The metagabbros, orthogneisses and paragneisses of the Connemara complex, western Ireland

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Abstract: Although now largely disappeared within the 400 Ma-old Galway Granite, the syntectonic Connemara metagabbro–gneiss complex, which crystallized at 490 Ma (Arenig), is the largest intrusion into the Dalradian rocks. It is part of widespread Cambro–Ordovician volcanism and plutonic injection into continental crust in the Appalachian–Caledonide orogenic belt, being synchronous in crystallization with the widely obducted 490 Ma ophiolites within the orogeny. The peridotites and hornblende gabbros were injected, broken up, and shouldered aside by quartz diorite, granodiorite, granite and trondhjemite gneisses, and it is shown that these orthogneisses are not the in situ differentiation products of the gabbro magma. The hornblende in the metagabbros is mainly igneous but is partly metamorphic and replaces olivine (Fo$_{75-92}$), orthopyroxene (En$_{95-92}$), clinopyroxene (Wo$_{48-52}$En$_{10-19}$Fs$_{5-14}$) and plagioclase typically An$_{80-90}$ (range An$_{80-90}$). An aureole at least 10 km wide in the sillimanite zone was imposed, and cordierite-garnet-sillimanite Dalradian hornfelses were partially melted at temperatures up to 1000 °C near to the gabbros at 4.5 ± 1 kbar corresponding to c. 18 km depth. This suggests that the complex forms part of the root of a now eroded batholith of calc–alkaline affinities, the gabbros corresponding to the transition zone to a basic bottom which is often supposed to underlie many batholiths. Within the orthogneisses are sheets of paragneiss formed from Dalradian metasediments which have been folded up from the floor and down into sides of the magma chamber, which process could be illustrative of the means by which basic magma can intimately interact with crustal material. The $^{18}$O/$^{16}$O, D/H, Nd and Sr isotope evidence, and the existence of inherited zircons in the gneisses, indicate that the gabbro and gneiss magmas were significantly contaminated with crustal, possibly Dalradian, material both before and after intrusion, with the lowest initial $^{87}$Sr/$^{86}$Sr at 490 Ma being 0.708 even in samples far removed from metasediments. The metagabbros are tholeiitic to high alumina basalt in character but the gneisses have distinct calc–alkaline geochemistry. The chemistry, igneous hornblende and highly calcic plagioclase match many arc plutons in the western USA. The syntectonic nature and the ubiquitous gneissic fabric in the quartz diorites, trondhjemites and granites is a consequence of early movements which were probably in part connected with the separation of the Connemara massif, and which culminated in slicing off the largely inverted complex and carrying it southwards on the Mannin Thrust which underlies the whole of Connemara. The complex is thus a fragment of a now disrupted Cambro–Ordovician continental magmatic arc or continent-island arc environment which can be traced along the SE edge of the Laurentian continent.

Introduction

Connemara is a southwardly thrusted and eastwardly strike-slip faulted fragment of Dalradian rocks (Leake et al. 1983) in Co. Galway, western Ireland (Fig. 1). Intruded into the Dalradian metasediments and pre-dating the basal Mannin thrust which underlies the whole of Connemara, is the largest igneous complex in the Dalradian rocks of Scotland or Ireland. This E–W-striking metagabbro and quartz diorite–granodiorite–granite gneiss complex extends from Slyne Head in the west to east of Galway City, with no visible termination at either end of the strike length of over
Fig. 1. Sketch map of the geology of Connemara, western Ireland showing the metagabbro-orthogneiss complex, the fringing paragneiss and the sillimanite isograd with sillimanite occurring to the south. A separate sillimanite isograd surrounds the northern intrusive complex, roughly corresponding to the paragneiss periphery. The Shannavara district shown in Fig. 2 is outlined showing the junction of the ortho- and paragneisses in particular. The true scale north–south cross-section, modified from Leake et al. (1983), shows the thrust bottom of the complex although the metagabbro sequence is inverted. B is the Wild Bellows Rock. Ornament in section is as on map, except Ballyconneely Amphibolite which is shown stipple with the ortho- and paragneiss grouped together.

80 km (Fig. 1). Most of the complex has been lost in the younger 400 Ma Galway Granite (Leggo et al. 1966) but from its northern intrusive edge with the Dalradian rocks, the complex now extends southwards 26 km (and more originally) until it is truncated by the E–W Skird Rock fault (Fig. 1). It includes, near its northern margin, paragneisses formed from the Dalradian country rocks. Similar peridotite, metagabbro and gneiss intrusions occur in north Connemara where the disrupted Dawros–Currywongaun–Doughruagh intrusion (Rothstein 1957; Kanaris–Sotiriou & Angus 1976; Bennett & Gibb 1983) is, like its southern counterpart, associated with a high grade metamorphic aureole.

The metagabbro has been dated by U–Pb, and Pb–Pb studies of zircon at 490 ± 1 Ma (Jagger et al. 1988), i.e. lower Arenig (Harland et al. 1982), which is closely similar to the reported Rb-Sr age of the Aberdeenshire gabbros (Pankhurst 1970), the zircon U–Pb age of 490 ± 2 Ma for the Baltimore gabbroic complex in Maryland (Shaw & Wasserburg 1984) and the 496 ± 14 Ma zircon U–Pb age for the Elkahatchee quartz diorite, the largest gabbro-gneiss complex in the Southern Appalachians (Drummond pers. comm.) The Connemara metagabbro–gneiss complex is therefore part of a major intrusive episode in the early Ordovician in the Appalachian–Caledonide orogenic belt.

Previous work on the complex (Fig. 1) includes studies of the Roundstone part of the intrusion by Wager (1932), Morton (1964) and Bremner & Leake (1980), the area north and northwest of Roundstone by Benjamin (1968), Evans & Leake (1970) and Downs-Rose (1985), the area east and northeast of Slyne Head by Ahmed & Leake (1978) and Leake (1986), the Cashel district by Leake (1958, 1970a, 1970b) Jagger (1985) and Jenkin (1988), the Glinsk district by Harvey (1967), and the Shannavara district by Senior (1973). Published work has concentrated largely on the metagabbros whereas the petrochemistries of the quartz
Orthogneisses and F3 folds in the Cashel and Shannavara within melted and partly dissolved, and corundum-spinel-magnetite restites are often all that remain. Descriptions of the hornfelses and the partial melting process are detailed in diorite to granite orthogneiss series, and the paragneisses produced from the Dalradian metasediments, are almost completely unpublished despite major thesis contributions by Harvey (1967), Senior (1973), Keeling (1981) and Jagger (1985). The present account will therefore summarize the available information on the whole complex, especially the gneisses, and includes a detailed geological map of a critical area—the Shannavara district (Fig. 2)—which is crucial in demonstrating the intrusive relationships of the orthogneisses to the Dalradian metasediments. A general overall setting of the complex (Leake et al. 1981) while Fig. 3 summarizes the relationships of the country rock metasediments (including paragneisses) to the metagabbros, orthogneisses and F3 folds in the Cashel and Shannavara districts.

Dalradian country rocks

The Dalradian rocks in close proximity to the intrusion are pelites, semipelites and feldspathic psammites of the Cashel Formation (Tanner & Shackleton 1979) with similar lithologies plus marble, quartzite and amphibolite occurring further north (Fig. 2). A regional post-D2 staurolite–garnet metamorphism, possibly with rare kyanite, has been thermally overprinted by widespread sillimanite, the northern limit of which is shown in Fig. 1 with an additional sillimanite-bearing area around the Dawros–Currywong-aun–Doughraugh body. The metasediments were converted into hornfelses, especially near the metagabbros, into paragneisses, especially near, or as inclusions within, the orthogneiss part of the intrusion or into mixed hornfelses and paragneisses. Temperatures progressively increased southward from the sillimanite–cordierite–biotite hornfelses within c. 2 km of the intrusion, to mobilized sillimanite–cordierite–garnet hornfelses within 0.5 km of the metagabbro. Pelitic xenoliths within the metagabbros were partially melted and partly dissolved, and corundum–spinel–magnetite restites are often all that remain. Descriptions of the hornfelses and the partial melting process are detailed in Leake & Skirrow (1960), Evans (1964), Leake (1970b) and Ahmed-Said & Leake (unpublished). According to Treloar (1981, 1985), garnet–biotite–cordierite compositions that peak temperatures increased from over 700 °C about 3 km north of the Cashel metagabbros to over 800 °C within 100 m of the contact, all at a pressure of 4.5 ± 1 kbar. Temperatures probably exceeded 1000 °C in the partially melted xenoliths in the metagabbros.

The contact of the main outcrop of the Dalradian country rocks with the northern edge of the complex shows signs of strong high-temperature tectonic movement with disrupted fragments of metagabbro and peridotite (the latter often now serpentinite) in the country rocks and strongly foliated orthogneiss injections, but there is no possibility that the igneous complex crystallized elsewhere and was tectonically brought into contact with the Dalradian rocks of Connemara while still hot. Numerous examples of metagabbro intrusion into the Dalradian rocks occur north of the edge of the complex (Leake 1986), the country rock xenoliths in the complex are identical to the Dalradian rocks adjoining the intrusion; the metagabbros can be seen in outcrop to have partially assimilated Dalradian metasediment. Orthogneiss injections into the country rock also occur (Fig. 2).

Where the country rocks come into contact with the orthogneiss, as distinct from metagabbro, or form inclusions within the orthogneiss (Fig. 2), there is extensive development of paragneiss, typically quartz-porphyroblastic andesine (An30) biotite gneiss with or without variable amounts of K-feldspar (<30%), magnetite and ilmenite (<10%), garnet (<10%), cordierite (<30%), andalusite (<1%) and sillimanite (<5%). This gneiss is clearly a recrystallized semipelite with ribs or boudins of more resistant feldspathic psammitic and lenses of pelitic material, often containing garnets. Although sericitization, chloritization and shearing have retrograded the high temperature assemblages there is a clear distinction from the paragneisses which lack the traces of sedimentary layering and quartzo-feldspathic leucosomes in micaeous palaeosomes.

Barber & Yardley (1985) proposed that trondhjemitic leucosomes, containing cordierite and andalusite, formed in the migmatic paragneisses in the aureole and melting or segregation took place at about 750 °C in the pressure range 4.5 to 6 kbar (as deduced from the palaeosome minerals) but crystallization of the leucosomes took place at pressures below 3.5 kbar, i.e. there was very rapid uplift, possibly even with isothermal melting, between segregation and solidification. Such rapid uplift at 480–490 Ma is independently confirmed from K–Ar age studies of hornblends in the metagabbros, the orthogneisses and in amphibolites in the Dalradian rocks (Elias et al. 1988). The paragneisses are an important part of the whole complex.

Earlier studies (Senior & Leake 1978) suggested that the metasediments within 1–2 km of the igneous complex had suffered metasomatic changes compared with those further away but this was not confirmed by subsequent work (Barber 1985). It is not possible to trace continuously one stratigraphical horizon or member from outside the aureole into the inner aureole, as the stratigraphy essentially parallels the complex. This led to incorrect correlations. Taking samples from a single area, Shannavara (Fig. 2) as studied by Senior (1973), and comparing paragneisses with non-gneissic metasediments (Figs 4 and 5), shows that both have similar trends and compositional ranges, and that the paragneisses are isochemically recrystallized semipelites. The absence of gneisses with less than about 9% Al2O3 (Fig. 5) is simply a consequence of the difficulty of developing much feldspar in rocks low in Al2O3 (such as quartzite and marble) which therefore resist conversion to paragneisses. The correlation of elements such as Ti, Zn and Rb with Sr, Sr does not significantly enter sediments in clay minerals.

Potassium feldspar is commonly absent in both the leucosomes and the paragneisses (although some K-feldspar-bearing paragneisses occur in the Shannavara area) and most of the K is in biotite. The lack of any K-feldspar in many of the leucosomes, which are essentially quartz and andesine An30–40 indicates that many of these leucosomes are metamorphic segregations rather than partial melts (Tracy 1985; Ahmed-Said, Pers. Comm.). The rocks closely resemble the isochemically produced paragneisses described by Amit & Eyal (1976) and were produced by recrystallization induced by temperature increase, fluid movement due to dehydration and synchronous tectonic movement which provoked slip along the foliation planes.
The Dalradian country rocks were severely hornfelsed and partially melted near to the larger metagabbro intrusions with the production of granitic partial melts. Some of the melts may have been incorporated into the basic magma, but at Cashel some of the melt was segregated into a granite sill in a slip zone along which the Cashel intrusion and its immediately adjoining mobilized hornfelses moved laterally relative to the more distant (ca. 30–300 m) hornfelses. The concordant granite sill has been described and analysed (Leake 1970b; Ahmed-Said, Pers. Comm.); it is a K-rich granite tending to be syenitic; it closely agrees with the calculated composition of the material obtained by partially melting typical Dalradian Connemara schist and was clearly segregated onto the movement zone. Jagger (1985) has confirmed the partial melt origin by determining the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios at 490 Ma as 0.720 which is well within the range of the hornfelsed Dalradian metasediments and much higher than any of the orthogneisses or metagabbros. The detailed description of the composition of the material removed from the hornfelses and the formation of ‘S-type’ granite is given in Ahmed-Said & Leake (unpublished).

Metagabbros

The metagabbros are the earliest intrusions in the complex and include peridotites and anoroshites but are at least 90% composed of hornblende gabbros or hornblende gabbro–norites with hornblende and bytownite (often An$_{60}$–80) or labradorite with relic diopside–salite and sometimes orthopyroxene. Both pyroxenes and plagioclase are considerably replaced by hornblende. Magnetite, apatite and pyrite are accessory minerals. Apart from Dawros (Fig. 1) which is mainly herzolite, wehrlite and harzburgite with some chrome spinel-rich cumulates (Rothstein 1957), the peridotites form disrupted pods mainly at Roundstone. Everywhere the metagabbros are injected and broken up by the later gneiss with extensive agmatite formation, and hornblende is both a late-state igneous mineral and metamorphically-produced, as along the margins of metagabbro against gneiss. Iugneous layering is generally poorly preserved, and rocks are massive or poorly metamorphically foliated metagabbros. The existence of xenoliths of earlier-crystallized basic rock in later phases and disruption of igneous layering by later gabbroic injections reveals a complex igneous history only partly understood. Detailed descriptions of the various parts of the intrusion are given in the references already listed.

Above the Mannin Thrust plane (Fig. 1) which underlies the whole complex, the metagabbros and orthogneisses were ground down, recrystallized into fine-grained, N–S lineated, Ballyconneely amphibolites and siliceous tectonites and thrust over the metarhyolites of the Delaney Dome Formation (Leake & Singh 1986) which underlie the Mannin Thrust (Leake 1986). As the Mannin Thrust is folded by F4 and F5 folds in the Connemara fold sequence, this dates the metagabbros as pre-F4. They are also folded by the F3 Cashel synform and antiform, and the writer previously

Fig. 4. Plots of Niggli parameters for the metasediments (crosses), quartzofeldspathized metasediments i.e. paragneisses (crosses inside circles) and strongly hornfelsed pelites (circles) from the Shannavara district. Analyses from Senior (1973). No systematic displacement of the paragneisses from the range of metasediment variation is apparent. W is oxidation ratio.
Fig. 5. Plots of trace elements against wt % $\text{Al}_2\text{O}_3$ for Shannavara metasediments (crosses) and quartzo-feldspathized metasediments i.e. paragneisses (crosses inside circles). Analyses from Senior (1973).
Table 1. Chemical analysis of hornblends from metagabbros and gneisses

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<tr>
<th>BL</th>
<th>1798</th>
<th>1443</th>
<th>1951</th>
<th>830</th>
<th>931</th>
<th>1396</th>
<th>500</th>
<th>652</th>
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<td>12.23</td>
<td>12.59</td>
<td>5.89</td>
<td>11.10</td>
<td>11.02</td>
<td>10.54</td>
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<td>4.76</td>
<td>4.56</td>
<td>1.14</td>
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<td>2.34</td>
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<td>MnO</td>
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<td>0.23</td>
<td>0.36</td>
<td>0.44</td>
<td>0.25</td>
<td>0.48</td>
<td>0.53</td>
<td>0.39</td>
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<td>CaO</td>
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<td>11.45</td>
<td>11.26</td>
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<td>1.21</td>
<td>1.88</td>
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<td>0.03</td>
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<td>2.31</td>
<td>2.16</td>
<td>2.34</td>
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</tbody>
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Total 100.08 99.96 100.32 100.12 99.52 99.93

Ions to 24 \((O, OH)\)

| SL  | 7.00  | 6.41  | 6.44  | 6.35  | 6.37  | 7.20  | 6.28  | 6.27  | 6.48  |
| Al⁺⁺ | 1.00  | 1.59  | 1.56  | 1.65  | 1.63  | 0.80  | 1.72  | 1.73  | 1.52  |
| Al⁺⁺ | 0.23  | 0.29  | 0.17  | 0.45  | 0.58  | 0.20  | 0.24  | 0.29  | 0.39  |
| Ti⁺⁺ | 0.05  | 0.17  | 0.17  | 0.14  | 0.18  | 0.04  | 0.18  | 0.18  | 0.16  |
| Fe⁺⁺ | 0.36  | 0.52  | 0.53  | 0.50  | 0.53  | 0.30  | 0.27  | 0.61  |       |
| Fe⁺⁺ | 0.95  | 1.13  | 1.15  | 1.25  | 1.66  | 1.10  | 1.70  | 2.65  | 2.51  |
| Mn²⁺ | 0.03  | 0.05  | 0.03  | 0.04  | 0.05  | 0.03  | 0.06  | 0.07  | 0.05  |
| Mg²⁺ | 3.46  | 2.91  | 3.00  | 2.68  | 2.30  | 2.56  | 1.84  | 2.03  |       |
| Ca²⁺ | 1.80  | 1.74  | 1.79  | 1.76  | 1.85  | 1.70  | 1.86  | 2.01  | 2.00  |
| Na⁺⁺ | 0.32  | 0.31  | 0.53  | 0.34  | 0.53  | 0.25  | 0.28  | 0.63  | 0.23  |
| K⁺⁺  | 0.14  | 0.14  | 0.17  | 0.14  | 0.25  | 0.09  | 0.29  | 0.38  | 0.32  |
| OH⁻  | 2.02  | 2.41  | 2.02  | 2.21  | 2.29  | 2.06  | 2.34  | [2.00] | [2.00] |

Cell dimensions

| b Å  | 18.096| 18.045| 18.044| 18.043| 18.111|
| c Å  | 5.305 | 5.308 | 5.319 | 5.309 | 5.306 |
| β    | 104.95| 104.925| 104.873| 104.927| 104.786|
| V Å  | 914.8 | 911.1 | 912.1 | 909.9 | 915.5 |

* Total Fe as FeO.

BL 1798. Magnesio-hornblende. Hornblende-saussuritized plagioclase gabbro. Peninsula SE of the northern island and NNE of the second most northern island in Loughaunemlagh, Cappaghoosh Townland. This, and all following samples are located on 6 inch (1:10560) sheet Co. Galway 51 and were (wet) analysed by B. E. Leake except BL 652 & 679.

BL 1443. Tschermakitic hornblende. Poikilitic 2 cm diameter hornblends, partly replaced by prehnitized and chloritized biotite in a poikilitic gabbro layer with some altered bytownite. Southern point of Lough Wheelaun; northern part of Lettershinna Townland.


BL 931. Potassic ferroan pargasitic hornblende with labradorite, quartz, chloride, magnetite, epidote and apatite in gabbro injected by gneiss. 300 m SSW of the western point of Lough Nambrackkeagh, NW Lettershinna Townland. Rock analysis in Leake (1970a).

BL 1396. Magnesio-hornblende. Bright green metamorphic amphibole from hornblendite aegmate. Bunahown Townland. 204 m east of BM 63.1.


BL 679. Potassic ferroan pargasitic hornblende from a gabbro injected by K feldspar granite gneiss 325 m SE of the Zetland Arms Hotel, Bunahown Townland. Electron microprobe analysis.
concluded (1970a) that the syn-magmatic deformation was therefore, syn-F2 in the Connemara fold sequence. Tanner (pers. comm.) however has pointed out that there is no evidence of F2 involvement, and that intrusion pre-F3 or contemporaneous with the early phases of F3 fits the available evidence best. This seems most likely to be correct in view of the syn- to post-F3 nature of the sillimanite isograd in Connemara, which appears to be the result of regional heating by the igneous complexes of both south and north Connemara.

Everywhere hydrous alterations of hornblende to chlorite and epidote are usual, also of plagioclase to saussurite and sericite, of pyroxene to chlorite and serpentine, of olivine to serpentine and magnetite, and of biotite to chlorite and sometimes prehnite. Jenkin (1988) has shown that this low temperature episode was distinct from the magmatism of the rocks and was due a later hydration unconnected with the water-rich gabbroic magma.

Mineralogy

Olivine is invariably much serpentinized but relict grains from Dawros yield F092-98 (Bennett & Gibb 1983) although the most common range in the Roundstone, Cashel and other bodies in the main intrusive complex is F076-90 with a very strong concentration at F090-92. The most iron-rich grains determined are F075 and thus there is comparatively limited iron-enrichment, probably because of the common crystallization of magnetite.

The clinopyroxenes are extensively replaced by hornblende but relict cores survive especially in plagioclase-poor rocks. The compositions determined range from Wo46En63Fs5 (at Roundstone, Cashel and other bodies in the main intrusive complex is F076-90 with a very strong concentration at F090-92). The most iron-rich grains determined are F075 and thus there is comparatively limited iron-enrichment, probably because of the common crystallization of magnetite.

The clinopyroxenes are slightly but significantly richer in Ca than those crystallized from typical tholeiitic magmas (e.g., En30-43 at En95-40), and approach the high Ca values long known to occur in some distinctly alkaline suites (Murray 1954; Wilkinson 1956). Nevertheless, the lowest Al2O3, generally less than 2.5%, low TiO2 (<0.50%), high SiO2 (>51%) contents of the clinopyroxenes, together with the common coexistence of orthopyroxene makes it quite clear that the magma did not have alkaline affinities (Le Bas 1962; Deer et al. 1978). The high Ca of the Connemara clinopyroxenes almost certainly results from the high water content of the magma leading to depression of the liquidus and solids, a conclusion supported by the scarcity of exsolved orthopyroxene lamellae (Elsdon 1971) together with the abundant amphibolitization of the pyroxenes.

The orthopyroxenes show a wide range of composition, from En92 to En70 at Dawros (Bennett & Gibb 1983) and En63-62 at Currywongaun-Doughruagh (Kanaris-Sotiriou & Angus 1976), but compositions more magnesian than En45 are generally unusual; most range between En35 and En55; with the lower limit (below En00) remaining to be determined. Nevertheless the absence of inverted pigeonite even in compositions near En00 implies that the temperature of crystallization of the magma was unusually depressed relative to the orthorhombic—monoclinic pyroxene inversion curve and the most likely cause of this was the high water content of the magma.

The plagioclases, which are invariably partly saussuritized and sericitized, range from An00 (Leake 1964) to about An60 and compositions An60-90 are quite common. The extremely calcic compositions suggest crystallization under high pH2O which promotes enhanced An percentages in typical basaltic magma (Thy 1987).

The amphiboles (Table 1; BL1798, 1443, 1951, 830, 931) are original igneous hornblendes ranging from tschermakitic, pargasitic, and magnesio-hastingsitic, hornblende to magnesio-hornblende using the nomenclature of Leake (1978). Often significant is the enrichment in K and OH, with the latter frequently exceeding the commonly assumed 2.0 OH per 24 (O, OH) and resulting in cation totals of c. 15.3 instead of the more usually supposed 15.5. These features suggest a basic magma unusually rich in K and water. Fe3+ is often 25–33% of the total iron which indicates a rather oxidized magma, a conclusion supported by the common presence of significant amounts of magnetite. Metamorphic replacements of orthopyroxene by anthophyllite, of clinopyroxene by tremolite—actinolite and of pyroxene plus plagioclase by actinolitic of magnesio-hornblende are usual, especially in amphibole vein networks and in the peripheries of basic agmatic masses broken off by intruding gneiss (Table 1, BL 1396). Gabbro injected by K-feldspar granitic gneiss can develop K-rich hornblende demonstrating late, postmagmatic (with respect to the gabbro) crystallization (Table 1, BL 679). In short, the amphiboles range from igneous megacrysts through late-stage igneous to metamorphic types.

Biotite, sometimes grown along the amphibole cleavages, together with sulphides,apatite and small amounts of late replacive quartz are widespread. Some samples contain up to 10% of ilmenite plus magnetite.

Orthogneisses

In terms of internationally agreed nomenclature (Streckeisen 1976) these gneisses range from quartz diorite through tonalite, granodiorite and granite to alkali granite but also include some trondhjemite and are unusually quartz-rich, a fact first emphasized by Benjamin (1968). There is complete gradation between all these varieties and it is convenient to consider the spectrum of orthogneisses under three headings which in order of intrusion are hornblende quartz diorite gneiss, hornblende-free quartz diorite gneiss and K-feldspar gneiss. K-feldspar can occur in any of the quartz diorite gneisses but an arbitrary minimum of 20% is taken as the lower limit of the K-feldspar gneiss, which therefore is usually granitic in composition.

Hornblende quartz diorite gneiss is formed of roughly equal proportions of green hornblende, plagioclase An60-40 and quartz with lesser biotite and a grain size of 1–5 mm. It is both intimately associated with the metagabbros and quite separate. Some varieties contain augite relics inside the hornblende, others have variable contents of K-feldspar, and in the latter rocks amphibole may form up to 1 cm poikilitic crystals of K-rich hornblende (Table 1, BL 500, 652). Apatite, titanite, zircon, orthite and iron ore are accessory minerals. Quartz and K-feldspar commonly corrode the plagioclase which is heavily saussuritized and sericitized. The hornblende-free varieties are similar but have a more sodic plagioclase, typically An35-40. They grade into trondhjemites or K-feldspar gneisses and are not intimately associated with the metagabbros although, like all the gneisses, they disrupt the metagabbros. The K-feldspar gneisses contain microcline (20–60%), quartz (20–40%), andesine (10–30%) and up to 10% biotite 2–6 mm in grain diameter with accessory apatite, zircon, magnetite, pyrite and zoned orthite. Fine grained K-feldspar-rich aplites,
sometimes extending from aplopegmatite patches are common in and near K-feldspar gneiss.

The orthogonises invariably inject, break up or enclose fragments of metagabbro and are clearly later than the metagabbros. The gneisses were emplaced during strong F₃ tectonic movements which resulted in a syntectonic foliation, drawing out of Dalradian countryrock xenoliths and intense disruption of the earlier metagabbros, as clearly brought out both in individual outcrops and in the overall mapped distribution of metagabbro (Figs 1 and 2). The foliation in the gneisses is usually free of small folds and is weakest in massive K-feldspar-rich granite patches which are especially well developed in the Cashel and Shannavara districts e.g. Lettershinna Hill (Leake 1970a; Jagger et al. 1988). This suggests the crystallization of the K-feldspar gneiss was last in the gneiss sequence while the injection of K-feldspar and hornblende-free quartz diorite into the hornblendic variety identifies the latter as the earliest gneiss.

There is no regular distribution of gneiss types within the intrusive complex in the manner commonly found in zoned diorite, granodiorite or granite plutons, but K-feldspar gneiss is rare west of Cashel whereas it is extremely common within and to the east of the Cashel district. Typically layers of different orthogonises lie next to each other enclosing fragments of metagabbros and sheets of country rock xenoliths, often over 1 km long, forming leasoid shapes. Where K-feldspar gneiss adjoins quartz diorite gneiss there may be a gradation to K-feldspar-bearing quartz diorite gneiss, and K-feldspar porphyroblasts suggest K-feldspathization has sometimes occurred. Clearly the distribution of the different gneisses and metagabbros is inconsistent with fractionation in situ, but is consistent with injection of different magma pulses into the Dalradian rocks and into earlier injections, with some marginal mixing and metasomatic activity. The last two processes are well demonstrated by the development of K-feldspar-rich quartz diorite containing potassian hornblende (e.g. BL 652, Table 1) where hornblended quartz diorite adjoins K-feldspar-rich granitic gneiss.

Petrogenesis

Geochemoical variations

The metagabbros display trends of chemical variation consistent with overall control by igneous fractionation, probably from one parent magma. Thus Niggli mg (= Mg/(Mg + Fe² + Fe³ + Mn)) falls with declining Cr, Ni and fm and increasing u, p, Rare Earth elements and alk (Fig. 6). The peridotites are among the earliest crystallized metagabbros, and the Ballyconnely amphibolites (Fig. 1) are the most differentiated and latest rocks. Figure 7 shows rather poor correlations of TiO₂, FeO, MgO, Al₂O₃ and K₂O with SiO₂ for the metagabbros but a significant decline of CaO and Niggli mg and a rise of Na₂O with increase in SiO₂. The scatter on the metagabbro plots is indicative of accumulative assemblages e.g. olivine-rich (high MgO low CaO, Al₂O₃, TiO₂ and Na₂O), plagioclase-rich (high CaO and Al₂O₃, low MgO and FeO) or magnetite (high FeO and TiO₂, low SiO₂). The highest Na₂O values of the Ballyconnely amphibolite might in part be influenced by shearing above the Mannin Thrust. However there are other influences than simple magmatic differentiation. Thus if the metagabbros from the Shannavara district, as studied by Senior (1973), are compared with those from Glinsk and Cashel, it is clear that they are chemically very similar (Fig. 5) except for Niggli k (i.e. mol K₂O/mol (K₂O + Na₂O)). The Shannavara metagabbros are systematically higher in K throughout the whole mg range which indicates that the enrichment in K is not due to magmatic differentiation but probably correlates with K metasomatism linked to the abundance of K feldspar granite gneiss in the Shannavara area rather than trondhjemitic. This is manifest in the partial replacement of hornblende by biotite growing along the amphibole cleavage. Accompanying the increase in K were Ba and Rb while Ca and sometimes Na may have been lost (Fig. 8). Similarly, throughout the whole complex, silicification of patches of metagabbro, especially in aamatises and when injected by quartz diorite gneiss, gives rise to quartz replacing hornblende or plagioclase. Most silicified samples have been excluded from the summary plots, but the process was studied in detail at Roundstone by Downs-Rose (1985) who showed that other elements such as P, Zr, Sr, Rb, Ba and light to middle REE (La–Gd) were added with the Si.

Overall the metagabbros clearly belong to a tholeitic magma based on an AFM plot (Fig. 9), the common occurrence of two pyroxenes, and the presence of small amounts of q, not ne, in the norm although a number of analysed metagabbros just spread from the tholeite fold into the edge of the alkaline fold on the K₂O + Na₂O versus SiO₂ plot of Irvine & Baragar (1971). There is a strong tendency for high-alumina basalt magma with about 40% of the available analyses possessing over 17% Al₂O₃ which is a feature recognized as common in arc basalts. It is important to note that although superficially the gneisses appear to follow on from the metagabbro fractionation trends this is not the correct interpretation if the data are examined carefully. Thus the Na₂O plot shows that the metagabbros fractionate with increasing SiO₂ to the Ballyconnely amphibolites with 3–6% Na₂O, whereas the gneisses form a completely different trend, and a similar contrast occurs with TiO₂. The metagabbro CaO trend at SiO₂ values above 50% parallels at a lower level the gneiss trend rather than abutting it. Likewise, in the Niggli si versus mg plot (Fig. 10), the gneisses clearly do not fractionate from the end differentiate of the metagabbro which is the Ballyconnely amphibolite. Cr and Ni plots confirm this interpretation as there is substantial overlap of the late, low Ni and low Cr-bearing metagabbro fractions with the gneisses whereby the Ballyconnely amphibolites reach much lower values than a great many of the gneisses (Figs 10 and 11). There are distinctly different trends of variation for the metagabbros and gneisses which are brought out by Figs 7, 9 and 11 and the si–mg plot of Fig. 10.

The gneisses as a whole show calc-alkaline (not tholeiitic) differentiation trends similar to those determined for the classical 'Caledonian' igneous suite of Scotland by Nockolds & Mitchell (1948) and Nockolds & Allen (1953). Figures 7 and 9 show that there is a clear fractionation trend from the hornblended quartz diorite gneisses through the hornblende-free varieties to the K-feldspar and trondhjemitic gneiss with only the K₂O showing great scatter at high SiO₂ contents. This reflects the K-rich and K-poor nature of the K-feldspar and trondhjemitic gneisses, with many intermediate samples having low to moderate contents of K-feldspar. The existence of trondhjemitic and K-feldspar gneisses does not favour in situ fractionation, which would be expected to give a more uniform end-stage magma, but
favours injection of different magma batches which variably mixed in the complex.

Moreover, the distribution of the metagabbros and gneisses shows (Figs 1 and 2) that the latter cross-cut and inject the former in a manner most compatible with separate injections into the Connemara complex. The existence of numerous metasedimentary layers within the complex, and the arrangement of the different magmatic members, which is not systematic from metagabbro through quartz diorite gneiss to K-feldspar granitic gneiss, does not agree with significant igneous fractionation at the level now exposed.

The distribution of the Rare Earth elements (REE) in the complex is summarized in Fig. 12 based on Downs-Rose (1985). There is small, but significant, increase in REE with

Fig. 6. Plots of Niggli parameters and trace elements (in ppm) against Niggli mg for 44 metagabbros from Cashel (Leake 1958) and Glinsk (Harvey 1967) which plot within the field outlined. 19 metagabbros from Shannavara (squares) confirm the same trends except for Niggli $k(=\text{mol K}_2\text{O/mol (K}_2\text{O + Na}_2\text{O)})$ which is systematically higher in the Shannavara samples. La, Ce, Ga and Zn values for the Shannavara samples only (Senior 1973).
fractionation of the metagabbros, the latest differentiates, the Ballyconneely amphibolites, having a narrow range of variation with generally the highest REE contents. There is a slight light REE (LREE) enrichment with the normalized La/Lu ratio (i.e. $^{*}\text{La}/^{*}\text{Lu}$) being generally in the range 1.2 to 4. The Eu anomalies vary from slightly negative to strongly positive but most metagabbros have a very small, generally insignificant, positive anomaly which suggests that the magma was sufficiently oxidized that Eu$^{2+}$ substitution into plagioclase was not important. The overall pattern is similar to that of many tholeiitic to high-alumina or calc alkaline arc basalts (e.g. Kay et al. 1982; Gromet & Silver 1987).

The quartz diorite gneisses have a different REE pattern...
Fig. 7 cont.
from the metagabbros, being strongly LREE enriched with typically \(^{\text{La}}/^{\text{Lu}}\) values of 5–15 (Fig. 12). They grade into the K-feldspar granitic gneiss which has an even more pronounced LREE enrichment with \(^{\text{La}}/^{\text{Lu}}\) in the range 15–60. All gneiss varieties have a range of Eu anomalies from negative to positive.

Although there are differences between the metagabbro and gneiss patterns, the lowest silica gneisses (54–56% SiO\(_2\)) overlap in their REE patterns with the most LREE enriched metagabbros, and the overall picture of variable Eu anomalies and variable LREE enrichment is similar to the patterns of a great many calc-alkaline magmatic arc and batholithic rocks (e.g. Arth et al. 1988; Henderson 1983; Snoke et al. 1981). The patterns are consistent with either a mixing or fractionation relationship between the gabbros and the gneisses. As typical post-Archaean metasediments, including Dalradian rocks, exhibit a similar LREE-enriched pattern, assimilation of such metasediments would promote the strong LREE enrichment but it is entirely feasible that the REE patterns are essentially those of a primary tholeiitic magma initially enriched in LREE.

Gromet & Silver (1987) modelled the production of LREE-enriched tonalite magma by 30% partial melting of tholeiitic to high alumina basalt at high pressure, while the formation of arc basalt is generally accepted as partial melting of the mantle wedge under the influence of water released from subducted oceanic crust (Wyllie 1984; Plank & Langmuir 1988).

**Hornblende**

A major question is the origin of the metagabbro hornblende which partially replaced both pyroxene and plagioclase. The evidence is clear that it is late magmatic to metamorphic in crystallization and was not a primary fractionating igneous mineral. Thus an AFM plot of the metagabbros (Fig. 9) shows a clear trend away from the position of olivine and pyroxenes, using the range of compositions determined in the Connemara metagabbros, but not away from the range of analysed hornblendes until the quartz diorite gneisses formed. Hornblende occurs on the end of the metagabbro tholeiite trend. Likewise log-log plots of TiO\(_2\) and Zr (Fig. 12) show that olivine and, or pyroxenes, dominated the mafic fractionation of these elements with some metagabbro compositions being influenced by the common modal magnetite but hornblende apparently having little influence. Similarly Keeling (1981) showed by means of the CMAS plot (O’Hara 1976), using a range of analysed metagabbro minerals, that hornblende could not have been a significant fractionating phase. This was further confirmed by the flat pattern of chondrite-normalized heavy to middle Rare Earth element (*HREE to *MREE) plots which is inconsistent with substantial hornblende fractionation from the magma (Fig. 12). Finally Jenkin (1988) showed that the \(\delta^D\) and \(\delta^{18}O\) values of definite subscluidus-grown hornblendes in the metagabbros are the same as in the ‘magmatic’ hornblende, which suggests that all the amphiboles crystallized from similar late-stage magmatic fluids and range from late magmatic to

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Fig. 8. Plots of Connemara metagabbros demonstrating the K, Ba and Rb-richer nature of the Shannavara metagabbros compared to metagabbros from elsewhere in Connemara which are not so intimately associated with K-feldspar granitic gneiss.
auto-metamorphic, the fractionation of the metagabbro magma being accomplished by other minerals. The crystallization of hornblende is therefore ascribed to the high water content of the magma. The fact that the K-Ar age of late magmatic hornblende from the Cashel-Lough Wheeler intrusion is 486 ± 9 Ma (Elias et al. 1988) while the same hand specimen yields zircon with a Pb–Pb age of 490 ± 1 Ma (Jagger et al. 1988) suggests that this hornblende must have grown as part of the magmatic episode and is not an entirely later superimposed effect.

It is clear however that the hornblende grown peripherally inwards into metagabbro fragments in agmatite, the hornblende grown around veins of quartz diorite or K-feldspar gneiss injections into metagabbro, and the actinolite-tremolite replacements of pyroxenite layers, are metamorphic even if immediately post-magmatic amphibole growth passed into metamorphic growth.

The hornblende in the orthogneisses is clearly entirely of igneous origin, and the high K₂O (1.40–2.00 wt %) content of the amphibole is directly related to the amount of K-feldspar in the gneiss. The AFM plot (Fig. 8) shows the gneisses fractionating away from the hornblende field. The distribution of the gneisses on the TiO₂ & Y–Zr plot (Fig. 13) is ambiguous as regards hornblende fractionation presumably because other minerals than hornblende such as zircon, biotite and very large modal contents of feldspar, influence the plot and the affect of the relatively small proportion of hornblende is hidden. The REE patterns of the gneisses are overall convex downwards which is indicative of some MREE depletion which would be consistent with hornblende fractionation (Hanson 1980).

Isotopic evidence

Jagger (1985) showed that the initial $^{87}$Sr/$^{86}$Sr ratios of the metagabbros at 490 Ma are never below 0.708, and this value is obtained uniformly from the Dawros peridotite, the Roundstone intrusion (which is several kilometres from any metasediment) and the centre of the Cashel intrusion. The metagabbro magma had therefore an unusually high $^{87}$Sr/$^{86}$Sr ratio for a basaltic magma which suggests either an enriched mantle source or significant crustal contamination before emplacement. Samples from the edge of the Cashel metagabbro, which contain visible metasedimentary xenoliths in all stages of solution, invariably yield initial $^{87}$Sr/$^{86}$Sr ratios higher than 0.708 at 490 Ma, ranging up to 0.714 (Fig. 14). This is consistent with the assimilation of Connemara Dalradian metasediment which Jagger (1985) has shown typically had $^{87}$Sr/$^{86}$Sr at 490 ma of 0.716 to 0.727.

Jagger (1985) also showed that the Cashel metagabbros without xenoliths had $^{143}$Nd/$^{144}$Nd ratios of 0.5116 to 0.5118 at 490 Ma, the metasediment contaminated metagabbros have very slightly lower ratios (0.5115 to 0.5116) whereas the metasediments range from 0.5111 to 0.5114. An eSr–eNd plot (Fig. 15) suggests that the non-xenolithic metagabbros had suffered some crustal contamination before emplacement into the present metasedimentary envelope. It is unlikely to be metasediment assimilation at the exposed level of erosion because of the distance from any metasediment shown by some of the non-xenolithic metagabbros. Figure 15 also shows that it is unlikely that Cambrian–Ordovician seawater was a significant circulating fluid responsible for the Sr–Nd contamination, as most of
Fig. 10. Plot of Niggli mg against Si, Ni and Cr ppm for metagabbros, Ballyconneely amphibolites and gneisses.
Fig. 11. Plot of SiO$_2$ wt % against Ni and Cr ppm for the Connemara metagabbros and gneisses.
the samples of both metagabbros and gneisses have too high εSr and too low εNd. This is confirmed by the δ¹⁸O and δD studies of Jenkin (1988).

Both Jagger (1985) and Jenkin (1988) have concluded from δ¹⁸O studies of the Cashel metagabbro (typically δ¹⁸O 7 to 10%) that the magma (calculated δ¹⁸O c. 7.0%) was enriched in ¹⁸O before intrusion and this enrichment was most probably the result of assimilating metasediment—possibly Dalradian metasediment—at depth and was quite distinct from the evident results of assimilating metasediment at the exposed level of erosion. In particular Jagger (1985) showed that there was no correlation of δ¹⁸O and (8⁷Sr/⁸⁶Sr)₀₀. Jenkin (1988) has also shown that the magmatic hornblendes in the metagabbro were crystallized from a magma with δD = −70 ± 5‰ and that much of the water in the magma was probably crustally derived, putatively from the assimilation of Dalradian metasediment or possibly an amphibolitic Lewisian-like basement. It is not possible at present to identify or exclude specifically a contribution of water derived from a subducting slab of oceanic crust.

Although the gneisses do not appear to be the differentiation products from the crystallization of the metagabbros, there is nevertheless a close genetic relationship between the magmas which produced the metagabbro and the gneisses. This is well brought out by the constant mutual association of the two suites and the similar range of initial ⁸⁷Sr/⁸⁶Sr ratios at 490 Ma extending from 0.708 to 0.715 within both suites (Figs 14 and 15). Over 20 years ago Leggo et al. (1966) demonstrated that closely geographically associated K-feldspar gneisses did not yield a Rb–Sr isochron, implying that either different samples had variable initial ⁸⁷Sr/⁸⁶Sr ratios or that the rocks had been variably ‘reset’ by later events or that both possibilities were true. It is still unclear what is the cause of this variation. Jagger (1985) identified two parallel isochrons, a lower one comprising nine samples of gneisses and nine samples of metagabbros giving an intercept of 0.709874 ± 0.00008 (MSWD 31) and an age of 517 ± 8 Ma or 462 ± 28 Ma if the gneiss samples alone are included, and an upper isochron, composed of 24 gneiss samples which gave an intercept of 0.71240 ± 0.0035 (MSWD 137) and an age of 508 ± 30 Ma (Fig. 16). Ages are calculated with λ⁸⁷Rb 1.42 × 10⁻¹⁰a⁻¹. All these ages overlap or are close to the Pb–Pb zircon age of the metagabbro of 490 Ma (Jagger et al. 1988) and might result from mixing of slightly inhomogeneous magmas. Geographically however, closely associated samples (tens of metres apart) fall on different isochrons with no intermediate samples being identified. The fact that the chlorite and epidote in the metagabbros and gneisses are of post-magmatic generation, possibly much later according to δD and δD values (Jenkin 1988), raises the prospect of late fluid disturbance of the Rb–Sr systems, but leaves unresolved the time when this may have taken place or the reason for the dual distribution of the gneiss samples.

Jagger et al. (1988) have shown that the K-feldspar gneiss at Cashel contains zircons of quite different

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**Fig. 12.** Representative normalized Rare Earth Element ranges of the metagabbros, quartz diorite gneisses and K-feldspar granitic gneisses from the Roundstone area. The metagabbros are divided into three broad fractionation stages with the latest being the Ballyconnely amphibolites. Data from Downs-Rose (1985) based on 40 rock samples, normalized to Nakamura (1976) values.
morphology from the primary igneous ones in the metagabbro. The gneiss zircons yield a lower intercept age of $454 \pm 14$ Ma and project back to a Proterozoic pre-history of $1807 \pm 150$ Ma. This demonstrates that the gneisses contain variable contents of Proterozoic pre-cursors and are not solely of 490 Ma igneous crystallization; crustal contamination below the present level of exposure is involved.

![Log-log plots of TiO$_2$ wt % and Y ppm against Zr ppm for representative Connemara metagabbros and orthogneisses.](image)

Fig. 13. Log-log plots of TiO$_2$ wt % and Y ppm against Zr ppm for representative Connemara metagabbros and orthogneisses.

![Histograms showing the variation in initial ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios at 490 Ma for the Connemara metagabbros and orthogneisses. Data from Jagger (1985).](image)

Fig. 14. Histograms showing the variation in initial ($^{87}\text{Sr}/^{86}\text{Sr}$) ratios at 490 Ma for the Connemara metagabbros and orthogneisses. Data from Jagger (1985).

![Plot of $\varepsilon_{\text{Nd}}$ and $\varepsilon_{\text{Sr}}$ at 490 Ma for the Connemara metagabbros, orthogneisses and Dalradian metasediments. Data from Jagger (1985).](image)

Fig. 15. Plot of $\varepsilon_{\text{Nd}}$ and $\varepsilon_{\text{Sr}}$ at 490 Ma for the Connemara metagabbros, orthogneisses and Dalradian metasediments. Data from Jagger (1985).
Pidgeon (1969) showed that the Dalradian rocks contain detrital zircons with an original age of crystallization of 1300–1700 Ma, so it is possible that the dissolved crust was either Dalradian or older Proterozoic basement.

In conclusion the isotopic evidence does not rule out derivation of a mantle-derived magma from an enriched mantle source but that alone is insufficient to explain the mineralogical, chemical and isotopic picture. Substantial crustal involvement is essential to explain the relict zircons, and the O, D, Sr and Nd evidence. The complex has an early tholeiitic to high alumina light REE-enriched gabbroic component and a slightly later calc-alkaline component, and gneisses were derived by crystal fractionation from a deeper, unexposed magma chamber in which gabbroic magma differentiated and assimilated country rock. The fractionation was not in the chamber exposed at present. Whether the trondhjemites represent mobilized restite out of which K-feldspar has been melted, or whether they represent the fractionation products of a separate magma chamber from the K-feldspar granitic material, remains to be determined by detailed isotopic studies of other systems such as Pb.

Structure of the complex

The occurrence of talc serpentinite and rare peridotite nodules along the tectonized northern edge of the complex together with the fractionation sequence deduced at Cashel, provide evidence that the northern contact was originally close to the bottom of the metagabbro intrusion and the Ballyconneely amphibolite, now inverted, is clearly the latest fraction. This is demonstrated not only by the Ballyconneely amphibolite analyses plotting at the end of the metagabbro geochemical trends (Figs 7 and 10) but also by the changes in chemical composition across the thickness of the amphibolite. There is a general decline in Ni, Cr, normative An percentage and Niggli mg (Fig. 17) from the metagabbro, through the variably sheared transition zone to the Ballyconneely amphibolite and through the amphibolite to the basai Mannin Thrust (Leake 1970b; Singh 1984). The inversion may have been connected with the early movements on the Mannin thrust, and these probably accompanied the injections of the orthogneiss imposing the ubiquitous strong foliation and causing the disruption of the metagabbro by synmagmatic movements. Tectonic movements must however have taken place during the metagabbro crystallization, as the complex relationships entirely within the metagabbros, seen for instance at Roundstone (Bremner & Leake 1980), must in part precede the gneiss injections. These gneiss injections forced apart the northern edge of the Roundstone body from the metasediments to the north.

Judging from the flat nature of the metagabbro from east of Slyne Head to east of Glinsk and down to the south at least as far as Mile Rock (Fig. 1), a major part of the body was flat-lying before the intrusion of the Galway Granite destroyed most of the complex. Chemical traverses show that in addition to the Ballyconneely amphibolites, the Glinsk metagabbros (Harvey 1967) and the metagabbros west of Roundstone (Bremner & Leake 1980) are also inverted fractionation sequences so that a major part of the metagabbro is upside-down. Using the way-up evidence of rare gravity-graded layers, the cryptic variation of the pyroxenes and the fractionation trends of the rock series, the overall structure of the complex is shown schematically in Fig. 18.

As an example of a mid-crustal contaminated mantle intrusion, it is significant that Fig. 18 shows complex infolding of metasediment and intrusive rock with long prongs of Dalradian rock extending both up from the floor of the intrusion and down from the sides of the body.

Such geometries, when combined with the syntectonic nature of the complex, enable the assimilation and interaction of magma and country rock to be far more extensive than is possible with either a simple sheeted model or a globular intrusion. This reduces the difficulty of explaining the widely internally distributed inherited zircons and the crustally contaminated isotopic contents of many granitoid plutons, especially if the crust-magma interaction can be intimate and pervasive through the intrusion and not confined to the periphery of an intrusion of simple geometry.

Accepting the pressure estimates of Treloar (1981, 1985)

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**Fig. 16.** Plot of $^{87}$Rb/$^{86}$Sr against $^{87}$Sr/$^{86}$Sr for the Cashel metagabbros and gneisses showing how the gneisses plot on two nearly parallel isochrons (Jagger 1985).

**Fig. 17.** Plot of Niggli mg against distance above the Mannin Thrust expressed as a percentage of the thickness of the Ballyconneely amphibolite at the sample locality. This scale is necessary to overcome the varying thicknesses of the amphibolite in different localities around the domal structure.
THE CONNEMARA COMPLEX OF IRELAND

Quartz - diorite gneiss
Granitic gneiss
Metagabbro & Peridotite
Metasediment
Direction of younging in basic rocks

Fig. 18. Schematic profile through the western and central part of the Connemara metagabbro-gneiss complex. C, Cashel; R, Roundstone; S, Shannavara; M, Clifden; G, Glinsk. Localities on Fig. 1.

and Ahmed-Said & Leake (unpub.) of 4.5 ± 1 kbar for the hornfels indicates that about 18 km of cover has been stripped off so that the present level of exposure of the batholithic complex is likely to be towards the lower part of the original body rather than towards the top. This suggests that the flat metagabbro ‘bottom’ to the complex, with its underlying thrust and overlying calc-alkaline granitoid gneiss, might correspond to the interpreted thrust and reflective lower crust identified in deep seismic profiles as seen across the Cornubian batholith (Brooks et al. 1984; BIRPS & ECORS 1986).

Tectonic setting of the complex

The plate tectonic setting which matches best the Connemara intrusive complex is that of a magmatic arc at a continental margin above a subduction zone. The assemblage has great similarities with numerous hornblende- and very calcic plagioclase-bearing plutonic complexes occurring along the western margin of the Americas such as the amphibole- and anorthite-rich gabbers and olivine-pyroxene gabbro–norites of the Peninsular Ranges gabbers, California (Smith et al. 1983); the Bear Mountain igneous complex of the Klamath Mountains, California (Snoke et al. 1981) which has a sequence with early ultramafic and hornblende-plagioclase rocks, later diorites, hornblende-rich gabbers to diorite and then leucocratic rocks, chiefly tonalite and granodiorite; the Smartville intrusive complex of the northern Sierra Nevada with its hornblende gabbro pegmatites rich in calciic bytownite or anorthite (Beard & Day 1986, 1988); the quartz diorite, tonalite, granodiorite and granite of the Coast Range batholith, British Columbia (Arth et al. 1988) and many other parts of the magmatic arc of the western Americas. Some of these closely match the relations seen in the Connemara complex, particularly those of the gabbros of the Peninsula Ranges (Walawender & Smith 1980) where the plutons are multiple intrusions with heterogeneously distributed peridotite, anorthosite, troctolite, gabbronorite, norite, hornblende gabbro, sometimes with diorite and quartz diorite.

This implies generation of the magmas above a subduction zone under the SE continental edge of Laurentia. Subsequent major strike slip faulting which is generally agreed to have taken place (Dewey & Shackleton 1984; Hutton & Dewey 1986; Soper & Hutton 1984; Soper 1986; Hutton 1987), would have laterally displaced portions of the plutonic complexes into widely separated regions in a manner similar to that of the displaced terranes of the west coast of the United States and Canada.

It is significant that the southern edge of the Dalradian block of Connemara should be made of this igneous complex which is not present in the southwestern part of the Dalradian outcrop of western Scotland or northern Ireland. This suggests that there was a relationship between the emplacement of the intrusion and the displacement of Connemara relative to the main Dalradian outcrop. It may be relevant that recent studies have revealed the tectonic emplacement of the Aberdeenshire gabbros shortly after intrusion along major steeply dipping shear zones, probably during D3 of the regional deformation, at an estimated 481 ± 15 Ma (Ashcroft et al. 1984). The Connemara block is thought to have been displaced by a combination of major southward-thrusting with east to northeast strike-slip motion.
(Leake et al. 1983) from an original west or southwest extension of the main Dalradian outcrop across Ireland.

The REE patterns clearly distinguish the complex from the LREE-depleted Tremadoc– Arenig volcanic rocks of the Lough Nafooey area (Fig. 1) which are virtually synchronous in age (Ryan et al. 1980). This makes it most unlikely that the Lough Nafooey volcanic rocks were erupted anywhere geographically near the Connemara massif, although they were deposited in association with deep water cherts and probably in a back-arc basin (Ryan et al. 1980).

Because many plutonic rocks in magmatic arcs are accompanied by volcanic effusions of calc-alkaline andesites and basalts (Snake et al. 1981), it must be a possibility that volcanic rocks were formed above Connemara c. 490 Ma ago but have been completely stripped off by erosion. Plots of the gneisses on trace element discrimination diagrams for the tectonic setting of granitic rocks as formulated by Pearce of the gneisses on trace element discrimination diagrams for continent-island arc can be identified along the Appalachian, Appalachians, early Ordovician tonalitic to granodioritic pi. Melrose, Columbia, Occoquan, Georgetown, Port Deposit, Arden and most extensive of all, the Elkhatchee Quartz Diorite (Wones & Sinha 1988; Drummond pers. comm.). with these plutonic rocks are the volcanic suites of the James HSUC volcanics) and plutons of tonalite and granodiorite associated with the Bronson Hill anticlinorium.

Fragments of this Cambro-Ordovician continental arc or continent-island arc can be identified along the Appalachians and in Newfoundland. Thus in the central and southern Appalachians, early Ordovician tonalitic to granodioritic bodies constitute the intrusive complexes of Leatherwood, Melrose, Columbia, Occoquan, Georgetown, Port Deposit, Arden and most extensive of all, the Elkhatchee Quartz Diorite (Wones & Sinha 1988; Drummond pers. comm.). with these plutonic rocks are the volcanic suites of the James Run Formation (and correlated suites), well preserved in central Virginia (Pavlides 1981). There are many mafic plutons in the central and southern Appalachians but only the Baltimore complex has been studied in detail, dated precisely (U-Pb 490 ± 2 Ma) and demonstrated to involve extensive crustal contamination (Shaw & Wasserburg 1984) as part of the Cambro-Ordovician continental margin arc complex (Sinha & Hanan 1987). In New England, Lower and Middle Ordovician volcanic sequences (e.g. Ammonosuc volcanics) and plutons of tonalite and granodiorite associated with the Bronson Hill antcline form remnants of a magmatic arc stretching from Connecticut to Maine (Tracy et al. 1984; Wones & Sinha 1988).

In Newfoundland, especially in the Dunning zone central volcanic belt, there are both plutons and calc-alkaline non-opholithic volcanic rocks of Lower–Middle Ordovician age (Mattinson 1977; Kusky & Kidd 1984). Although the possible collision of island arcs with the SE edge of Laurentia must complicate modelling, the position of the Connemara metagabbro-gneiss complex on the southern side of the Dalradian exposure suggests a magmatic arc above a northwestward-dipping subduction zone. The metarhyolites of the Delaney Dome Formation under the Mannin Thrust must be older than 454 ± 11 Ma (Leake et al. 1984) and younger than the Dalradian rocks, and might therefore be part of the volcanism associated with the magmatic arc. Likewise the south Connemara putative Ordovician (Fig. 1) pillow lavas and breccias are probably a fragment of the fore-arc formed above the subduction zone.

Also in a general position near the southeast side of the Dalradian outcrop is the synkinematic Sieve Gamph tonalite–granodiorite–granite complex of the Ox Mountains, Mayo, Ireland dated at 477 ± 6 Ma by Rb–Sr whole rock studies (Pankhurst et al. 1976) and the Aberdeen gabbros, dated by the same method at 489 ± 17 Ma (Pankhurst 1970). The Connemara complex is among the best preserved and best studied plutonic remnants of a major Cambro–Ordovician magmatic arc.

References


Fig. 19. Plot of Rb ppm against Y + Nb ppm for the orthogneisses which, according to Pearce et al. (1984), identifies the samples as coming from a volcanic arc environment.


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LEGEND

METASEDIMENTS
- PELITE
- QUARTZITE
- MARBLY
- SEMIPELITE, IMPURE MARBLE & CALC SEDIMENT
- MOBILIZED OR PERMIXED METASEDIMENT

METAMORPHOSED BASIC ROCKS
- STRIPED AMPHIBOLITE
- METAGABBRO

ORTH- & PARA-GNEISSES
- MOST COMMONLY GRANITIZED METASEDIMENT
- QUARTZ-PLACIOCLASE-HORNBLENDE & BIOTITE GNEISS
- QUARTZ-PLACIOCLASE-HORNBLENDE-BIOTITE — K-FELDSPAR GNEISS
- QUARTZ-PLACIOCLASE-BIOTITE GNEISS
- K-FELDSPAR RICH GNEISS

ORTH- & PARA-GNEISSES
- K-FELDSPAR RICH GNEISS
- The ornament is combined with other gneiss ornaments to indicate moderate K-feldsparization

LATE INTRUSIVE ROCKS
- OUGHTERRARD GRANITE
- GALWAY GRANITE
- PORPHYRY DYKE
- FELSITE DYKE
- DOLERITE DYKE

SYMBOLS
- GEOLOGICAL BOUNDARY
- inferred boundary
- FAULT
- inferred fault
- DRIP & SOURCE OF MAIN FOLIATION SCHISTOSITY
- SPOT OF VERTICAL FOLIATION
- NO EXPOSURE

Fig. 2. Geology of the Shannavara district at the junction of the Connemara schists and the intrusive complex. The relationships of the quartz-feldspar-rich Dolerite dyke and metasediments (largely paragneisses), the orthogneisses and the metagabbro bodies are displayed with mobilized hornfels being associated with the metagabro. Mapping by Senior (1975) except for the western strip which is by Leake. This map exactly adorns that of the Cudden district published by Leake (1978b).
Fig. 3. Sketch map of the traces of the main fold axes (F3) in the Cashel and Shannavara districts and the distribution of metagabbro against Dalradian metasediment and as fragments in the orthogneiss.