1. Introduction

In many eclogite-bearing terranes of continental affinity, eclogite occurs as small pods or boudins surrounded by felsic or pelitic gneiss or schist that show low-pressure assemblages, ranging from greenschist- to granulite-facies (see, for example, Heinrich, 1982; Coleman & Wang, 1995). The close occurrence of such different metamorphic assemblages may be explained in three ways. First, it has been suggested that eclogite pods were tectonically emplaced into country rock that never experienced high-pressure conditions (Smith, 1988). Tectonic emplacement of high-density eclogite into low-density gneiss is, however, mechanically implausible and is generally not accepted (Cuthbert, Harvey & Carswell, 1983; Cuthbert & Carswell, 1990). In our study area (the Western Gneiss Region of Norway) there is no field evidence, such as steep shear zones adjacent to eclogite, to support this hypothesis (Krabbendam & Wain, 1997).

Secondly, the country rock experienced eclogite-facies conditions but behaved metastably, retaining pre-orogenic assemblages. Metastability at high pressure has been demonstrated in several terranes. In the Bergen Arcs, southwest Norway, eclogitization is restricted to shear zones and reaction fronts adjacent to fluid channels of various scales (Austrheim, 1987; Austrheim, Erambert & Engvik, 1997). Similar relationships are now being recognized in the Western Gneiss Region (Engvik, Austrheim & Andersen, 2000, and this paper). Outside the Caledonides, metastability at high pressure has been documented in the Zermatt–Saas Fee Zone (Wayte et al., 1989) and in the Sesia Zone (Koons, Rubie & Frueh-Green, 1987), both in the Alps.

Lastly, the country rock equilibrated at high-pressure conditions but eclogite-facies assemblages re-equilibrated extensively to low-pressure assemblages, whilst mafic eclogites retained their high-pressure assemblages (Griffin & Carswell, 1985; Cuthbert & Carswell, 1990). Based on work in the Adula Nappe in the Alps, Heinrich (1982) proposed a mechanism whereby retrogression from eclogite-facies assemblages is favoured in pelitic rocks, as it involves dehydration reactions that are crossed from the low-temperature side during decompression. Retrogression of mafic rocks, on the
other hand, requires fluid infiltration to produce amphibolite-facies assemblages. The mechanism of Heinrich (1982) is probably also applicable to quartzo-feldspathic gneisses, since felsic eclogite-facies assemblages contain significant amounts of hydrous minerals, such as zoisite and phengite (Austrheim & Griffin, 1985; Koons, Rubie & Frueh-Green, 1987; Black, Brothers & Yokoyama, 1988).

Whether country rocks in a high-pressure terrane equilibrated at high-pressure conditions (and subsequently retrogressed) or did not develop eclogite-facies assemblages has a number of metamorphic and tectonic implications. Firstly, a failure to recognize widespread metastability or extensive retrogression may lead to incorrect interpretations of the metamorphic, tectonic and geochronological evolution and of the tectono-stratigraphic architecture of a high-pressure terrane. Secondly, metamorphic reactions are not just the result of a particular tectonic evolution of an orogen, but may also play an active role during orogenesis (Austrheim, Erambert & Engvik, 1997). Extensive eclogitization is increasingly invoked in geodynamic modelling. For instance, Dewey, Ryan & Andersen (1993) proposed a model whereby eclogitization of an orogenic root can result in very thick (≥120 km) crust and hence explain ultrahigh-pressure metamorphism in the Western Gneiss Region. Le Pichon, Henry & Goffé (1997) describe a model where the eclogite to granulite transition may be responsible for the uplift of the Tibetan Plateau. On the basis of mass balance calculations and structural restorations of the Alps, Butler (1986) and Laubscher (1990) suggested that large masses of eclogitized continental crust had returned into the mantle underneath the Alps. To assess whether extensive eclogitization as modelled by these studies is plausible it is necessary to estimate the degree of eclogitization in former orogenic root zones with reasonable accuracy.

In this paper we present lithological, petrological and structural data of three kilometre-size bodies within the Western Gneiss Region in southwest Norway. The Flatraket, Ulvesund and Kråkenes bodies contain relics of igneous assemblages and three different metamorphic assemblages: granulite-, eclogite- and amphibolite-facies that occur in mafic, intermediate and felsic rocks. We describe the spatial and temporal relationships between the different assemblages and structures that show that the granulite-facies assemblages pre-date the eclogite-facies metamorphism. The data demonstrate that the bodies were low-strain zones and behaved metastably during the Caledonian high-pressure event. We compare the three bodies with the surrounding gneisses and suggest that they were subjected to similar pressure–temperature conditions during Caledonian time but responded differently to these conditions. These different responses can be explained by a difference in Pre-Caledonian metamorphic assemblages in different domains within the Western Gneiss Region.

An earlier paper (Krabbendam & Wain, 1997) describes in detail the quartzo-feldspathic gneisses surrounding these three bodies and focuses on the late-Caledonian evolution of this area. A detailed documentation of the mineral chemistry and pressure–temperature conditions recorded in the Flatraket Body is found in Wain (A. Wain, unpub. Ph.D. thesis, Univ. Oxford, 1998) and will be presented elsewhere (Wain, Waters & Austrheim, unpub. data). Here, we will focus on the essential field relationships, structures and mineralogy of all three bodies.

2. Geological setting

2.a. The Western Gneiss Region

The Western Gneiss Region is a large basement window in west Norway, overlain by a series of Caledonian nappes. The Western Gneiss Region is mainly composed of Proterozoic quartzo-feldspathic gneisses with broadly granodioritic to granitic compositions (Tucker, Krogh & Råheim, 1990) and minor anorthosite-bearing rocks. The gneiss surrounding the eclogite is predominantly quartzo-feldspathic gneisses with broadly granodioritic to granitic compositions (Tucker, Krogh & Råheim, 1990) and minor anorthosite, ultramafic rocks, metasediments and mafic rocks (see, for example, Bryhni, 1989), reworked during the Scandian phase of the Caledonian orogeny (see, for example, Kullerud, Torubbakken & Ilebekk, 1986). Eclogites occur in an area of some 25 000 km² (Griffin et al., 1985), with ultrahigh-pressure (coesite-bearing) eclogites occurring in the far northwest, in an area at least 100 km long but of unknown width (Smith, 1984, 1988; Wain, 1997). Most preserved eclogite-facies rocks are mafic, although evidence of felsic eclogite-facies rocks is increasingly being found (Wain, 1997; Engvik, Austrheim & Andersen, 2000). The gneiss surrounding the eclogite is predominantly amphibolite-facies grade (Bryhni & Andréasson, 1985; Andersen, Osmundsen & Jolivet, 1994; Krabbendam & Wain, 1997) although in several places granulite-facies assemblages have been recorded (Griffin et al., 1985; Straume & Austrheim, 1999).

The Scandian Phase of the Caledonian orogeny was responsible for (ultra)high-pressure metamorphism in the Western Gneiss Region and has been dated at 420–400 Ma (Griffin & Brueckner, 1980, 1985; Gebauer et al., 1985; Mørk & Mearns, 1986). Cooling ages in southwest Norway indicate rapid exhumation between c. 410 and 385 Ma (Berry et al., 1994; Andersen, 1998; Fossen & Dallmeyer, 1998). Exhumation took place by east–west extension. This extension resulted in strong non-coaxial deformation along the extensional Nordfjord-Sogn Detachment. Near-coaxial extensional to constrictional strain along granulite- and amphibolite-facies conditions occurred at structural deeper levels within the Western Gneiss Region (Andersen & Jamtveit, 1990; Krabbendam & Wain, 1997; Andersen, 1998; Krabbendam & Dewey, 1998; Straume & Austrheim, 1999).
2.b. Outer Nordfjord area

The outer Nordfjord area (Fig. 1) is situated in the northwestern part of the Western Gneiss Region. The bulk of the area is composed of layered, micaceous quartzo-feldspathic gneisses with about 10% mafic pods. In general, eclogites are predominantly mafic and are preserved as boudins within felsic gneisses. Other rock types in outer Nordfjord include thin layers of quartzite, anorthosite and ultramafic bodies (Bryhni, 1966).

Figure 1. Geological map of outer Nordfjord area, showing geological setting of the Kråkenes, Flatraket and Ulvesund bodies. Metamorphic zonation after Wain (1997); additional data after Bryhni (1966).
1966; Lappin, 1966; Krabbendam & Wain, 1997). Most quartzo-feldspathic gneisses equilibrated under amphibolite-facies conditions and were highly strained during late-Caledonian extension (Krabbendam & Wain, 1997; Krabbendam & Dewey, 1998). In the area north of Nordfjord, however, there are several kilometre-size bodies that contain felsic, intermediate and mafic rocks and experienced little or no Caledonian deformation. These bodies preserve either granulite-facies assemblages or igneous textures and minerals. Three such bodies have been studied in some detail and are the subject of this paper: the Flatraket, Ulvesund and Kråkenes bodies (Figs 2, 4, 5). These three bodies are bounded on all exposed sides by layered quartzo-feldspathic gneiss containing eclogite pods, typical of the Western Gneiss Region (Fig. 1). Their contacts are sub-parallel with the main extensional foliation of the enclosing gneisses (Figs 2, 4, 5). The Flatraket and Ulvesund bodies occur within the ‘mixed’ high-pressure–ultrahigh-pressure zone (Wain, 1997), with both high-pressure and ultrahigh-pressure eclogites occurring in the direct vicinity (Fig. 1). Coesite-eclogite pods occur structurally below and above the Flatraket Body (Fig. 2). Recent work by Austrheim & Engvik (2000) demonstrates that the Kråkenes Gabbro Body was affected by eclogite-facies metamorphism. No coesite-eclogites have, however, been observed on Vågsoy, so the relationship of the Kråkenes Body with the ultrahigh-pressure rocks is, as yet, unclear.

3. Lithologies and assemblages

Amphibolite, eclogite and granulite-facies assemblages were distinguished mainly on the basis of mineralogical and textural criteria. Clinopyroxene and garnet with distinct mineral chemistries occur in both granulite and eclogite-facies assemblages. In the following discussion, ‘augite’ refers to unaltered granulite-facies calcic clinopyroxene (<3% jadeite) and ‘omphacite’ refers to clinopyroxene compositions that have been partially reset (<10% jadeite) or have equilibrated under eclogite-facies conditions (~40% jadeite). In rocks where mineral chemistry has not been measured, the term clinopyroxene is used, and the facies association was determined from textural relationships.

3.a. Amphibolite-facies gneisses

The dominant rock type, comprising about 80% of the outer Nordfjord area (Fig. 1), is layered micaceous quartzo-feldspathic gneiss. Locally, kilometre-size bodies of relatively uniform granitic augen gneiss occur (Fig. 1). The gneisses have the amphibolite-facies assemblage of plagioclase + quartz + K-feldspar + biotite + epidote ± hornblende ± white mica ± sphene ± garnet. A well-developed foliation and lineation is defined by the amphibolite-facies assemblage, indicating pervasive deformation under late-Caledonian amphibolite-facies conditions (Krabbendam & Wain, 1997). Eclogite-facies assemblages are not commonly preserved in these gneisses.

3.b. Eclogite and eclogite-facies gneisses

Eclogite occurs throughout the quartzo-feldspathic gneisses as pods, usually less than 50 m across. These pods generally possess an amphibolite rim foliated parallel to the enclosing gneisses. The foliated amphibolite-facies rims and external amphibolite-facies gneisses show compatible pressure–temperature conditions, suggesting they both re-equilibrated during exhumation (A. Wain, unpub. Ph.D. thesis, Univ. Oxford, 1998). The layering and amphibolite-facies foliation of the enclosing gneisses commonly wraps eclogite pods, truncating eclogite-facies structures. Long tails of amphibolite stretch from the eclogite into the enclosing gneisses. In metre-scale pods, the core consists of the least retrogressed eclogite with increasing retrogression towards the margin. In larger (>10 m) mafic bodies, however, several ‘fresh’ eclogite zones occur, separated by a network of amphibolite-facies alteration and shear zones.

Eclogite-facies material also occurs within layered packages, up to 1 km thick, including mafic eclogite, eclogite-facies garnet-phengite gneiss and meta-anthorthosite (Wain, 1997). Both high-pressure (P~20–24 kbar) and ultrahigh-pressure eclogites (P≥28 kbar) occur in all settings (Wain, 1997). Felsic eclogite-facies mineralogies or textures are only preserved in amphibolite-facies low-strain zones associated with mafic eclogite pods, similar to observations of Engvik, Austrheim & Andersen (2000). In domains of amphibolite-facies high strain, the felsic eclogites have been recrystallized to foliated biotite–plagioclase–quartz gneiss with relict garnet (A. Wain, unpub. Ph.D. thesis, Univ. Oxford, 1998).

3.c. Megacrystic gneiss and mafic dykes in the Flatraket Body

The core of the Flatraket Body (Fig. 2) is mainly composed of weakly deformed gneiss of quartz-monzonitic composition. The rock, hereafter referred to as megacrystic gneiss, is characterized by large (3–10 cm) ovoidal megacrysts of K-feldspar (Bryhni, 1966; Lappin, 1966; Fig. 6a). Plagioclase (oligoclase–andesine) occurs as smaller ovoids (5–10 mm). The fine-grained matrix is composed of plagioclase, quartz, garnet, biotite and hornblende and/or augite. In weakly deformed gneiss, the mafic minerals (biotite, augite and hornblende) occur as irregular clusters, locally separated from plagioclase by coronas of garnet. Much of the megacrystic gneiss is sheared and has the amphibolite-facies assemblage of K-feldspar + plagioclase (oligoclase) + quartz + garnet + biotite ± hornblende ± zoisite (Table 1). However, some K-
Table 1. Mineral assemblages within the Flatraket, Ulvesund and Kråkenes bodies, separated by rock-type and state of deformation

<table>
<thead>
<tr>
<th>Rock type; state of deformation</th>
<th>Igneous</th>
<th>Granulite-facies</th>
<th>Eclogite-facies</th>
<th>Amphibolite-facies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flatraket Body</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Megacrystic gneiss, undeformed</td>
<td>Kfs megacrysts</td>
<td>Kfs + Pl + Grt + Qtz + Ilm + Bt ± Aug ± Hbl</td>
<td>–</td>
<td>Kfs + Pl + Qtz + Bt + Hbl ± Czo ± Ms</td>
</tr>
<tr>
<td>Megacrystic gneiss, sheared</td>
<td>Kfs megacrysts</td>
<td>Kfs ± Grt</td>
<td>–</td>
<td>Kfs + Pl + Qtz + Bt + Hbl ± Czo ± Ms</td>
</tr>
<tr>
<td>Layered garnetiferous gneiss, undeformed</td>
<td>–</td>
<td>Kfs + Qtz + Grt ± Aug ± Ilm</td>
<td>Qtz + Omp + Grt ± Rt</td>
<td>Kfs + Pl + Qtz + Bt + Hbl ± Czo ± Ms</td>
</tr>
<tr>
<td>Layered garnetiferous gneiss, deformed</td>
<td>–</td>
<td>Kfs + Pl + Aug + Grt ± Qtz ± Ilm</td>
<td>Qtz + Zo + Omp ± Rt</td>
<td>Kfs + Pl + Qtz + Bt + Hbl ± Czo ± Ms</td>
</tr>
<tr>
<td>Intermediate gneiss</td>
<td>± Opx?</td>
<td>Pl + Grt + Aug + Qtz + Ilm ± Bt ± Hbl ± Kfs</td>
<td>Qtz + Cpx + Grt ± Zo ± Ky ± Rt</td>
<td>Kfs + Qtz + Pl + Hbl + Bt ± Grt</td>
</tr>
<tr>
<td>Mafic dykes, layers and pods, undeformed</td>
<td>Pl + Cpx ± Bt</td>
<td>Grt + Aug + Pl ± Bt ± Ilm</td>
<td>Grt + Omp ± Qtz ± Zo ± Ky ± Ph ± Rt</td>
<td>Amp, Pl, Bt, Ep (symplectite)</td>
</tr>
<tr>
<td>Mafic dykes, layers and pods, deformed</td>
<td>± Opx?</td>
<td>Pl + Grt + Aug ± Opx ± Bt ± Ilm ± Kfs</td>
<td>–</td>
<td>Amp, Pl, Bt, Ep (symplectite)</td>
</tr>
<tr>
<td>Meta-anorthosite, undeformed</td>
<td>–</td>
<td>Pl?</td>
<td>Zo + Ky + Qtz + Ph + Grt ± Omp ± Rt</td>
<td>Pl + Qtz + Amp + Czo ± Mrg ± Kfs</td>
</tr>
<tr>
<td>Meta-anorthosite, deformed</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Ulvesund Body</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Felsic gneiss, including megacrystic gneiss, undeformed</td>
<td>–</td>
<td>Kfs + Grt + Qtz ± Bt</td>
<td>Qtz + Ph ± Rt?</td>
<td>Kfs + Pl + Qtz + Bt + Ms + Ep</td>
</tr>
<tr>
<td>Felsic gneiss, including megacrystic gneiss, sheared</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Layered garnetiferous gneiss, undeformed</td>
<td>–</td>
<td>Qtz + Kfs + Grt + Cpx</td>
<td>–</td>
<td>Kfs + Pl + Qtz + Bt + Ms ± Hbl + Ep</td>
</tr>
<tr>
<td>Layered garnetiferous gneiss, deformed</td>
<td>–</td>
<td>Qtz + Kfs + Grt + Cpx</td>
<td>–</td>
<td>Kfs + Pl + Qtz + Hbl + Bt + Ep</td>
</tr>
<tr>
<td>Intermediate gneiss/pods, undeformed</td>
<td>–</td>
<td>Fsp + Grt + Cpx ± Qtz</td>
<td>Qtz + Zo + Grt + Cpx ± Rt</td>
<td>Qtz + Pl + Bt ± Ep ± Spn</td>
</tr>
<tr>
<td>Intermediate gneiss/pods, deformed</td>
<td>–</td>
<td>Kfs + Qtz + Grt ± Cpx ± Pl</td>
<td>Qtz + Zo + Grt + Cpx + Ky</td>
<td>Qtz + Pl + Bt ± Ep ± Grt</td>
</tr>
<tr>
<td>Mafic layers and pods, undeformed</td>
<td>–</td>
<td>Grt + Pl + Cpx ± Qtz</td>
<td>Grt + Omp ± Qtz ± Ph ± Zo</td>
<td>Hbl, Fsp, Bt, Ep, (symplectite)</td>
</tr>
<tr>
<td>Mafic layers and pods, deformed</td>
<td>–</td>
<td>–</td>
<td>Grt + Cpx ± Qtz ± Ph ± Zo</td>
<td>Hbl + Fsp + Bt ± Ep</td>
</tr>
<tr>
<td>Kråkenes Gabbro</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gabbro, undeformed</td>
<td>Pl + Cpx + Ol ± Bt</td>
<td>Opx + Grt coronas?</td>
<td>Grt + Omp*</td>
<td>Hbl coronas?</td>
</tr>
<tr>
<td>Gabbro, deformed</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Pl + Hbl + Bt + Grt ± Sp ± Ilm</td>
</tr>
<tr>
<td>Megacrystic gneiss</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Kfs + Pl + Qtz + Bt + Ms ± ZO ± Ky</td>
</tr>
</tbody>
</table>

feldspar, garnet and plagioclase appear to represent relics of an older granulite-facies assemblage and augites are locally pseudomorphed by amphibole.

Numerous mafic to intermediate dykes cut the megacrystic gneiss (Figs 2, 6a). Primary, intrusive contacts with the surrounding gneiss are commonly preserved although minor shearing along dyke margins is common. Some mafic and intermediate dykes preserve a granulite-facies assemblage of garnet + augite + plagioclase ± quartz ± K-feldspar ± biotite (Table 1, Fig. 7e), commonly with a well-defined granoblastic texture. Augite aggregates are commonly rimmed by garnet. In other dykes, the absence of plagioclase and the presence of the assemblage garnet + omphacite + quartz + zoisite ± rutile ± white mica indicates partial or complete equilibration at eclogite-facies conditions (Table 1). Several mafic dykes and pods are strongly altered with symplectite, very fine-grained feldspar and turbid clinopyroxene present. In these cases it is ambiguous whether the plagioclase and clinopyroxene are relics of a granulite-facies assemblage or if plagioclase is associated with retrogression from an eclogite-facies assemblage. The different assemblages are difficult to distinguish in the field and many dykes that superficially may look like eclogite are mafic granulites (cf. Bryhni, 1966).

3.d. Meta-anorthosite and eclogite near Seljeneset

On the eastern side of the Flatraket Body, meta-anorthosite occurs, interlayered with eclogite, studied in some detail by Cotkin, Valley & Essene (1988) and Cotkin (1997). The meta-anorthosite is layered with pale-grey and pale-green layers and commonly contains pink or white clots about 1 cm across. The pale layers are predominantly composed of plagioclase with granoblastic texture, zoisite, quartz, blue-green amphibole and accessory biotite and rutile. The pale-green layers contain the same minerals but more amphibole and zoisite and less plagioclase. Thin layers of almost pure zoisite also occur. The pink clots are aggregates of coarse margarite in a very fine matrix of symplectitic feldspar and micas. The white clots are aggregates of quartz and plagioclase, free of other minerals. The current assemblage of plagioclase + quartz + amphibole + zoisite + margarite ± biotite ± K-feldspar suggests amphibolite-facies equilibration. Cotkin, Valley & Essene (1988) suggested that the current assemblage evolved from an eclogite assemblage of kyanite + zoisite + quartz; the possibility of metastability at eclogite-facies conditions was, however, not discussed.

3.e. The margins of the Flatraket Body

The margin of the Flatraket Body is best exposed along a stream section on the western side. To the west and south, the megacrystic gneiss is bounded by layered garnetiferous felsic gneiss that lacks K-feldspar megacrysts (Figs 2, 6a). Primary, intrusive contacts with the surrounding gneiss are commonly preserved although minor shearing along dyke margins is common. Some mafic and intermediate dykes preserve a granulite-facies assemblage of garnet + augite + plagioclase ± quartz ± K-feldspar ± biotite (Table 1, Fig. 7e), commonly with a well-defined granoblastic texture. Augite aggregates are commonly rimmed by garnet. In other dykes, the absence of plagioclase and the...
Pre-Caledonian granulite and gabbro enclaves in the Western Gneiss Region, Norway

Figure 3. Geological map of the western contact zone of the Flatraket Body. For location see Figure 2.
domains represent a retrogressive transition towards an amphibolite-facies assemblage from an earlier granulite-facies assemblage. Generally, the amount of very fine-grained material increases with stronger subsequent deformation so that in high-strain zones most feldspar is extremely fine-grained with finely dispersed mica and zoisite. At the highest strains this developed into a mylonitic fabric, with a pervasive amphibolite-facies assemblage of plagioclase (oligoclase) + quartz + biotite (2) ± K-feldspar ± hornblende ± epidote ± white mica (Table 1).

Along the stream section, several 10–30 cm wide mafic layers occur concordant with the compositional layering of the surrounding felsic garnetiferous gneiss (Figs 3, 6b). The centre of some layers contains an eclogite-facies assemblage of garnet + omphacite + quartz ± rutile + phengite. Towards the rim, increasing retrogression to a symplectite of feldspar + green amphibole + biotite is responsible for the dark, green-coloured margin (Fig. 6b, Table 1). Other mafic layers have a granulate-facies assemblage of garnet + augite + plagioclase (andesine) in the centre, but have an eclogite-facies assemblage of garnet + omphacite + quartz ± rutile developed along the margins or in narrow zones within the layer.

Pods of dark-pink, fine-grained rock of dioritic to gabbroic composition occur in several places along the stream section. The largest of these pods, Pod 916 (Fig. 3), contains locally relics of an igneous texture with ophitic, lath-like plagioclase (Fig. 7b). Most of the pod, however, shows the granulate-facies assemblage garnet + clinopyroxene + plagioclase ± biotite, with a relict granoblastic texture and remnants of garnet coronas separating feldspar and clinopyroxene. This assemblage has been strongly affected by amphibolite-facies retrogression, as evidenced by turbid clinopyroxene and feldspar recrystallized to a very fine grain-size with very finely dispersed zoisite, biotite and hornblende needles. A sample from the margin of this pod contains medium to fine-grained garnet and clinopyroxene, in a matrix of fine omphacite + quartz + biotite + zoisite, but without any feldspar. This assemblage is interpreted as eclogite-facies. Thus, this mafic pod contains igneous, granulate-facies, eclogite-facies and amphibolite-facies assemblages. The eclogitization only affected the margin of the pod.

Near the first waterfall in the stream section (Fig. 3), a weakly deformed pod comprises white to pale-pink coronitic meta-anorthositic gneiss with large (~1 cm) garnet coronas. This pod contains a well-preserved granulate-facies assemblage of garnet + plagioclase (andesine) + augite ± K-feldspar ± biotite ± quartz with a well-developed granoblastic texture. Orthopyroxene occurs as armoured relics within coronas of augite and garnet. Garnet occurs preferentially along the contacts of plagioclase and ferro-magnesian minerals (Fig. 7d). Similar rocks occur in a road cut near the southern margin of the Flatraket Body.

Near the first waterfall, several narrow (~5–10 cm) felsic eclogite-facies shear zones occur (Fig. 3). The mylonitic matrix of these shear zones has the assemblage of kyanite + zoisite + quartz + phengite ± omphacite (Fig. 7f,g). Micro-lithons within the mylonite have a more ferro-magnesian composition and have the assemblage of garnet + omphacite ± quartz ± phengite. One of the shear zones deforms (and hence post-dates) the margins of the granulite-facies coronitic meta-anorthosite described in Section 3.d. The felsic eclogite-facies shear zones are generally associated with mafic layers that also possess a sheared eclogite-facies fabric.

In the drain that branches off the stream (Fig. 3), a trail of small (≤1 m) mafic eclogite pods and slivers occurs in a matrix of pale green, felsic to intermediate rock. In thin section, quartz + garnet + clinopyroxene ± rutile ± phengite suggest an eclogite-facies assemblage.

3.f. The Ulvesund Body

Most of the Ulvesund Body comprises medium fine-grained garnetiferous felsic gneiss, resembling the garnetiferous felsic gneiss in the Flatraket stream section. A finely spaced (1–4 mm) layering of alternating felsic and garnet + amphibole or pyroxene-rich layers is commonly present. Most of the felsic gneisses are deformed and contain amphibolite-facies assemblages (Table 1). This amphibolite-facies assemblage commonly occurs as a very fine-grained matrix surrounding coarse porphyroclasts of garnet ± K-feldspar ± clinopyroxene ± quartz (Fig. 7h). This is similar to textures of amphibolitized granulites in the Flatraket body, and so is interpreted as representing remnants of a granulate-facies assemblage. In some cases it is ambiguous, however, whether these porphyroclastic assemblages represent remnants of a granulate-facies assemblage or an eclogite-facies assemblage. On the west coast of Ulvesund, leucocratic patches and anastomosing zones occur, suggesting partial melting. Felsic gneiss with ovoidal K-feldspar megacrysts occurs throughout the Ulvesund Body (Fig. 4). In general, the megacrysts are more recrystallized and more intensely deformed than at Flatraket.

Mafic dykes or pods are less common than at Flatraket. Most mafic pods are small and have well-equilibrated assemblages of garnet + clinopyroxene ± quartz ± phengite ± rutile ± zoisite, which is interpreted as eclogite-facies. On Hanekammen (Fig. 4), some eclogite pods are particularly fresh; some have well-developed eclogite-facies fabrics, others appear undeformed. About 1 km north of Måløy, an eclogite contains a well-developed layering of garnet-rich and pyroxene/symplectite-rich layers. This eclogite layering is strongly folded. Locally, felsic rocks, closely associated with mafic eclogite, have assemblages of quartz + zoisite + white mica + garnet or quartz + white mica that are interpreted as eclogite-facies assemblages.
Bodies of medium- to fine-grained, dark-pink intermediate rocks, commonly associated with mafic rocks, occur on the summit of Hanekammen and on the west coast of Ulvesund (Fig. 4). These intermediate rocks preserve the best evidence of granulite-facies assemblages within the Ulvesund Body: garnet + augite + plagioclase ± K-feldspar ± quartz occur as coarse porphyroclasts, commonly with relict granoblastic textures, although fine-grained domains of feldspar + amphibole + biotite ± epidote/zoisite indicate that partial amphibolitization occurred in all rocks.

3.g. The Kråkenes Body

The core of the Kråkenes Body consists of a 250 m wide sheet of gabbro, bounded on either side by recrystallized megacrystic felsic gneiss (Fig. 5). Where undeformed, the gabbro at Kråkenes preserves an ophitic texture that is clearly visible in the field. Locally, 10–50 cm widely spaced igneous cumulate layering occurs; this layering dips 60–70° to the north-northeast. In these domains, the igneous assemblage is plagioclase + clinopyroxene + olivine ± biotite ± ilmenite. Plagioclase crystals show igneous (euhedral, lath-like) habit in a radial or ophitic texture (Fig. 7a).

Partial transition to metamorphic assemblages is evident from coronas in all samples studied (Table 1). Observed reaction textures include (Fig. 7a): garnet coronas around plagioclase; red biotite coronas...
around opaque minerals; sphene mantling rutile and/or ilmenite; fine fibrous radial orthopyroxene surrounding or replacing olivine or igneous clinopyroxene and thin garnet coronas, surrounding the above orthopyroxene coronas. The igneous clinopyroxene is coarse and commonly strongly turbid, whereas new-grown pyroxenes are clear but fine-grained. Locally, a third shell of hornblende ± biotite coronas surrounds garnet and orthopyroxene coronas, suggesting a multi-stage corona development. All samples with ophitic relics exhibit corona textures; all these samples are undeformed. Similar corona textures have been observed in meta-dolerites and meta-gabbros elsewhere in southwest Norway (Griffin & Heier, 1973; Mørk, 1985, 1986).

Within the gabbro, fractures occur that resemble pseudotachylite. In these fractures, euhedral garnet, low-Al orthopyroxene and omphacite have been observed (Austrheim & Engvik, 2000), suggesting that the Kråkenes gabbro experienced eclogite-facies conditions at pressures of 24–29 kbar and temperature of 670 °C (Austrheim & Engvik, 2000). The preservation of abundant igneous plagioclase, however, indicates that the body largely failed to equilibrate at eclogite-facies conditions.

To the south, a 100–200 m wide zone of strongly altered and hydrated meta-gabbro occurs. Here, the igneous and corona textures are obliterated by the growth of amphibolite-facies assemblages with hornblende, plagioclase, biotite, garnet and zoisite. All deformed meta-gabbro has been totally recrystallized to amphibolite-facies assemblages. Locally, however, total recrystallization occurred without deformation.

To the south, the meta-gabbro is bounded by felsic gneiss. In places, the margin of the felsic gneiss contains friable, schistose layers consisting predominantly of coarse biotite, indicating hydration under low-grade metamorphic conditions. Further south, the felsic gneiss becomes progressively more deformed with flattened relics of K-feldspar megacrysts, ultimately to give way to a layered gneiss, similar to gneisses elsewhere in the Western Gneiss Region, except for a higher content of K-feldspar. This transition is gradual over about 200 m. Within the felsic gneiss, a doleritic dyke occurs, now strongly altered but with relict ophitic textures similar to the main gabbro body. North of the gabbro, felsic megacrystic gneiss occurs, similar in appearance to the megacrystic gneiss at Flatraket, albeit more recrystallized at amphibolite facies. A narrow (~30 cm) shear zone separates the gabbro and the megacrystic gneiss. The lack of a strong mylonitic fabric in this shear zone suggests limited displacement implying that the gabbro and the megacrystic gneiss probably crystallized close to each other.

The Kråkenes gabbro has yielded a Sm–Nd age of 1258 ± 56 Ma (E. W. Mearns, unpub. Ph.D. thesis, Univ. Aberdeen, 1984, reported in Kullerud, Tørudbakken & Ilebekk, 1986). This age suggest that the gabbro is Mid-Proterozoic in age so that it was emplaced prior to the Caledonian high-pressure event. The gabbro underwent very little reaction under these conditions and behaved even more metastably than the meta-gabbro described by Mørk (1985, 1986). Whether or not the gabbro experienced granulite-facies conditions remains an open question.

Figure 6. Field photographs. (a) Poorly deformed megacystic gneiss (top) with mafic dyke, Flatraket Body. The dyke–gneiss contact is not deformed. Coastal outcrop southwest of Naveneset. Hammer is 40 cm long. (b) Mafic layers with pale eclogite-facies core and dark symplectitic margins (arrows), within garnetiferous layered gneiss with relics of granulite-facies assemblages. The folding and shearing of the layers is associated with late amphibolite-facies fabrics. Western contact zone of the Flatraket Body. Notebook is 20 cm long. Plan view, top to the south.
4. Structural analysis

4.a. Evidence for low strain

Within the pervasively deformed quartz-feldspathic gneisses of outer Nordfjord, low-strain zones are more exceptional than high-strain zones (Krabbendam & Wain, 1997). In the Kråkenes Gabbro, the absence of any strain is evident from the very good preservation of igneous cumulate layering, ophitic textures and coronas. Within the megacrystic gneiss at Kråkenes and Flatraket, low strain is indicated by the preservation of the near-spherical K-feldspar megacrysts. Many mafic dykes at Flatraket preserve near-original contacts, also indicating low strain.

4.b. Structures within the Flatraket Body

Within the Flatraket body, K-feldspar megacrysts are near-spherical in about 30% of the body, indicating low strain. Much of the megacrystic gneiss is weakly to moderately deformed, with K-feldspar megacrysts aspect ratios of about 1:2-3. Both L>S and S>L fabrics occur. The L>S fabric is subvertical in many places, whereas the S>L fabric is moderately to steeply east-dipping. The matrix surrounding the megacrysts shows a moderately developed amphibolite-facies foliation and it appears that the matrix has taken up more strain than the megacrysts themselves. These structures affect relatively large domains (up to 100 m across) in a homogeneous way and cross-cut the mafic dykes or are deflected around them.

In several places, distinct 1–2 m wide mylonite zones cross-cut the megacrystic gneiss and the older structures described above. These mylonite zones are characterized by a progressive flattening and rotation of megacrysts. In the centre of the mylonite zones, megacrysts are destroyed and replaced by a finely spaced (<1 mm) mylonitic layering and well-defined amphibolite-facies foliation. Most shear zones are sub-parallel to the boundary of the Flatraket Body and the dominant foliation outside the body. The lineations, however, are shallow north–northwest or south–southeast plunging, highly discordant to the dominant east–west plunging lineations outside the Flatraket Body (compare Fig. 8b and 8c).

Shear sense is best indicated by the progressive rotation of the shear fabric into the shear zone. Of the 20 shear zones where shear sense has been determined, 10 are dextral and 10 are sinistral. This suggests that the bulk strain regime was near-coaxial during the development of the mylonite zones, resulting in an anastomosing network of shear zones with opposite shear senses.

4.c. Structures in the Flatraket stream section

The stream section at Flatraket (Fig. 3) provides a well-exposed section from typical Western Gneiss Region quartz-feldspathic gneiss through a complicated transition zone to the megacrystic gneiss in the core of the Flatraket Body.

The quartz-feldspathic gneiss northeast of the drain (Fig. 3) and further outside the Flatraket Body shows an east dipping, well-developed finely spaced layering and parallel mica-foliations. The dominant lineation, defined by biotite ± epidote ± chlorite is down-dip to the east (Fig. 8c). Minor tight to isoclinal folds have axial surfaces parallel with the dominant foliation and fold axes with plunge directions varying between northeast to southeast. These structures were formed under (low) amphibolite-facies conditions and are similar to elsewhere in the outer Nordfjord area (Krabbendam & Wain, 1997; Krabbendam & Dewey, 1998).

The eclogite-facies shear zones near the first waterfall (described in Section 3.e, Fig. 7f) dip steeply to the east. Eclogite-facies lineations plunge gently (5–10°) to the north or south, highly discordant to the east-plunging amphibolite-facies lineations outside the Flatraket body (Fig. 8c).

Above the second waterfall (Fig. 3), clear overprinting relationships occur between two sets of planar structures (Fig. 6b). The older finely spaced layering, defined by modal variation in granulite-facies minerals, was probably formed during the granulite-facies event. Mafic layers with eclogite-facies assemblage in their centres (see Section 3.e) are parallel with this layering. Where younger deformation is at its lowest, the layering has an east–west strike and a moderate southerly dip (Fig. 3). The fine layering and the mafic layers are folded into open to close, north–south trending folds, with a steeply east dipping, amphibolite-facies axial planar fabric defined by hornblende and biotite. The limbs of these folds are strongly deformed and locally amphibolite-facies high-strain zones have obliterated the older layering (Fig. 6b).

4.d. Structures within and adjacent to the Ulvesund Body

Only the lower part of the Ulvesund Body is preserved; this part has a scoop-shaped geometry (Fig. 9). Planar structures inside the Ulvesund are represented by a finely spaced compositional layering in garnetiferous felsic gneiss and a poorly defined layer-parallel mineral fabric of probable granulite-facies grade. The mineral fabric cuts and deforms leucocratic melt patches, suggesting that partial melting in the garnetiferous felsic gneiss occurred before or coeval with granulite-facies metamorphism. Along the western shore of Ulvesund, the layering is folded by recumbent and upright folds. Locally, these folds have amphibolite-facies axial surface fabrics.

The felsic gneiss within the Ulvesund Body has, in general, been deformed and recrystallized to a higher degree than in the Flatraket Body, commonly with highly flattened and recrystallized megacrysts. On
Figure 7. For legend see facing page.
All rocks within the three bodies are of igneous origin. Planar structures (layering and foliations) are flatly oriented or gently inclined for a significant part of the body, sub-parallel to foliations outside the body. Lineations within the Ulvesund body, however, are consistently north–northwest or south–south–east oriented. This is highly discordant to the lineations outside the Ulvesund body. All studied contacts of the Ulvesund Body show evidence of intense deformation, with 10–50 m wide amphibolite-facies mylonite and ultramylonite zones. Highly non-cylindrical folds and sheath folds with amphibolite-facies axial planar fabrics are locally developed. Top-to-the-west shear sense indicators occur both north and south of the body. South of the body, the gneissic layering and amphibolite-facies foliation dip gently northwards, and east–west trending late-Caledonian folds have a northward vergence (Figs 4, 9). North of the body, these structures are mirrored with gently south-dipping gneissic layering and southward verging gently inclined folds. Structurally below the body, that is, along Sorpollen, the gneissic layering and fold axial surfaces are sub-horizontal or gently east-dipping (Figs 1, 8f). The high-strain zones along the margins of the Ulvesund Body can be interpreted as compensating for the relatively low strain within the body during late-Caledonian extension.

5. Summary of lithological, metamorphic and structural observations

The structural, lithological and metamorphic observations presented above can be summarized as follows. All rocks within the three bodies are of igneous origin. However, igneous textures are preserved only where little or no deformation occurred (e.g. in the core of the Kråkenes gabbro and Pod 916 and in some dykes). These domains were low strain zones during all subsequent tectonic and metamorphic events.

After magmatic crystallization, the rocks in the Flatraket and Ulvesund bodies show evidence of transitions to three metamorphic assemblages: granulite-, eclogite- and amphibolite-facies. In many places, these transitions are only partial or absent. Only rarely (e.g. in Pod 916 in the Flatraket stream section) do four different assemblages occur within the same rock body. In all rock types, partial or complete retrogression to amphibolite-facies assemblages is evident.

Granulite-facies metamorphism was associated with deformation and possible partial melting in the garnetiferous gneisses in the Flatraket stream section and at Ulvesund. No deformation, however, was associated with the granulite-metamorphism that affected the megacrystic gneiss. All felsic gneisses, where unaffected by subsequent eclogite or amphibolite-facies metamorphism, show evidence for granulite-facies equilibration. This suggests that the granulite-facies metamorphism was widespread in all felsic gneisses of the Flatraket and Ulvesund bodies, regardless of deformation.

Granulite-facies metamorphism of mafic rocks was less widespread, as indicated by the preservation of igneous textures and assemblages in the Kråkenes Gabbro. Well-equilibrated granulite-facies assemblages, however, occur in several mafic dykes and intermediate layers, especially in the Flatraket Body. Most mafic rocks that carry a granulite-facies assemblage are relatively undeformed (Table 1). In dioritic granulite, anorthositic granulate and the megacrystic gneiss
within the Flatraket body, granulite-facies pressure–
temperature conditions were estimated at 9–11 kbar,
data).

Eclogitization of felsic gneisses appears to be rare
(less than 2% by volume of the rock) and is only
observed where these rocks were deformed under
eclogite-facies conditions (Fig. 7f, g), or in felsic rocks
intimately associated with mafic eclogite. All felsic
eclogites possess a hydrous eclogite-facies assemblage
rich in phengite and zoisite (Table 1). The best evi-
dence for eclogite-metamorphism of felsic rocks
occurs in the Flatraket stream section (Section 3.e).
Pressure–temperature conditions of eclogite-facies
assemblages in the shear zones were estimated at
data).

About half of the mafic dykes and layers in the
Ulvesund and Flatraket bodies are affected by eclogiti-
зation (Table 1). However, only very localized eclogiti-
зation occurred in the Kråkenes Gabbro (Austrheim &
Engvik, 2000). Deformation accompanying eclogitiza-
ton is not so obvious in mafic rocks, although tight
eclogite-facies folds occur locally. Most mafic eclogites
contain only accessory hydrous eclogite-facies miner-
als, although some contain zoisite and/or phengite as
main constituents of their high-pressure assemblage
(Table 1). In the dioritic pods and layers, eclogitiza-
tion is restricted to their margins, whereas the cores of
these bodies preserve igneous or granulite-facies
assemblages. Overall, eclogitization affected less than
5%, by volume, of the three bodies.

Amphibolite-facies retrogression has affected all
rock types to varying degrees (Table 1). Pervasive
amphibolitization, however, is mostly restricted to
those rocks that have undergone substantial deforma-
tion; in these rocks, a medium- to coarse-grained
amphibolite-facies assemblage occurs. Granulite-
facies relics, however, are commonly still present in
domains that have undergone substantial deforma-
tion. In these rocks, amphibolite-facies retrogression
and deformation resulted in a very fine matrix of
amphibolite-facies minerals, suggesting incomplete
recrystallization under amphibolite-facies conditions.

Figure 8. Stereographic plots of structural data. Dots are foliation poles and open squares are lineations within the Flatraket
and Ulvesund bodies. Open circles are foliation poles and diamonds are lineations outside the bodies. Great circles are π planes
of planar data; large grey squares are poles to π planes.
The eclogite- and granulite-facies structures are highly discordant to the strongly developed late-Caledonian amphibolite-facies structures outside the bodies. This indicates that the Kråkenes, Flatraket and Ulvesund bodies were low strain zones during the late-Caledonian amphibolite-facies extensional deformation. These observations suggest that equilibration at certain pressure–temperature conditions is highly dependent on deformation and fluid availability and that older metamorphic assemblages are easily destroyed by later deformation and fluid-assisted reaction kinetics.

6. Discussion

The observations of different igneous and metamorphic assemblages preserved in the low strain zones of the Flatraket, Ulvesund and Kråkenes bodies raise the following issues: (1) the temporal relationship between granulite and eclogite-facies metamorphism; (2) the metamorphic evolution of the bodies and whether or not the occurrence of granulite-facies assemblages imply metastable behaviour at high pressures; (3) the causes of this metastable behaviour, the role of deformation and the importance of fluid infiltration; (4) the relationship between the three bodies and the surrounding gneisses; (5) the protoliths of the Western Gneiss Region as a whole and the role of the protolith during orogenesis.

6.a. Temporal relationship of granulite and eclogite: metamorphic evolution

The close spatial occurrence of granulite-facies and eclogite-facies assemblages in the Flatraket and Ulvesund bodies can be explained in different ways, each of which would have important implications for the tectonic evolution of the Western Gneiss Region. Three possibilities can be envisaged: (1) the granulites were isofacial to the eclogites, (2) the granulites pre-date the eclogites or (3) the granulites post-date the eclogites and were related to late-Caledonian exhumation.

If the granulites are isofacial with associated eclogites, as suggested elsewhere in the Western Gneiss Region by Krogh (1980), bulk rock composition, fluid composition or water activity would control the development of granulite (plagioclase-bearing) or eclogite (plagioclase-free) assemblages. However, this possibility can be discounted, as eclogitization affected both basic and felsic rocks. The presence of aqueous fluid will lower the pressure of plagioclase-out reactions, especially at high $X_{\text{An}}$ (Wayte et al. 1989). However, the equilibrium pressures of eclogite-facies shear zones are 20–23 kbar (at 650–800°C) which is significantly higher than equilibrium conditions of the granulite-facies assemblages (9–11 kbar, 700–850°C: A. Wain, unpub. Ph.D. thesis, Univ. Oxford, 1998; Wain, Waters & Austrheim, unpub. data). These calculations are not dependent on fluid composition, and also indicate pressures that are significantly higher than plagioclase-out reactions for all plagioclase compositions (Wayte et al. 1989). Therefore, granulite-facies assemblages would indicate metastability at high pressures if they pre-dated eclogite-facies metamorphism.

Three lines of evidence suggest that granulite-facies metamorphism pre-dated eclogite-facies metamorphism. Firstly, eclogite-facies shear zones in felsic rocks deform or cross-cut granulite-facies rocks or structures. Secondly, the mafic Pod 916 in the Flatraket stream section shows all transitions from an igneous assemblage, via granulite and eclogite to amphibolite-facies assemblages (Section 3.e). Granulite-facies metamorphism affected most of the pod whereas eclogitization only occurs along the margin. Finally, several mafic layers in which the bulk of the layer has a granulite-facies assemblage show very localized eclogitization in thin, distinct zones. The reverse situation of a narrow zone of granulite in a more pervasive eclogite is not observed.

The preservation of widespread granulites during
subsequent eclogite-facies metamorphism implies a high degree of metastability at eclogite-facies conditions within the bodies described here, because only few rocks display eclogite-facies assemblages.

The three bodies described in this paper, therefore, underwent the following overall evolution (Fig. 10): intrusion, granulite-facies metamorphism, eclogite-facies metamorphism (peak-Caledonian) and finally amphibolite-facies metamorphism (late-Caledonian). The pressure–temperature estimates of the eclogite- and granulite-facies assemblages (see Section 5) are based on the work of A. Wain (unpub. Ph.D. thesis, Univ. Oxford, 1998; Wain, Waters & Austrheim, unpub. data). The retrograde pressure–temperature path of the Flatraket body and the surrounding gneisses remained within the kyanite field (Cotkin, Valley & Essene, 1988; Cuthbert, 1991; M. Dransfield, unpub. Ph.D. thesis, Univ. Oxford, 1994; A. Wain, unpub. Ph.D. thesis, Univ. Oxford, 1998). The eclogite-facies conditions are similar to those estimated for non-coesite-bearing eclogites embedded in the surrounding gneisses (Wain, 1997), suggesting that the pressure–temperature evolution of the three bodies was similar to at least some (that is, probably not the coesite-bearing eclogites) of the rocks outside the bodies (but see discussion in Section 6.e). The Caledonian pressure–temperature evolution of the three bodies was thus roughly similar to the pressure–temperature evolution proposed for the Western Gneiss Region as a whole (see, for example, Dunn & Medaris, 1989; Wain, 1997). Nevertheless, different rocks clearly responded differently to the same changes in pressure and temperature and the extent of reaction is strongly linked to deformation and fluid availability (see next section).

Other uncertainties in the history as depicted in Figure 10 include the pressure–temperature path between intrusion and granulite-facies metamorphism and between granulite- and eclogite-facies metamorphism, the intrusion ages of the felsic and mafic rocks and the age and nature of the granulite-facies metamorphism. Further work is required to solve these problems.

6.b. Metastability at high-pressure: the role of fluid and deformation

Experiments and natural examples suggest that survival of relatively dry plagioclase-bearing assemblages outside their stability field (in the study area at pressures above 20 kbar) is associated with sluggish reaction kinetics caused by limited availability of a free, hydrous fluid phase (Ahrens & Schubert, 1975; Rubie, 1986; Wayte et al. 1989; Austrheim, Erambert & Engvik, 1997). As a result, the availability of water exerts a strong control on the extent of plagioclase breakdown towards high-pressure assemblages. The role of fluids in metamorphism is threefold: fluids can be components in metamorphic reactions, they can be catalysts during reactions and different fluid composition may affect the stability of certain mineral assemblages (Austrheim, Erambert & Engvik, 1997). As we have no data on fluid composition we will restrict ourselves to the first two points (although the scarcity of calc-silicate minerals in all assemblages suggest low $X_{CO2}$, so that the role of different fluid compositions may not have been significant).

Generally, mafic eclogites contain only minor hydrous minerals. Felsic eclogites, on the other hand, contain significant amounts of hydrous minerals such as zoisite and phengite (Koons & Thompson, 1985; Austrheim & Griffin, 1985; Black, Brothers & Yokoyama, 1988; Bousquet et al. 1997). This suggests that incomplete equilibration of mafic eclogites is mainly the result of lack of fluids as a catalyst, whereas incomplete equilibration of felsic eclogites is also the result of lack of fluids as a component. Thus, for eclogitization to occur in dry rocks, fluid infiltration is required for all compositions, but the amount of water required may be greater for felsic compositions than for mafic compositions.

Within the Ulvesund and Flatraket bodies, 30–40% of the mafic rocks were eclogitized whereas only 2% of the felsic rocks did so. In the felsic and intermediate eclogite-facies rocks, hydrous assemblages (those containing substantial phengite and zoisite) dominate. The eclogitized mafic rocks, on the other hand, contain

![Figure 10. Intrusive, metamorphic and \( P-T-t \) evolution of the Flatraket, Ulvesund and Kråkenes bodies. Pressure–temperature conditions are approximate. Age of the Flatraket megacrystic gneiss after Lappin, Pidgeon & van Breemen (1979); age of the Kråkenes Gabbro after E. W. Mearns (unpub. Ph.D. thesis Univ. Aberdeen, 1984, reported in Kullerud, Torrubakken & Ilebekk, 1986).](image-url)
both hydrous and (near)-anhydrous assemblages. These observations can be explained by the fact that felsic granulite requires more fluid infiltration to equilibrate than mafic granulite and dolerite. Ecloritization of felsic rocks is focused in shear zones and the contacts between mafic and felsic rocks; these settings probably provided easy pathways for fluid access.

The above analysis, however, does not explain the extensive metastable behaviour of the Kråkenes Gabbro. Clearly, processes controlling eclogitization are more complex than sketched above. Fluid infiltration into dry rocks not only catalyses and controls metamorphic reactions, but also enhances deformation (see, for example, Carter et al. 1990). Deformation enhances both fluid infiltration and metamorphic reactions (see, for example, Brodie & Rutter, 1985). If metamorphic reactions result in reaction softening (‘reaction-enhanced ductility’) and involve a negative volume change, it enhances both deformation and fluid infiltration (Klaper, 1990; Rubie, 1990). Consequently, fluid infiltration, deformation and metamorphic reactions can be linked into a vicious circle of mutual enhancement (Austrheim, Ernabert & Engvik, 1997). This mutual enhancement is expected to result in strongly localized zones of fluid infiltration, strain and metamorphic reaction (Carter et al. 1990), leaving large domains untouched. This implies that, to explain metastable behaviour, (lack of) deformation can be as important as (lack of) fluid. One possible explanation of the metastable behaviour of the Kråkenes Gabbro is that it was a large, uniform and mechanically competent body that escaped virtually all Precambrian as well as Caledonian deformation. Fluids were unable to pervasively infiltrate into the body even though fluids may have been abundantly available in the direct vicinity (see next section).

Fluid infiltration is enhanced by deformation and it is interesting that all felsic eclogites in our study have well-developed fabrics, whereas mafic eclogites occur both with and without eclogite-facies fabrics. Eclogite-facies re-equilibrium of felsic granulite was, apparently, only possible when fluid infiltration was combined with deformation.

Concluding, this study confirms that metamorphic reactions are not only a function of pressure, temperature and rock compositions but are also highly dependent on fluid availability and deformation.

6.c. Relationship with amphibolite-facies gneisses: fluid sources

The data presented here show that, within the three bodies, Caledonian eclogitization affected only about 5% of the rocks, whereas 95% of the rock retained their pre-Caledonian assemblages under high-pressure conditions. Whilst these bodies display similar features of eclogitization and amphibolitization to the granulites of the Bergen Arcs (Austrheim & Griffin, 1985), rocks external to these bodies are quite different in character. In large parts of the northwestern part of the Western Gneiss Region, late-Caledonian amphibolite-facies assemblages dominate with about 5–10% Caledonian peak-pressure assemblages preserved, mainly as mafic eclogite pods, but with very little evidence of Pre-Caledonian assemblages (Bryhni & Andréasson, 1985; Andersen, Osmundsen & Jolivet, 1994; Krabbendam & Wain, 1997). Two (end-member) scenarios can be envisaged to explain these differences:

1) The protolith of the Western Gneiss Region gneisses comprised relatively anhydrous igneous and granulite-facies rocks, but was somehow hydrated during orogenesis. Hydration was pervasive in ~90% of the terrane, except for small remnants which behaved metastably and retained pre-Caledonian granulite-facies assemblages. This scenario requires large volumes of externally derived fluid.

2) Before the Caledonian Orogeny, the Western Gneiss Region was composed of both hydrous amphibolite-facies domains and domains comprising anhydrous granulites and igneous rocks. This is a common feature of many exposed high-grade gneiss terranes (see, for example, Fountain & Salisbury, 1981). During the Caledonian, the hydrous amphibolite-facies domains may have experienced extensive eclogitization. The anhydrous igneous and granulite-facies rocks domains behaved largely metastably, with only very localized eclogitization. During exhumation, felsic eclogite (formed in the hydrous domains) readily retrogressed (as in the model of Heinrich, 1982), but mafic eclogite and granulite-facies domains did not equilibrate at amphibolite-facies conditions. Fluids migrating within the Western Gneiss Region resulted in local eclogitization of granulitic and gabbroic bodies during burial and in hydration of the margins of many mafic eclogites during exhumation and of the margins of the Kråkenes Gabbro. However, no large-scale, pervasive fluid infiltration into the Western Gneiss Region is required.

We favour the second explanation for several reasons. Firstly, mineral inclusions (mainly hornblende and epidote, also plagioclase) in prograde zoned garnets in eclogites suggest pre-Caledonian amphibolite-facies equilibration (Bryhni & Griffin, 1971; Krogh, 1982; A. Wain, unpub. Ph.D. thesis, Univ. Oxford, 1998; Engvik & Andersen, in press). Secondly, mafic rocks outside the three bodies show a high degree of eclogitization (>90%), whereas the mafic pods and dykes within the three bodies show a medium degree (30–40%) of eclogitization and virtually no reaction in the Kråkenes Gabbro. In the Nordfjord–Stadlandet area, no igneous or granulitic relics have been found in more than 100 pods studied (see also Smith, 1988; M. Dransfield, unpub. Ph.D. thesis, Univ. Oxford, 1994; A. Wain, unpub. Ph.D. thesis, Univ. Oxford, 1998). This suggests that eclogitization was more pervasive outside the three bodies. Thirdly, pervasive fluid infiltration on a vast
some 100 km south of the study area. Two kilometre-
Austrheim) and near Lavik (Skår, pers. comm., 1998),
(unpublished observation by T.B. Andersen and H.
granulites which are partially eclogitized occur in Gulen
augen gneisses is a real possibility. Well-preserved felsic
features suggest that metastable behaviour of these
observed in Flatraket (Griffin & Carswell, 1985). These
these gneisses with very similar field relations to those
ilar to the megacrystic gneiss at Flatraket (Harvey,
clinopyroxene. Geochemically, these rocks are very sim-
and contains garnet coronas and rare symplectitic
features. This is corroborated by a fluid inclusion study
in gneisses further north that suggest an influx of aque-
ous fluid during exhumation and retrograde metamor-
phism (Larsen, Eide & Burke, 1998). Increased activity of
H2O-rich fluids during exhumation is satisfactorily
explained by dehydration of felsic or pelitic eclogites
(Heinrich, 1982). An external source of fluids, such as a
subducting oceanic slab, as forwarded by Larsen, Eide
& Burke (1998), may have been operating during burial
but is unlikely to have been present during exhumation.

6.d. Granulite-facies relics elsewhere in the Western Gneiss
Region

If our scenario of both hydrous and anhydrous
domains prior to the Caledonian is correct, it is impor-
tant for the tectonic and metamorphic evolution of the
Western Gneiss Region as a whole to constrain the ratio
of these two domains. To date, incomplete eclogitiza-
tion of rocks in the Western Gneiss Region is described
in mafic rocks in the north by Mork (1985, 1986) and on
Bårdsholmen in Sunnfjord, where small occurrences of
felsic granulate occurred that experienced partial eclogitiza-
tion (Austrheim & Engvik, 1997; Engvik, Austrheim &
Andersen, 2000). Further evidence of partial eclogitiza-
tion in conjunction with metamorphic transitions in
the three bodies was more widespread during exhumation
than during burial or at peak-pressure condi-
tions. This is corroborated by a fluid inclusion study
in gneisses further north that suggest an influx of aque-
ous fluid during exhumation and retrograde metamor-
phism (Larsen, Eide & Burke, 1998). Increased activity of
H2O-rich fluids during exhumation is satisfactorily
explained by dehydration of felsic or pelitic eclogites
(Heinrich, 1982). An external source of fluids, such as a
subducting oceanic slab, as forwarded by Larsen, Eide
& Burke (1998), may have been operating during burial
but is unlikely to have been present during exhumation.

Further north in the Western Gneiss Region, late-
Caledonian decompression occurred at higher temper-
atures and resulted in granulite- rather than
amphibolite-facies metamorphism (see, for example,
Dunn & Medaris, 1989; Straume & Austrheim, 1999).
This implies that not all granulite-facies rocks in the
Western Gneiss Region are necessarily metastable Pre-
Caledonian relics.

6.e. Implications for the tectonic and metamorphic evolution
of the Western Gneiss Region

In conjunction with the findings of Engvik, Austrheim
& Andersen (2000), this study shows that at least cer-
tain parts of the Western Gneiss Region were at gran-
ulite-facies prior to the Caledonian and behaved
metastably during the Caledonian high-pressure
event. The tectono-metamorphic history of the three
bodies, which may be applicable to wider parts of the
Western Gneiss Region, is summarized in Figure 10.

A problem considering the pressure-temperature
evolution of the three bodies is the proximity of
coesite-bearing ultrahigh-pressure eclogites. Two
coesite-bearing eclogites indicating P > 28 kbar occur
in the immediate vicinity of the Flatraket Body (Fig.
1), one less than 200 m structurally below the
megacrystic gneiss and another one structurally above
on the east coast of Nordpollen (Wain, 1997). Wain
(1997) explained the present proximity of ultrahigh-
pressure and high-pressure rocks by tectonic juxtapo-
sition, although a kinetic explanation cannot be ruled
out. The absence of amphibolite-facies high strain
zones between the coesite-bearing eclogites and the
Flatraket body and other non-coesite-bearing eclog-
ites (also in areas of good exposure) indicates that any
juxtaposition must have occurred prior to amphibol-
ite-facies conditions, that is, in an early phase of
exhumation (Krabbendam & Wain, 1997; A. Wain,
with the fact that the Western Gneiss Region may have
been composed of quite different lithologies with dif-
ferent Pre-Caledonian metamorphic grade, this sug-
gests that relatively large tectonic movements have
occurred within the Western Gneiss Region. The late-
Caledonian extensional structures and pervasive
amphibolite-facies re-crystallization largely obliterate
the structural evidence of these movements.

A further implication of this study concerns density
changes and their effect on the mechanics of colli-
sional tectonics. Dewey, Ryan & Anderson (1993) pre-
sented a model whereby extensive eclogitization in the
Western Gneiss Region resulted in increasing density and decreasing buoyancy of the entire Caledonian orogenic crust. They proposed that by this mechanism a crustal thickness of 120 km could be achieved by collisional tectonics. The validity of this model is highly dependent on the actual density changes during the Caledonian Orogeny. If metastability within the Western Gneiss Region proves to be widespread (rather than restricted to small domains) significant density changes may not be plausible.

7. Conclusions

The Flatraket, Ulvesund and Kråkenes bodies occur within the mixed high-pressure–ultrahigh-pressure zone within the Western Gneiss Region and are surrounded by quartzo-feldspathic gneisses which experienced late-Caledonian strain and equilibration. The Flatraket, Ulvesund and Kråkenes bodies preserve igneous and granulite-facies metamorphic assemblages, textures and structures that pre-date the Caledonian Orogeny. The three bodies behaved mainly as low strain zones during the Caledonian. The three bodies show very localized eclogitization in felsic and mafic rocks eclogites (about 5%), commonly related to shear zones or lithological contacts, and have experienced high-pressure conditions (20–23 kbar), possibly up to 24–29 kbar (Austrheim & Engvik, 2000). The preservation of the felsic and mafic igneous and granulite-facies assemblages in these bodies, therefore, indicates widespread (~95%) metastability at pressures that are higher than other areas in Norway where metastability has been demonstrated. This study confirms that metamorphic reactions are not only a function of pressure, temperature and rock compositions but are also highly dependent on fluid availability and deformation, and metastability in the studied rocks occurred where there was a lack of both fluid and deformation. The contrasting behaviour of the three bodies with respect to the surrounding gneisses can be explained by difference in metamorphic grade of the respective protoliths and we suggest that, before the Caledonian Orogeny, the Western Gneiss Region comprised both hydrous amphibolite-facies domains and anhydrous igneous and granulite-facies domains.

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Note added in proof

Alice Wain was tragically killed in a car accident on May 3rd, 2000, while carrying out fieldwork in Scotland. We mourn her loss. Alice was a dedicated and enthusiastic geologist. She loved the rocks and scenery of West Norway. We dedicate this paper to her memory. MK & TBA.

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