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

BRUCE W. D. YARDLEY
Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, England

JOHN P. BARBER*
Department of Earth Sciences, The Open University, Milton Keynes MK7 6AA, England

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 H$_2$O-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 H$_2$O-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 H$_2$O-saturated melting is only possible if the metamorphism involves addition of H$_2$O 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 H$_2$O as they crystallized. In view of the strongly endothermic character of melting reactions, it is probable that, had there been no addition of H$_2$O 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 H$_2$O-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 H$_2$O to cause significant H$_2$O-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; Paterson, 1989).

This evidence notwithstanding, the possibility of significant H$_2$O-saturated melting cannot be precluded, provided there are geological settings in which H$_2$O 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 H$_2$O-saturated melting. For example the dehydration melting reaction biotite + sillimanite + quartz = cordierite + garnet + potassium feldspar + melt, which is univariant in the KMFASH system, effec-
Fig. 1. Metamorphic map of Connemara, after Yardley et al. (1987).

Fig. 1. Metamorphic map of Connemara, after Yardley et al. (1987).
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 iso-
bars moved downward as a consequence of unroofing. 
This means that the observed zonal sequence is not iso-
baric 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 temper-
ature range at higher pressures, so that muscovite broke 
down by a melting reaction.

A particularly significant aspect of the geology of Con-
memara 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 stratigraph-
ically 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 indistin-
guishable except for a significantly higher Ti content 
in the Kylemore Formation. Because of the greater struc-
tural 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 For-
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 $X_{\text{Fe}}$ values, and con-
tain abundant staurolite at appropriate grades. Their as-
semblages 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 Bennabola 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 Shanagareena. 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**

<table>
<thead>
<tr>
<th>Streamstown Formation assemblages</th>
<th>Cashel Formation assemblages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper sillimanite</td>
<td>sil + Kfs + bio + ms + plag + qz</td>
</tr>
<tr>
<td>Incipient migmatite</td>
<td>sil + Kfs + bio + ms + plag + qz</td>
</tr>
<tr>
<td>Cordierite migmatite</td>
<td>sil + cd + bio + plag + qz</td>
</tr>
<tr>
<td>Garnet-cordierite migmatite</td>
<td>sil + cd + gt + bio + plag + qz</td>
</tr>
<tr>
<td>Upper sillimanite</td>
<td>sil + gt + bio + plag + qz</td>
</tr>
<tr>
<td>Garnet-cordierite migmatite</td>
<td>sil + cd + gt + bio + plag + qz</td>
</tr>
</tbody>
</table>

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

Widespread leucosomes are trondhjemitic, 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.

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 KFASH and KMASH systems have been constructed by Thompson (1982), Grant (1985), and Vielzeuf and Holloway (1988). Considering first the endmember KFASH (or KMASH) system, the sequence of melting reactions represented by the zones observed can be modeled as follows:

\[
\begin{align*}
\text{biotite + sillimanite + potassium feldspar + quartz + } & H_2O = \text{melt} \\
\text{biotite + sillimanite + quartz + } & H_2O = \text{cordierite + melt} \\
\text{biotite + sillimanite + quartz} & = \text{cordierite + potassium feldspar + melt.}
\end{align*}
\]

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 Schreinemakers net of reactions in KMASH involving the above phases plus garnet. The reactions are:

\[
\begin{align*}
\text{potassium feldspar + sillimanite + biotite + garnet + quartz + } & H_2O = \text{melt} \\
\text{potassium feldspar + sillimanite + biotite + quartz + } & H_2O = \text{cordierite + melt} \\
\text{sillimanite + biotite + quartz + } & H_2O = \text{cordierite + garnet + melt} \\
\text{sillimanite + biotite + quartz} & = \text{potassium feldspar + cordierite + garnet + melt.}
\end{align*}
\]

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 KMASH 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 KMASH 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 KMASH phases, sillimanite, biotite, and quartz are almost invariably present,
b) 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$_2$O 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$_2$O. In summary, most of the pelitic assemblages of the migmatites in this zone appear to result from significant H$_2$O-saturated melting. In some cases, H$_2$O appears to have persisted throughout the melting interval, but assemblages including cordierite + potassium feldspar are indicative of reduced H$_2$O activity (Holdaway and Lee, 1977). Hence the final activity of H$_2$O at the peak of metamorphism was internally buffered at different values in different layers, with both H$_2$O-saturated and H$_2$O-absent melting occurring.

Assemblages of the cordierite-garnet migmatite zone are similarly consistent with extensive H$_2$O-saturated melting, until no H$_2$O remained, so that all the solids involved in Reaction 6, persist in the rock.

In conclusion, comparison of the observed sequence of
assemblages with reactions in the model KMFASH system indicates that H_2O-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, \( C_{i,m} \) 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 \( C_{i,m} \) 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 reanalyzing 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

<table>
<thead>
<tr>
<th></th>
<th>Unmigmatized Pelites</th>
<th>Pelitic Restites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>s.d.</td>
</tr>
<tr>
<td><strong>SiO_2</strong></td>
<td>59.45</td>
<td>3.89</td>
</tr>
<tr>
<td><strong>Al_2O_3</strong></td>
<td>21.25</td>
<td>2.73</td>
</tr>
<tr>
<td><strong>TiO_2</strong></td>
<td>1.29</td>
<td>0.21</td>
</tr>
<tr>
<td><strong>Fe_2O_3</strong></td>
<td>1.22</td>
<td>0.66</td>
</tr>
<tr>
<td><strong>FeO</strong></td>
<td>7.90</td>
<td>1.19</td>
</tr>
<tr>
<td><strong>MgO</strong></td>
<td>2.71</td>
<td>0.38</td>
</tr>
<tr>
<td><strong>CaO</strong></td>
<td>1.33</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>Na_2O</strong></td>
<td>2.34</td>
<td>0.81</td>
</tr>
<tr>
<td><strong>K_2O</strong></td>
<td>3.59</td>
<td>0.76</td>
</tr>
<tr>
<td><strong>MnO</strong></td>
<td>0.14</td>
<td>0.04</td>
</tr>
<tr>
<td><strong>P_2O_5</strong></td>
<td>0.26</td>
<td>0.11</td>
</tr>
</tbody>
</table>

**Trace elements (ppm)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Mean</th>
<th>s.d.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>867</td>
<td>1136</td>
<td>0</td>
<td>2752</td>
</tr>
<tr>
<td>Sc</td>
<td>23.6*</td>
<td>2.4</td>
<td>17</td>
<td>30</td>
</tr>
<tr>
<td>V</td>
<td>15.6*</td>
<td>2.74</td>
<td>104</td>
<td>208</td>
</tr>
<tr>
<td>Cr</td>
<td>122.0</td>
<td>13.2</td>
<td>88</td>
<td>180</td>
</tr>
<tr>
<td>Ni</td>
<td>94.6</td>
<td>3.4</td>
<td>24</td>
<td>45</td>
</tr>
<tr>
<td>Cu</td>
<td>35.3</td>
<td>3.5</td>
<td>208</td>
<td>107</td>
</tr>
<tr>
<td>Zn</td>
<td>190.3</td>
<td>4.2</td>
<td>44</td>
<td>134</td>
</tr>
<tr>
<td>Rb</td>
<td>106.3</td>
<td>2.5</td>
<td>58</td>
<td>184</td>
</tr>
<tr>
<td>Sr</td>
<td>191.5</td>
<td>7.2</td>
<td>66</td>
<td>414</td>
</tr>
<tr>
<td>Y</td>
<td>38.2</td>
<td>5.8</td>
<td>26</td>
<td>53</td>
</tr>
<tr>
<td>Zr</td>
<td>268.2</td>
<td>61.3</td>
<td>135</td>
<td>437</td>
</tr>
<tr>
<td>Nb</td>
<td>25.8*</td>
<td>4.8</td>
<td>19</td>
<td>39</td>
</tr>
<tr>
<td>Ba</td>
<td>756</td>
<td>204</td>
<td>354</td>
<td>1383</td>
</tr>
<tr>
<td>La</td>
<td>52.1</td>
<td>10.0</td>
<td>35</td>
<td>78</td>
</tr>
</tbody>
</table>

**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 \( n = 20 \).**
the Cashel Formation and its equivalents. Also tabulated is an enrichment factor E, where

\[ E = \frac{C_{\text{r}}}{C_{\text{i}}}. \]

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 \( C_{\text{r}} \) 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 apparent 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 \( H_2O \)-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 \( H_2O \)-saturated melting that is possible utilizing free \( H_2O \) present in the pores of a high-grade rock must be very small. If the \( H_2O \)-saturated melt contains about 10% \( H_2O \) 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% \( H_2O \)-saturated melt can be formed. Alternatively, however, if \( H_2O \) is added to the rock while it undergoes \( H_2O \)-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 \( H_2O \)-saturated melting.

The evidence presented here shows that extensive (ca. 20%) melting has taken place, predominantly by \( H_2O \)-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 \( H_2O \) to permit such extensive melting to take place.

There are two likely sources for the infiltrating \( H_2O \) 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 \( H_2O \)-rich character (Leake, 1969), or \( H_2O \) 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 \( H_2O \)-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 \( H_2O \).

We propose therefore that extensive melting is possible under \( H_2O \)-saturated conditions in the upper amphibolite facies provided there is an external source of \( H_2O \) as well as heat at the peak of metamorphism. In view of the strongly endothermic character of melting reactions, it is possible that, had \( H_2O \) not been added, the heat supplied to the highest grade zones might have been sufficient to raise their assemblages into the granulite facies. Patterson (1989) reported extensive \( H_2O \)-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 \( H_2O \) acted as a constraint on the rise in temperature in the proximity of
the intrusions. In light of this comparison, we suggest that where H_2O is added to melting metasediments, such metasediments will be unable to attain extreme metamorphic temperatures.

ACKNOWLEDGMENTS

This work was largely carried out while J.P.B held a NERC Research Studentship at the University of East Anglia. We are indebted to P.K. Harvey and B.P. Atkins (University of Nottingham) and A. Gray (Leeds) for assistance with the XRF analysis.

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Manuscript received January 31, 1990
Manuscript accepted February 7, 1991