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# کیانیت در هاله‌های دگرگونی

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**چکیده:** مدلهای مختلفی جهت تفسیر علت حضور کیانیت در فاز پایداری در هاله‌های دگرگونی مجاورتی بخصوص آنهایی که دارای سایر انواع سیلیکاتهای آلومینیوم نظیر آندالوزیت و سیلیمانیت یا فیبرولیت هستند ارائه شده‌است. تبلور متوالی کیانیت←آندالوزیت←سیلیمانیت در چنین هاله‌هایی را می‌توان به افزایش درجه حرارت در فشار ثابت (پایین تر از نقطه سه گانه سیستم $Al_2SiO_5$) نسبت داد. تبلور متوالی کیانیت←سیلیمانیت (فیبرولیت) می‌تواند حاصل افزایش درجه حرارت در فشار ثابت (بالاتر از نقطه سه گانه سیستم $Al_2SiO_5$) باشد. تشکیل کیانیت را می‌توان حاصل شکسته شدن کانی پیروفیلیت یا به احتمال بیشتر مجموعه کلریت بعلاوه مسکویت دانست. عدم حضور کیانیت در برخی از هاله‌های دگرگونی را می‌توان به عدم وجود ترکیب شیمیایی مناسب در سنگهای مادر یا افزایش نرخ سریع درجه حرارت و در نتیجه اوراستپینگ واکنشهای تشکیل دهنده کیانیت نسبت داد.

**واژه‌های کلیدی:** کیانیت، آلومینیوم سیلیکات، هالهٔ دگرگونی.

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# Kyanite in thermal aureoles

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**Abstract:** Different models are discussed to interpret the presence of kyanite as a stable phase in contact aureoles especially in the andalusite-, sillimanite-bearing aureoles. In such aureoles the polymorphic sequence kyanite → andalusite → sillimanite can be explained in terms of an essentially isobaric path during which kyanite initially crystallises from the breakdown of pyrophyllite or more likely muscovite + chlorite beneath the pressure of the triple point (3-4 kbar 10-14 km depth), followed by andalusite and sillimanite crystallisation. The sequence kyanite-sillimanite and/or fibrolite can be seen in thermal aureoles subjected to isobaric metamorphism above the triple Al2SiO5 point (5-8 kbar 17-28 km depth). The absence of kyanite in some thermal aureoles can be explained on the basis of either compositional constraint or overstepping of low-temperature reactions due to high heating rates.

**Keywords:** *Kyanite, Aluminium silicates, contact aureole.*

## 1 Introduction

Kyanite is the high-pressure low-temperature polymorph of $Al_2SiO_5$. It occurs typically as a mineral in regional metamorphism of pelitic, or more rarely psammitic rocks. Kyanite as a stable phase is rare in contact metamorphic rocks, but may often be present as a result of previous regional metamorphism (e.g., Ross of Mull aureole – [5, 21]; Easky aureole – [32]).

In a review by Pattison and Tracy [24] of 68 contact aureoles containing metapelitic assemblages, only 5 aureoles are reported to contain stable kyanite, namely:

1) Ardara and Main Donegal aureoles, NW Ireland, [22,23,25,4,16];
2) the Kwoiek aureole, British Columbia [14,15];
3) the Ronda aureole, Spain [19,20];
4) the Barrovian-type Caplongue aureole, Spain [7].

Recently the presence of kyanite as a stable phase has been reported from three more contact aureoles including:

1) the Scousburgh aureole, south Shetland [9];
2) the Skaw Granite aureole, North Shetland [9];
3) Northeastern Brazil aureoles (Caby and Sial, personal communication).

There is no a general agreement about the way in which kyanite is formed in contact aureoles especially in the andalusite-, sillimanite-bearing aureoles. Here, we address the problem of kyanite occurrence in thermal aureoles by providing a short description of the aureoles which contain stable kyanite followed by a discussion of the different models can be suggested for kyanite occurrence in these contact aureoles.

## 2 Ardara aureole, County Donegal, Ireland

The Ardara pluton 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 pluton represents a forcibly emplaced, diapiric intrusion [1].

The contact metamorphism of the Ardara pluton has been studied in detail by many previous workers [2,26,23,16]. 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 [25]. The steepening of regional structures can be seen from 800 metres to 1 kilometre from the contact [31].

The Ardara aureole has been divided into two units [2] (Fig. 1):

(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 [23] (Fig. 1) on the basis of prismatic $Al_2SiO_5$ polymorphs found;

I. an outer kyanite-bearing andalusite zone,

II. a middle kyanite-free andalusite zone,

III. an inner prismatic sillimanite zone.

Kyanite was not recorded by Akaad [2] and in only one slide by Pitcher and Read [26], but was shown by Naggar [22] to occur extensively in the outer part of the inner aureole and to be an aureole mineral. He demonstrated that the southern limit of the occurrence of kyanite coincides with the sharp increase in magnesium content of the pelites found by Pitcher and Sinha [28] suggesting a compositional control for kyanite growth. However, Naggar [22] considered that andalusite and sillimanite were not dependent on the MgO/(MgO+FeO) ratio of the rock but rather were dependent on distance from the granite contact.

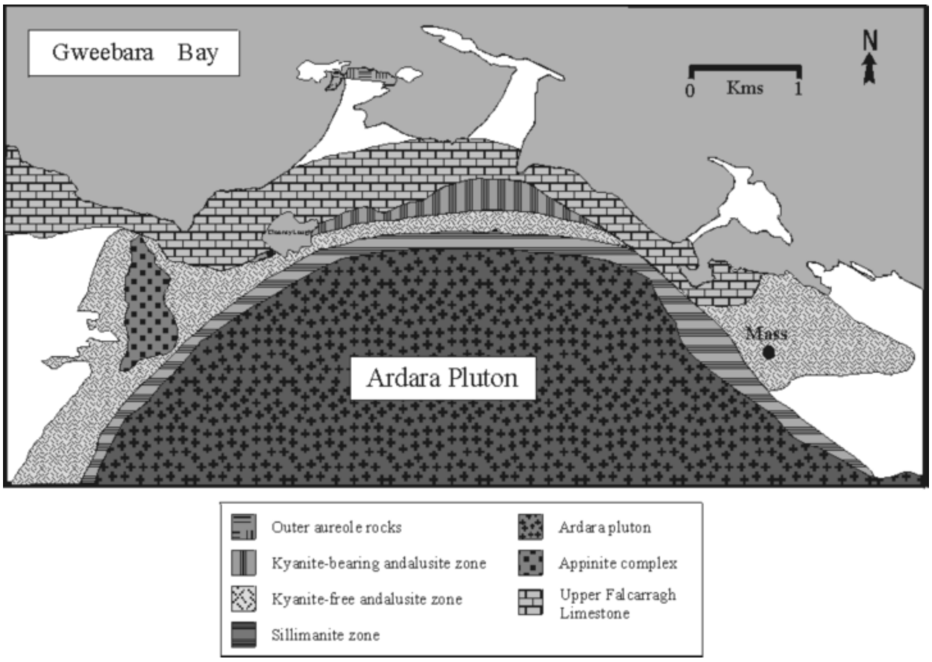


**Fig. 1** Geology of the northern portion of the Ardara pluton and surrounding country (modified from Akaad, 1956b and Naggar and Atherton, 1970).

Naggar and Atherton (1970) in the study of pelitic rocks of the Donegal granite aureoles considered the status of the aluminum silicates in the Ardara aureole. They showed that in this aureole there were three successive reactions, each forming a unique mineral assemblage; i.e. the first reaction produced kyanite, staurolite, garnet; the second reaction formed andalusite and sillimanite formed from the third reaction.

A summary of the petrography and textural characteristics of the contact aureole of the Ardara pluton is presented here from Homam [16]. 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. 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. Garnet also occurs as inclusions in andalusite, plagioclase and staurolite suggesting it 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 [16]. 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 [17]. Sillimanite appears as long prisms, growing from the groundmass as well as large grains to show symplectic intergrowth with quartz in the groundmass. Staurolite occurs as tiny subhedral grains throughout the groundmass. 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.

### 3 Main Donegal aureole, County Donegal, Ireland

The Main Donegal granite, 35 km. long and 10 km. wide, is elongated parallel to the regional NE-SW strike of the enclosing Dalradian metasediments (Fig. 2) and consists mainly of medium-grained biotite granodiorite varying to coarse-grained granodiorite [25].

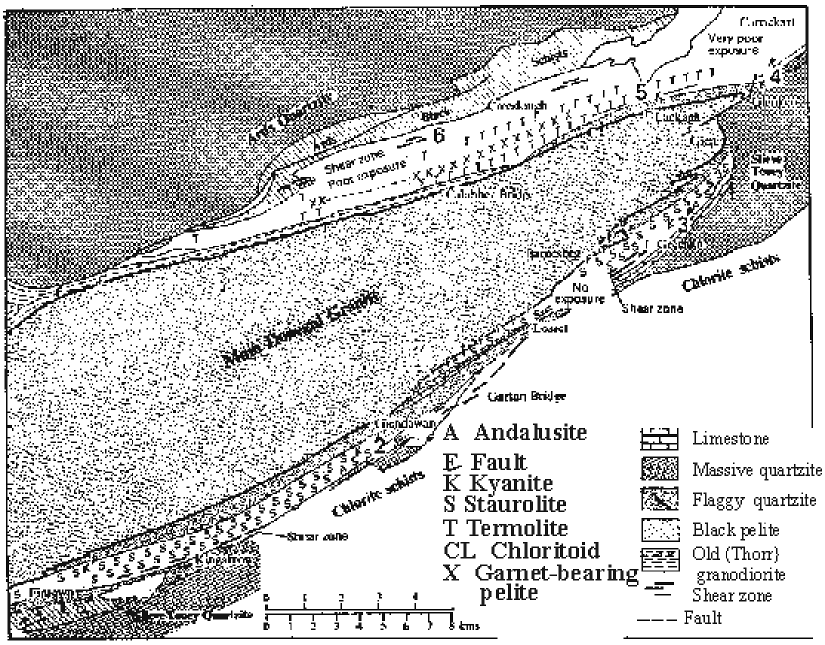


**Fig. 2** Sample localities within the aureole of the Main Donegal granite. 1. Fintown, 2. Glenaboghil, 3. Loch Reelan, 4. Glenkeo, 5. Lachagh Bridge, 6. Owennagreeve river. (From Naggar and Atherton, 1970, Fig. 4).

Detailed mapping of the Main Donegal granite and its envelope was performed in the 1950s by the Imperial College Donegal Research Team and was summarized by Pitcher and Read [26,27]. They recognized a biotite-granite with a medium-grained facies in the south and east and a coarse-grained facies in the north and west displaying a uniform vertical banding which was attributed to flow banding. Pitcher and Read [26,27] noted that contact schists together with the marginal parts of the pluton show intensive shear structures and near horizontal lineation. According to them the production of these structures was contemporaneous with the crystallization of the contact schists and is related to the emplacement of the pluton. A medium grade aureole was described with staurolite, kyanite, plagioclase, garnet, andalusite and sillimanite. Pitcher and Read [26,27] noted that the aureole has several characteristics of regional metamorphism with many of the early minerals showing rotation by subsequent deformation.

Pitcher and Read [27] considered that the formation of kyanite in the Main Donegal aureole was possibly related to the directional pressure which existed during metamorphism produced by intrusion emplacement.

According to Berger [6] the Main Donegal granite was emplaced into a pre-existing "root zone" of intensely deformed and high metamorphosed rocks and much of the apparent aureole actually pre-dates the emplacement of the granite.

Naggar [22, p.186) in disagreement with Berger [6] stated: "the carapace around the Main Donegal granite is a true aureole of the granite and the minerals it contains, namely, fibrolite, kyanite, staurolite and andalusite are aureole minerals, in the sense that they result from the granite intrusion".

Naggar and Atherton [23] showed that as in the Ardara aureole there were three successive reactions, each forming a unique mineral assemblage. According to them the aureole of Main Donegal granite was a low temperature aureole, which underwent fairly rapid heating and a slow cooling.

Naggar and Atherton [23] studied rocks containing the aluminium silicate in six localities around the Main Donegal pluton (Fig. 2). A summery of prtrography and textural characteristics of the aluminium silicate from these localities is presented here.

Kyanite occurs as elongated prisms often cutting across biotite. Kyanite is present in the schists of Glenaboghil (locality 2, Fig. 2) where it clearly overprints biotite and may also enclose garnet. Staurolite shows the same textural features as kyanite and may also enclose garnet. Feldspar often occurs as porphyroblasts, and may enclose kyanite and garnet. Fibrolite increases in abundance towards the contact and often replaces biotite.

Coarse andalusite-kyanite schists were reported from Loch Reelan area (locality 3, Fig. 2). Staurolite is present as idioblastic grains or spongy crystals with idioblastic outlines. Andalusite is present as big spongy crystals or elongated grains which tend to lie along the foliation. Andalusite porphyroblasts may contain inclusions of garnet, kyanite and staurolite. When garnet, kyanite and staurolite occur as inclusions in andalusite they show no reaction and no relation to the crystallographic direction of andalusite.

Schists near Glenkeo (locality 4, Fig. 2) contain fibrolite and kyanite, with or without staurolite. In the kyanite schists, augen with decussate texture occur within the foliated rock. The augen consists of quartz, biotite, and numerous kyanite prisms showing a clear hornfelsic texture. The kyanite is undeformed and overprints the original schistosity. Outside the augen the rock is affected by a late strain slip cleavage which may deform the kyanite prisms. Staurolite occurs as idioblastic crystals containing quartz and sometimes garnet. Schists at Lackagh Bridge (locality 5, Fig. 2) and Owennagreeve River (locality 6, Fig. 2) contain kyanite whilst staurolite and andalusite are absent.

Andalusite-bearing schists occur south of Fintown in the outer part of the aureole staurolite zone (Fig. 2, locality 1). Andalusite occurs as well-developed rectangular crystals or curved irregular crystals overprinting the groundmass. Staurolite is uncommon and occurs as idioblastic crystals in andalusite. Numerous small aureole garnets are also present as euhehral crystals. Kyanite occurs close to the contact with the pluton and overprints the original schistosity.

Considering the occurrence of kyanite and andalusite in the Main Donegal aureole Pitcher and Read [27, p. 249] stated that: “The kyanite in the Main Granite aureole has so similar a mode of occurrence to the staurolite - the two minerals may even be intergrown-…. In the special case [south of Fintown] where kyanite and andalusite occur together, there is no hint of replacement and they are independent mineral phases with the same time relationships as the pair staurolite-andalusite. But if not separated in time these two minerals do show some separation in space, and andalusite is more typically the mineral of the outer aureole where one might expect conditions of lower temperature and pressure”.

Atherton et al. [4, p.436] in disagreement with Pitcher and Read [27] emphasized that: “Indeed in one particular locality, [south of Fintown] where Pitcher and Read [27] thought there was some degree of spacial separation of andalusite and kyanite, it is now clear that all the kyanite rocks recently studied contain andalusite, and in a few places andalusite occurs closer to the contact than kyanite-bearing rocks. Between these kyanite rocks and the contact, we found the more usual staurolite schists, notably lacking andalusite and kyanite ”.

They also considered that andalusite-bearing rocks at Fintown are not related to the Main Donegal granite but are part of the Carbane Gneiss aureole.

**4 The Ronda aureole, Spain**

Loomis [19] studied the contact aureole of the Ronda ultramafic intrusion in southern Spain and identified two contact metamorphic sequences consisting of a gneiss series developed adjacent to the steeply dipping margin of the intrusion and a hornfels series developed on the roof of the intrusion. A summary of the petrography and textural characteristics of the Ronda aureole from Loomis [19] is presented here.

In the gneiss series, the sequence of contact minerals into the aureole is biotite, andalusite, garnet, staurolite, fibrolitic sillimanite and cordierite (Fig. 3). At the biotite isograd, biotite developed from chlorite. Andalusite, staurolite and the first occurrence of garnet come in over a short distance in muscovite-chlorite-biotite-quartz schist. Andalusite forms idioblastic porphyroblasts including carbonaceous material. Garnet first appears between the andalusite and staurolite isograds as inclusions in andalusite. Staurolite of lower grade occurs as small subhedral crystals accompanied by andalusite and garnet. No textural evidence is presented by Loomis [19] of replacement or consumption of andalusite and garnet to form staurolite. At higher grade staurolite is enclosed in andalusite porphyroblasts as irregular masses. Up grade from the staurolite isograd fibrolitic sillimanite formed, followed by muscovite-quartz breakdown to give sillimanite-K-feldspar assemblages. A short distance upgrade of the sillimanite-K-feldspar isograd new garnet appears, accompanied by a decrease in staurolite, producing the assemblage garnet-biotite-quartz- K-feldspar. The cordierite zone has the highest grade in which the assemblage K-feldspar-biotite-cordierite-garnet is present.

The hornfels series are exposed as scattered masses with steeply dipping contacts overlying the massif or as lenses along the northern, faulted contact. Lower grade assemblages in the hornfels series are defined by the presence of andalusite and staurolite. No garnet was found in the low grade assemblages. Andalusite in the high-grade hornfels assemblages is rare and is always extensively replaced by sillimanite and hercynite. Sillimanite commonly forms fibrous mates inside cordierite porphyroblasts, usually associated with hercynite grains. The highest-grade assemblage is cordierite-biotite-quartz- K-feldspar.

Kyanite appears only in the gneiss series at about the sillimanite isograd. In its first appearance, kyanite occurs as small rare blades along with abundant fibrolitic sillimanite. Kyanite increases in size and abundance up to the igneous contact. No kyanite was found in the hornfels series

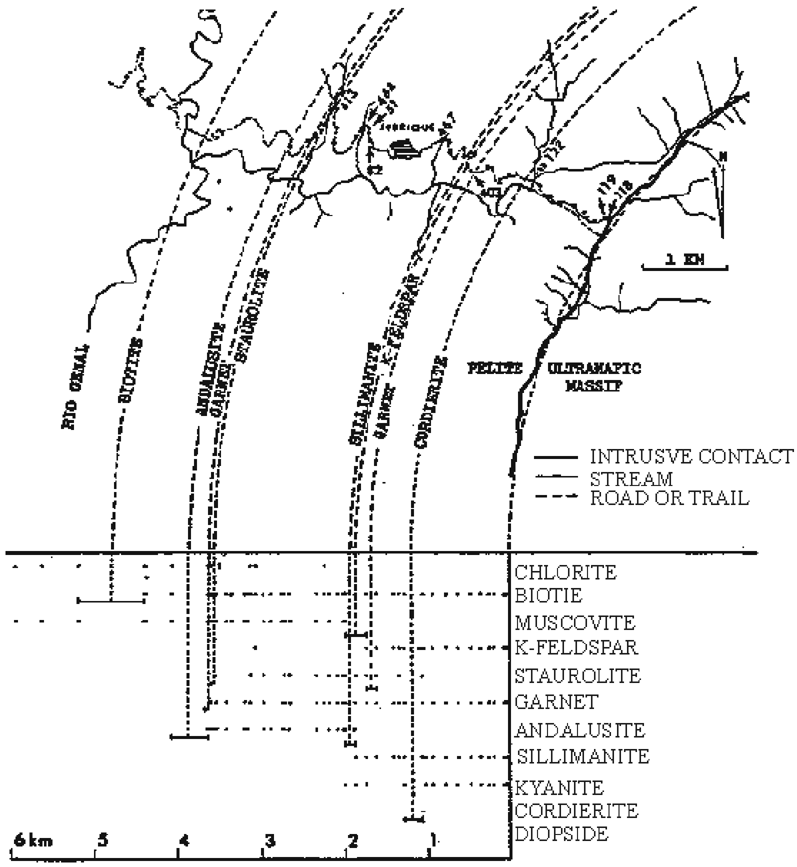


**Fig. 3** Map of the Jubrigne sample traverse, north-west part of the Ronda aureole "Gneiss Series", Spain. (From Loomis, 1972, Fig.2).

## 5 Kwoiek area, British Columbia

The contact metamorphic terrain adjacent to the Coast Range batholith (Kwoiek area, British Columbia) has been studied by Hollister [14,15]. The major rock type within the Kwoiek area is graywacke. According to Hollister [14,15] the metamorphic grade increases continuously from chlorite through biotite, garnet, staurolite, and up to sillimanite as the quartz diorite bodies of the batholith are approached. The presence of all three aluminium silicate polymorphs (andalusite, kyanite and sillimanite) has been reported by Hollister [14,15] who noted that they may occur singly or in combinations of any two, although the most abundant pair was kyanite-sillimanite and the rarest pair was andalusite-kyanite. Hollister [15] found that in the Kwoiek area andalusite, kyanite and sillimanite all occur in square-outlined areas with chiastolite-type patterns of inclusions. Hollister [15] also reported the occurrence of sillimanite as mats of fine needles near the edges of the prismatic volumes containing kyanite and andalusite.

The textural evidence outlined above made Hollister [15] to conclude that the aluminum silicate polymorphs in Kwoiek area grew in the order of kyanite → andalusite → sillimanite.

## 6 The Scousburgh aureole, south Shetland, and the Skaw Granite aureole, North Shetland

Flinn et. al. [9] studied the Scousburgh aureole, South Shetland (Fig. 4) and Skaw Granite aureole (Fig. 5) of north Shetland. They recognised two types of country rock viz.: chloritoid-muscovite-chlorite-quartz-kyanite phyllite and muscovite-chlorite-quartz phyllite. They demonstrated that the thermal metamorphic zones developed in the chloritoid-bearing phyllites differ radically from those developed in the chloritoid-free phyllite.

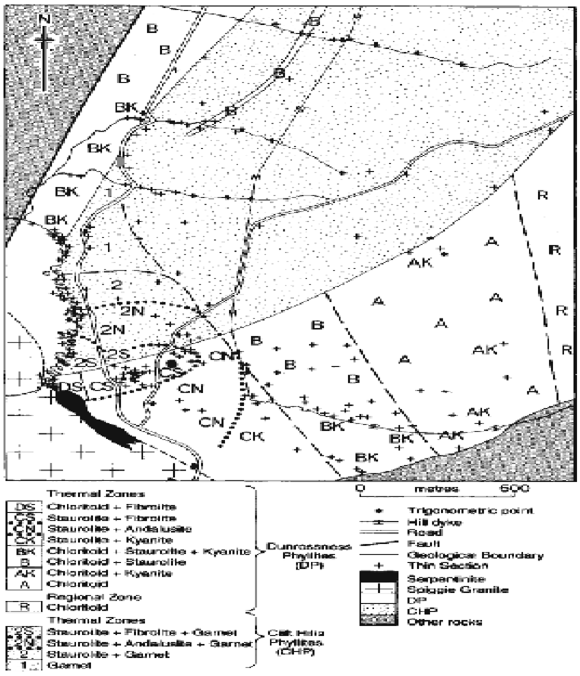


**Fig. 4** Map of the isograds and sample locations in the Scousburgh aureole. (From Flinn et al., 1996 Fig. 6).

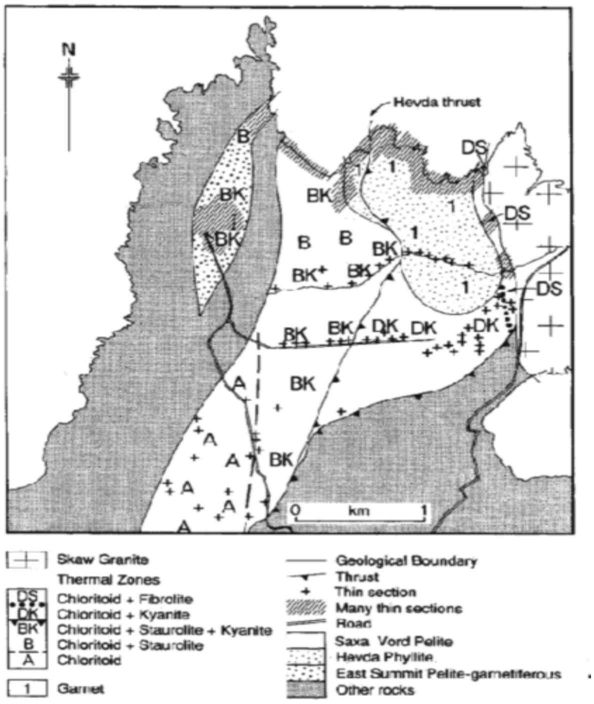


**Fig. 5** Map of the isograds and sample locations in the Skaw aureole. (From Flinn et al., 1996 Fig.7).

In the chloritoid-bearing pelites of the Scousburgh aureole, Flinn et al. [9] distinguished zones based on incoming of chloritoid, chloritoid-staurolite, staurolite-biotite and retrograde chloritoid. They also recognised that in the same pelites the sequence kyanite-andalusite-fibrolite is progressively developed towards the granite.

Thermal zones in the chloritoid-free pelite were distinguished by the incoming of garnet, staurolite-biotite, andalusite and fibrolite. No kyanite was found in these pelites.

The Skaw granite produced similar zones to those developed in the Scousburgh aureole except that within the Skaw granite aureole the sequence kyanite-fibrolite was developed and thermal andalusite is absent.

## 7 Caplongne aureole, Massif Central, France

Contact metamorphism of pelitic rocks in the Caplongne aureole, Massif Central, France, was studied by Delor et al. [7] who distinguished chlorite, biotite, garnet, staurolite and kyanite zones around the syntectonic Caplongne granodiorite (Fig. 6).

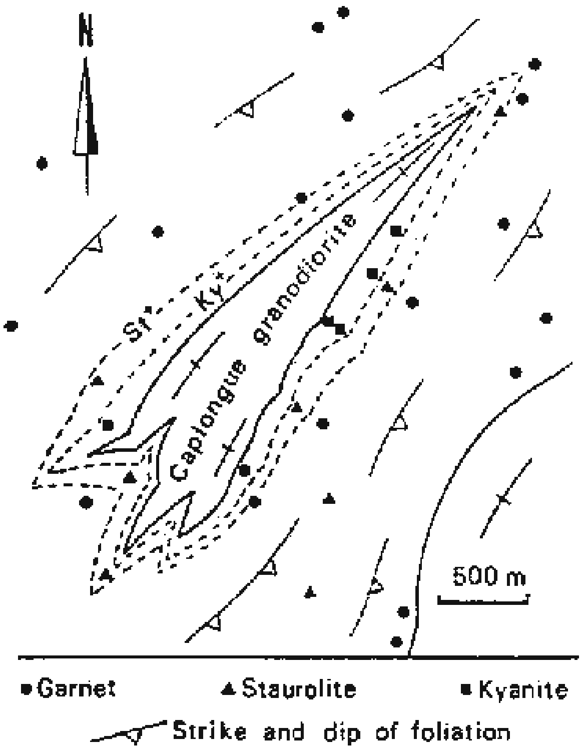


**Fig. 6** Map of the isograds and sample locations in the aureole surrounding the Caplongne granodiorite, Massif Central, France. (From Delor et al., 1984, Fig 2, p.57).

In the garnet zone, garnet appears in biotite-muscovite-chlorite-plagioclase-quartz schists. Down grade of the staurolite zone, the first appearance of staurolite coincides with the disappearance of primary chlorite indicating chlorite+muscovite breakdown to give staurolite+quartz. Upgrade in the middle staurolite zone, a new staurolite producing reaction took place in the presence of plagioclase and absence of chlorite. Proceeding upgrade in the kyanite zone, kyanite first appears in association with plagioclase porphyroblasts and Na-poor muscovite from paragonite+quartz breakdown. Close to the contact with the pluton, kyanite porphyroblasts grew at the expense of staurolite giving kyanite-biotite-almandine assemblage. Needles of fibrolite together with pinite was found in one sample in the kyanite zone at lower grade than muscovite + quartz breakdown.

## 8 Contact aureoles from Northeastern Brazil

Caby and Sial (personal communication) studied some kyanite-bearing aureoles around Neoproterozoic magmatic epidote-bearing granitoids (tonalites to granodiorites) in the Cachoeirinha- Salgueiro Foldbelt in Northeastern Brazil. According to Caby and Sial these aureole rocks are composed of garnet, kyanite, staurolite, muscovite, biotite, plagioclase and quartz. The occurrence of fibrolite was reported only very close to the tonalite. In the aureoles kyanite is rimmed or replaced by margarite. Caby and Sial suggested a pressure about 8 Kbar for kyanite-bearing aureoles in Northeastern Brazil.

## 9 Discussion

As mentioned earlier, of 71 contact aureoles containing metapelitic assemblages reviewed, only 8 aureoles contain stable kyanite. The sequences in time of assemblages as well as the estimated temperature and pressure for metapelitic rocks from these contact aureoles are given in Table 1. On the basis of the sequences of assemblages in these aureoles they can be divided into two categories:

1) aureoles in which the sequence kyanite-sillimanite (fibrolite) is found with increasing grade;
2) aureoles in which kyanite, andalusite and sillimanite (fibrolite) have all been identified.

The sequence kyanite-fibrolite is seen in the thermal aureoles of Caplongne, Massif Central, France, [7], the Skaw aureole in Shetland [9] and contact aureoles from Northeastern Brazil. To the present author's knowledge, these thermal aureoles represent the highest pressure aureoles which have been recognized on the basis of a prograde metapelitic sequence. Kyanite in these aureoles crystallized in the kyanite stability field at pressures above the $Al_2SiO_5$ triple point (5-8 kbar ≈ 17-28 km depth), followed by crystallization of fibrolite along an essentially isobaric path.

| Aureole | Location | References | Intrusion | Protolith (+Mus-Qtz) | Assemblages | | | | | | T °C | P kbar |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | All assemblages contain Qtz+Bt | | | | All assemblages contain Kfs+Bt | | | |
| Ardara | Donegal, NW, Ireland | Pitcher & Read (1963), Naggar and Atherton (1970) | Diorite to granodiorite | Chl-Bt-Grt | Mus-Chl | St-And± Ky±Grt± Fib±Mus | St-And± Grt±Fib± Mus | St-Crd- Sil-Grt- Fib | | | ~ 600 | 4±1 |
| Main Donegal | Donegal, NW, Ireland | Pitcher & Read (1963), Naggar and Atherton (1970) | Granodiorite | Chl-Bt-Grt | St-And± Grt±Mus | St-And± Grt±Mus ±Ky±Crd | St-Grt-Fib ±Mus±Ky ±Crd | | | | ~ 550 | 4±1 |
| Ronda | Spain | Loomis (1972a; b) | Peridotite | Chl | St-Chl- Mus±Grt | And+Mus ±Grt | And+St- Mus±Grt | St-Sil- Mus±And ±Grt±Ky | Qtz-Grt- Sil±St±Ky | Qtz-Grt- Crd±Sil | 800±100 | 4.3±1 |
| Scousburgh | South Shetland | Flinn et al. (1996) | Granite | Chl-Bt-Mus Grt±Ctd±Ky | Chl-Mus- Cld±Ky | Chl-Mus- Cld-St±Ky | Chl-Mus- St±Ky±And | Mus-Fib | | | | Below the $Al_2SiO_5$ triple point |
| Kwoiek | British Columbia, Canada | Hollister (1969a; b) | Diorite | Chl | Chl-Mus- Grt | Mus-Grt- St | | Mus-St±Grt -Ky,And,Sil | | | | 5.5-7.1 |
| Caplongue | France | Delor et al. (1984) | Granodiorite | Chl | Chl-Mus- Grt | Mus-Grt- St | Mus-St- Grt-Ky | Mus-St- Grt-Ky- Fib | | | ~ 650 | ~ 6.5 |
| Skaw | North Shetland | Flinn et al. (1996) | Granite | Chl-Bt-Mus Grt±Ctd±Ky | Chl-Mus -Cld | Chl-Mus- Cld-St±Ky | | Mus-Cld ±Fib±Ky | | | | Above the $Al_2SiO_5$ triple point |
| Brazil aureoles | NE, Brazil | Caby & Sial (1999) | Tonalte to granodiorite | | Mus-St -Ky | | | Mus-St- Ky-Fib | | | ~ 650 | ~ 8 |

Table 1. The sequences of assemblages and estimated temperature and pressure of metapelitic rocks from kyanite-bearing contact aureoles.

More controversial are occurrences of kyanite as an apparently stable phase in the andalusite-, sillimanite-bearing aureoles, such as the thermal aureoles of

Kwoiek area, British Columbia, Ardara and Main Donegal, NW Ireland, Scousburgh, north Shetland and the Ronda aureole, Spain.

An enigmatic aureole is Kwoiek, British Columbia [15]. Kyanite, andalusite and sillimanite have all been reported from this aureole, with sillimanite replacing kyanite which in turn replaced andalusite. Hollister [15] suggested two possible prograde metamorphic paths to describe the aluminium silicate paragenetic relations that he inferred from textural evidence (Fig. 7). He considered the possibility of an equilibrium model (path C, Fig. 7) in which the andalusite→ kyanite transformation would be consistent with the crossing of the andalusite-kyanite equilibrium along the lower grade part of path C. He concluded that the implied pressure increase along path C could have resulted from either an increase in tectonic overpressure resulting from the forceful implacement of the intrusion or an increase of fluid pressure over the lithostatic pressure due to rapid dehydration of the country rocks near the pluton contact. Subsequently, he favoured an isobaric process (path A, Fig. 7) in which andalusite grew metastability in the kyanite field followed by inversion to the stable polymorph (Fig. 7). Atherton et al. (1975), Kerrick (1990), Pattison and Tracy (1991) considered an alternative explanation for the andalusite-kyanite relationship in the Kwoiek area. They suggested that andalusite in this area is most probably a product of an early low pressure metamorphism followed by a high pressure metamorphism that resulted in the alteration of andalusite to kyanite.

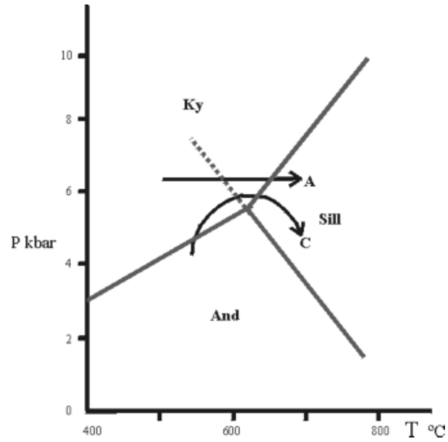


**Fig. 7** Two progade P-T paths (A and C) considered by Hollister (1969) for contact metamorphism in the -Kowiek -area, British Columbia. (From Hollister, 1969b, Fig. 6).

If the conclusion of Atherton et al. [4], Kerrick, [18], Pattison and Tracy [24] is valid, then as in contact aureoles of Caplongne, Skaw and Northeastern Brazil, kyanite in Kwoiek area was formed in the kyanite field at pressures above the $Al_2SiO_5$ triple point, followed by crystallisation of sillimanite along an essentially isobaric path.

Loomis [19] in his study on the Ronda contact aureole (Spain) noted that kyanite was confined to the inner zones of this aureole which show strong fabrics, typically parallel to the margins of the intrusion. He suggested that during diapiric intrusion the envelope rocks underwent progressively greater transport from depth as the contact is approached. Therefore on the basis of Loomis's [19] model deeper level kyanite-bearing rocks on the margin of the ascending pluton were dragged upwards to pressures where andalusite and sillimanite were stable. Loomis [20] extended his model to other kyanite-bearing contact aureoles e.g. Ardara and Main Donegal aureoles, and so questioned the traditional supposition of isobaric metamorphic conditions at the present level of exposure in kyanite-bearing thermal aureoles.

Atherton et al. [4] in a critical paper questioned Loomis's model. They noted that if envelope rocks had been dragged upward from depth during or after the growth of the porphyroblastic minerals, a bending upward of the pre-existing axial planes should be expected. However their geological field evidence showed no upward bent pre-existing folds in the Ardara and Main Donegal aureoles. Considering the Ardara aureole Atherton et al. [4] noted that the bedding planes and the axial planes of the pre-existing folds are progressively bent downward and inward on approaching the Ardara pluton. Atherton et al. [4, p.433] state that:

"The situation is even more clearly shown in the Main Donegal granite…. The pre-existing, regional fold axes are bent downward along one flank and upward along the other, in such a way that neither upward nor downward drag can be involved and that the effect is solely due to an early outward shouldering aside."

In addition to structural evidence, Atherton et al. [4] also considered mineral zoning in the Ardara and Main Donegal aureoles. They referred to Naggar and Atherton's [4] work and emphasized that kyanite in the Ardara aureole occurs in the outer part of aureole where it coincides with a relatively magnesium-rich pelites of the envelope rocks. Therefore, they concluded that the occurrence of kyanite in the Ardara aureole is due to envelope rock chemistry in contrast to Loomis's model.

The sequence of aluminium silicates in contact with the Main Donegal granite is more complicated than that in the Ardara aureole because of the lithological variation across the aureole and the difference in succession on either side of the Main Donegal granite [4]. However Atherton et al. [4, p. 438) emphasised:

" ... the inner aureole developed in situ with the main deformation causing flattening parallel to the contact and a subhorizontal stretching, the kyanite growing late in this deformation history and then only in the magnesium rich rocks".

In an alternative explanation to that of Hollister [15] and Loomis [20] for the presence of kyanite in thermal aureoles, Atherton et al. [4] followed Holdaway's [12] work who showed that the assemblage kyanite-quartz can be produced from the breakdown of pyrophyllite at pressure as low as 2.5 Kbar. They explained the occurrence of kyanite in the aureoles in terms of simple equilibrium crystallisation in the kyanite field beneath a relatively low pressure triple point, which continued along an isobaric path into the andalusite and sillimanite field. They also explained the complexity of kyanite occurrence in terms of metastable persistence, compositional restraint and overstepping of low temperature reactions.

Some workers [6, Pattison, personal communication] suggested that kyanite and staurolite in the Ardara and Main Donegal aureoles are related to regional metamorphism. However, based on the following reasons kyanite and staurolite are undoubtedly aureole minerals:

1) the regionally metamorphosed rocks outside the influence of the Donegal granites are fine-grained chlorite-muscovite schists [2,28,27,8,23,3]
2) staurolite and kyanite are most closely connected in time and space with the contact affects of the Ardara and Main Donegal plutons [23,25].

Some workers attributed the coexistence of all aluminium silicate polymorphs in one area to their crystallisation close to the P-T conditions of the triple point [11]. However, crystallisation of all aluminium silicate polymorphs close to the P-T conditions of the triple point in so-called "triple point" rocks has been questioned by many workers [30,10,33]. The presence of all aluminum silicate polymorphs in pelitic schists of the Mt. Moosilauke, New Hampshire made Hodges and Spear [11] suggest that these rocks crystallized close to the P-T conditions of the triple point. Accordingly they used samples from Mt. Moosilauke to calibrate garnet-biotite thermometry and GASP barometry. However, Spear [30] emphasized that the Mt. Moosilauke area is part of a nappe, which carries low pressure rocks over intermediate pressure rocks. According to him andalusite-sillimanite bearing rocks in this area are independent of the kyanite-bearing rocks and a thrust fault separates these two assemblages. He suggested that andalusite-sillimanite bearing rocks may have crystallized at a pressure as much as 1-1.5 kbar below the aluminum silicate triple point but kyanite-bearing rocks may have crystallized as much as 1-2 kbar above the triple point.

Yardley [33] in agreement with Spear [30] stated that:

> "…there are not true triple point assemblages, because there are no rocks of any sort anywhere, outside the laboratory, in which all the phases grew at the single P-T condition and also chemically equilibrated with respect to all components at that condition."

According to him many pelitic rocks may have passed by the triple point during their metamorphic history, but aluminum silicate polymorphs did not develop in most of them because the breakdown of staurolite + muscovite + quartz lies at higher temperatures than the $Al_2SiO_5$ triple point. He emphasised that even if a suitable rock experienced metamorphism exactly at the true triple point it would contain sillimanite rather than andalusite or kyanite, because sillimanite nucleates so much easier.

Guidotti [10] suggested that only in uncommonly Al-rich rocks (i.e., those that contain pyrophyllite in the green schist facies) aluminium silicate polymorphs may develop after the rock has passed the P-T conditions of the triple point. Guidotti [10] in agreement with Yardley [33] suggested that even in this situation sillimanite is most likely to be the aluminium silicate polymorph to nucleate.

In agreement with Atherton et al. [4], we believe that occurrences of kyanite as a stable phase in the andalusite-, sillimanite-bearing aureoles resulted from an essentially isobaric crystallisation P-T path during which kyanite initially crystallises from the breakdown of pyrophyllite or more likely muscovite + chlorite beneath the pressure of the triple point (3-4 kbar ≈ 10-14 km depth), followed by andalusite and sillimanite crystallisation. The occurrence of coexisting aluminosilicate polymorphs resulted from metastable persistence of the early-formed aluminum silicates.

The kyanite-producing reaction in kyanite-, andalusite-, sillimanite-bearing aureoles is enigmatic. The occurrence of staurolite and kyanite intergrowths in the Ardara and Main Donegal aureoles led Naggar and Atherton [23] to suggest the following reaction for the production of kyanite in these aureoles:

$$\text{Mg/Fe chlorite+muscovite = kyanite+staurolite+biotite+}H_2O \qquad (1)$$

Pattison and Tracy [24] considered two possibilities for kyanite-producing reactions:

1) Kyanite might be produced from pyrophyllite breakdown at low grade;
2) Kyanite first appears by the reaction:

$$\text{Muscovite + staurolite + chlorite + quartz =} \\ \text{kyanite/sillimanite + biotite + } H_2O \qquad (2)$$

However, both reactions are problematic. The problem with the first reaction is that evidence for pyrophyllite in kyanite-, andalusite-, sillimanite-bearing aureoles is typically lacking. The problem with the second reaction is that based on the themodynamic calculation it must occur at higher temperatures than the $Al_2SiO_5$ triple point (Fig. 8) unless a reduction in $aH_2O$ occurs resulting in its displacement to lower temperatures into the kyanite and andalusite fields.

Assuming the production of kyanite from pyrophyllite breakdown as suggested by Atherton et al. [4] and using aluminosilicate triple point of Haas and Holdaway [12] and $aH_2O$ = 1.0, kyanite + quartz within andalusite-bearing aureoles is confined to380-500 ºC and 2.25-3.8 kbar (Fig. 9). However, assuming P-T conditions of about 4.8 kbar and 560 ºC for the triple point [24], and $aH_2O$ = 1.0, then kyanite + quartz within andalusite-bearing aureoles is restricted to 395-560 ºC and 2.8-4.8 kbar (Fig. 9).

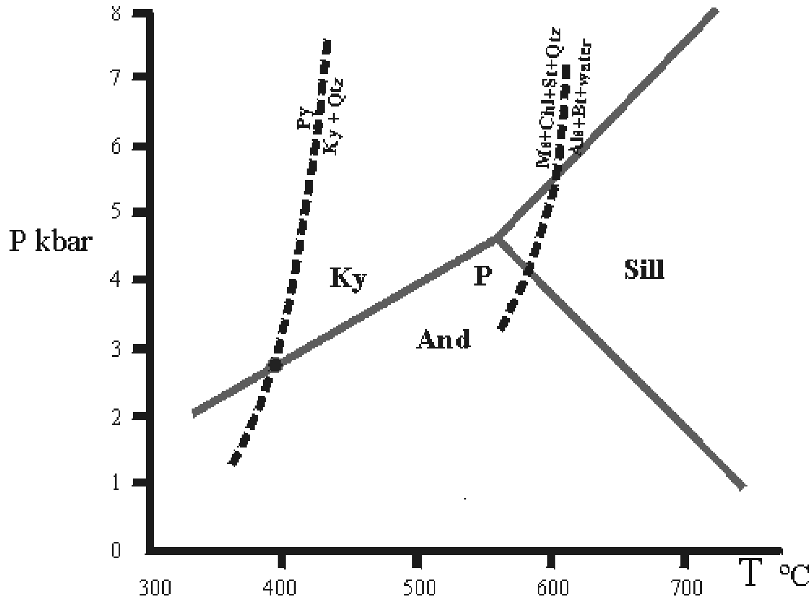


**Fig. 8** The $Al_2SiO_5$ stability relations and position of reaction (2) from Pattison (1992). The invariant point (filled circle) formed by the intersection of the pyrophyllite = $Al_2SiO_5$ + quartz + water equilibrium with the kyanite = andalusite equilibrium marks the lowest pressure for kyanite + quartz in a system with aH2O = 1.0. Pyrophyllite breakdown reaction from Spear and Cheney (1989). Solid lines show the aluminium silicate polymorphs stability field of Pattison (1992).

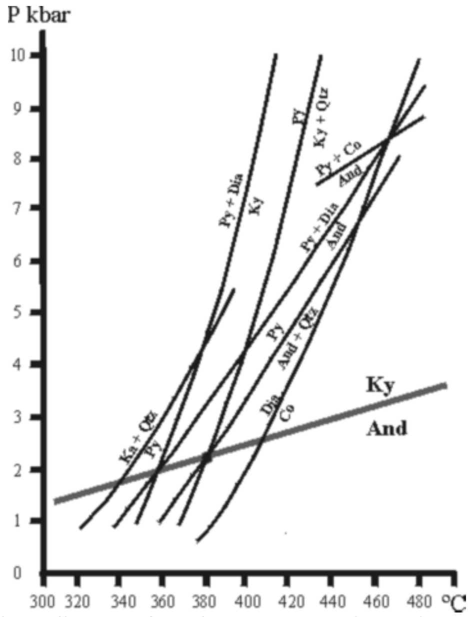


**Fig. 9** Phase equilibrium diagram for the system $Al_2O_3$-$SiO_2$-$H_2O$. The invariant point (filled circle) formed by the intersection of the pyrophyllite = $Al_2SiO_5$ + quartz + water equilibrium with the kyanite = andalusite equilibrium indicates the lowest pressure for kyanite + quartz in a system with $aH_2O = 1.0$. (From Holdaway, 1971).

The reasons for absence of kyanite in most thermal aureoles can be explained on the basis of the following reasons:

1) Compositional restraints: kyanite in the contact aureoles of Ardara and Main Donegal are confined to an anomalously Mg-rich horizon (MgO/(MgO + FeO) > 0.50) of the Upper Falcarragh Pelite [23]. Pelitic rocks from the Main Donegal and Ardara aureoles show significantly higher MgO and MgO/(MgO + FeO) ratio in comparison with pelitic rocks from the other suites of metamorphic rocks suggesting that the Upper Falcarragh Pelites provide a particular composition. Therefore, the absence of kyanite in most contact aureoles may be explained on the basis of the lack of rocks of suitable MgO/(MgO + FeO) values in these aureoles.
2) Overstepping of low-temperature reactions due to high heating rates of contact aureoles. As noted by Pitcher and Read [27] there is a relationship between the mode of emplacement of the intrusions and the texture and mineralogy of the contact rocks. Rapid injection of hot magma into tensional features in the upper crust provides conditions for

maximum overstepping whilst a slow rising magma into the upper levels of the crust gives much less overstepping. Therefore, in the case of rapid injection of hot magma, the overstepping of the kyanite producing reaction is possible.

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