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WATER AVAILIBILITY AND PARTIAL MELTING IN THE CONNEMARA SCHISTS, IRELAND

BRUCE W. D. YARDLEY[1] and JOHN P. BARBER[2]

[1] Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, England
[2] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, England

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Abstract: The Connemara Schist terrane provides evidence of extensive melting under amphibolite facies conditions, and the inferred reaction sequence suggests that much, though not all, of the melting took place in the presence of an aqueous fluid phase. The general disposition of the migmatites appears to suggest however that fluid was derived from crystallising, deep-derived magmas whose heat gave rise to the migmatisation, rather than from dehydration reactions occurring in pelitic rocks at lower grades below the migmatite isograd.

Key words: water, fluid, metamorphism, partial melting, migmatites, Connemara Schists, Ireland.

Introduction

It has been understood since at least the late 18th century that sediments can be metamorphosed to crystalline rocks, and that volatiles, notably water, are driven off in the process. Implicitly, the fluid so released makes it way out of the region where metamorphism is taking place, and recently some progress has been made in identifying pathways along which fluid has flowed (Rumble et al., 1982; Tracy et al., 1983; Yardley, 1986; Oliver and Wall, 1987; Ferry, 1987; among others).

At the highest grades of metamorphism, melting takes place and is promoted by the presence of water, which becomes dissolved in the melt. The solubility of water in anatectic melts at moderate pressures is large (c. 10%, Clemens, 1984), relative to the amount of water likely to be available in the pore space of a high grade rock undergoing metamorphism, so that the amount of 'wet' melting that can take place is likely to be restricted by the amount of water present. This raises the possibility that at the highest metamorphic grades there may be a reversal of fluid flow patterns. Water may move up temperature into regions where water activity has been lowered by dissolution of H_2O in the anatectic melt, rather than being driven off into lower grade regions as is usually assumed to happen in metamorphism. Wickham (1987) has argued that a similar influx of water has affected migmatites from the Pyrenees, and that it accounts for the extensive partial melting that has taken place there.

On the other hand, if aqueous fluid is unable to infiltrate a region undergoing melting, the melt will become undersaturated with respect to H_2O once all the initial pore water has dissolved in it; further melting takes place via dehydration melting reactions of hydrous phases (Thompson, 1982; Powell, 1983; Clemens and Vielzeuf, 1987). Evidence for such dehydration melting has been reported in a number of field studies (Tracy, 1978; Tracy and Robinson, 1983; Sawyer, 1987). In this paper we attempt to evaluate the relative importance of water saturated and undersaturated melting reactions across the migmatite zone of Connemara, western Ireland, and hence determine the role of fluid infiltration in promoting melting.

The Connemara Schists

The Connemara region is an inlier of Dalradian (Eocambrian to Cambrian) metasediments that are close stratigraphic correlatives of the Dalradian rocks of the Scottish Highlands. They were subjected to medium- to high-grade metamorphism as part of the Grampian phase of the Caledonian orogeny (c. 480 Ma, Leake et al., 1988). Early stages of the metamorphism took place at moderate pressures (c. 6 kb), culminating in kyanite-staurolite zone conditions, but these assemblages were then overprinted due to further heating at lower pressures (4–5.5 kb) (Yardley et al., 1987). This thermal overprint is essentially a regional scale contact effect driven by the emplacement of a syn-orogenic calc-alkaline intrusive suite, primarily to the south of the presently-exposed metasediments. The highest grade metasediments are migmatites which formed during the low pressure thermal overprint and occur adjacent to the intrusives (Fig. 1). An anatectic origin for these migmatites has been inferred because a) they develop at temperatures where melting of pelites is known to take place, b) because the appearance of leucosomes is accompanied by complementary changes in the chemistry of

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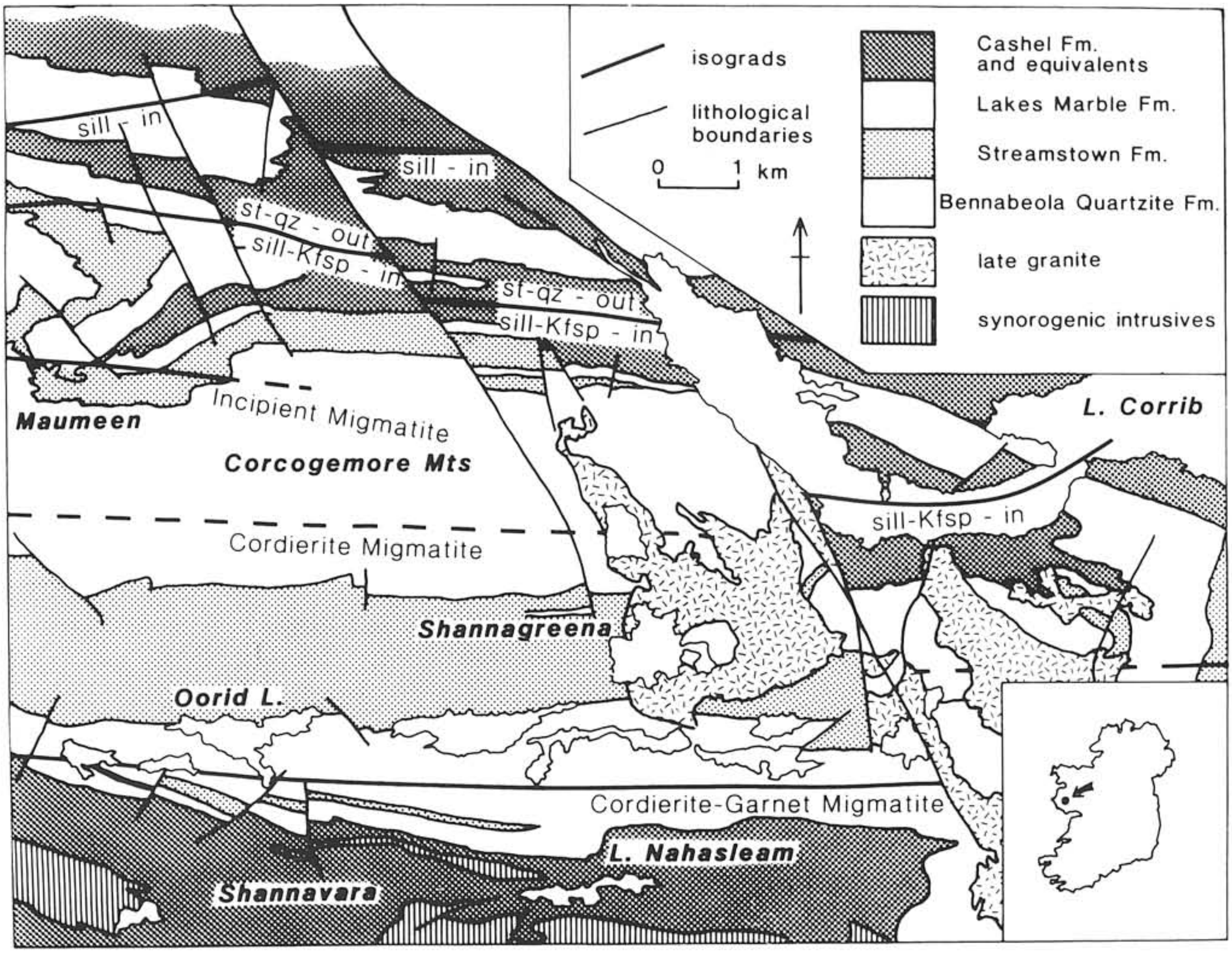

Fig. 1. Geological and metamorphic map of eastern Connemara (see inset) illustrating the distribution of migmatite zones relative to stratigraphic formations and synorogenic intrusions. Based on Leake (1981), Barber & Yardley (1985) and Yardley et al. (1980).

the host schist, such as an enrichment in compatible trace elements (Ni, Ti, Cr etc.) compared to equivalent lower grade pelites (i.e. the schists hosting leucosomes are restites), and c) because Sr isotope systematics show that leucosomes are derived from the adjacent schists (Barber, 1985; Barber and Yardley, 1985; Barber, Halliday and Yardley, in preparation).

High-grade metamorphic zones in the Connemara Schists

The zonal pattern in the Connemara Schists has been described by Yardley et al. (1980), Leake (1981) and Yardley et al. (1987), and the detailed zonation of eastern Connemara is illustrated in Fig. 1. The zones are defined on the basis of pelite assemblages, but other rock types, notably quartzite, psammite, amphibolite and calcite marble are also present. Indeed the first appearance of migmatites in the prograde sequence is difficult to study because quartzite generally outcrops between migmatised and unmigmatised pelite over much of the area shown in Fig. 1.

There are two compositionally-distinct types of pelite within the stratigraphic succession. The lower pelite unit occurs in the Streamstown Formation, which also includes variable proportions of psammite and semi-pelite. At a higher level in the stratigraphy, above the distinctive Lakes Marble Formation, two pelite-bearing formations occur: the Ballynakill Fm. and the Kylemore Fm. (Tanner and Shackleton, 1979). Their metamorphism has been described by Yardley et al. (1980), and is distinctive because of the lack of both muscovite and K-feldspar at the higher grades. Because these two formations are effectively indistinguishable, we follow Leake (1981) in grouping them together as the Cashel Formation. For the purposes of this paper we therefore distinguish only between melting reactions in the Streamstown Fm. and in the Cashel Fm.

The regional strike of bedding and foliation is broadly parallel to the isograds, and so although the same formations do reappear at different grades due to folding, it is not possible to trace a full sequence of zones within any one formation. Successive migmatisation zones tend to be developed predominantly in one formation or the other and in the following account care has been taken to keep track of the distinction between the formations.

Upper sillimanite zone:

Immediately on the low grade (i.e. northern) side of the first appearance of migmatite leucosomes, Streamstown Fm. pelites contain the sub-assemblage muscovite + K-feldspar + sillimanite (fibrolite) + quartz, together with biotite, plagioclase, accessory ilmenite and occasional garnet, usually mantled and partially replaced by fibrolite. In contrast, Cashel Fm. pelites at this grade have the assemblage biotite + garnet + fibrolite + plagioclase + quartz with accessory ilmenite and tourmaline (Tab. 1). Armoured relics of staurolite in plagioclase are not uncommon. Garnets in these schists often have a distinct new growth around their rims, attributed by Yardley et al. (1980) to the breakdown of staurolite + quartz, which developed at about the same temperature as sillimanite + K-feldspar appeared in the Streamstown Fm.

Migmatite zones:

Incipient zone: Migmatite leucosomes of truly granitic composition (as opposed to quartz veins with sporadic plagioclase, tourmaline, muscovite or andalusite) first appear in the Streamstown Fm. at Maumeen (Fig. 1), where they occur as sparse, irregular-shaped, flattened lenses, typically a few cms thick and 10 to 50 cm across and with a grain size of a few mm. These leucosomes make up around 1% of the outcrop, and the host pelites retain the normal upper sillimanite zone assemblages, with apparently primary muscovite remaining. In the direction of increasing metamorphic grade the outcrops of the Streamstown Formation are succeeded by quartzites which do not develop migmatite features, and so the transition to the next zone is not seen.

Cordierite migmatite zone: Pelites at Shannagreena, to the south and east of Maumeen, have well developed stromatic leucosomes and also contain cordierite, which here coexists with sillimanite for the first time in the prograde sequence. Muscovite, where present, appears to be secondary; an interpretation which is borne out by the occurrence of coexisting corundum + K-feldspar (albeit partially retrogressed to muscovite) in rare quartz-free layers. The range of common pelite assemblages in the Streamstown Fm. at this grade is indicated in Tab. 1. The leucosomes with which they are intimately associated are typically thin (a few cm) and discontinuous. They are granitic, being composed primarily of quartz, plagioclase and K-feldspar, but with occasional cordierite. More commonly, cordierite is particularly abundant in the schist immediately adjacent to leucosomes. Both K-feldspar and cordierite can occur in leucosomes when absent from the immediately adjacent schist, and are then probably magmatic; in contrast biotite in leucosomes appears to be almost invariably accidentally trapped xenocrysts.

In addition to small stromatic leucosomes, distinct, larger granitic bodies occur throughout this zone and at higher grades to the south. These bodies have dimensions of metres to tens of metres and are inferred to be intrusive bodies linked to the synorogenic calc-alkaline suite (Senior, 1973) because of their textural and mineralogical uniformity, cross-cutting relationships and occurrence in a wide range of host rocks, and because they are isotopically distinct from the host metasediments whereas the smaller scale stromatic leucosomes are not (Barber, 1985). They will not be further considered.

Table 1. Mineral assemblages of high grade pelites according to stratigraphic formation and metamorphic zone

Streamstown Formation assemblages	
Upper sillimanite	sil + Kfs + bio + ms + plag + qz
	sil + Kfs + gt + bio + ms + plag + qz
Incipient migmatite	sil + Kfs + bio + ms + plag + qz
Cordierite migmatite	sil + cd + bio + plag + qz
	sil + bio + plag + qz
	sil + Kfs + bio + plag + qz
	sil + cd + Kfs + bio + plag + qz
Garnet-cordierite migmatite	sil + gt + Kfs + bio + plag + qz
	sil + cd + gt + bio + plag + qz
	sil + cd + Kfs + bio + plag + qz
	gt + Kfs + bio + plag + qz
Cashel Formation assemblages	
Upper sillimanite	sil + gt + bio + plag + qz
Garnet-cordierite migmatite	sil + cd + bio + plag + qz
	sil + cd + gt + bio + plag + qz
	cd + gt + bio + plag + qz

Abbreviations: bio - biotite; cd - cordierite; fl - fluid; gt - garnet; Kfs - K-feldspar; ms - muscovite; plag - plagioclase; qz - quartz; sil - sillimanite.

Mineral assemblages and compositions of the pelitic restites in this zone are plotted in Fig. 2, projected from sillimanite, quartz and fluid onto the KFM face of the AKFM tetrahedon, in contrast to the more usual Thompson AFM projection. This is done so that assemblages lacking both muscovite and K-feldspar can be shown. Note that cordierite appears in this

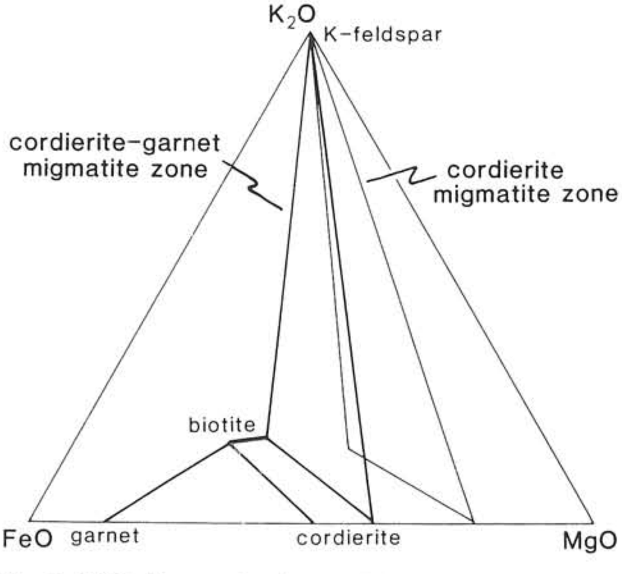

Fig. 2. KFM diagram showing cordierite-bearing pelitic restite assemblages from the Streamstown Formation, projected from sillimanite, quartz and fluid. Note the shift to more Fe-rich cordierite with increasing grade.

zone only in bulk compositions with relatively high X_{Mg} values, intermediate compositions lack both cordierite and garnet.

Cordierite-garnet migmatite zone: To the south of Shannagreena, migmatites are not very well exposed and there are non-pelitic lithologies tectonically repeated in a "steep belt". In the vicinity of Shannavara Mountain and Lough Nahasleam (Fig. 1), however, pelitic migmatites show evidence for more extensive melting with disruption of competent psammitic beds in a matrix of pelitic migmatite which here is often nebulitic in character.

Most of the migmatites in this zone belong to the Cashel Fm., but some Streamstown Fm. migmatites occur also, facilitating comparison with lower grade zones. Cashel Formation pelitic rocks in this zone are invariably Al-rich restites, silica depleted by comparison with lower grade equivalents (Barber, 1985). They contain biotite, cordierite and usually sillimanite with plagioclase but often only minor quartz (Tab. 1). Garnet is common, and often forms large (c. 2 cm) porphyroblasts unlike garnets at lower grades. These large garnets occur in pelitic restites, in nebulitic migmatite and as xenocrysts in some leucosomes. Leucosomes in the Cashel Formation are usually trondjhemitic; K-feldspar only appears if also present in the host pelite. Cordierite, and rarely andalusite, are sometimes present in leucosomes, and since they are texturally distinct from grains of the same minerals in the restites they are assumed to have crystallised in the leucosomes rather than having been caught up as xenocrysts.

Streamstown Formation rocks in this zone also develop an almandine-rich garnet in some instances, and are thus distinct from the cordierite migmatite zone assemblages. The range of mineral assemblages present in this zone is summarised in Tab. 1, and mineral compositions are plotted in Fig. 2. Note that cordierite, which is stable to the right of the biotite-K-feldspar tie line, now occurs in a much wider range of rock compositions than at lower grades, in accordance with its appearance in the Cashel Fm. Despite the extensive melting that appears to have affected the pelitic rocks in this zone, the assemblage garnet + K-feldspar + cordierite has never been found, while clinopyroxene occurs only rarely in associated amphibolites. Granulite facies conditions were not attained.

Melting reactions and their bearing on water activity gradients

The chemographic relationships between melting reactions amongst pelitic minerals in the KMFASH system have been summarised by Thompson (1982) and Grant (1985). Whereas Thompson treats the liquid phase as having a lower X_{Mg} value than any of the solid phases, including garnet, Grant treats the liquid phase as more magnesian than garnet. The discrepancy between these treatments is not significant for the present study.

Mineral assemblages in the first two migmatite zones of the Streamstown Formation can be interpreted by considering reactions amongst biotite, sillimanite, cordierite, K-feldspar, quartz, aqueous fluid and liquid (i.e. silicate melt). The possible continuous reactions amongst these phases in system KMFASH are listed in Tab. 2, and are shown as discontinuous reactions in system KFASH, oriented schematically with respect to pressure and temperature, in Fig. 3a.

Table 2. Relevant melting reactions in the model pelite system KFMASH (Abbreviations as in Tab. 1)

Univariant reactions		
U1:	bio + sil + Kfs + qz + fl = cd + melt	(gt)
U2:	bio + sil + qz + fl = gt + cd + melt	(Kfs)
U3:	bio + sil + qz = gt + cd + Kfs + melt	(fl)
Divariant reactions		
D1:	bio + sil + Kfs + qz + fl = melt	(gt, cd)
D2:	bio + sil + qz + fl = cd + melt	(gt, Kfs)
D3:	bio + sil + qz = cd + Kfs + melt	(gt, fl)
D4:	bio + sil + qz = cd + Kfs + fl	(gt, melt)
D5:	bio + cd + Kfs + qz + fl = melt	(gt, sil)
D6:	cd + Kfs + qz + fl = sil + melt	(gt, bio)

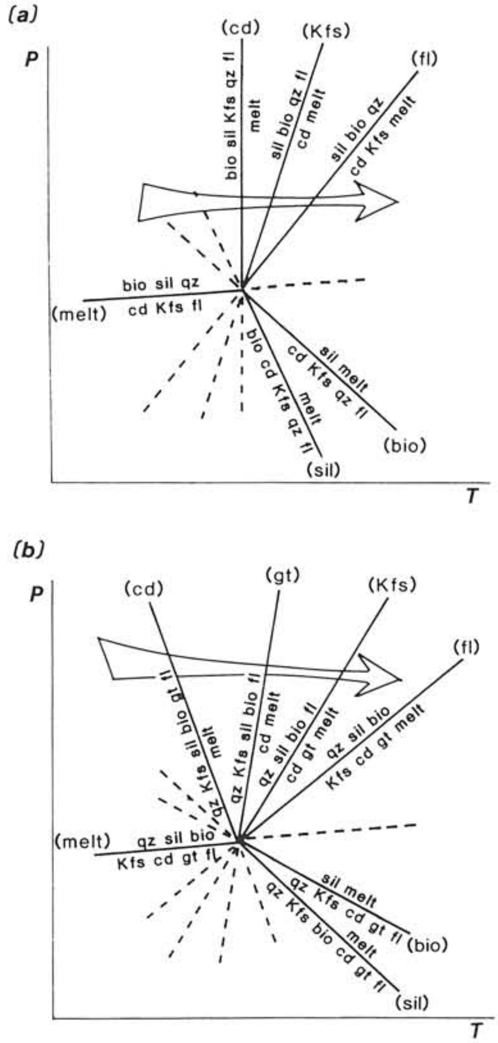

Fig. 3. Schematic P–T diagrams to illustrate reaction sequences in the model pelite system. Abbreviations as in Tab. 1.

(a) Net of garnet-absent end-member reactions in system KFASH. The reactions portrayed are the divariant reactions of Tab. 2.

(b) Disposition of univariant reactions in system KFMASH after Grant (1985). The sequence of assemblages found corresponds to the arrowed path.

Above the invariant point in Fig. 3a, the sequence of reactions corresponds closely to the sequence of assemblages described above. Melting is first possible under H_2O-saturated conditions, and produces liquid alone (i.e. without the appearance of any new solid phases) from rocks that lack cordierite initially. This corresponds to the situation observed at Maumeen, where melt first appears. With further heating, if K-feldspar is consumed but water remains, melting leads to the appearance of cordierite due to incongruent melting, and this corresponds to the cordierite migmatite zone at Shannagreena.

More rigorous analysis is possible in the 6-component KMFASH system. Fig. 3b illustrates schematically the relationships between the discontinuous reactions in this system (given in Tab. 2). These correspond to limiting reactions only; extensive reaction takes place along continuous reaction loops under conditions intermediate between those of the discontinuous reactions.

Fig. 4 illustrates the arrangement of continuous reaction loops about the garnet-absent discontinuous reaction U1 (Tab. 2) on a $T-X_{Mg}$ section construction for an appropriate pressure (c. 4.5 kb: Barber and Yardley, 1985). On this projection it can be seen that reaction D1, the initial cordierite-absent melting reaction, takes place over a range of temperatures driving biotite to progressively more magnesian compositions with increased T. Assuming that the system is water saturated in the first instance, melting continues until the temperature of the univariant reaction (U1) is attained, when cordierite appears as an additional phase. Melting will then continue to take place at this temperature until one of the reacting phases, i.e. biotite, sillimanite, K-feldspar, quartz or aqueous fluid, is entirely consumed. The different assemblages recorded from pelitic restites at Shannagreena (Tab. 1) reflect the result of this melting reaction, while the spatial association of cordierite with granitic leucosomes reinforces the role of melting reactions in cordierite production. Of the KMFASH phases, sillimanite, quartz and biotite are invariably present in the Shannagreena restites, however the full association of sillimanite + biotite + cordierite + quartz + K-feldspar (+ plagioclase) is not particularly common. More usually cordierite and/or K-feldspar is absent. In terms of Fig. 4, we can explain the formation of this range of assemblages at the same grade as follows.

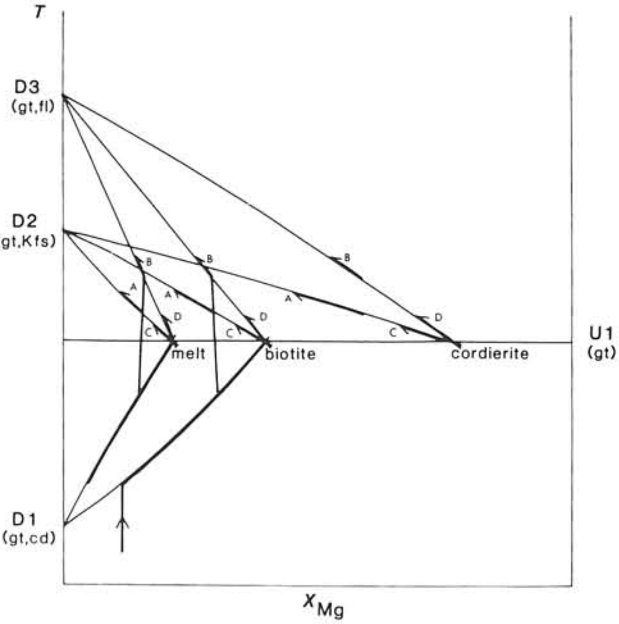

Fig. 4. Schematic $T-X_{Mg}$ diagram to illustrate progressive reaction in the incipient and cordierite migmatite zones of the Streamstown Formation. The $T-X_{Mg}$ loops shown represent the divariant reactions given in Tab. 2.

Arrowed paths represent alternative reaction sequences according to rock composition and fluid availability (see text).

Cordierite-absent rocks did not experience reaction U1, because one of the essential reactant (K-feldspar or fluid) was totally consumed by reaction D1. In the case of rocks that lack K-feldspar as well as cordierite at this grade, further melting with accompanying production of cordierite will occur when they are heated to intersect the T−X loop for reaction D2 (i.e. path A on Fig. 4), whereas fluid-absent rocks follow a path similar to B, eventually producing cordierite at higher temperatures due to fluid-absent melting (reaction D3). Cordierite restites that lack K-feldspar are not uncommon, and these are believed to result from reaction U1 continuing under water-saturated conditions until all K-feldspar was consumed, followed by further water-saturated melting by reaction D2 (path C, Fig. 4). Restites that contain the full suite of solid phases involved in reaction U1 can be interpreted as having reacted until the fluid phase was exhausted by this reaction, after which further reaction was possible by D3 (path D). These restites, and those cordierite-absent restites with K-feldspar, imply that water-absent conditions were attained, whereas the other common restite assemblages suggest water-saturated melting throughout. In other words, water availability appears to have been heterogeneous; there was extensive melting in the presence of aqueous fluid, but this had been locally exhausted within the cordierite migmatite zone in some layers. There is no obvious correlation between the amount of leucosome present and whether or not the assemblages indicate water-saturation.

The effect of further reaction at temperatures above that of U1 in assemblages that contain biotite + sillimanite + quartz is to drive cordierite to progressively more Fe-rich compositions. That this has occurred is demonstrated by the shift in mineral compositions from the cordierite migmatites to the cordierite-garnet migmatites (Fig. 2), and also by zoning to Fe-rich rims within individual cordierite grains (Barber and Yardley, 1985).

With further heating beyond reaction U1, univariant reaction U2 will be encountered by fluid-bearing assemblages containing biotite + sillimanite + quartz (and therefore lacking K-feldspar). This reaction leads to the production of cordierite + garnet + melt (Tab. 2, Fig. 3b), and hence marks the transition to the cordierite-garnet migmatite zone. There are examples of this assemblage from both the Streamstown Fm. south of Oorid Lough, and the Cashel Fm., especially at Lough Nahasleam. The textural evidence for the growth of new garnet, quite distinct from that present in Cashel Fm., rocks of the staurolite zone, was noted above and clearly indicates the production of garnet and cordierite during melting reactions. In detail however, cordierite is seen to grow at the expense of garnet + sillimanite (Barber and Yardley, 1985), indicative of continued pressure drop. Melting around reaction U2 appears to have been particularly important in the Cashel Formation, whose rocks lack muscovite or

K-feldspar in the upper sillimanite zone and probably only melted extensively at this grade.

Further heating beyond reaction U2 permits extensive fluid-absent melting by reaction U3, to produce the restite assemblage garnet + cordierite + K-feldspar. This reaction takes place at 750–800° C at appropriate pressure, according to Thompson (1982) and Grant (1983), and marks the onset of the granulite facies. It is notable that the assemblage garnet + cordierite + K-feldspar does not occur in Connemara, so that reaction U3 provides the upper limit to the conditions of migmatisation.

Implications of the reaction sequence for water activity and fluid flow

The Connemara migmatites show extensive melting, up to the order of 40% (Barber, 1985), without attaining granulite facies temperatures. It is apparent from the discussion of the reaction sequence, above, that although much of the melting took place under water-saturated conditions, the fluid phase was however totally consumed by melting in certain layers. In other words, a fluid phase was often present during melting, but was not universal.

We conclude therefore that if fluid influx did occur to promote melting it was not pervasive; instead water activity varied between beds on a scale of metres. The question remains as to whether or not fluid influx was necessary to produce the amount of melting observed. This can only be resolved if an estimate can be made of the pore volume of a high grade metamorphosing rock.

Assuming that a water-saturated granitic melt at an appropriate pressure contains about 10% dissolved H_2O by weight (Clemens, 1984), then at one extreme a metamorphic porosity of 2.5% by volume would permit the formation of about 10% melt under water-saturated conditions, sufficient to account for much of the observed migmatisation below the cordierite-garnet migmatite zone. A much smaller porosity, such as the value of 0.1% proposed by Clemens and Vielzeuf (1987) permits less than 1% melting. In a situation where metamorphism is relatively rapid due to high-level magmatic heating, schists must have an appreciable permeability, and hence porosity, in order for fluid to escape as fast as it is produced (Walther and Orville, 1982; Yardley, 1986). While the porosity that this implies has not been quantified, it seems likely to be in the 0.1% to 1.0% range.

The amounts of leucosome observed with the onset of anatexis at Maumeen are very small, and can almost certainly be accounted for utilising original pore fluid from the high grade schists. For this reason, and because all the solid reactants (reaction D1) persist in the restite, it seems unlikely that there has been significant influx of H_2O across the migmatite isograd from lower grades. Any such influx should lead to extensive melting over a narrow temperature interval. Unfortunately, the absence of suitable lithologies at intermediate grades up to the cordierite migmatite zone precludes more rigorous testing of this hypothesis.

On the other hand the very extensive migmatisation of the cordierite-garnet migmatites, apparently under water-saturated conditions in large part, appears to require influx of water, though not necessarily equally to all layers. Previously, Senior and Leake (1978) suggested that there was extensive metasomatism of the migmatite zone metasediments. Their model has been comprehensively disproved by Barber (1985), on the basis of sampling with more precise stratigraphic control. The amount of fluid inflow required to flux the additional melting is unlikely to have had a significant effect on bulk rock chemistry. In view of the lack of evidence for infiltration of water from lower grades into the migmatites (despite the existence of chemical potential gradients to drive such flow), it is more likely that water was derived from the crystallisation of the synorogenic magma suite immediately to the south, that was itself the heat source for the melting process. It has been noted previously by Leake (1969) that these magmas were unusually hydrous.

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