

Melting reactions in the Connemara Schists: The role of water infiltration in the formation of amphibolite facies migmatites

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ABSTRACT

High-grade metapelites in Connemara have undergone extensive migmatization under amphibolite facies conditions and define a series of zones progressing from an unmigmatized upper sillimanite zone through an incipient migmatite zone (in which granitic leucosomes first appear) and a cordierite migmatite zone (in which cordierite appears with evidence of renewed melting) to a garnet-cordierite migmatite zone (in which new growths of coexisting garnet and cordierite appear). This zonal sequence closely matches the predicted sequence of H₂O-saturated melting reactions for KMFASH model pelites in the upper amphibolite facies. In particular, the development of migmatite leucosomes accompanied by growth of cordierite or garnet and cordierite in the restite, without the appearance of potassium feldspar, is diagnostic of H₂O-saturated conditions.

Comparison of the bulk chemical composition of unmigmatized pelites and their migmatized equivalents suggests that there has been about 20% partial melting in the garnet-cordierite migmatites, and the melt produced was dominated by quartz and albite with a relatively small potassic component.

Such extensive H₂O-saturated melting is only possible if the metamorphism involves addition of H₂O as well as heat, and it is proposed that contemporaneous calc-alkaline intrusions, which acted as the heat source for the high-level regional metamorphism, also yielded H₂O as they crystallized. In view of the strongly endothermic character of melting reactions, it is probable that, had there been no addition of H₂O during heating, not only would the amount of melting have been less, but temperatures in the highest grade zone might have attained those indicative of granulite facies conditions.

INTRODUCTION

Studies of the high-grade metamorphism of pelitic rocks continue to play a central role in metamorphic geology and are now used to draw conclusions about many aspects of crustal behavior, quite apart from their petrologic significance. Much of this work has its roots in the quantitative approaches to pelite phase equilibria developed by Jim Thompson in the 1950s, and this paper, although describing rocks very removed physically from New England, derives much of its spiritual influence from the philosophy developed in Thompson (1955, 1957) and Thompson and Norton (1968).

The importance of melting reactions in the metamorphism of pelites at high grades is now firmly established. Early studies (notably the experimental investigations of Winkler, 1979) sought to prove the feasibility of anatexis by demonstrating the geologically low temperature of the solidus under H₂O-saturated conditions. However, many

later investigations have emphasized the importance of melting in the absence of an aqueous phase because the porosity of a high-grade rock is likely to be too small to contain sufficient H₂O to cause significant H₂O-saturated melting (Hensen and Green, 1973; Thompson, 1982; Powell, 1983; Grant, 1985; Clemens and Vielzeuf, 1987; Vielzeuf and Holloway, 1988). The importance of fluid-absent, dehydration melting reactions has now been demonstrated in a number of studies (e.g., Tracy, 1978; Tracy and Robinson, 1983; Sawyer, 1987; Waters, 1988; Pattison, 1989).

This evidence notwithstanding, the possibility of significant H₂O-saturated melting cannot be precluded, provided there are geological settings in which H₂O can infiltrate high-grade rocks. Particularly likely candidates for this type of melting are migmatites developed at relatively low temperatures, i.e., in the upper amphibolite facies, because dehydration melting requires higher temperatures than H₂O-saturated melting. For example the dehydration melting reaction $\text{biotite} + \text{sillimanite} + \text{quartz} = \text{cordierite} + \text{garnet} + \text{potassium feldspar} + \text{melt}$, which is univariant in the KMFASH system, effec-

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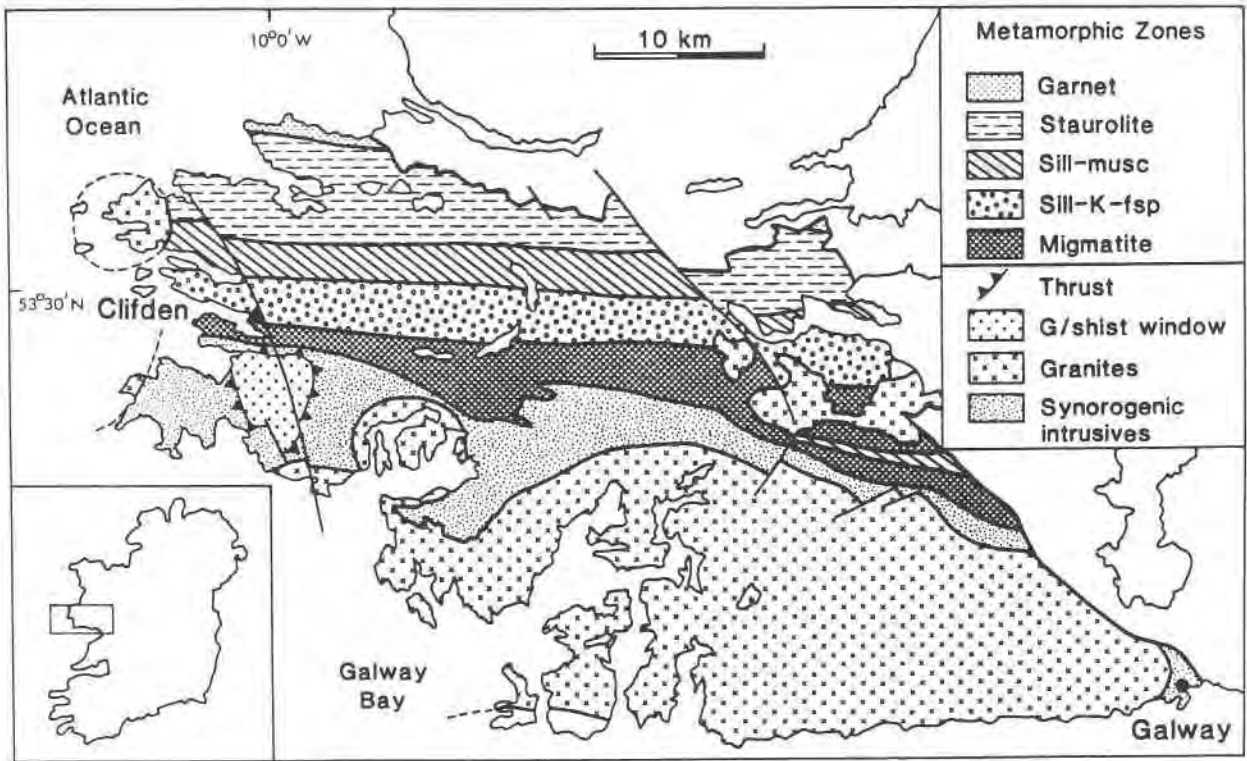


Fig. 1. Metamorphic map of Connemara, after Yardley et al. (1987).

tively marks the beginning of the granulite facies at medium to low pressures. Melting reactions that take place at lower temperatures than this are more likely to require H_2O .

In this paper we describe the mineral assemblages of upper amphibolite facies migmatized metapelites from the Connemara region of western Ireland and deduce from them the likely sequence of melting reactions. We also combine these results with calculations of the degree of melting based on bulk rock analyses in order to limit the thermal and fluid budgets of the high-temperature event.

HIGH GRADE METAMORPHISM OF THE CONNEMARA SCHISTS

The Connemara region (Fig. 1) is an inlier of late Precambrian metasediments of the Dalradian Supergroup. The history of metamorphism and deformation of the region can be summarized as follows. An early phase of isoclinal regional folding took place under garnet zone conditions and was followed by lower amphibolite facies metamorphism to produce widespread staurolite but sparse kyanite at pressures of about 6 kbar. This was followed by a higher temperature but somewhat lower pressure overprint that was broadly coeval with a second major phase of folding and nappe formation (Yardley et al., 1980, 1987). The thermal overprint is essentially a regional scale contact effect driven by the emplacement of a series of progressively more siliceous calc-alkaline intrusives, which lie primarily to the south of the exposed

metasediments (Figs. 1, 2). These have been reviewed by Leake (1989), and their relative timing is discussed by Tanner (1990). The most notable feature of the thermal overprint for this study is the development of a broad zone in which pelitic rocks are migmatized, flanked to the north by a distinct zone with sillimanite and potassium feldspar that is unmigmatized. The metamorphic temperature near the onset of migmatization at Maumeen (Fig. 2) has been estimated at about 650 °C (Yardley et al., 1980), whereas the highest grade migmatites at Lough Nahasleam were metamorphosed at about 750 °C (Barber and Yardley, 1985). An intermediate temperature of 700 °C was obtained from Oorid Lough by Yardley et al. (1980). Neither pelitic nor basic rock types contain assemblages indicative of granulite facies conditions, except for hornfels in the immediate vicinity of the earliest, basic members of the synorogenic intrusive suite. Thus, neither is there orthopyroxene in the metabasites (and clinopyroxene is restricted to minor occurrences in vein walls), nor does the association of garnet + cordierite + potassium feldspar occur in the pelitic migmatites.

Pressures during the melting reactions were in the range of 4–5.5 kbar, but there is also evidence for rapid uplift and unroofing of these rocks while they were still close to peak temperatures (Barber and Yardley, 1985). Yardley et al. (1987) were able to demonstrate from the distribution of aluminum silicate polymorphs that isotherms effectively moved northward through the metasediments

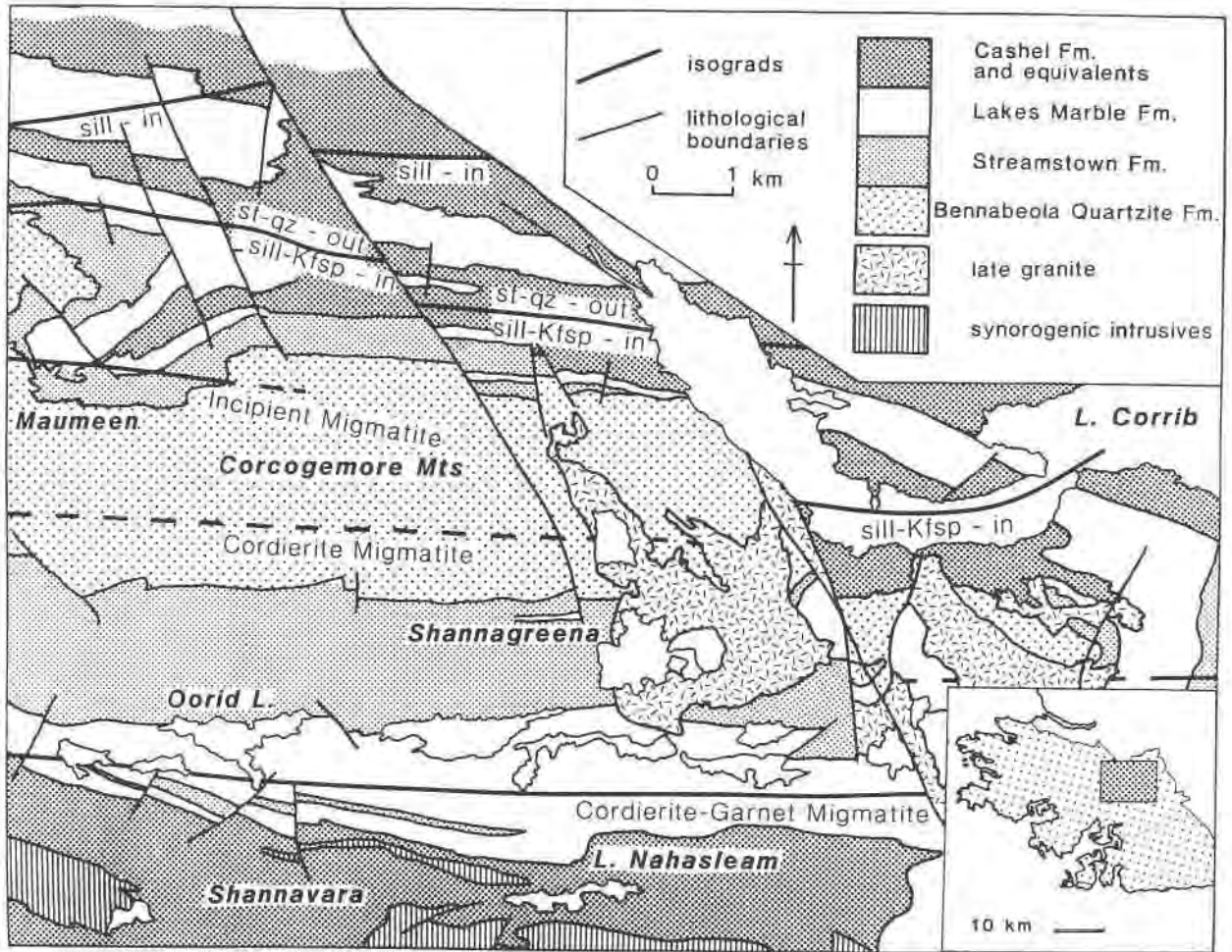


Fig. 2. Geological and metamorphic map of eastern Connemara illustrating the distribution of migmatite zones relative to stratigraphic formations and synorogenic intrusions. Based on Leake (1981), Barber and Yardley (1985), and Yardley et al. (1980).

from the intrusive heat source in the south, whereas isobars moved downward as a consequence of unroofing. This means that the observed zonal sequence is not isobaric and does not reflect the progressive reaction path of the high-grade rocks. In particular, the presence of an upper sillimanite zone without migmatization suggests distinctly low pressures (ca. 4 kbar), but it is possible that the higher grade zones were heated through this temperature range at higher pressures, so that muscovite broke down by a melting reaction.

A particularly significant aspect of the geology of Connemara is that it has a clearly defined stratigraphy with several distinctive marker horizons of marble, quartzite, and boulder bed. These have been mapped in detail throughout the area (Leake, 1981), and as a result it is possible to compare migmatized metasediments with their close stratigraphic equivalents at lower grades. In Figure 2, this is illustrated for the eastern part of the region, from which the samples for this study were taken.

The best examples of pelites are developed stratigraphically

above the distinctive Lakes Marble Formation. In the northern part of the area shown in Figure 2, these pelites have been separated into two distinct units, the Ballynakill Formation and the Kylemore Formation, and detailed analytical studies have shown them to be indistinguishable except for a significantly higher Ti content in the Kylemore Formation. Because of the greater structural complexity of the southern part of the area, it has not proved possible to sustain this distinction, and Leake (1981) has grouped together rocks that may belong to either the Ballynakill Formation or the Kylemore Formation as the "Cashel Formation." For the purposes of this paper, it is convenient to refer to the pelites overlying the Lakes Marble Formation as belonging to the Cashel Formation, irrespective of whether they are from the north or south of the area. Cashel Formation pelites are reduced and generally graphite free, have low X_{Mg} values, and contain abundant staurolite at appropriate grades. Their assemblages and mineral chemistry up to the appearance of migmatites were described by Yardley et al. (1980)

who noted that, because of their bulk composition, muscovite generally disappears before staurolite so that potassium feldspar is only very rarely produced at higher grades.

Between the Lakes Marble Formation and the Benna-beola Quartzite Formation, which dominates the central mountains of Connemara, lies the Streamstown Formation, which also contains pelite members. In contrast to pelites of the Cashel Formation, these lack staurolite at lower grades but contain abundant muscovite, so that the second sillimanite isograd is well displayed. Because of this significant difference in bulk chemistry between the two pelites, their assemblages are treated separately below.

MINERAL ASSEMBLAGES OF THE PELITIC MIGMATITES

The migmatite belt in the Connemara Schists is defined by the occurrence of irregular, but internally homogeneous, leucosomes of broadly granite composition (i.e., quartz + plagioclase, sometimes with potassium feldspar, muscovite, or both) as opposed to quartz veins with sporadic accessory andalusite, tourmaline, muscovite, or plagioclase found at lower grades. It can be subdivided into three zones (Fig. 2) whose assemblages are summarized in Table 1.

Incipient migmatite zone

This zone is seen in the Streamstown Formation at Maumeen. It is distinguished only by the presence of sparse irregular lenses of granite leucosome. These leucosome pods are typically a few centimeters thick and 10–50 cm across, with grain sizes of a millimeters. The assemblages of the host pelite are indistinguishable from those of equivalent rocks in the upper sillimanite zone.

Cordierite migmatite zone

Again developed in Streamstown Formation pelites, this zone is marked by the appearance of cordierite together with more abundant leucosome stringers giving rise to a distinct stromatic migmatite (see for example Yardley, 1989, Fig. 3.5a). It is well exposed at Shannagreena. Leucosomes form thin concordant layers up to a few centimeters thick that are markedly discontinuous; they can make up 10–30% of the outcrop. Leucosomes are often truly granitic in composition, (i.e., potassium feldspar bearing) but potassium feldspar is only present if it also occurs in the host schist. Cordierite can occur in the leucosomes, but its most distinctive mode of occurrence is in the host rock immediately adjacent to a leucosome stringer.

Cordierite-garnet migmatite zone

The highest grade migmatite zone includes examples of both Cashel Formation and Streamstown Formation pelites. In this zone, garnet becomes well developed for the first time in the Streamstown Formation and coexists with cordierite or potassium feldspar, not both (Table 1).

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

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

Widespread leucosomes are trondjhemitic, or rarely granitic if potassium feldspar is present in the host. The Cashel Formation in this zone is likewise extensively migmatized, and nebulitic migmatite becomes widespread (e.g., Yardley, 1989, Figure 3.5b). The degree of melting is locally sufficient for more refractory beds to have become disrupted and rotated. The pelitic portions of the migmatites are restites and include layers rich in cordierite (now largely pinitized) and coarse garnets, which are texturally quite distinct from those encountered at lower grades. Barber and Yardley (1985) noted in detail that both garnet and sillimanite were sometimes replaced by cordierite, suggesting a drop in pressure at peak temperatures. Potassium feldspar is rarely present in either leucosomes or restites in this formation. Some leucosomes contain coarse subhedral grains of cordierite or andalusite, nearly devoid of inclusions, which are texturally distinct from matrix grains and thus appear to be magmatic. In contrast, sporadic biotite and garnet in leucosomes are texturally identical to those in the restite and appear to be xenocrysts in many cases.

PHASE RELATIONS, REACTION SEQUENCE, AND H₂O AVAILABILITY IN MELTING

It is apparent from the compositions of the leucosomes observed in the field that the melt phase produced had a composition that was dominated by feldspar. This is explored in detail below. Nevertheless, it is also valuable to consider the melting reactions in terms of the plagioclase-absent model pelite system, since these reactions produce distinct solids in the restite. As a result, it is possible to determine from the KMFASH mineralogy whether the melting reactions that took place are likely to have been H₂O saturated.

The sequence of assemblages (excluding melt) from the migmatites is illustrated graphically in Figure 3 in the form of diagrams projected onto the KFM face of the

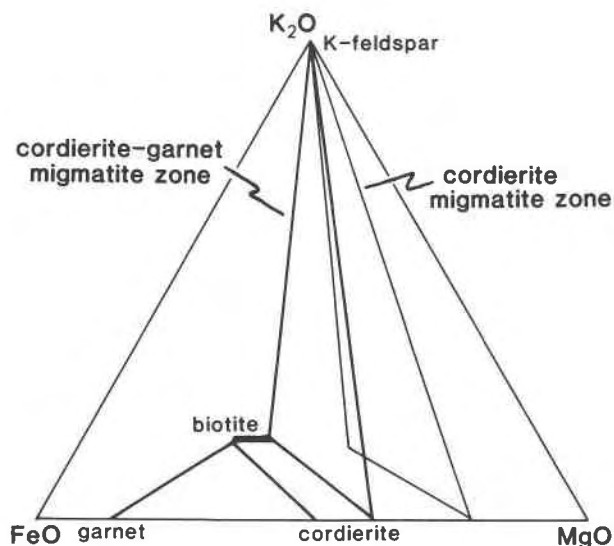
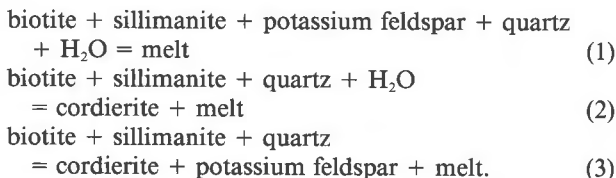


Fig. 3. KFM diagram showing cordierite-bearing pelitic restite assemblages from the Streamstown Formation, projected from sillimanite, quartz, and fluid. Bold lines = cordierite-garnet migmatite zone, light lines = cordierite migmatite zone.

AKFM tetrahedron from sillimanite, quartz, and H_2O . The reason for utilizing this projection, rather than the better known AFM diagram of Thompson (1957), is that most pelites of the Cashel Formation lack both muscovite and potassium feldspar, whereas sillimanite is much more widespread (Table 1). Note the marked shift in cordierite toward more Fe-rich compositions with increasing grade.

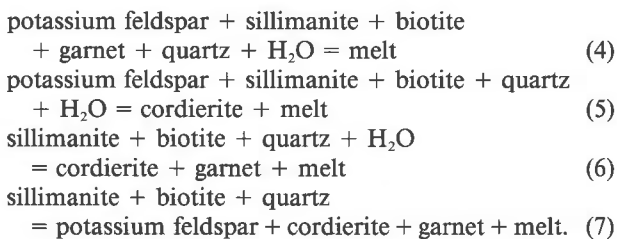
Relevant petrologic grids describing melting reactions in the KFLASH and KMFASH systems have been constructed by Thompson (1982), Grant (1985), and Vielzeuf and Holloway (1988). Considering first the end-member KFLASH (or KMASH) system, the sequence of melting reactions represented by the zones observed can be modeled as follows:



Vielzeuf and Holloway (1988) located curves for these reactions for the case of $X_{Mg} = 0.5$, and the relevant portion of their grid is illustrated in Figure 4a. For the purposes of this discussion, it is the relative, not the absolute, location of the curves that is significant, and the sequence observed in the field, whereby the appearance of melt alone is followed by the development of cordierite with renewed melting, strongly suggests that the early stages of melting can be modeled by Reaction 1 followed by more widespread melting by Reaction 2. It is clear from Figure

4a that this is consistent with a drop in pressure at the peak temperatures.

Figure 4b displays schematically a Schreinemaker net of reactions in KMFASH involving the above phases plus garnet. The reactions are



Of these, Reaction 6 provides a realistic model for the onset of the cordierite-garnet migmatite zone, but Reaction 7, likely to mark the beginning of significant dehydration melting, has not taken place. It is significant to note that all of the H_2O -absent melting reactions listed above produce potassium feldspar as a solid product; it is the comparative scarcity of potassium feldspar in the Connemara migmatites (see Barber, 1985, for a detailed assemblage map) that provides the best evidence for H_2O -saturated melting.

The onset of melting can be modeled in KMFASH by Reaction 4 or, in rocks lacking garnet, Reaction 1. Because initial migmatites retain the full assemblage of solid reactants, melting may have been arrested by consumption of pore H_2O or, possibly, by the limited supply of heat.

The development of the assemblages of the cordierite migmatite zone can be discussed more fully with the aid of a $T-X_{Mg}$ diagram for the KMFASH system, in which Reactions 1–3 appear as continuous reaction loops around the univariant Reaction 5 (Fig. 5). Paths A–D in Figure 5 illustrate schematically the types of reaction pathways that are possible, following initial H_2O -saturated melting by Reaction 1, according to the availability of H_2O and solid reactants. A and B are paths along which Reaction 5 has never taken place because one of the essential reactants is consumed before Reaction 5 commences. In the case of path A, it is potassium feldspar that is consumed by the initial melting reaction so that melting restarts at a temperature above that of Reaction 5 when the phase compositions intersect the loops for Reaction 2. Similarly B represents the reaction history when it is H_2O that is completely consumed by Reaction 1. Paths C and D illustrate reaction sequences along which Reaction 5 does take place, consuming either potassium feldspar (to give rise to path C) or H_2O (path D).

The mineral assemblages of the cordierite migmatite zone (Table 1) can be used to evaluate which of these paths have occurred. We have assumed that the intimate association of cordierite with granitic leucosomes in these rocks demonstrates that the peak P - T conditions exceeded those for Reaction 5. Of the KMFASH phases, sillimanite, biotite, and quartz are almost invariably present,

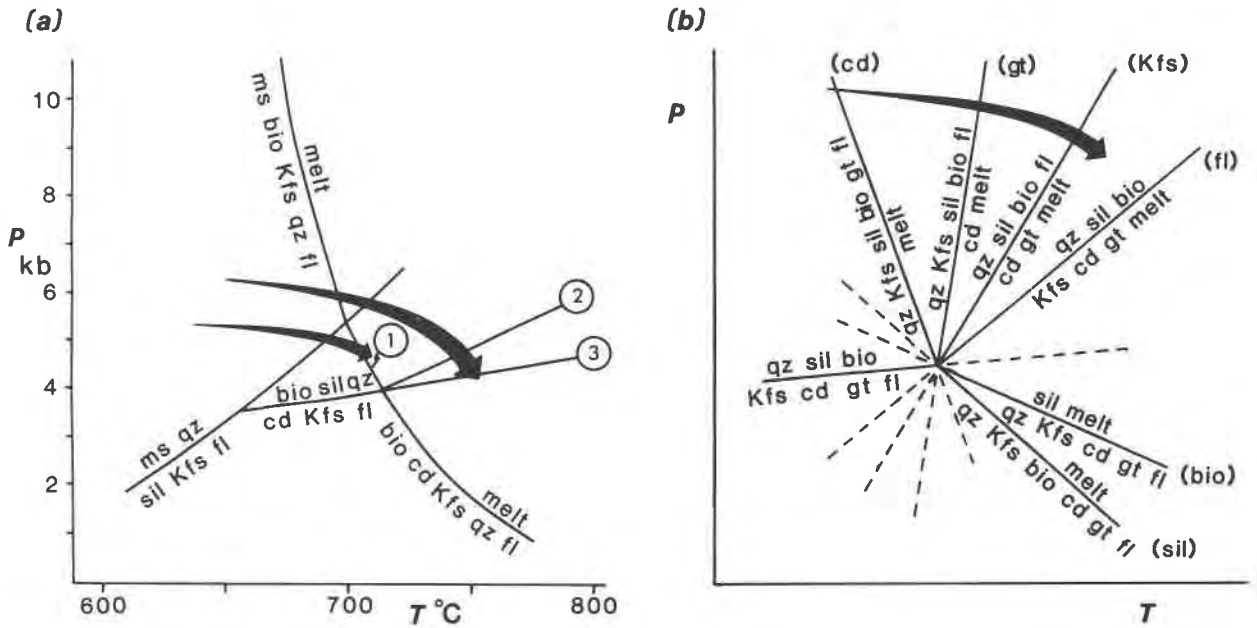


Fig. 4. P - T diagrams to illustrate reaction sequences in the model pelite system. Abbreviations as in Table 1. (a) H_2O -saturated melting for reactions in system KMFASH constructed for $X_{Mg} = 0.5$, after Vielzeuf and Holloway (1988). (b) Disposition of univariant reactions in system KMFASH after Grant (1985). In both parts, the sequence of assemblages found corresponds to the arrowed path, and in a separate paths are shown for the incipient migmatite zone (below) and cordierite-garnet migmatite zone (above).

but the full association of them with cordierite and potassium feldspar (and plagioclase) is relatively uncommon. More usually cordierite, potassium feldspar or both are absent. In terms of Figure 5, we can interpret rocks with the full assemblage of phases involved in Reaction 5 as having melted by this reaction until all H_2O was consumed and as having evolved subsequently by Reaction 3 (path D). In contrast, cordierite-absent rocks cannot have experienced Reaction 5 and must be following paths such as A or B (depending on whether potassium feldspar is present), without having attained a sufficient temperature for Reactions 2 or 3 to commence. Lastly, cordierite-bearing pelitic restites that lack potassium feldspar are not uncommon and are inferred to have developed by melting along path C in the presence of H_2O . In summary, most of the pelitic assemblages of the migmatites in this zone appear to result from significant H_2O -saturated melting. In some cases, H_2O appears to have persisted throughout the melting interval, but assemblages including cordierite + potassium feldspar are indicative of reduced H_2O activity (Holdaway and Lee, 1977). Hence the final activity of H_2O at the peak of metamorphism was internally buffered at different values in different layers, with both H_2O -saturated and H_2O -absent melting occurring.

Assemblages of the cordierite-garnet migmatite zone are similarly consistent with extensive H_2O -saturated melting, until no H_2O remained, so that all the solids involved in Reaction 6, persist in the rock.

In conclusion, comparison of the observed sequence of

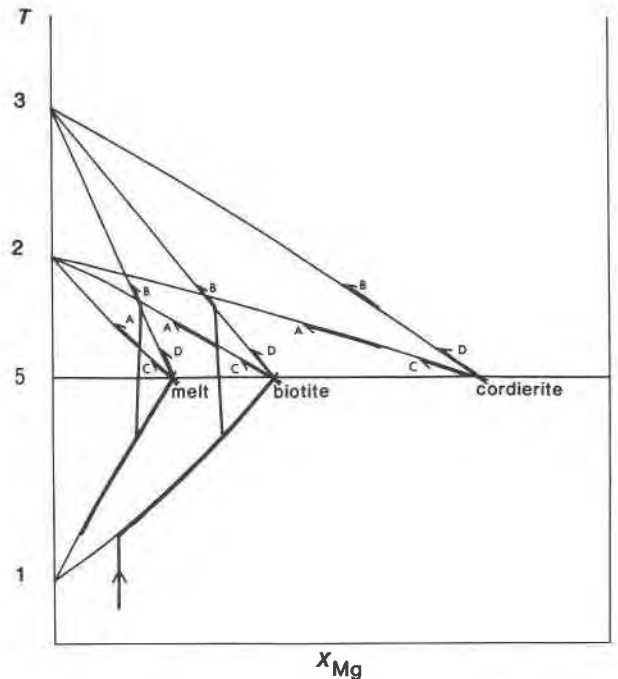


Fig. 5. Schematic T - X_{Mg} diagram to illustrate progressive reaction in the incipient and cordierite migmatite zones of the Streamstown Formation. The T - X_{Mg} loops shown represent the divariant Reactions 1-3. Arrowed paths represent alternative reaction sequences according to rock composition and fluid availability (see text).

TABLE 2. Summary of analytical data for migmatized and unmigmatized Cashel Formation

	Unmigmatized Pelites (<i>n</i> = 54)				Pelitic Restites (<i>n</i> = 42)				<i>E</i>	Composition of melt removed*
	Mean	s.d.	Min	Max	Mean	s.d.	Min	Max		
SiO ₂	54.95	3.89	45.13	66.48	50.37	4.59	41.66	60.82	0.917	73.27
Al ₂ O ₃	21.25	2.73	14.85	26.69	20.72	2.64	14.73	27.28	0.975	23.37
TiO ₂	1.29	0.21	0.71	1.73	1.92	0.44	0.91	2.90	1.488	0
Fe ₂ O ₃	1.22	0.66	0.15	4.00	3.09	1.45	0.96	7.68	1.243	0.24
FeO	7.90	1.19	5.34	10.57	8.41	1.76	5.04	12.22		
MgO	2.71	0.38	1.75	4.29	3.47	0.50	2.46	4.76	1.280	0
CaO	1.33	0.69	0.40	3.61	1.65	0.73	0.25	3.98	1.241	0.50
Na ₂ O	2.34	0.81	0.57	5.21	2.05	0.69	0.48	3.25	0.876	3.50
K ₂ O	3.58	0.76	1.65	5.71	4.28	0.93	2.82	7.94	1.195	0.78
MnO	0.14	0.04	0.07	0.29	0.16	0.06	0.08	0.36	1.143	0.06
P ₂ O ₅	0.26	0.11	0.10	0.72	0.18	0.06	0.07	0.87	0.692	0.58
Trace elements (ppm)										
S	867	1136	0	2752	346	458	0	1939	0.400	2949
Sc	23.6**	3.2	17	30	21.6	5.0	10	34	0.913	32
V	154.6**	27.4	104	208	193.8	35.3	119	289	1.253	0
Cr	122.0	13.2	88	160	147.4	24.0	107	207	1.208	20
Ni	56.1	9.6	24	75	68.2	16.2	27	104	1.216	8
Cu	52.5	32.4	2	140	35.3	20.8	3	84	0.672	121
Zn	129.0	44.2	44	334	169.7	45.0	83	290	1.315	0
Rb	126.3	25.0	58	184	151.1	33.6	100	239	1.196	27
Sr	191.5	72.7	66	414	237.0	136.9	29	822	1.238	10
Y	36.2	5.8	26	53	35.4	12.9	17	82	0.977	39
Zr	266.2	61.3	135	437	352.4	79.6	177	480	1.324	0
Nb	26.8**	4.8	19	39	34.0	9.7	17	57	1.269	0
Ba	756	204	354	1383	1050.1	412.2	409	2131	1.388	0
La	52.1	10.0	35	78	51.1	12.7	28	80	0.981	56

Note: Data of Barber, 1985 and Yardley, 1974, revised. Also shown are enrichment factors, *E*, and the calculated composition of the melt removed.

* Calculated assuming $X_m = 0.2$.

** Based on $n = 20$.

assemblages with reactions in the model KMFASH system indicates that H₂O-saturated melting reactions were important at all grades in the migmatite zones, often reacting until all fluid was consumed. The amount of melting that was required to attain this condition is the subject of the next section.

PELITE CHEMISTRY AND THE AMOUNT OF MELTING

Simple visual estimates indicate that, except at the lowest grades, migmatite outcrops typically contain 10–40% leucosome material. However, there is considerable uncertainty in interpreting such observations directly as representing the degree of melting. Melt may have entered or left, leading to outcrops locally enriched or depleted in leucosome. Some melt may have left the system entirely, and the possibility of introduction of externally derived melt cannot be excluded, although this usually forms distinct larger masses with meter-scale dimensions. We have therefore employed a chemical mass balance approach to determine the degree of melting, comparing the same stratigraphic units inside and outside the migmatite zones. For any component that is not introduced to the system as part of the melting process, we can write a simple balance

$$C_{i,p} = C_{i,m}X_m + C_{i,r}(1 - X_m)$$

where C_i denotes concentration of component i with the subscripts p, m, and r to denote unmigmatized protolith, melt, and restite, respectively, and X_m is the fraction of

melt formed. Of these terms, $C_{i,p}$ and $C_{i,r}$ can be measured directly while X_m is the unknown to be calculated. The equation can be solved by choosing refractory components such as Cr, Ni, V, etc., for which $C_{i,m}$ can be reasonably assumed to be 0.

We have attempted to perform calculations of this type for both of the formations of interest (Barber, 1985), estimating $C_{i,p}$ and $C_{i,r}$ from the means of large sets of rock analyses from the work of Yardley (1974) and Barber (1985). A practical problem, discussed by Barber (1985) is that these two data sets, although both prepared using superficially similar XRF methods (Harvey et al., 1972; Leake et al., 1969) are discrepant for certain trace elements and for Na. We have now resolved this by re-analyzing a subset of samples from the earlier study and have recalibrated this data set to be consistent with the later work.

In practice, mass balance calculations for the Streamstown Formation have not proved helpful because there is a considerable lithological diversity within this unit, and the standard deviations on the mean analyses for most elements are too large for the differences between the unmigmatized pelites and the migmatite restites to be clearly defined. These data will not be discussed further.

In contrast, the pelites of the Cashel Formation are a distinctive and coherent set of rocks of limited compositional range. Table 2 summarizes our data on 54 samples of unmigmatized pelites and 42 pelitic restites from

the Cashel Formation and its equivalents. Also tabulated is an enrichment factor E , where

$$E = C_{ir}/C_{ip}$$

Elements for which $E < 1$ are enriched in the melt, whereas $E > 1$ indicates enrichment in the restite. It is apparent from a general inspection of Table 2 that the most extreme chemical changes accompanying melting of the pelites of the Cashel Formation are oxidation of Fe and loss of S, Cu, P, and quartz and albite components to the melt (or other mobile phases). B should almost certainly be added to this list, since tourmaline is common in unmigmatized pelites, but almost unknown in the pelitic restites.

The main group of refractory elements yields values of E in the range 1.21–1.28. This group includes Fe, Mg, Ca, V, Cr, Ni, Sr, and Nb. A few elements yield higher enrichment factors, but these are not believed to be significant. In most cases they probably reflect large relative standard deviations for the elements concerned, but, in the case of Ti, it is likely that the stratigraphic variability noted above is the cause of the extreme E -value. The high-Ti Kylemore Formation may be overrepresented in the restite data set compared to the protolith data set.

A mean value for E for the refractory elements is near 1.25, and this yields $X_m = 0.2$, i.e., there has been on average 20% melting in the highest grade migmatite zone. The uncertainty of this estimate is less than $\pm 5\%$. Taking $X_m = 0.2$, we have then calculated values of $C_{i,m}$ for the full range of elements analyzed to produce a computed analysis of the melt phase, also listed in Table 2. There are two important reservations regarding this calculation. First, for some elements the calculation is very sensitive to the precise values of means to which appreciable uncertainties are attached, hence it should only be used as a semiquantitative indicator of melting behavior. The apparently extreme Al content of the melt is a case in point. Second, our calculation cannot in fact distinguish between material entering a granite melt phase and material being mobilized in some other form (e.g., a renewed episode of quartz veining) during the high-grade event. For the metallic elements considered here, however, the amounts added or removed by aqueous fluids are unlikely to be significant compared to the amounts present in restite or melt.

Despite these reservations, it is clear from Table 2 that the melt produced by H₂O-saturated melting reactions in these pelites was in fact dominated by quartz and albite. Overall, the contribution of melting reactions involving biotite and releasing K to the melt was in general small, although local garnet and cordierite-enriched restites attest to more extensive biotite breakdown in certain bulk compositions than the few percent implied by the mean data used here.

DISCUSSION

The amount of H₂O-saturated melting that is possible utilizing free H₂O present in the pores of a high-grade

rock must be very small. If the H₂O-saturated melt contains about 10% H₂O by weight (Clemens, 1984) and the porosity of a high-grade rock is 0.1% by volume (Clemens and Vielzeuf, 1987), then much less than 1% melting is possible. Even for a metamorphic porosity of 1%, only about 4% H₂O-saturated melt can be formed. Alternatively, however, if H₂O is added to the rock while it undergoes H₂O-saturated melting, then the limits to the generation of melt are provided by the availability of solid reactants and much more extensive melting may be possible. The remarkable uniformity of plagioclase composition in the high-grade Connemara migmatites noted by Leake (1969) may reflect buffering by H₂O-saturated melting.

The evidence presented here shows that extensive (ca. 20%) melting has taken place, predominantly by H₂O-saturated melting reactions under upper amphibolite facies conditions. The resulting melts were dominated by quartz and albite with only a minor potassic component. While the final distribution of aqueous fluid in the migmatites may have been patchy and locally buffered, there must have been significant infiltration of H₂O to permit such extensive melting to take place.

There are two likely sources for the infiltrating H₂O that facilitated melting: crystallization of synorogenic intrusions to the south, which acted as heat source for the melting reactions and are known to have been of a distinctly H₂O-rich character (Leake 1969), or H₂O derived from subsolidus dehydration reactions in lower grade pelites further north. The distribution of the migmatites firmly favors the first of these alternatives. The highest grade garnet-cordierite migmatites in the south have clear evidence of extensive H₂O-saturated melting, whereas the lowest grade migmatites contain only a very small amount of leucosome and generally retain the full assemblage of solid phases required for melting by Reaction 1. Hence, they have probably been infiltrated very little and may indeed have formed primarily from the participation of pore H₂O.

We propose therefore that extensive melting is possible under H₂O-saturated conditions in the upper amphibolite facies provided there is an external source of H₂O as well as heat at the peak of metamorphism. In view of the strongly endothermic character of melting reactions, it is possible that, had H₂O not been added, the heat supplied to the highest grade zones might have been sufficient to raise their assemblages into the granulite facies. Pattison (1989) reported extensive H₂O-undersaturated melting in the Ballachulish aureole, which was generated by the emplacement of a range of magma types that were broadly similar to those found in Connemara, although at lower pressures. Restites in the Ballachulish aureole have widespread potassium feldspar, in marked contrast to the rocks described here, and the assemblages range into the granulite facies with temperatures exceeding 750 °C. In the case of the Connemara migmatites, more extensive lower grade melting caused by the addition of H₂O acted as a constraint on the rise in temperature in the proximity of

the intrusions. In light of this comparison, we suggest that where H₂O is added to melting metasediments, such metasediments will be unable to attain extreme metamorphic temperatures.

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