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Regional metamorphism in the Ballachulish area, SW Highlands, Scotland: new perspectives on a famous old debate, with regional implications

DAVID R. M. PATTISON[1]

[1]*Department of Geoscience, University of Calgary, Calgary, Alberta, T2N 1N4, Canada*
(e-mail: pattison@ucalgary.ca)

Abstract: The Ballachulish region of the SW Highlands of Scotland was the focal point of a famous debate in the 1920s between Sir Edward Battersby Bailey and Professor Cecil Edgar Tilley concerning the identity, geometry and timing of development of metamorphic zones in the SW Highlands. New mineral assemblage data, microstructural observations, and rock and mineral compositional data are combined with phase equilibrium modelling to reassess the metamorphism in this area. The newly revised chlorite, biotite and garnet zones are similar to those of Bailey. Compositional difference between lithologies is the primary cause of the irregular distribution of mineral assemblages in the region. Microstructural observations suggest that metamorphism occurred in the latter stages of the deformation history, in agreement with previous studies. Pressure–temperature conditions of the garnet isograd are estimated to be *c.* 7 kbar, *c.* 500 °C. These are compared with *P–T* estimates of the garnet zone elsewhere in Scotland.

Supplementary materials: Appendix 1 lists mineral assemblages, Appendix 2 lists whole-rock compositions, and Appendices 3–7 list representative mineral compositions (garnet, biotite, muscovite, chlorite and plagioclase–epidote, respectively). Appendices 8 and 9 are the compositional input and thermodynamic input files for Theriak-Domino used to calculate the phase diagrams in this paper. The appendices are available at www.geolsoc.org.uk/SUP18586.

The Ballachulish area of the SW Highlands of Scotland (Figs 1–4) was the focal point of a famous debate in the 1920s and 1930s between two of the giants of British geology: Sir Edward Battersby Bailey, a field geologist of the Geological Survey of Great Britain and later the University of Glasgow (Fig. 5a), and Professor Cecil Edgar Tilley, a petrologist at the University of Cambridge (Fig. 5b). At issue were conflicting interpretations of the identity, geometry and timing of development of metamorphic zones in the SW Highlands, and the implications these carried for the tectonic evolution of the region. The point of contention in the Ballachulish area was the cause of the abrupt disappearance of garnet, in the direction of increasing metamorphic grade, in shoreline exposures on Loch Leven west of the town of Ballachulish (Figs 2, 3d and 5). Contributing to the debate was the fact that the garnet-bearing and garnet-free rocks are separated by a major fault, the Ballachulish Slide (Fig. 2). Bailey attributed the abrupt disappearance of garnet to differing bulk composition of rocks of the same metamorphic grade on either side of the slide, interpreting the slide to be pre-metamorphic (Bailey & Maufe 1916, 1960). Tilley (1925), and later his Cambridge colleague Gertrude Elles and he, attributed the abrupt disappearance of garnet to mechanical juxtaposition of rocks of different metamorphic grade, implying that the slide was post-metamorphic (Elles & Tilley 1930).

The kernel of the debate, grade versus bulk composition as the cause of differences in metamorphic mineral assemblages, is one of the timeless concerns of metamorphic petrology, so that reinvestigation of this matter carries relevance beyond the historical and geographical specificity of the locality. The first part of the paper summarizes the historical development of the debate, showing how different interpretations of the metamorphism contributed to Bailey's and Tilley's opposing views of the tectonic evolution of the SW Highlands. In the second part of the paper, the metamorphic zones in the region, especially the garnet isograd, are reassessed using an expanded database of mineral assemblages, microstructural observations, and rock and mineral compositions.

Phase equilibrium modelling is used to estimate pressure–temperature (*P–T*) conditions of the garnet isograd. Published *P–T* estimates of the garnet zone from other areas in the SW and central Highlands are assessed in the light of these results.

Historical background

In 1910 Edward Battersby Bailey of the Geological Survey of Great Britain published a seminal paper outlining the structural architecture of the SW Highlands of Scotland, in which the essential element was a series of large (up to 20 km amplitude) recumbent folds, or nappes, of the Dalradian metasedimentary stratigraphy, later buckled by a series of upright folds. Between the limbs of some of the recumbent folds were prominent faults, described by Bailey (1910) as 'slides', which thinned or cut out parts of the stratigraphy. Figure 2 shows a current geological map of a key portion of this region, little modified from Bailey's 1910 original. Bailey's recognition of Alpine-style nappe tectonics in the SW Highlands attracted considerable attention because it contrasted with the thrust tectonics famously recognized in the NW Highlands by Bailey's colleagues in the Geological Survey in previous decades (e.g. Peach *et al.* 1907).

A major difficulty encountered by Bailey in understanding the nappe structures and their tectonic significance was his inability at the time to decide on the younging direction of the Dalradian stratigraphy outlined in Figure 2. If the rocks within the core of the synformal nappe structures were youngest, the sense of movement of the nappes was to the NW, similar to the sense of thrust motion in the NW Highlands (Peach *et al.* 1907), whereas if the synforms were cored by the oldest rocks, the sense of nappe movement was to the SE. In addition to evidence from sedimentary structures, Bailey weighed the possibility that the metamorphic state of the rocks might give a clue, the unstated assumption being that the deeper, older strata might be expected to be more metamorphosed.
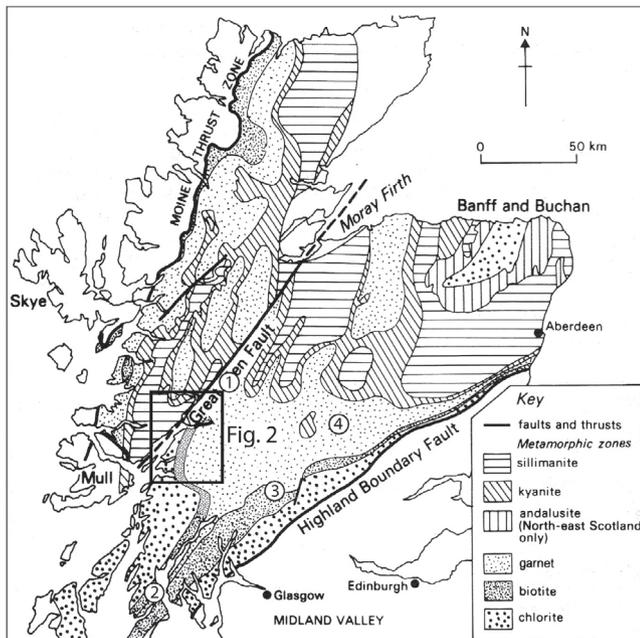
Fig. 1. Metamorphic zones of Scotland, from Gillen (1982). The metamorphic zones in the study area (box) have been modified from Gillen (1982) to fit better with their disposition in this study. Numbers refer to localities discussed in the section 'Comparison of *P–T* results at Ballachulish with *P–T* conditions of the garnet zone elsewhere in the SW and central Highlands'.

He rejected this notion early on, however, because he noted that the same stratigraphic units showed varying degrees of metamorphism across the region. Based on tentative stratigraphic correlations with rocks in other districts, and a belief that faults on the scale of the observed slides were more likely to be thrust faults than normal faults, Bailey (1922) proposed a stratigraphic sequence that was in fact backwards to what is now known, implying nappe movement to the SE.

Included at the end of Bailey's 1922 structure paper, and expanded on in a dedicated article in 1923, was a synthesis of his interpretation of the metamorphism of the SW Highlands and its relation to the structures, including a map of metamorphic zones. The portion of his metamorphic map that covers the area of Figure 2 is shown in Figure 3a. Bailey's metamorphic zones, in order of increasing grade, were: (1) mica (meaning biotite) inconspicuous; (2) mica (biotite) conspicuous; (3a) mica with garnet. A fourth zone, (3b) mica with albite, occurs outside the area of Figure 3a. An important conclusion of his study was written in italics by Bailey (1923, p. 332): '*The metamorphic zones of the South-West Highlands are superimposed upon one another in order of increasing crystallization from above downwards. The surfaces separating the various metamorphic zones are often gently, though distinctly, inclined with reference to the surfaces separating the various tectonic zones or nappes; and, through much of the district, their relative inclination is downwards towards the northwest.*' Part of Bailey's evidence included the downthrow of lower grade (biotite zone) rocks in the Ben Nevis and Glencoe caldera complexes against garnet zone metasediments outside these complexes (Clough *et al.* 1909; Bailey & Maufe 1916; see Figs 3 and 4).

The next year, 1924, Cecil Edgar Tilley of Cambridge University presented a different interpretation of the metamorphism of some of the same ground in a paper read at the Geological Society of

London, subsequently published in 1925 (Tilley 1925). Tilley had been strongly influenced by the pioneering work of George Barrow (1893, 1912) in the northeastern Highlands, who had mapped for the first time metamorphic zones characterized by the presence of critical index minerals in metapelitic rocks (e.g. garnet, staurolite, kyanite). Tilley noted that Barrow's scheme was 'the first attempt in the petrological literature to bring precision to the study of regional metamorphism'. Tilley was therefore highly critical of Bailey's more vaguely defined metamorphic zones in the SW Highlands, and sought to redress the situation by attempting to extend Barrow's zones through the central Highlands into the SW Highlands.

The metamorphic zones Tilley (1925) mapped were the chlorite, biotite and almandine (garnet) zones, the higher grade Barrovian zones being absent in the central and SW Highlands (Fig. 1). Tilley also weighed in on the relation of metamorphism to structure. Based on the apparent topographic variation across hilly terrain of the 'garnet isograd' (more specifically, the interface between garnet-bearing rocks and garnet-free rocks), and the displacement of this interface across late faults, he concluded that the garnet isograd in the Loch Tay area dipped north at about 15° but was inverted, with the garnet-bearing rocks lying above the garnet-free rocks. He therefore inferred that all the metamorphic zones were inverted in a manner broadly similar to the stratigraphy (whose younging direction in that area was known, and faced down), with rocks of lower stratigraphic position and higher metamorphic grade lying structurally above those of higher stratigraphic position and lower metamorphic grade. This in turn led to his proposition that the metamorphic zones were folded during nappe formation and therefore were established beforehand, broadly during burial. In summary, Tilley's views of the identity of the metamorphic zones in the SW Highlands, their orientation, and their timing with respect to nappe formation, were completely different from Bailey's.

In the written record of the discussion that followed Tilley's presentation to the Geological Society (pp. 110–112 of Tilley 1925), Bailey acknowledged Tilley's arguments that garnet-bearing rocks overlie garnet-free rocks in the Loch Tay area. However, he questioned whether it implied a metamorphic inversion, noting that in the Ballachulish area 'the development of garnet is relatively delayed [in some units] by chemical composition'. In Bailey & Maufe (1916), he noted the 'very fine crystallization' of the Ballachulish Slate compared with the porphyroblastic Appin Phyllites and Leven Schists, and proposed a 'selective metamorphism which is probably connected with the large amount of finely disseminated carbon' in the slates that causes a 'delay of metamorphism'. Tilley dismissed Bailey's comment by stating that until Bailey 'produced a detailed metamorphic map of the Ballachulish area, it was scarcely possible to deal with the supposed difficulties'.

Meanwhile, new developments had taken place with regard to reading the younging direction of the Dalradian sediments in the Ballachulish area. In 1924 Thorolf Vogt of Norway and colleagues visited the Ballachulish area and convinced themselves, based on cross bedding in the abundant quartzites, that the younging direction of the stratigraphic sequence was the opposite to what Bailey proposed in 1922. Bailey remained unconvinced until 1929 when T. L. Tanton of the Geological Survey of Canada and his colleagues from the Princeton Summer School visited the same area and finally convinced him that Vogt's interpretation was correct. Bailey spearheaded publication of a series of papers back-to-back (Bailey 1930; Tanton 1930; Vogt 1930) that summarized the episode. The result was a new interpretation, subsequently more completely developed in Bailey (1934), of the nappe tectonics of the SW Highlands, the essence of which stands to this day. In this interpretation, the transport direction was to the NW rather than to the SE.
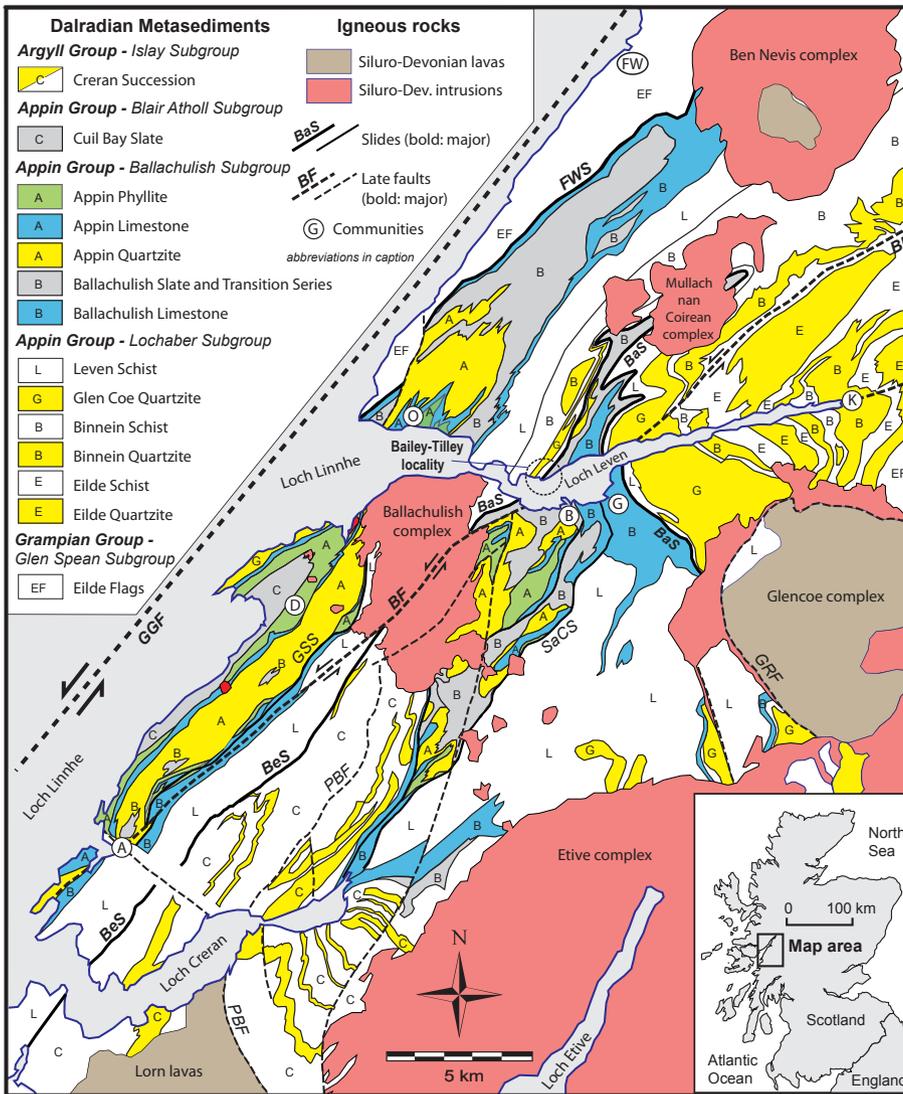
Fig. 2. Geological map of a part of the SW Highland of Scotland, based on Bailey (1910), Bailey & Maufe (1916, 1960), Hickman (1975), Roberts (1976), Litherland (1980), Pattison (1985), Weiss & Troll (1989) and Droop & Moazzen (2007). Letters within circles or ellipses are abbreviations for the following communities: A, Appin; B, Ballachulish; D, Duror; FW, Fort William; G, Glencoe; K, Kinlochleven; O, Onich. Abbreviations for slides: BaS, Ballachulish Slide; BeS, Benderloch Slide; FWS, Fort William Slide; GSS, Glen Stockdale Slide; SaCS, Sgorr a'Choise Slide. Abbreviations for late faults: GGF, Great Glen Fault; BF, Ballachulish Fault; GRF, Glencoe Ring Fault; PBF, Pass of Brander Fault.

However, the differences between Bailey and Tilley concerning the metamorphism remained. In 1930 Tilley and his Cambridge colleague Gertrude Elles, a distinguished palaeontologist with a lifelong interest in the geology of the Highlands, published a paper (Elles & Tilley 1930) whose object was 'consideration of the structure of the Central and SW Highlands as shown up by the metamorphic condition of the beds'. This paper was accompanied by a map of metamorphic index mineral zones, the portion of which that covers the area of Figure 2 is shown in Figure 3b. Translation of the metamorphic zones from Elles & Tilley's map to Figure 3b is inexact because the Elles & Tilley map is a rather approximate representation of the geography of the SW Highlands.

Three major features of Elles & Tilley's work contrast with that of Bailey. First, the disposition of Elles & Tilley's chlorite, biotite and garnet zones is more complex than Bailey's zones (compare Fig. 3a and b). In Elles & Tilley's map, a tongue of garnet zone rocks extends SW from the main garnet zone in the north towards the (post-metamorphic) Ballachulish igneous complex, opposite from which is a narrowing promontory of chlorite zone rocks that extends NE from the main chlorite zone in the south towards the Ballachulish complex. Second, Elles & Tilley confirmed Bailey's observation that just east of the garnet isograd where it crosses Loch Leven, there is an abrupt eastward transition from garnet-bearing

schists to garnet-absent slates across the Ballachulish fault (compare Figs 2 and 3b). This abrupt transition marks the eastern boundary of the tongue of garnet zone rocks in their map shown in Figure 3b. However, Elles & Tilley (1930, their fig. 7) interpreted the garnet zone rocks to have been mechanically juxtaposed, via the Ballachulish Slide, against lower grade rocks to the east. Third, Elles & Tilley retained their view that the metamorphic state of the Dalradian metasediments of the SW Highlands was attained early on in their history, and that the metamorphic zones were subsequently folded along with the strata (the possibility of radioactive self-heating of thickened strata was not appreciated at this time). An interesting side note is that during this period of obvious scientific disagreement, Bailey wrote to Tilley in August 1930, saying 'I'm very glad to have the Elles–Tilley paper safely published'; implying an editorial role in support of a paper that so pointedly criticized his own work.

The Elles & Tilley (1930) paper was the last dedicated publication pertaining to the matter. Their map of the metamorphic zones of the SW Highlands, including the peculiar pattern in the Ballachulish area, has been reproduced in most subsequent syntheses of Dalradian metamorphism (e.g. Atherton 1977; Fettes 1979; Fettes *et al.* 1985; Harte 1988). Even Bailey, in his updated version of the Bailey & Maufe (1916) Memoir (Bailey & Maufe 1960),
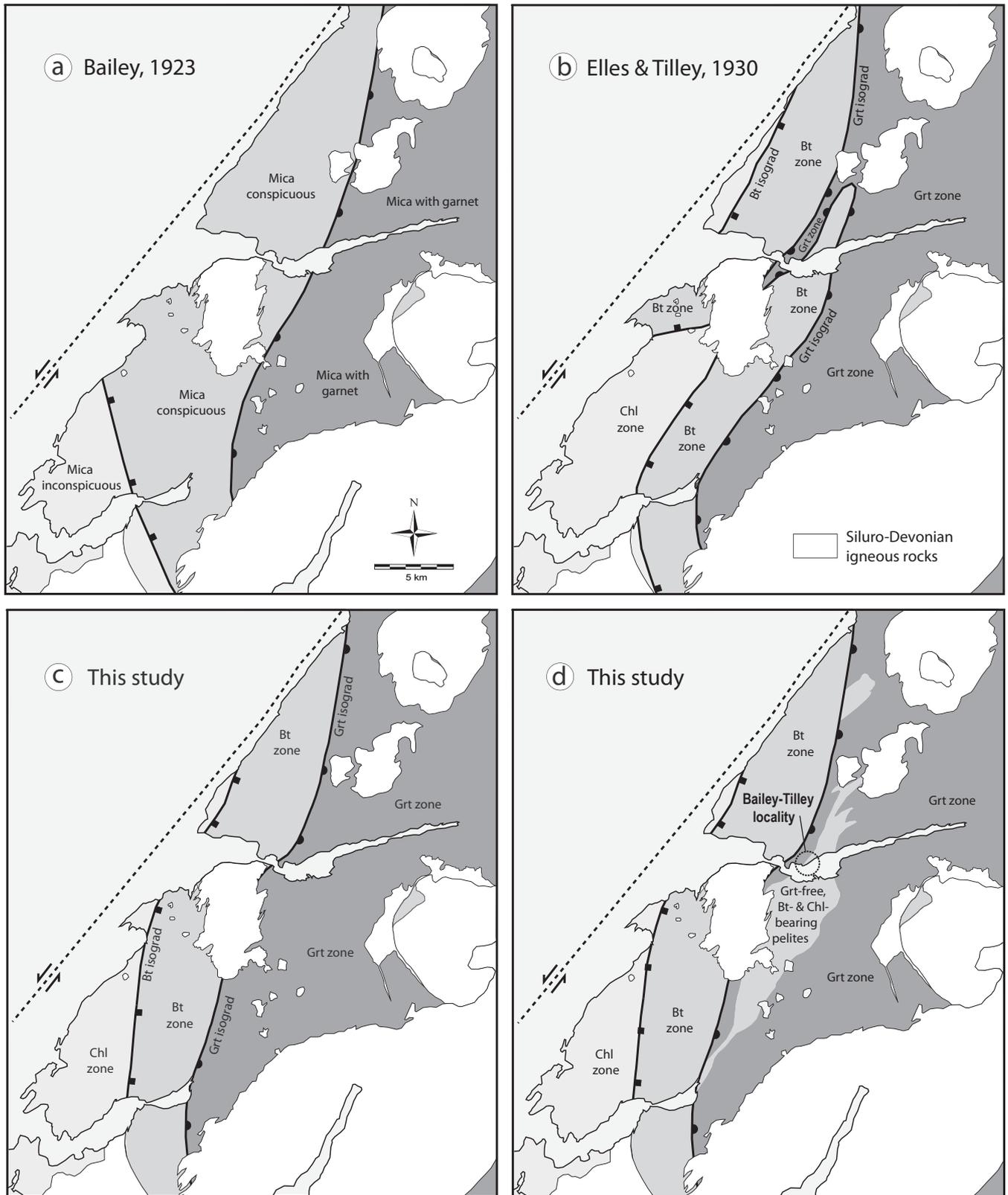
Fig. 3. Different interpretations of metamorphic mineral assemblage zones in the region covered by Figure 2. The zones of Bailey (1923) and Elles & Tilley (1930) have been transcribed as closely as possible from their original maps; exact transcription was difficult because of inaccuracies in the portrayal of the geography in their maps.
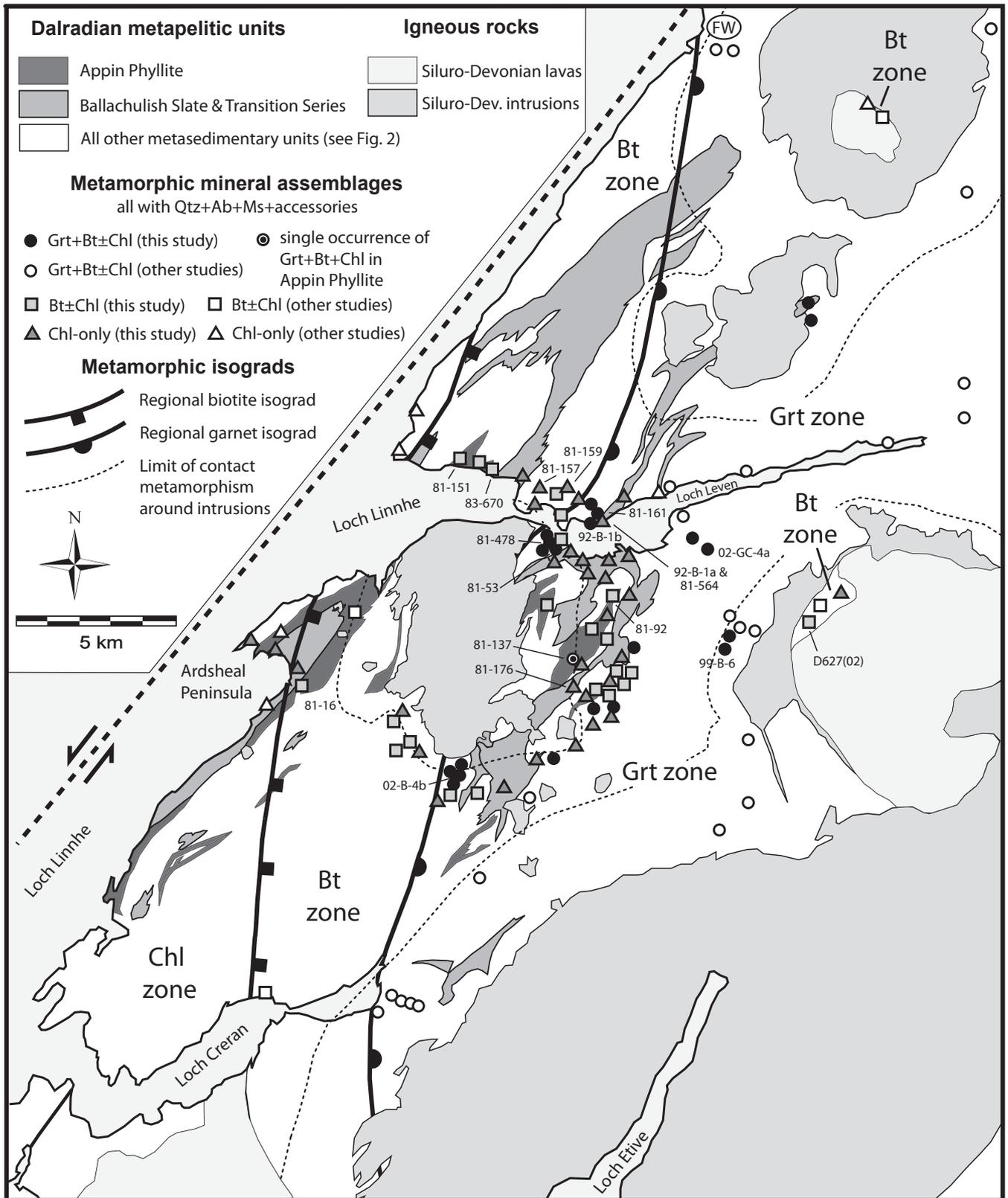
Fig. 4. Mineral assemblage and isograd map of the region covered by Figure 2, based on this study. Sources of data other than the author include Bailey & Maufe (1916, 1960), Elles & Tilley (1930), Droop & Moazzen (2007), and unpublished occurrences of G. T. R. Droop (University of Manchester). The ellipse with the letters FW is the location of the town of Fort William. Labelled samples are those that are illustrated in photomicrographs or were analysed chemically. Samples 81-161, 81-564, 92-B-1a and 92-B-1b come from the Bailey–Tilley locality (see Figs 2 and 3d).
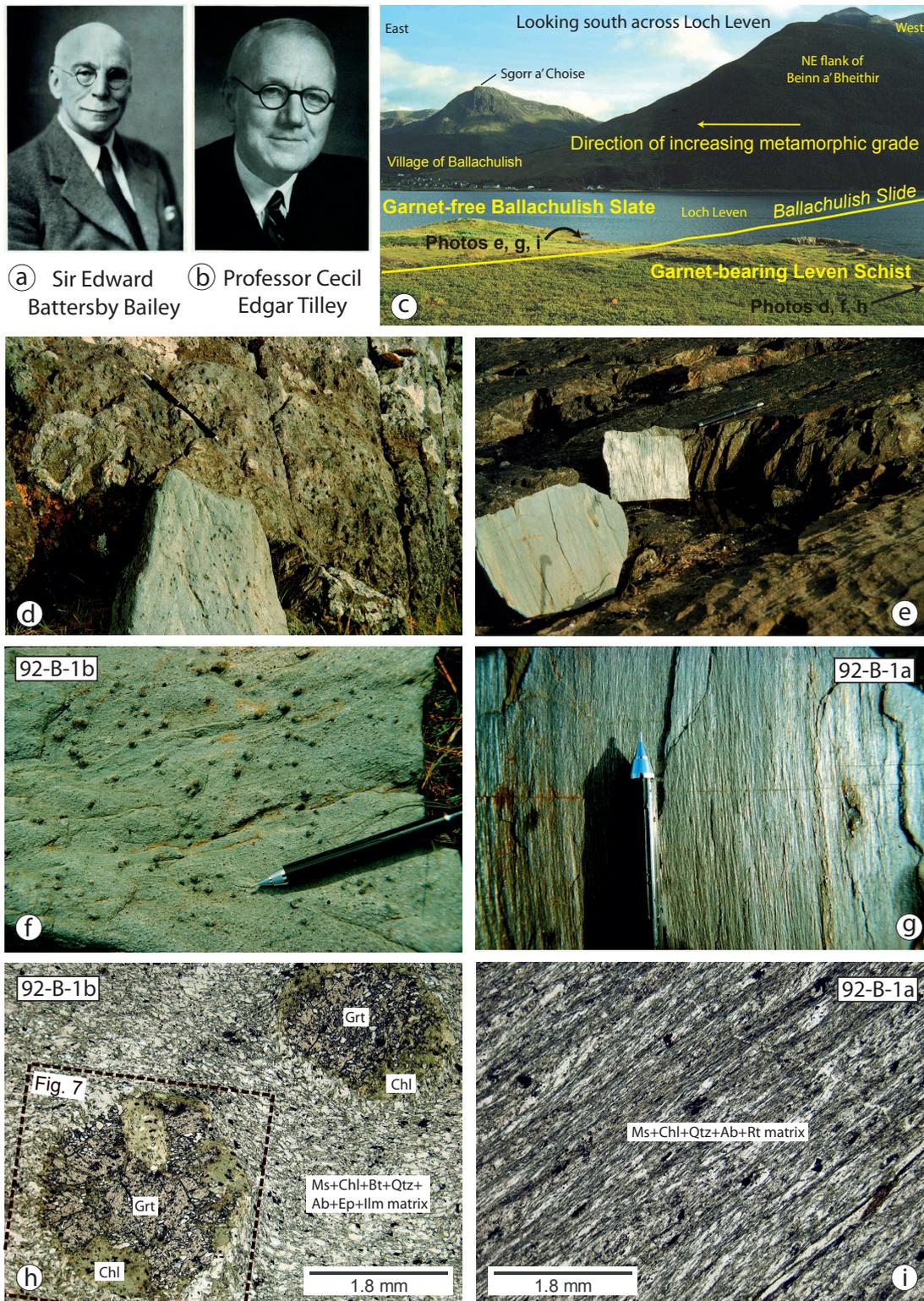
Fig. 5. Features of the Bailey–Tilley locality (for location, see Figs 2 and 3d). (**a**) Photograph of Sir Edward Battersby Bailey, used with permission from the Royal Society of London. (**b**) Photograph of Professor C. E. Tilley, used with permission from the Cambridgeshire Collection—Ramsey & Muspratt Archive, Cambridge Central Library. (**c**) Overview photograph of the Bailey–Tilley locality on the north shore of Loch Leven, taken looking south across the loch. (**d**) Outcrop photograph of garnetiferous Leven Schist. (**e**) Outcrop photograph of Ballachulish Slate. A band of Ballachulish Limestone is in the immediate foreground of the outcrop. (**f**) Detail of garnetiferous Leven Schist, showing garnet porphyroblasts (largely chloritized) and biotite. (**g**) Detail of finely crenulated Ballachulish Slate. (**h**) Photomicrograph of garnetiferous Leven Schist sample 92-B-1b (for location, see Fig. 4). Inclusion-filled garnet is partly replaced by chlorite. The S_1 foliation, trending approximately east–west across the photomicrograph, has been deformed into warps and microfolds interpreted to be due to D_2. Inclusion trails in garnet are at various angles to S_1 and the D_2 features. The box surrounding the large garnet shows the area covered by the element maps in Figure 7. (**i**) Photomicrograph of Ballachulish Slate sample 92-B-1a (for location, see Fig. 4).

described the trace of the garnet isograd in the Ballachulish–Glencoe area with reference to the Elles & Tilley disposition. On the other hand, the Elles & Tilley interpretation of the relation between structure and metamorphism has not met with broad acceptance, consensus instead coalescing around Bailey's position that metamorphism and deformation were intimately related, with metamorphism post-dating the development of early nappes and slides and their associated microstructures (e.g. Clough 1897; Bowes & Wright 1973; Roberts 1976; Phillips et al. 1999).

The final published word by either of the main protagonists occurs in the Bailey & Maufe (1960) Memoir, in which Bailey repeated his view that Elles and Tilley 'have sometimes been misled by not sufficiently recognizing what a contrast of metamorphic response may be expected by rocks of different chemical composition', noting that 'if allowance is made for this phenomenon, there is no reason to follow Elles & Tilley (1930, fig. 7) and admit a mechanically induced "break" in metamorphism associated with the Ballachulish Slide'.

Reinvestigation of the problem

In 1981–1983 the author collected samples of regionally metamorphosed rocks in the Ballachulish area as part of his PhD study of the contact metamorphism associated with the Ballachulish igneous complex (Pattison 1985). Further samples in the Ballachulish–Glencoe area were collected subsequently. Samples were examined petrographically and several were selected for whole-rock and mineral composition analysis and phase equilibrium calculations.

Geological setting

The area of interest shown in Figure 2 is dominated by the Dalradian metasedimentary sequence described by Bailey (1910). The Dalradian rocks comprise variably deformed and metamorphosed pelite, semipelite, psammite, quartzite, limestone and dolostone units of the Grampian, Appin and Argyll groups (Bailey & Maufe 1916, 1960; Harris & Pitcher 1975; Hickman 1975; Litherland 1980; Anderton 1985; Stephenson & Gould 1995). The names and stratigraphic order of the units are shown in the legend to Figure 2; lithological details may be found in the references cited above. These units were deposited in the late Proterozoic (Prave 1999), and were deformed and regionally metamorphosed in the Grampian phase of the Caledonian orogeny in the Ordovician, c. 470 Ma (Soper et al. 1999; McKerrow et al. 2000).

As first noted by Bailey (1910), the Dalradian rocks were deformed into a series of large recumbent folds (nappes), later buckled by a series of upright folds (Bailey 1910, 1922, 1934; Bailey & Maufe 1960; Roberts 1976; Roberts & Treagus 1977a,b). Other interpretations of the structure have been proposed (see summary by Stephenson & Gould 1995), but all models involve two main folding episodes (D_1 and D_2). Associated with the development of the nappes were Bailey's 'slides', faults that cut out or thinned the stratigraphy, the more important of which are labelled in Figure 2. Small-scale deformation features associated with the folding include a penetrative cleavage or schistosity in micaceous units that is axial planar to the first-phase folds (S_1), and later, variably developed, crenulations and crenulation cleavages (S_2) that affect the S_1 cleavage and are thought to be associated with the later folds (Roberts 1976; Roberts & Treagus 1977b).

Regional metamorphism, described in more detail below, spans the chlorite, biotite and garnet zones (Fig. 1). Regional metamorphism overlapped with regional deformation, based on microstructural evidence suggesting that metamorphic minerals grew following the first phase of foliation development (S_1) and

approximately during the second (S_2) (Clough 1897; Bowes & Wright 1973; Roberts 1976; Phillips & Key 1992).

Intrusive and extrusive igneous rocks were emplaced into and onto the deformed and metamorphosed Dalradian strata in the late Silurian and early Devonian, c. 430–408 Ma (Thirlwall 1988; Stephenson & Gould 1995; Soper et al. 1999; Fraser et al. 2004; Morris et al. 2005; Neilson et al. 2009; Porter & Selby 2010). Intrusive complexes include the Ben Nevis, Ballachulish, Glencoe and Etive complexes (Fig. 2). These complexes show dominantly intrusive rocks, but at the time of formation they were probably connected to overlying volcanic sequences, now partly preserved in downthrown blocks within the caldera complexes of Glencoe and Ben Nevis, and more extensively developed in the Lorn Plateau lavas in the south of the area (Neilson et al. 2009; see Fig. 2).

Contact aureoles surround the intrusive complexes, extending 1–3 km from their margins (Bailey & Maufe, 1960; Pattison & Harte 1985, 1991, 1997; Droop & Moazzen 2007; see Fig. 4). Metapelitic rocks within the aureoles are spotted or pitted cordierite-rich hornfelses that statically overprinted the regional metamorphic rocks. Regional structures and textures (including regional porphyroblasts, or pseudomorphs thereof) can nevertheless be recognized in the aureoles except within a few hundred metres of the intrusive contacts where recrystallization is more complete. The pressure range of contact metamorphism in the region is between 2 and 3 kbar (Pattison 1989; Droop & Moazzen 2007).

Later faults transect the region shown in Figure 2. The most prominent is the Great Glen fault, a major, NE–SW-trending, crustal-scale transcurrent fault zone that bounds the area to the NW. It has been active since at least the Silurian, with late Caledonian sinistral movement of possibly hundreds of kilometres, and post-Caledonian dextral movement of tens of kilometres (Stewart et al. 2001). Another important, less appreciated, NE–SW-trending transcurrent fault that transects the area is the Ballachulish fault, which cuts the Ballachulish complex and its contact metamorphic aureole (Pattison & Harte 1985). Post-Caledonian sinistral displacement of the order of 0.5–1.5 km is indicated by displacements of lithological contacts, contact metamorphic zones and the trace of Ballachulish Slide where it crosses Loch Leven (Hickman 1975; Roberts 1976; Pattison 1985).

Metamorphic zones

Figure 4 shows the distribution of regional metamorphic mineral assemblages in the area covered by Figure 2, in addition to the approximate outer limits of the contact aureoles associated with the later intrusions. Although the coverage in Figure 4 is uneven, it is sufficient to reasonably well constrain the trace of the regional garnet isograd, the main gap in control being between Fort William and Loch Leven. In contrast, there is less control on the regional biotite isograd; in particular, it is possible that the biotite zone incorporates all of Ardsheal Peninsula (see Fig. 4), as shown on the maps of Bailey (1923) and Elles & Tilley (1930), but not confirmed in this study owing to lack of samples. Of special note are the two downthrown blocks of lower grade (biotite zone) rocks within the Ben Nevis and especially Glencoe complexes, outside of which are garnet zone rocks.

A simplified version of Figure 4 is presented in Figure 3c to allow comparison with the metamorphic maps of Bailey (1923; Fig. 3a) and Elles & Tilley (1930; Fig. 3b). Apart from modest differences in the position of the isograds, the simple overall pattern of metamorphic zones of this study is more like that of Bailey (1923) than that of Elles & Tilley (1930). With regard to the latter, Figure 4 shows the outcrop extent of graphitic slates of the Ballachulish Slate and Transition Series and metapelites of the Appin Phyllite. Examination of the distribution of mineral assemblages in the low-grade part of

the garnet zone, up to *c*. 5 km east of the garnet isograd, shows that garnet-bearing rocks are absent from these two units, apart from a single sample (81-137) in the Appin Phyllite. In contrast, garnet-bearing assemblages are abundant in the other pelitic units in this domain, mainly comprising the Leven Schist and Creran Succession (compare with Fig. 2).

Figure 3d illustrates in a simplified form the garnet-free domain within the low-grade part of the garnet zone. The map pattern of the garnet-free domain shows similarities to the complex map pattern of the garnet isograd of Elles & Tilley (1930), suggesting that the complexity in the Elles & Tilley (1930) metamorphic map may derive more (or entirely) from compositional factors rather than differences in grade. This possibility is tested below. As grade increases to the east of the garnet isograd, garnet develops in all units, including the Ballachulish Slate (e.g. NE margin of the Mullach nan Coirean complex; Figs 2 and 4).

A notable feature of Figure 4 is the intermingling of biotite-bearing and biotite-absent mineral assemblages within the biotite zone. This feature is also seen in the garnet zone, in which garnet-free, biotite-bearing and biotite-absent mineral assemblages are intermingled with garnet-bearing assemblages. The intimate association of different mineral assemblages in the same metamorphic zone implies compositional control. The lowest grade occurrences of biotite are in carbonate-bearing metapelites, such as in exposures of Appin Phyllite interbedded with Appin Limestone near Onich (Fig. 4).

Accepting the most westerly occurrences of biotite in Figure 4 as the low-grade margin of the biotite zone (i.e. the biotite isograd), the chlorite and biotite zones of this study (Fig. 3c and d) resemble the 'mica inconspicuous' and 'mica conspicuous' zones of Bailey (1923) (Fig. 3a). The unusual pattern of the chlorite and biotite zones of Elles & Tilley (1930) (Fig. 3b) does not find support in the distribution of mineral assemblages in Figure 4.

The Bailey–Tilley locality on Loch Leven

Of special note are localities on the south and especially north shore of Loch Leven between Ballachulish and Ballachulish Bridge that became the focus of the Bailey–Tilley debate. A field description of the best exposed locality, on the north shore of Loch Leven (circled in Figs 2 and 3d), is provided on pages 46–50 of the field guide of Pattison & Harte (2001). Figure 5 illustrates features of this locality. Coarsely porphyroblastic garnet-bearing schists of the Leven Schist occur west of the Ballachulish Slide, whereas fine-grained garnet-absent slates of the Ballachulish Slate occur east of the slide. The garnet-absent rocks occur in the direction of increasing metamorphic grade (Figs 2 and 4), the opposite to what is expected if grade alone controlled the development of the mineral assemblages.

Petrography

Figures 5h, i and 6 show photomicrographs of rocks from the area, with the location of the illustrated samples indicated in Figure 4. Figure 6a shows a representative Ms + Chl + Ep + Ab + Qtz + Ilm-bearing phyllite (abbreviations of Kretz 1983) from the Leven Schist just west of the garnet isograd on the north shore of Loch Leven. The dominant penetrative cleavage (S_1) has been deformed by later crenulations to the point of development of an incipient spaced crenulation cleavage (S_2). Although this sample is biotite-free, other rocks in the vicinity are biotite-bearing and have textures resembling those in Figure 6f.

Figures 5h and 6b show garnet-bearing samples of the Leven Schist from the Bailey–Tilley locality, about a kilometre to the east of the sample illustrated in Figure 6a, just upgrade of the garnet isograd. The mineral assemblage is Ms + Chl + Grt + Bt + Ep + Ab

+ Qtz + Ilm. The garnets are partially to wholly altered to chlorite. Both cleavages visible in Figure 6a are present in Figure 5h (weak) and Figure 6b (stronger), with garnet in Figure 6b appearing to overgrow at least the first and possibly the second cleavage.

Figure 5i shows the typical texture of the Ballachulish Slate immediately to the east of the garnetiferous Leven Schist, across the Ballachulish Slide, at the Bailey–Tilley locality. The mineral assemblage is Ms + Chl + Ab + Qtz + Gr + Rut (after Ilm). The grain size is finer than in the nearby garnetiferous schist, and the presence of abundant fine-grained graphite is indicated by the darker colour of the matrix. The dominant schistosity is defined by aligned fine-grained muscovite, chlorite, graphite and elongate rutile pseudomorphs after ilmenite.

Figure 6c shows porphyroblastic garnet and biotite in a rock south of the Ballachulish complex displaying both cleavages. Garnet and biotite overgrow the first cleavage but their relationship to the second crenulation cleavage is uncertain. Figure 6d shows coarser-grained garnet in a chlorite-free rock from well within the garnet zone. Inclusion trails within the garnet preserve a complex differentiated crenulation-foliation fabric, whereas the garnet is wrapped by a crenulation cleavage in the matrix, suggestive of overlap between garnet growth and development of the crenulations. Figure 6e and f shows samples of Leven Schist inside and outside the Glencoe cauldron subsidence. Outside, the schists are garnetiferous, whereas inside, they contain chlorite or chlorite + biotite (Fig. 4), with the biotite showing a porphyroblastic habit that postdates at least the first cleavage, similar to biotite in the other samples illustrated in Figure 6.

In summary, growth of garnet and biotite porphyroblasts in the region appears to have occurred after the development of the first cleavage (S_1) and broadly synchronously with development of an overprinting crenulation cleavage, or set of crenulation cleavages (S_2). Assuming that the S_2 crenulation cleavage is associated with the secondary folds that deform the S_1 cleavage, and that the S_1 cleavage is associated with the major first-phase nappes and slides, metamorphism must have postdated the slides. This conclusion is the same as reached by earlier workers (e.g. Roberts 1976; Phillips & Key 1992), and is consistent with the way the metamorphic isograds transect the stratigraphy, slides and folds in Figures 3 and 4, as originally noted by Bailey (1910, 1922, 1923).

Rock and mineral compositions

Mineral assemblages and compositional data from a representative suite of 12 samples from the area are given in Table 1. The samples are labelled in Figure 4. Apart from garnet, for which core and rim analyses are reported, the listed compositions are single analyses closest to the average composition of the minerals from the matrix of the rock. In samples showing evidence of a contact metamorphic overprint (e.g. samples 81-53 and 81-478, Fig. 4) mineral compositions (e.g. biotite) do not show any systematic within-sample variation. In some samples biotite shows evidence of chloritization, as revealed by low K_2O totals.

Whole-rock major element analyses were performed using conventional techniques in the XRF laboratories at Edinburgh University and McGill University, with carbon and sulphur analyses of selected samples performed in the McGill laboratory using combustion infrared absorption spectroscopy. Minerals were analysed by wavelength-dispersive spectrometry on a Cambridge Instruments Microscan Mark 5 electron microprobe at Edinburgh University and a JEOL JXA-8200 electron microprobe at the University of Calgary using standard operating conditions (15 kV; 20 nA; focused beam) and a range of well-characterized natural and synthetic standards (e.g. Nicholls & Stout 1988).
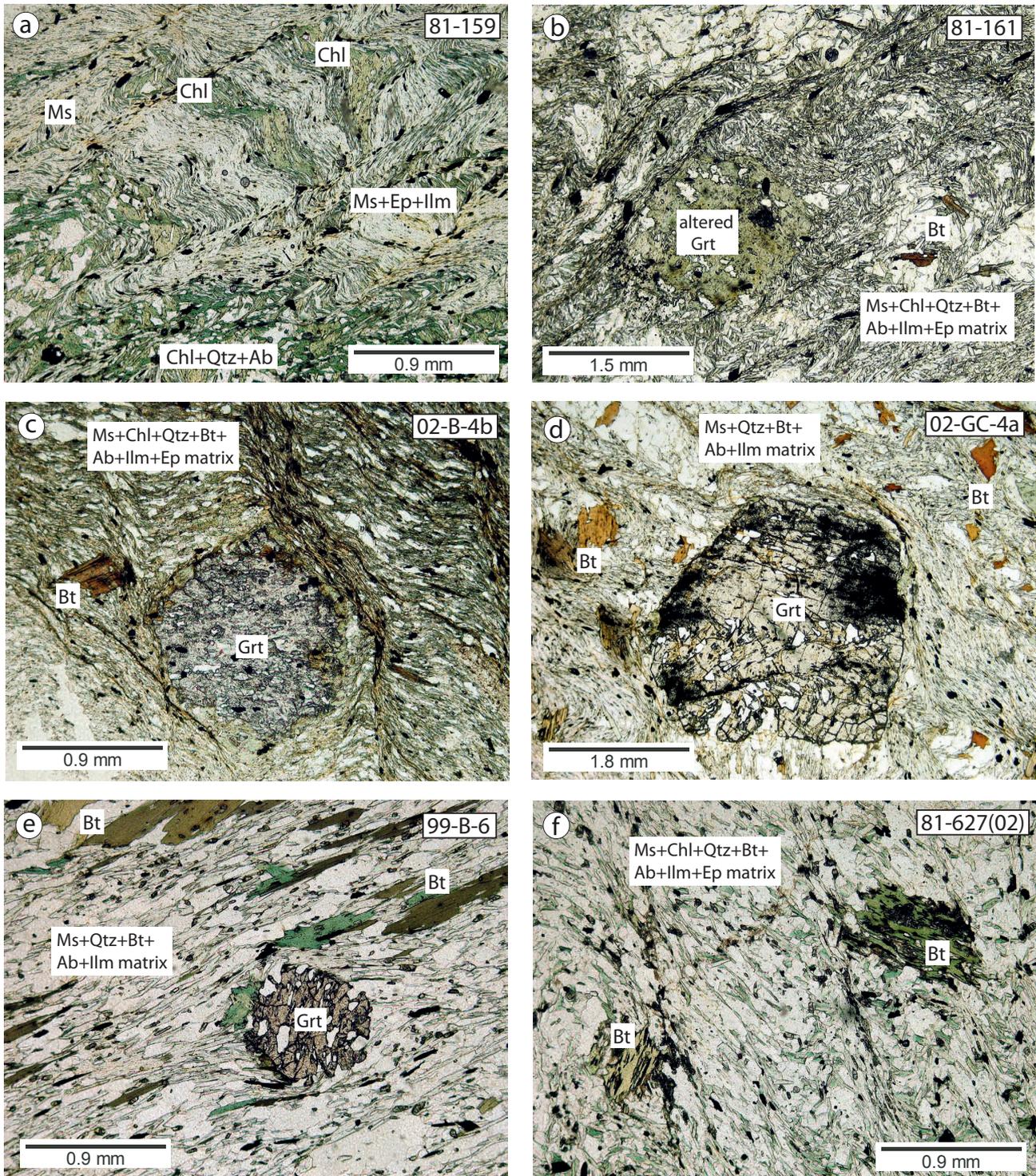
Fig. 6. Photomicrographs discussed in the text. Locations of samples shown in Figure 4. (**a**) Garnet- and biotite-free sample of Leven Schist from about 1 km west of the Bailey–Tilley locality, showing incipient development of a S_2 crenulation cleavage that deforms the penetrative S_1 cleavage. (**b**) Garnet-bearing sample of Leven Schist from the Bailey–Tilley locality, showing S_1 cleavage kinked and deflected into a spaced S_2 crenulation cleavage. Garnet, entirely replaced by chlorite, appears to overprint both cleavages. (**c**) Garnet and biotite porphyroblasts in sample of Creran Formation metapelite, south of the Ballachulish Complex, showing wavy S_1 cleavage deformed into a spaced S_2 crenulation cleavage. Garnet and biotite overgrow the S_1 cleavage but show ambiguous relationships with the S_2 cleavage. (**d**) Coarse garnet-bearing sample 2 km east of Glencoe village, in which garnet overgrows a complex crenulated fabric but is itself weakly wrapped by the foliation. (**e**) Garnet + biotite-bearing metapelite 2 km west of the Glencoe cauldron subsidence. Inclusion trails in garnet are at a high angle to the enclosing matrix foliation, and asymmetric muscovite concentrations on the margins of the garnet are suggestive of rotation of the garnet during or after growth. (**f**) Biotite-bearing, garnet-free metapelite from within the Glencoe cauldron subsidence, showing incipient development of a spaced crenulation cleavage that deforms an earlier, penetrative S_1 cleavage. Biotite porphyroblasts overgrow the penetrative cleavage but show ambiguous relationships with the S_2 cleavage.

Table 1. *Summary of whole-rock and mineral compositions*

Sample	Stratigraphic unit	Assemblage*	WR Mg#	WR Mg# (−S)	WR Mg# (−S, −Ti)	WR A	WR Mn#	WR Ca#	X_{Mn} Grt core	X_{Mn} Grt rim	X_{Ca} Grt core	X_{Ca} Grt rim	X_{Fe} Grt core	X_{Fe} Grt rim	X_{Mg} Grt core	X_{Mg} Grt rim	Mg# Bt	Mg# Chl	Si p.f.u. Ms	X_{An} Pl
81-157	LS	ChlEpIlm	0.377	0.378	0.405	−0.022	0.006	0.080	–	–	–	–	–	–	–	–	–	0.395	3.19	0.015
92-B-1b	LS	GrtBtChlEpIlm	0.339	0.341	0.375	0.119	0.012	0.071	0.148	0.054	0.270	0.201	0.556	0.704	0.026	0.041	0.342	0.376	3.12	0.024
81-0161	LS	GrtBtChlEpIlm	0.357	0.358	0.390	−0.071	0.009	0.049	0.149	0.096	0.252	0.223	0.568	0.641	0.031	0.040	0.377	0.414	3.16	0.008
81-478	LS	GrtBtChlIlm	–	–	–	–	–	–	0.157	0.115	0.244	0.225	0.573	0.628	0.026	0.032	0.363	0.396	3.20	0.004
81-53	LS	GrtBtChl(2)Ilm	–	–	–	–	–	–	0.225	0.151	0.211	0.197	0.536	0.612	0.028	0.040	0.387	0.420	3.26	0.006
Leven Schist and Creran Formation (n = 8) Average			0.347	0.347	0.380	0.056	0.009	0.052												
SD			0.020	0.021	0.021	0.086	0.003	0.017												
92-B-1a	BS	ChlRtPoPyGr	0.501	0.509	0.509	0.207	0.003	0.015	–	–	–	–	–	–	–	–	–	0.508	3.13	–
81-564	BS	ChlRtPoPyGr	0.550	0.568	0.568	0.193	0.004	0.003	–	–	–	–	–	–	–	–	–	0.608	3.12	0.005
81-176	BS	ChlRtPoPyGr	0.575	0.595	0.595	0.220	0.003	0.010	–	–	–	–	–	–	–	–	–	0.633	3.22	–
Ballachulish Slate (n =12) Average			0.541	0.560	0.560	0.240	0.004	0.013												
SD			0.046	0.050	0.050	0.028	0.001	0.021												
81-16	AP	BtChlIlm	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.520	0.536	3.33	–
81-151	AP	BtIlm	0.445	0.445	0.480	−0.390	0.004	0.032	–	–	–	–	–	–	–	–	0.582	–	3.28	–
83-670	AP	BtChlIlm	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.481	0.517	3.24	–
81-137	AP	Grt(a)BtChlIlm	0.384	0.384	0.417	0.263	0.006	0.001	–	–	–	–	–	–	–	–	0.363	0.410	3.15	–
Appin Phyllite (n = 8) Average			0.471	0.471	0.507	0.063	0.005	0.019												
SD			0.103	0.103	0.102	0.261	0.003	0.011												

*All assemblages contain Ms + Qtz + Ab + accessory phases. SD = 1σ standard deviation.

Mineral abbreviations from Kretz (1983). Grt(a), altered garnet; Chl(2), secondary chlorite; LS, Leven Schist; BS, Ballachulish Slate; AP, Appin Phyllite; WR, whole-rock; Mg# = Mg/(Mg + Fe); Mg# (−S) = Mg/(Mg + Fe), after projection from pyrrhotite; Mg# (−S, −Ti) = Mg/(Mg + Fe), after projection from pyrrhotite and ilmenite (not for Rt-bearing BS); A = (Al − Na − 2Ca − 3K)/2; Mn# = Mn/(Mn + Fe + Mg + Ca); Ca# = Ca/(Mn + Fe + Mg + Ca); X_{Mn} = Mn/(Mn + Fe + Mg + Ca); X_{Ca} = Ca/(Mn + Fe + Mg + Ca); X_{Fe} = Fe/(Mn + Fe + Mg + Ca); X_{Mg} = Mg/(Mn + Fe + Mg + Ca); Si p.f.u. in Ms = Si cations for 11 oxygens; X_{An} = Ca/(Ca + Na).
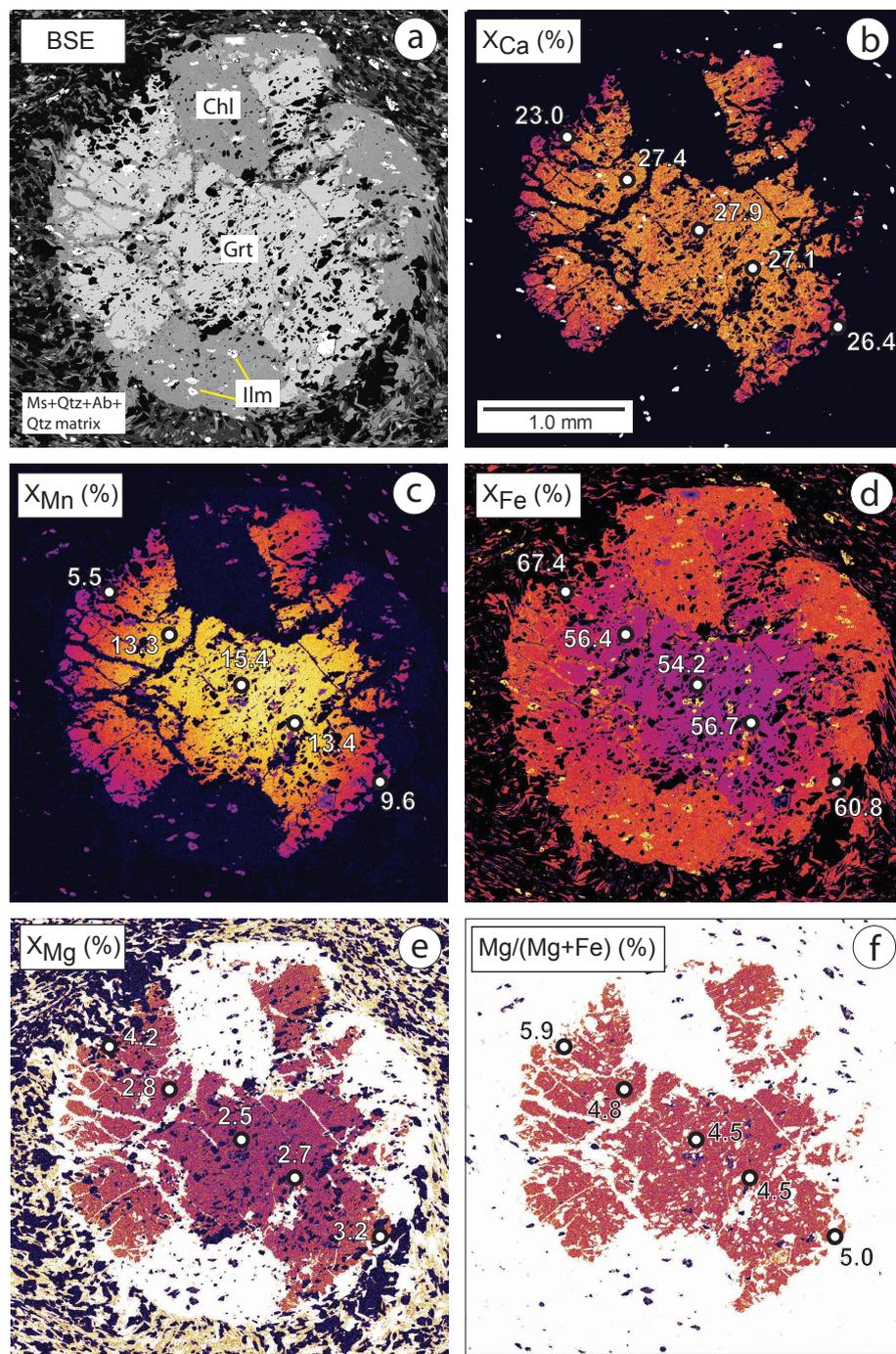
Fig. 7. Back-scattered electron image and maps of elemental zonation of the garnet in Figure 5h from the Bailey–Tilley locality. (**a**) Back-scattered electron image with location of quantitative analysis spots. (**b**) Ca zonation. X_{Ca} (%) = 100 × Ca/(Ca + Fe + Mg + Mn). (**c**) Mn zonation. X_{Mn} (%) = 100 × Mn/(Ca + Fe + Mg + Mn). (**d**) Fe zonation. X_{Fe} (%) = 100 × Fe/(Ca + Fe + Mg + Mn). (**e**) Mg zonation. X_{Mg} (%) = 100 × Mg/(Ca + Fe + Mg + Mn). (**f**) Zonation in per cent Mg/(Mg + Fe).

Garnet composition and zoning

Table 1 lists core and rim analyses of garnet, and Figure 7 shows maps of element zoning in a representative garnetiferous sample from the Bailey–Tilley locality (see Figs 4 and 5). The zoning is generally smooth going from core to rim, ranging in Ca:Mn:Fe:Mg from 21–27:15–22:54–57:2–3 in the cores to 20–23:5–15:61–70:3–4 in the rims.

Correlation between mineral assemblages and rock compositions

Figure 8 is an AFM plot of the mineral and whole-rock data, grouped by lithological unit (Leven Schist/Creran Formation, Ballachulish

Slate, Appin Phyllite). The samples from the Leven Schist/Creran Formation are all garnet-bearing with the exception of sample 81-157, illustrated in Figure 6a. Metapelites of the Leven Schist/Creran Formation and Ballachulish Slate units show relatively small variations in composition, as indicated by their small 1σ standard deviations (Table 1 and Fig. 8). In contrast, the metapelites of the Appin Phyllite show a broader range in composition.

The compositional differences between the units are strongly correlated with the different mineral assemblages they develop. The garnetiferous rocks, with one exception all from the Leven Schist/Creran lithologies, are the richest in iron, whereas the garnet- and biotite-free Ballachulish Slate assemblages are the most magnesian and aluminous. Samples from the compositionally diverse Appin Phyllite have an average composition between these two extremes,
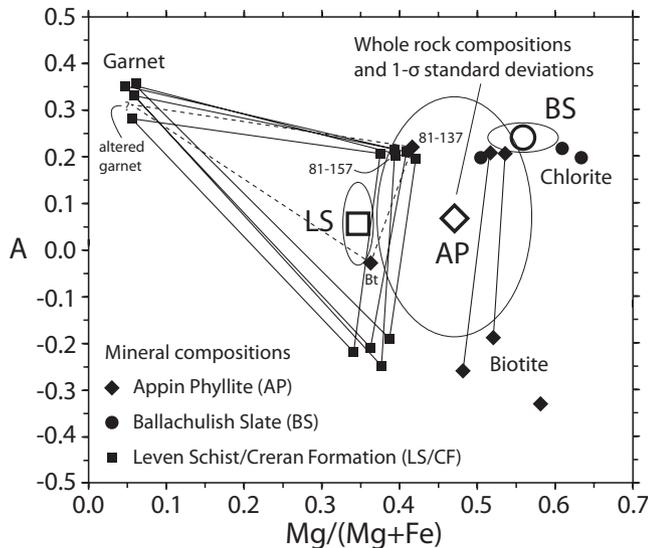
Fig. 8. AFM-type diagram showing plotting position of mineral and rock compositions from Table 1. A = (Al − Na − 2Ca − 3K)/2 (cations), representing a projection from the albite and anorthite components of plagioclase and from muscovite. Large open symbols within ellipses portray the mean and 1σ standard deviation of the whole-rock compositions. Dotted lines join mineral compositions from sample 81-137, in which garnet is completely replaced by chlorite and biotite has undergone partial chloritization. Locations of samples are shown in Figure 4.

typically developing garnet-free, biotite + chlorite-bearing assemblages, with the exception of one Fe-rich sample (81-137) that contains garnet.

Figure 8 shows that differences in Mg/(Mg + Fe) of the metapelites can account for the distribution of mineral assemblages in the vicinity of the garnet isograd. Other important compositional distinctions amongst the units, not illustrated in Figure 8, are listed in Table 1. In addition to being richest in iron, metapelites of the Leven Schist/Creran Formation are the richest in Mn and Ca, whereas metapelites of the Ballachulish Slate are low in both elements; metapelites of the Appin Phyllite on average have intermediate values. Elevated Mn and Ca both favour the development of garnet, as revealed by phase equilibrium modelling (below).

In contrast to the compositional control on the mineral assemblages, garnet- and biotite-free sample 81-157 from the Leven Schist (Fig. 6a) has whole-rock and chlorite compositions similar to those of the garnetiferous samples from the same unit to the east and south (Table 1 and Fig. 8). In this case, the difference in mineral assemblage most probably reflects a difference in metamorphic grade, as indicated by the garnet isograd that separates them (Fig. 4).

Phase equilibrium modelling

Phase diagrams for the different bulk compositions (Figs 9–11) were calculated in the 10-component chemical system MnNCKFMASHT (MnO–Na$_2$O–CaO–K$_2$O–FeO–MgO–Al$_2$O$_3$–SiO$_2$–H$_2$O–TiO$_2$, with C and P$_2$O$_5$ deleted from the whole-rock analysis, followed by projection from pyrrhotite). Pattison & Tinkham (2009, pp. 264–265) discussed differences between phase diagrams calculated using different chemical systems for a typical pelitic bulk composition. The advantages of the 10-component system, compared with simpler chemical systems such as KFMASH, are that: Ca and Mn are significant components of, and stabilize, garnet; epidote is common in

several rocks; the presence of albite v. Ca-bearing plagioclase is of petrological significance; and Ti-bearing oxides (including ilmenite, which sequesters Fe) are ubiquitous. The component Fe^{3+}, although present in epidote, was not included in the model chemical system because of the unknown Fe^{3+} content of the other minerals; epidote stability is discussed separately below.

The phase diagrams were calculated using the Theriak-Domino phase equilibrium modelling software (de Capitani & Brown 1987; de Capitani & Petrakakis 2010). The average compositions of the three lithological units is given in the caption to Figure 10. In the Theriak algorithm, sufficient oxygen was added to the bulk composition to achieve electroneutrality. Sixty moles of hydrogen (equivalent to 30 moles H$_2$O) were added to the anhydrous bulk composition to ensure that a_{H2O} was unity across the phase diagram (equivalent to aqueous fluid being available as a possible reactant or product across the diagram). The effect of C-bearing fluid species in the metamorphic fluid in graphitic rocks has been ignored because it results in only minor (<10 °C) displacements of the phase boundaries at the calculated P–T conditions (Connolly & Cesare 1993; Pattison 2006).

The thermodynamic database used for the calculations is that of Holland & Powell (1998), updated to dataset 5.5 in 2003 that incorporates the Al$_2$SiO$_5$ triple point of Pattison (1992). Activity models used in all calculations are those used by Tinkham & Ghent (2005) with the following exceptions: (1) margarite was not considered as a component in white mica; and (2) the ternary feldspar model of Holland & Powell (2003), using a molecular mixing model and asymmetric formalism, was used instead of separate plagioclase and pure orthoclase or sanidine.

Garnet stability

Figures 9a–c show the position of the garnet-in line for single samples, and the average composition, of the three lithological units. Figure 9d compares the position of the garnet-in line for the average composition of each of the three units. The garnet-in line occurs at the lowest grade in the Leven Schist/Creran Formation metapelites and at the highest grade in the Ballachulish Slate, the separation between the two garnet-in lines being of the order of 40–60 °C, depending on pressure. The implication is that at the conditions of the garnet isograd, garnet was stable in the Leven Schist rocks but not in the Ballachulish Slate and Appin Phyllite rocks, consistent with the inferences from Figure 8. The development of garnet in all units, including the Ballachulish Slate, further to the east implies an eastward increase in metamorphic grade, consistent with the eastward-facing distribution of the chlorite, biotite and garnet zones in Figures 1 and 4. This implies that the mineralogical effects of compositional differences amongst units are most accented in the low-grade part of the garnet zone, the effects diminishing as garnet becomes stable in a wider range of bulk compositions as grade increases.

Porphyroblast-forming reactions

Garnet-forming reaction

The garnet-forming reaction is of the form

$$Ms + Chl + Ep + Qtz + Ilm = Grt + Bt + H_2O \qquad (1)$$
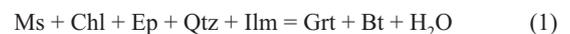
(Pattison & Voll 1991), wherein epidote provides the Ca component of garnet, and ilmenite provides the Ti component of biotite and perhaps some of the Mn component of garnet (see Pattison & Tinkham 2009). A more quantitative mass balance can in principle be derived using the Theriak software (de Capitani 1987) by subtracting the
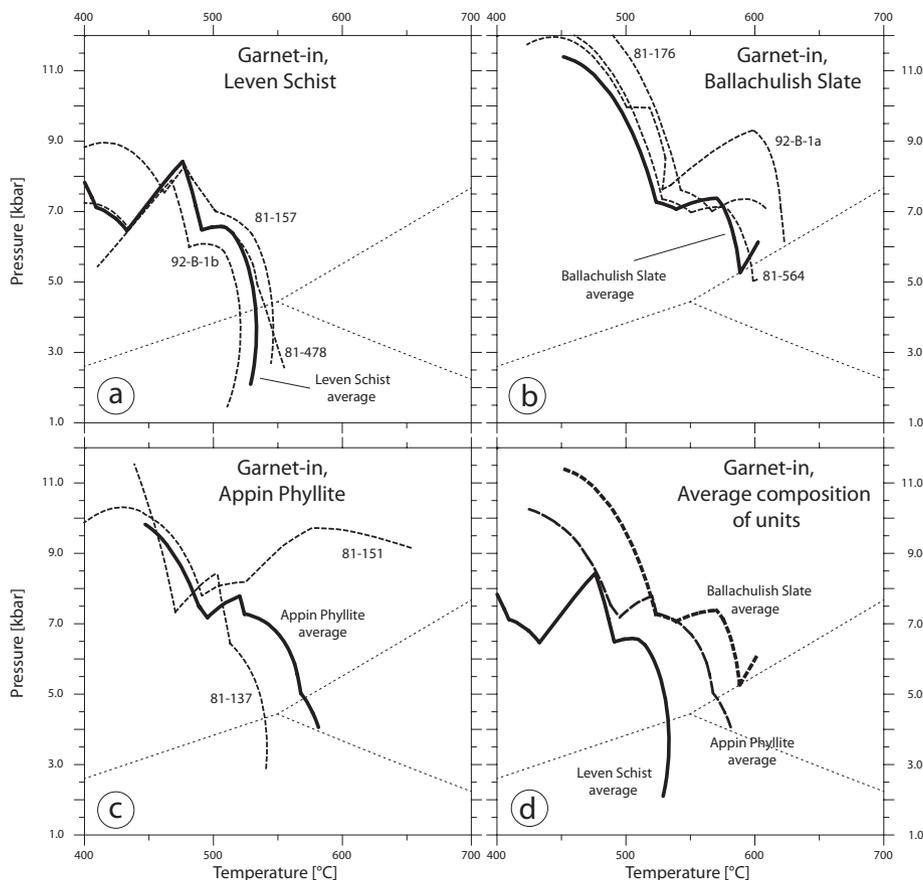
Fig. 9. Calculated position of the garnet-in line for average compositions and single samples of the three lithological units. Compositional data for the average compositions of the three lithological units are listed in the caption to Figure 10. Locations of samples are shown in Figure 4.

thermodynamically predicted moles of phases above and below the garnet-in line for the average Leven Schist composition (470 and 500 °C, respectively, for a pressure of 7.0 kbar), and renormalizing to 1 mole of garnet produced. The result is

$$0.89Ms + 3.78Chl + 0.52Czo + 5.77Ab + 0.36Ilm =$$
$$1.00Grt + 7.48Bt + 11.06Qtz + 8.78H_2O. \quad (2)$$
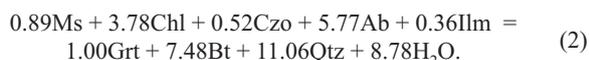
Whether reaction (2) is a better representation of the natural reaction than reaction (1) depends on two main factors. First, the stoichiometry of reaction (2) is specific to the bulk composition and is influenced by the predicted compositional changes with grade of the modally abundant white mica (*c.* 35% of the predicted modal mineralogy for this bulk composition). Increase of the paragonite (Na) component with grade in white mica results in albite being a reactant; the exchanged muscovite (K) component contributes to biotite production; decrease in the celadonite component of white mica with grade contributes further to biotite production. The result is modal mismatch between muscovite (reactant) and biotite (product), the magnitude of which depends on the thermodynamic activity–composition models. The second factor is that application of the above reaction to the natural rocks assumes continuous compositional equilibration between the minerals during progressive metamorphism, an assumption that has been questioned by Dempster (1992) in the case of white micas.

Biotite-forming reaction

Biotite formation in the carbonate-bearing metapelites, such as in the Appin Phyllite near Onich (Figs 2 and 4), was due to a reaction of the form

$$Ms + Dol + Qtz + H_2O = Bt + Chl + Cal + CO_2 \quad (3)$$

(Pattison & Voll 1991). In carbonate-free rocks, biotite most probably grew in response to decrease in the Tschermak (celadonite) component in chlorite and muscovite:

$$Ms + Chl = Bt + (Fe,Mg)_{-1}Si_{-1}Al_2 + Qtz + H_2O \quad (4)$$
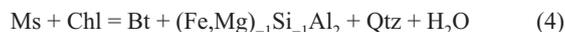
(Mather 1970; Pattison 1987). Taking the same approach as described above for garnet-forming reaction (2), a biotite-forming reaction was estimated by subtracting the predicted moles of phases at two temperatures within the biotite zone, and renormalizing to 1 mole of biotite produced (470 and 480 °C, respectively, for a pressure of 7.0 kbar). The result is

$$0.21Ms + 0.44Chl + 0.69Ab + 0.05Ilm =$$
$$1.00Bt + 1.56Qtz + 0.98H_2O. \quad (5)$$
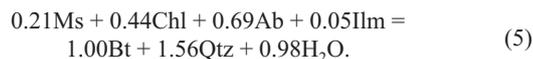
The reaction bears similarities to the simple KFMASH reaction (4) above. The Tschermak exchange, in addition to the other compositional exchanges described in garnet-forming reaction (2), are incorporated in reaction (5). The same caveats for reaction (2) apply to reaction (5).

Pressure–temperature conditions

P–T *estimation from mineral assemblages*

Figure 10a–c shows isochemical phase diagram sections for the average composition of the three lithological units, focusing on

Fig. 10. Calculated phase diagrams for the average compositions of the three lithological units. The observed mineral assemblages in samples close to the garnet isograd are shaded. (**a**) Composition (in moles) of average Leven Schist. Si, 103.16; Ti, 1.23; Al, 34.92; Fe, 9.50; Mn, 0.14; Mg, 5.05; Ca, 0.81; Na, 6.39; K, 8.35. (**b**) Composition (in moles) of average Ballachulish Slate. Si, 100.98; Ti, 1.05; Al, 39.12; Fe, 6.71; Mn, 0.07; Mg, 8.54; Ca, 0.22; Na, 4.84; K, 8.07. (**c**) Composition (in moles) of average Appin Phyllite. Si, 104.09; Ti, 1.02; Al, 35.66; Fe, 7.72; Mn, 0.08; Mg, 6.89; Ca, 0.21; Na, 4.84; K, 9.52. (**d**) Overlap of mineral assemblage stability fields.

mineral stability fields pertinent to the rocks under consideration. The *P–T* domains represented by the observed mineral assemblages in the vicinity of the garnet isograd are shaded.

Zoisite rather than clinozoisite is predicted to be stable in the Fe^{3+}-free phase diagrams. The phase boundaries involving zoisite, in particular the important zoisite-out/intermediate plagioclase-in phase boundary in Figure 10, are displaced down-temperature by an average of 10 °C if clinozoisite rather than zoisite is involved in the reactions (Pattison & Seitz 2012). For the natural rocks under consideration, however, this effect is counterbalanced by the presence

of Fe^{3+} in epidote. Moynihan & Pattison (2013) calculated that, relative to pure clinozoisite, the maximum up-temperature displacement of the clinozoisite-out/intermediate plagioclase-in phase boundary for Fe^{3+}-bearing epidote in a magnetite-free metapelite was 20 °C. The position of the curve in Figure 10 therefore lies in the middle of an uncertainty band of about 20 °C. Another feature of note in Figure 10 is a fairly substantial predicted stability field, mainly at moderate to high pressure, of coexisting K-rich and Na-rich white mica (paragonite). The reliability of this prediction is uncertain; no paragonite was noted in the samples.

Fig. 11. Pressure–temperature estimates in relation to key mineral stability boundaries. (**a**) Garnet isopleth intersections (core and rim) and key mineral stability boundaries for sample 92-B-1b, assuming no fractionation. (**b**) Garnet isopleth intersections (core and rim) and key mineral stability boundaries for sample 81-478, assuming no fractionation. (**c**) Garnet rim isopleth intersections and key mineral stability boundaries for sample 92-B-1b, assuming fractionation. Dashed mineral stability boundaries and garnet core isopleths are for the unfractionated starting composition (same as in Fig. 11a); solid mineral stability lines and garnet rim isopleths are for the fractionated composition. The fractionation path is the labelled bold solid black line. (**d**) Summary of P–T estimates from garnet core isopleth intersections and overlap of mineral stability fields (Fig. 10d), plotted with respect to the garnet-in line for the average composition of the three lithological units (Fig. 9d). X_{sps} = Mn/(Mn + Fe + Mg + Ca). X_{grs} = Ca/(Mn + Fe + Mg + Ca). X_{alm} = Fe/(Mn + Fe + Mg + Ca). Locations of samples are shown in Figure 4.

The P–T stability fields for mineral assemblages of the Leven Schist and Appin Phyllite in the vicinity of the garnet isograd (Fig. 10a and c) provide fairly tight constraints on P–T conditions, whereas the constraints provided by the Ballachulish Slate mineral assemblage (Fig. 10b) are broader. When the three mineral assemblage stability fields are superimposed on each other, they overlap in a small P–T interval of 6.5–7.1 kbar, 485–495 °C (Fig. 10d). The apparent tightness of the constraint almost certainly exaggerates the real precision of the estimate. Waters & Lovegrove (2002) and Powell & Holland (2008) discussed the numerous sources of error in the calculation of phase diagram sections and the assessment of natural mineral assemblages therein. A realistic estimate of uncertainty on the above P–T estimate is probably at least ±0.5 kbar and ±25 °C, but probably not more than ±1.0 kbar and ±50 °C.

P–T *estimation from garnet compositions*

Figure 11a and b shows isopleths of X_{Ca}, X_{Mn} and X_{Fe} for the core and rim compositions of garnet from samples 92-B-1b and 81-478, respectively. Isopleth intersections for garnet cores from the two samples are tight and nearly coincident at 510–515 °C, 6.8–7.0 kbar. They fall above the garnet-in line and close to the chlorite-out and zoisite-out/intermediate plagioclase-in lines, albeit a little above the latter, broadly consistent with the mineral assemblage constraints. The results are in the same pressure range but *c.* 20 °C higher than the P–T results from analysis of the mineral assemblages (Fig. 10d).

Garnet rim compositions for the two samples were plotted on the same set of calculated isopleths. The resultant P–T conditions are too high to reconcile with the mineral assemblages. To take account of modification of the reactive bulk composition owing to fractional growth of garnet, prograde fractionation paths were calculated for sample 92-B-1b using Theriak-Domino. Because the actual P–T path of the samples is unknown, the P–T path showing the most extreme fractionation is shown in Figure 10c, corresponding to a P–T path of increasing temperature and pressure passing through the garnet core temperature. Garnet was removed at 0.5 °C intervals between 6.0 kbar, 480 °C, the garnet-in line for the unfractionated bulk composition, and 7.0 kbar, 520 °C. During fractionation, the garnet-in line for the evolving, fractionated composition is continuously displaced as the matrix is depleted in garnet-forming components (mainly Mn). The garnet-in and chlorite-out lines for the end of the fractionation path are shown in Figure 10c.

The garnet rim isopleths for the fractionated composition intersect at *c.* 540 °C, 6.8 kbar, *c.* 50 °C higher than the phase equilibrium estimate and *c.* 30 °C higher than the garnet core estimate. These estimates are difficult to reconcile with the presence of albite and epidote rather than intermediate plagioclase in the rocks, and the physical location of the samples barely into the garnet zone (Fig. 4). The latter suggests that the conditions for garnet growth were only just reached, and that the temperatures did not rise substantially above conditions of initial garnet growth.

P–T *estimation from geothermobarometry*

Pattison & Voll (1991) presented geothermobarometric estimates for garnetiferous samples from near the garnet isograd. Using the Hodges & Spear (1982) calibration of the garnet–biotite geothermometer, which takes account of Mn and Ca in garnet, four samples (garnet rim compositions; data in Table 1) gave an average of 485 °C within a range of 467–506 °C, similar to the estimates above. The results for samples within the outer part of the Ballachulish aureole (81-53 and 81-478, Fig. 4) were not systematically different from those outside the aureole (81-161 and 92-B-1). The phengite geobarometer of Powell & Evans (1983) was applied to eight samples containing the subassemblage Ms + Chl + Bt + Qtz, yielding pressures from 8.6 to 12.2 kbar at 500 °C (Pattison 1985, pp. 418–420), much higher than the *c.* 7 kbar estimate of this paper. The high and variable pressures are probably due to a combination of calibration inaccuracy and lack of equilibration within and between minerals (see Dempster 1992), the latter suggested by the range in Si cations per formula unit in white mica in the samples (3.12–3.33 for an 11-oxygen formula unit; Table 1).

Summary of P–T *estimation*

Figure 11d is a summary diagram of P–T estimates. The results are broadly self-consistent in that they satisfy the observation that garnet occurs in the low-grade part of the garnet zone in the Leven Schist/Creran Formation lithologies, but not the Appin Phyllite and Ballachulish Slate lithologies (with the one exception from the

Appin Phyllite). From Figure 11d, the P–T conditions of the garnet isograd in the Ballachulish area are interpreted to be *c.* 500 °C and *c.* 7 kbar, implying a transitory geothermal gradient at the time of metamorphism of *c.* 20 °C km^{-1}, assuming an average rock density of 2.8 g cm^{-3}.

Comparison of *P–T* results at Ballachulish with *P–T* conditions of the garnet zone elsewhere in the SW and central Highlands

Although not directly pertaining to the Bailey–Tilley debate, the P–T results obtained at Ballachulish bear on reported P–T estimates of the garnet zone elsewhere in the SW and central Highlands. Figure 1 shows that Ballachulish lies on the edge of a large domain of garnet zone metamorphism SW of a domain of higher grade metamorphism characterized by staurolite, kyanite and sillimanite zones.

Thirty-five kilometres to the NE of the Ballachulish area, between Spean Bridge and Roy Bridge (location 1 in Fig. 1), samples of the Leven Schist from the garnet zone contain the assemblage Ms + Bt + Grt + Ep + Qtz + oligoclase ± Chl ± Cal (Richardson & Powell 1976). P–T estimates from multi-equilibrium geothermobarometry range from 5.0 to 7.5 kbar (Richardson & Powell 1976; Powell & Holland 1994) within a temperature range of 520–550 °C. The results are similar in pressure but a little higher in temperature than at Ballachulish, consistent with the presence of intermediate plagioclase rather than albite, the occurrence of garnet in graphitic schists as well as non-graphitic schists, and the occurrence of staurolite-bearing schists 7 km NE of the analysed samples (Phillips & Key 1992).

Eighty kilometres to the SW of Ballachulish, in the Tayvallich–Knapdale area (location 2 in Fig. 1), P–T conditions of the garnet zone were estimated from thermobarometry to be 8–12 kbar, 480–530 °C (Graham *et al.* 1983; Skelton *et al.* 1995; Vorhies & Ague 2011). The pressure estimates are largely based on the Powell & Evans (1983) phengite barometer that at Ballachulish yielded a range of 9–12 kbar. Where present, metapelitic mineral assemblages (Graham *et al.* 1983, fig. 6) are similar to those at Ballachulish, including presence of albite rather than Ca-bearing plagioclase. Based on a small number of published analyses (Graham *et al.* 1983; Vorhies & Ague 2011), mineral compositions fall within the same range as at Ballachulish, although the celadonite component of the four published white mica analyses (3.22–3.37 Si cations per formula unit) appears to be a little higher. In the absence of demonstrably higher pressure mineral assemblages or mineral compositions (e.g. paragonite, white mica distinctly richer in the celadonite component), the pressures in the Tayvallich–Knapdale region may not therefore be very much, if at all, higher than the *c.* 7 kbar estimate at Ballachulish (see also Dempster 1992).

Similar comments may apply to 8–11 kbar, 500–600 °C estimates from thermobarometry for the garnet zone in the south–central and central Highlands (Moles 1985; Watkins 1985; Vorhies & Ague 2011). The locations are labelled as 3 and 4 in Figure 1, and occur within Region III of Vorhies & Ague (2011). These P–T conditions are mostly above the upper stability limit of Ca-bearing plagioclase in common metapelites (see, e.g. Fig. 10; Pattison & Tinkham 2009, fig. 11; Pitra *et al.* 2010, fig. 7; Skrzypek *et al.* 2011, fig. 8; Vorhies & Ague 2011, fig. 13; Palin *et al.* 2012, fig. 10a). Yet, Ca-bearing plagioclase is reported in most of the mineral assemblages from this region, including in the samples used in the thermobarometry. In addition, the reported celadonite component of white mica is in the same range but overall lower than at Ballachulish and Tayvallich–Knapdale (3.12–3.24 Si cations per formula unit; Vorhies & Ague 2011), suggestive of some combination of lower pressure or higher temperature. The reported

8–11 kbar pressure estimates therefore seem high, perhaps by as much as 2–3 kbar, with respect to mineralogical considerations and in comparison with adjacent regions. In summary, peak metamorphic pressure for much of the broad garnet zone in the SW Highlands (Fig. 1) may be more in the *c.* 6–8 kbar range, although further work is required.

The Bailey–Tilley debate

The results of this study extend the pioneering work of Bailey, Tilley, Elles and their contemporaries on the metamorphism of the SW Highlands. With respect to the Bailey–Tilley debate, the evidence in this paper favours Bailey's contention that difference in bulk composition rather than difference in grade was the primary cause of the abrupt loss of garnet going upgrade in the Ballachulish area. Interestingly, Bailey's specific suggestion that the presence of graphite in the Ballachulish Slate was the primary compositional factor is probably misplaced. Graphite introduces carbon-bearing fluid species into the metamorphic fluid, reducing the thermodynamic activity of water and therefore promoting rather than retarding reaction (French 1966; Connolly & Cesare 1993). The magnitude of this effect at the *P–T* conditions of the Ballachulish region, however, is likely to be small (<10 °C; Connolly & Cesare 1993; Pattison 2006).

Other aspects of Bailey's interpretation of the metamorphism and structure of the SW Highlands also find support in this paper. Barring details, Bailey's mineral assemblage zones in the study area are essentially the same as the ones in this paper. His contention that metamorphism developed in the latter stages of, rather than before, the major folding and deformation events is also widely acknowledged.

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