearing andalusite zone)

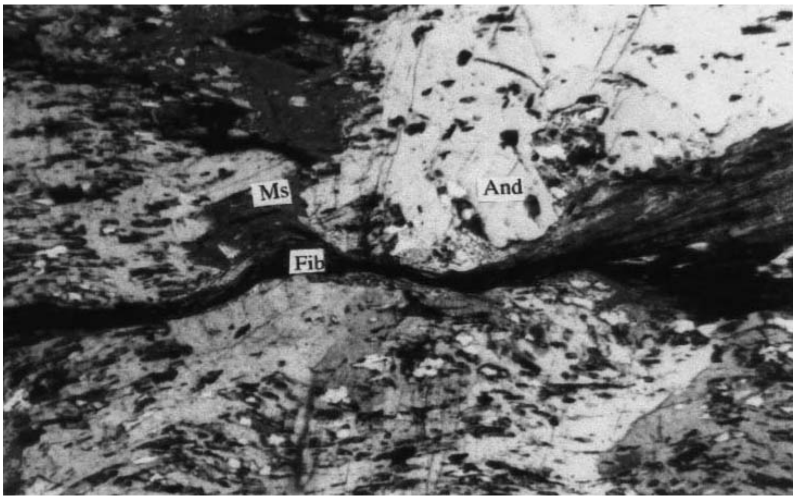

Figure 10. Replacement of andalusite porphyroblast by muscovite (Ms). Fibrolite (Fib) folia are concentrated in narrow high strain zone adjacent to the andalusite (And) porphyroblasts. Note fibrolite remains unaltered. Base of photo 3.2 mm. (PPL. slide 53, the kyanite-free andalusite zone)

overprints the groundmass in many examples and shows no optical evidence of deformation, whilst fibrolite preserved as inclusion in the andalusite, has curved or folded shapes (Fig. 8), suggesting metastable syn-kinematic fibrolite growth, before andalusite crystallisation. The metastable behaviour of fibrolite has been discussed elsewhere [12].

In an interesting sample from the inner part of the kyanite-bearing andalusite zone, the evidence for syn-kinematic fibrolite growth and post-kinematic andalusite growth is even more evident (Fig. 9). In this example, it seems that andalusite growth commenced in a static environment so that it overprinted the regional patterns (S_2-S_3). Then a dynamic stage occurred during which regional schistosity (S_2-S_3) was deflected around andalusite porphyroblasts. Fibrolite grew from biotite in the high strain shear planes around these porphyroblasts. Finally, after deformation, andalusite continued to grow and so enclosed fibrolite from formerly high strain zones.

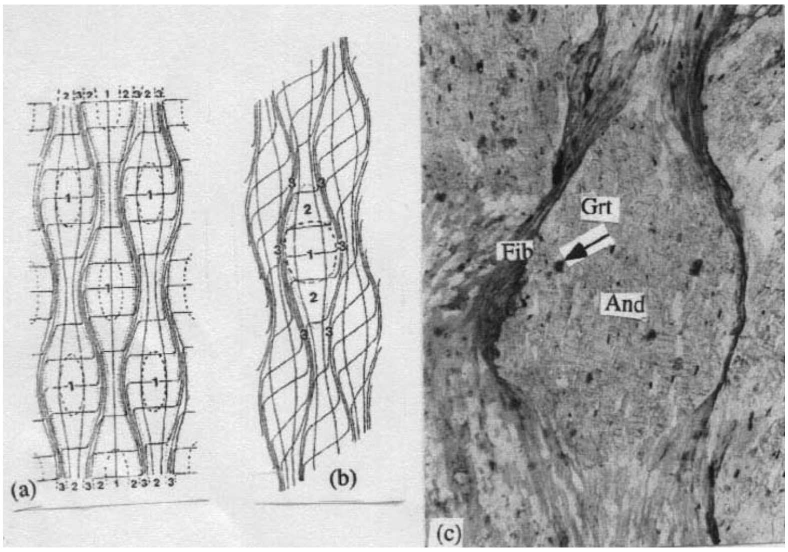

Figure 11. (a) The distribution of deformation partitioning on a strain-field diagram constructed for the XZ plane, representing a block of rock which has undergone non-coaxial progressive bulk inhomogeneous shortening. 1, No strain; 2, progressive shortening strain; 3, progressive shortening plus shearing strain. (After [4]). (b) Deformation partitioning around a porphyroblast resulting from non-coaxial progressive bulk inhomogeneous shortening. The porphyroblast is outlined by dashed line; the key for numbering is the same as in (a). (After [4]) (c) Deformation partitioning around andalusite (And) porphyroblast from Ardara aureole. Note concentration of fibrolite (Fib) folia in zones of high non-coaxial strain. Other minerals are biotite and garnet (Grt). Base of photo 3.5 mm. (PPL. slide 53, the kyanite-free andalusite zone)

Interesting microstructural evidence is also seen in narrow high strain zones between andalusite porphyroblasts where the preferential replacement of andalusite by retrograde muscovite occurs rather than adjacent fibrolite (Fig. 10). As noted by Vernon the preferential replacement of andalusite porphyroblasts is probably due to their response to deformation by the build up of many dislocations around their margins [28]. In this case, retrograde muscovite may be able to nucleate and grow more easily in the dislocation-rich andalusite. Fibrolite aggregates however, remain unaltered, as they are able to undergo strong strain by fibre sliding, without an appropriate production of dislocations.

The above-mentioned textural evidence suggests that the fibrolite in the Ardara aureole was formed in the zones of high non-coaxial strain (Fig. 11) during deformation caused by the intrusion of pluton [4].

The occurrence of fibrolite in the Ardara aureole brings to mind the positive relationship between mineral occurrence and shear stress [9,24]. Therefore, it seems reasonable to suggest a strain-assisted mechanism for the fibrolitisation of biotite in the Ardara aureole. However, in some samples, the occurrence of fibrolite cannot be obviously explained on the basis of deformation-induced fibrolitisation (see section 4-2).

The entire reaction mechanism in which fibrolite could have been concentrated in these high strain zones is not clear. However, it seems that Wintsch and Andrews' pressure solution model is the most likely explanation [24]. Accordingly, it may be concluded that localised, high deviatoric stress along shear planes produced an increase in the chemical potential of the biotite resulting from the following ionic reaction:

$$2[K(Mg_xFe_{1-x})Si_3AlO_{10}(OH)_2] + 14H^+ = Al_2SiO_5 + 5SiO_2(aq) + 2K^+ + 2(Mg_xFe_{1-x})^{++} + 9H_2O \quad (1)$$

From textural evidence the eventual fate of K, Mg, Fe and Si released into the fluid is unknown. In addition, there are no significant statistical differences in whole rock K_2O, MgO, FeO, SiO_2 contents between fibrolite-bearing and fibrolite-free rocks, suggesting no systematic depletion of K, Mg, Fe and Si from fibrolite-bearing rocks [12]. The most likely possibility is that the

Figure 12. Fibrolite (Fib), biotite (Bt) and muscovite (Ms) replacement of andalusite. Base of photo 5.2 mm. (PPL. slide 66, the middle kyanite-free andalusite zone, photo from [6])

components released from biotite decomposition along shear planes may have been deposited to form new biotite in low strain zones. However detection of new-formed biotite is not possible from textural evidence bringing to mind this statement of Foster that:

"Generally, the consumption of biotite by sillimanite (fibrolite) can be easily documented because sillimanite (fibrolite) directly replaces biotite. However, the production of biotite is usually difficult to detect…" [8].

4-2. Evidence for the Post-Kinematic Growth of Fibrolite

In contrast to the presence of clear evidence for the syn-deformation nature of fibrolite formation, some occurrences of fibrolite cannot be explained on the basis of this mechanism including:

1. Fibrolite grown from the biotite replacement of andalusite [3,6] (Fig. 12).
2. The occurrence of fibrolite in parallel to sub parallel aggregates (Fig. 13).
3. Fibrolite concentrated at grain boundaries of enclosing minerals, usually polygonal grains of quartz and plagioclase, commonly projecting into the grains at a high angle to the boundaries (Fig. 14) similar to those described by Vernon et al [22].

These features of fibrolite are consistent with the "disharmonious" texture of Vernon and Flood [21] indicating continuation of fibrolite growth after ductile deformation [23]. Since such occurrences of fibrolite are late in the metamorphic history of the Ardara aureole and restricted to the immediate contact with the pluton (the inner sillimanite zone and the inner part of the middle kyanite-free andalusite zone), they are probably formed as a result of a late-stage process, such as base cation leaching due to acid volatiles, as suggested by Kerrick [13].

5. Conclusion and Summary

1. In the Ardara aureole, fibrolite is dominantly intergrown with the biotite. In so many specimens, textural evidence suggests syn-kinematic fibrolitisation of biotite. Fibrolite was concentrated in zones of high non-coaxial strain, which wrap around zones of low co-axial strain, now occupied by minerals such as plagioclase (in the outer kyanite-bearing andalusite zone), andalusite (in the middle kyanite-free andalusite zone) and pods rich in biotite, quartz and plagioclase (in the inner sillimanite zone).
2. The entire reaction mechanism by which fibrolite could have been concentrated in these high strain zones

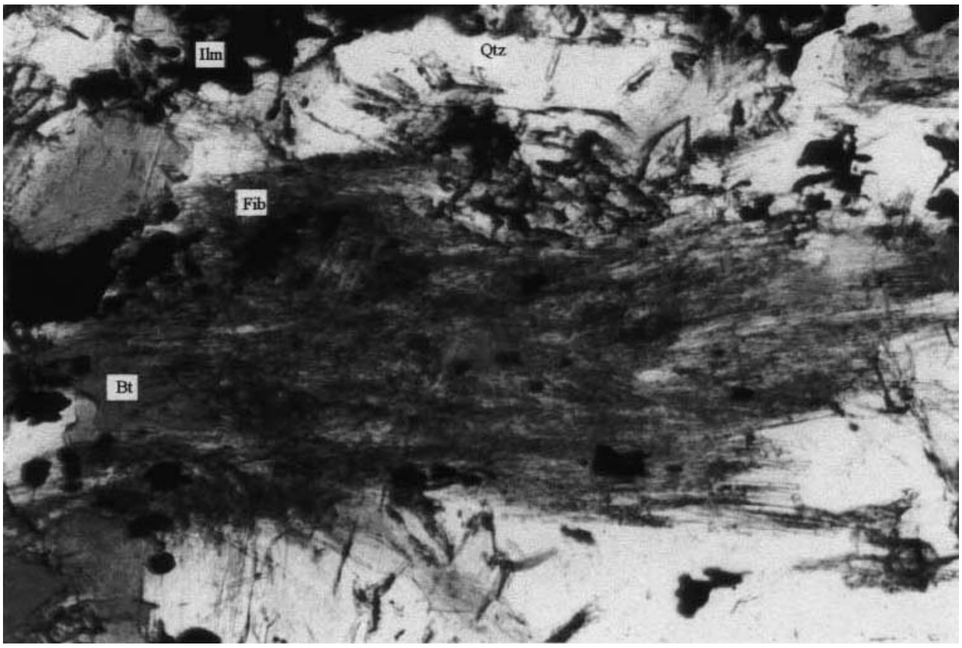

Figure 13. Parallel to subparallel aggregates of fibrolite (Fib). Other minerals are biotite (Bt), ilmenite (Ilm) and quartz (Qtz). Base of photo 2.8 mm. (PPL. slide 81, the inner sillimanite zone)

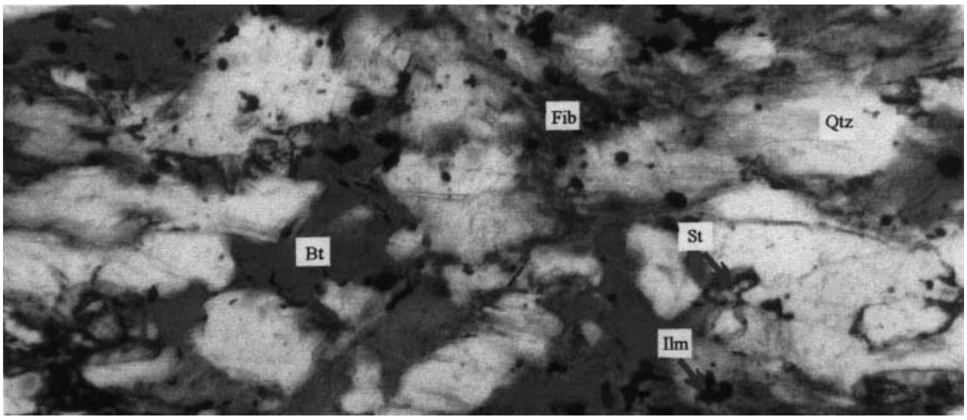

Figure 14. Fibrolite (Fib) is concentrated at grain boundaries of polygonal grains of quartz (Qtz), commonly projecting into the grains at a high angle to the boundaries. Other minerals are biotite (Bt), staurolite (St) and ilmenite (Ilm). Base of photo 1.9 mm. (PPL. slide 81, the sillimanite zone)

is not evident. However, a pressure solution model is the most likely explanation for most fibrolite formation in the Ardara aureole [24].

3. In contrast to the syn-deformation nature of fibrolite formation, some textural evidence, especially from the inner sillimanite zone cannot be explained on the basis of this mechanism, rather indicating continuation of fibrolite growth after ductile deformation.

Acknowledgements

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