Setting and summary of geology

Introduction

The Ballachulish (pronounced Ba-la-HOO'-lish) Igneous Complex and Aureole is one of the world's most comprehensively studied plutonic-metamorphic systems (Voll et al., 1991: Pattison & Marie, 1997). It has received this attention because it represents a relatively simple intrusive complex emplaced in host rocks showing a wide range of lithologies, leading to a great diversity of products of contact metamorphism. In addition, the area is easily accessible and the exposure is generally very good.

Two of the earliest references to the geology of the Ballachulish Complex are those of MacCulloch (1817) and MacKnight (1821) MacCulloch, an exponent of the Huttonian view of geology. drew attention to the way in which the intrusive rocks metamorphosed the host mica schists, sent veins into them. and contained many fragments of the schists as inclusions; whereas MacKnight, who was influenced by Wernerian theories, viewed the contact-altered rocks around the intrusion as gneisses occupying their normal position in a granite–gneiss–mica slate–clay slate succession. Bailey & Maufe's Geological Survey memoir (1916 first edition, revised 1960) provided the first comprehensive summary of the geology of the igneous complex and aureole, largely based on work in the two previous two decades by members of the Geological Survey.

From 1981 to 1991, the Ballachulish Igneous Complex and Aureole was the focus of an international multidisciplinary study examining equilibrium and kinetic processes in and around cooling plutons (Voll et al. 1991, and references therein). Since then, it has been used as a natural laboratory for investigating a wide range of igneous and metamorphic. The results of these studies have allowed an unusually detailed understanding of the physical and temporal evolution of the igneous complex and aureole such that, in a broader sense, the complex may serve as a type example of the intrusive process at moderate crustal depths (Paulson & Harte, 1997).

This guide has been prepared to encourage examination of the excellent field exposures of the igneous complex and aureole. Itineraries for five days of field excursions have been prepared, with an emphasis on petrological aspects, and are given in Part 2. In this first part we provide an overview of the main features of the igneous complex, host rocks and aureole. The Coloured Map (Map 1), in the back pocket of this guide, provides a summary of the main features of the Ballachulish Igneous Complex and Aureole.

The Southwest Scottish Highlands and the development of geological studies

The geology of the SW Highlands of Scotland is amongst the most renowned in the world. In the course of mapping this area at end of the nineteenth and the beginning of the twentieth century, members of the Geological Survey of Scotland such as C.T. Clough, E.B. Bailey and H.B. Maufe were able to use their field observations to introduce new concepts to many aspects of geological studies. The details of small-scale structures in the Dalradian rocks, under the analytical eve of C.T. Clough (1897), were first recognised as providing evidence of complex multi-phase structural and metamorphic histories in the Earth's crust, and provided the foundation for subsequent studies in the Scottish Highlands and throughout the world. The diversity of the Dalradian rocks, preserving evidence of sedimentary as well as metamorphic history, furthered Bailey's keen identification of rock types and Wrapping of lithostratigraphic relationships, leading to structure analysis and the application of the concepts of recumbent fold and nappe tectonics (Bailey, 1910). Also in this region, Bailey (1923) and Elles & Tilley (1930) further extended and debated the significance of the system of metamorphic zones first established by Barrow (1893) in the eastern Dalradian. Nearby, Wiseman (1934) applied similar concepts to the interpretation of mineral assemblages in metabasite rocks.

Erupting through the metamorphic rocks is an extremely wide variety of igneous rocks. In particular, the rocks of Glen Coe allowed Clough, Manic & Bailey (1909) to give the first account of the exposed subterranean structure of a volcanic cauldron. It was also classic territory for the early application of the concepts of fractional crystallisation and geochemical evolution to the understanding and petrogenetic evolution of natural igneous rocks (e.g. Nockolds Mitchell, 1948).

Field descriptions of many of the features of the SW Highlands are already available, not least through the original descriptions contained in the Memoirs of the Geological Survey of Scotland (see Bailey & Maufe, 1960 for the Ballachulish area). The interested reader is encouraged to contact the British Geological Survey, Murchison House, West Mains Rd, Edinburgh, for available geological maps, field guides and memoirs.

Regional setting of the Ballachulish Igneous Complex

The following synopsis of the regional geology sets the scene in a broad-brush manner for those unfamiliar with Scottish geology. The Ballachulish Igneous Complex and Aureole are located in Argyllshire, west Scotland, at the SE junction of Lochs Linnhe and Leven (Coloured Map (Map 1), (Figure 1) and (Figure 2). and (Photo 1), (Photo 2), (Photo 3)). The igneous complex is one of an extensive array of igneous complexes of cafe-alkaline affinity that intruded metamorphic rocks of the Scottish Highlands in what is commonly known as the Caledonian period. The term Caledonian is an old one, defined in several ways. Here, we broadly take it to refer to the events of dominantly Silurian and Devonian age, which assembled the major tectonic segments of Scotland (and much of the British Isles) into the overall pattern which largely persists today. These Caledonian orogenic events involved terrane accretion (by both thrusting and strike-slip displacement) coupled with metamorphism and igneous activity (Soper, 1988; Harte, 1988).

The Scottish Highlands form the northern part of Scotland, and are largely formed of two major series of polyphase metamorphic rocks. These are the Moine (Moinian) and Dalradian Series (supergroups), and they dominate the land respectively to the north and south of the Great Glen and its associated major fault (Figure 1). Both series are intruded by igneous complexes, which may be both 'early' and 'late' with respect to the major episode(s) of regional metamorphism, though the majority are 'late' (often called 'newer') intrusions. In the northwest, Moinian metamorphic rocks rest on the Northwest Foreland, with a boundary formed by the Moine Thrust. To the southeast, the Dalradian metamorphic rocks end at Highland Boundary Fault, which marks the boundary of the 'Highlands' with the Midland Valley of Scotland, where relatively young rocks of Upper Palaeozoic age outcrop. The Ballachulish Igneous Complex is emplaced within the deformed and regionally metamorphosed sediments of lower-middle sections of the Dalradian Supergroup, near the SW end of the Great Glen Fault (Figure 1). More detailed summaries of the Scottish Highland setting of the Ballachulish Igneous Complex and Aureole are given in Bailey & Maufe (1960), Harte & Voll (1991) and Paulson & Voll (1991).

The Ballachulish Igneous Complex in relation to the 'Newer' Granites

The Ballachulish Igneous Complex is part of the Argyll suite of the Caledonian (ca. 430–400 Ma) granitoid intrusions of the west-central Scottish Highlands (Bailey & Maufe 1960; Stephens, 1988). The Argyll Suite lies NW of the mid-Grampian line (Figure 1) and includes nearby complexes such as Glen Coe, Etive and Ben Nevis. The Argyll intrusions are classified as 'newer' or 'late' granitoids. Owing to their emplacement subsequent to regional deformation and metamorphic events affecting the Dalradian Supergroup in the Scottish Highlands (Harte & Voll 1991).

The present exposure level of the Caledonian igneous complexes shows dominantly intrusive rocks, but at the time of formation they were probably extensively connected to overlying volcanic edifices, now partly preserved at locations like Glen Coe and Ben Nevis, and witnessed by the Lorne Plateau lavas 15 km to the south of Ballachulish. In broad terms the rocks dominantly range from diorites (andesites) to granites (rhyolites), but include many unusual hornblende-rich rocks commonly referred to as 'appinites' (named after the district of Appin, where Ballachulish occurs). Although all are of ealc-alkaline affinity, the Caledonian complexes show regional geochemical variations (see summaries and references of Stephens, 1988, and Thirlwall, 1988). The Argyll suite, including Ballachulish, is characterised by high Ba and Sr, with old radiogenic Ph in zircons. The Caledonian granitoid intrusives have been associated with the presence of an underlying subduction zone, which dipped underneath the Highlands from a position close to the present southern boundary of Scotland, roughly along the line of the Iapetus suture (Figure 1).

The present erosion level at Ballachulish reveals rocks emplaced at a relatively deep crustal level (ca. 10 km, without volcanic sequences such as those found at Glen Coe and Ben Nevis. The age of the Ballachulish Igneous Complex is 424 ± 4 Ma (U-Pb dating of zircon: Fraser et al., 20001, which makes it one of the older intrusive complexes. Given that the nearby, but younger. Glen Coe cauldron subsidence (403 ±4 Ma, Fraser et al., 2000) involves volcanic rocks, it appears likely that strong uplift of the region (ca. 0.5 nun/a) was occurring during the period of emplacement of the late-Caledonian igneous

Host rocks to the Ballachulish Igneous Complex

Stratigraphy

The country rocks to the Ballachulish Igneous Complex are a diverse series of originally sedimentary rocks belonging to the Appin and Argyll Groups of the Dalradian Supergroup (Stephenson & Gould. 1995). They were deposited as sandstones, siltstones, mudstones, limestones and dolostones, in the late Proterozoic and possibly early Cambrian. During the Cambrian and Ordovician they underwent extensive deformation and regional metamorphism to form psammitic (including quartzite), semipelitic, and politic metamorphic rocks, as well as meta-carbonates (though these are still commonly referred to as limestones, despite their metamorphic state). The keys to the Coloured Map (Map 1) (back pocket) and (Figure 2) and (Figure 7) provide a list of the stratigraphic succession, and further details may be found in Bailey & Maufe (1960), Litherland (1980), and Paulson & Voll (1991).

Structure

(Figure 2) shows the major structural features in the area. All of these structures, except the Great Glen Fault and Ballachulish Fault. pre-date the intrusion of the Ballachulish Igneous Complex. The deformation history of the host rocks is complex, as first shown by Bailey (1910) and further developed in Bailey & Maufe (1960): it involved the early development of large-scale recumbent folds and slides (faults or thrust faults most likely formed at the same time as the recumbent folding).

The essence of Bailey's interpretation is widely supported (Roberts, 1976; Roberts & Treagus, 1977), and involves major fold episodes as follows:

An earlier (or primary) set of major recumbent folds, accompanied by a strong axial planar. penetrative cleavage or schistosity (e.g. Appin Syncline. Beinn Sgluich Anticline. Kinlochleven Anticline)

A later (or secondary) set of major upright folds, accompanied by a strong axial planar, strain-slip or spaced cleavage (e.g. Stob Ban Svnform)

The Loch Leven Antiform structure. which occurs largely to the east of the Ballachulish area, and causes a major swing of strike from NE–SW on north side of Loch Leven, to NE–SE on the south side of Loch Leven.

In the Ballachulish district. both primary and secondary major structures trend dominantly NE–SW (Figure 2), and may be difficult to separate into their different ages (Hickman. 1975: Litherland. 1982). Apart from more detailed characterisation of deformation histories in terms of minor structures. the most extensive supplementation and revision of Bailey's work has come front more detailed mapping and increased understanding of sedimentation history in the Dalradian rocks. This has led to the idea that some of the discontinuities in lithostratigraphy. which Bailey attributed to slides (faults formed during recumbent folding), might be interpreted as syn-sedimentary extensional faults (Litherland, 1980; Soper and Anderton, 1984).

Crosscutting the igneous complex and aureole is the NE–SW Ballachulish strike-slip fault (see Coloured Map (Map 1) and (Figure 2)), which has a post-intrusion sinistral displacement of 600–800 m (Paulson 1985; Weiss 1986), and a total fault length of at least 80 km. The Ballachulish Fault makes about a 15° angle with the nearby Great Glen Fault Zone, and may he a splay off this fault zone (Johnson and Frost 1977). It is marked along its length by crushed and shattered rock, giving it a prominent physiographic expression. Some of the fault rocks have been affected by contact metamorphism, suggesting that the Ballachulish Fault was active before as well as alter emplacement of the Ballachulish Igneous Complex.

Regional metamorphism

During the period of extensive regional deformation prior to the intrusion of the Ballachulish Igneous Complex, regional or orogenic metamorphism of the Dalradian rocks occurred. In the Ballachulish district, this reached metamorphic grades roughly equivalent to those of Barrow's (1893) Note and garnet grades, with grade increasing from NW to SE (Bailey & Maufe. 1960; Pattison & Voll, 1991). This metamorphism was probably associated with the major regional 'Grampian' Dalradian metamorphic event, largely thought, to occur in the 520–480 Ma time period (Dempster 1985: Harte 1988; Tanner & Leslie, 1994). Regional metamorphic temperatures in the area covered by the Coloured Map (Map 1) ranged from ca. 400°C in the NW to ca. 550 °C in the SE. at pressures of ca. 5–7 kbar (equivalent to 17–23 km depth) (Pattison & Voll, 1991).

The distribution of regional metamorphic garnet in the area is complex. The approximate location of the garnet isograd is shown on (Figure 2) and on the Coloured Map (Map 1). Going front NW to SE, the garnet zone first occurs in the Leven Schist, and Creran Succession at the isograd illustrated, extending from about 1 km east of Ballachulish Bridge in the north of the area to just east of the summit of Fraochaidh in the south. To the cast of this isograd garnet occurs in a 500–700 in wide NE–SW trending 'strip' (Figure 2), but with much of its extent cut out by the Igneous Complex. To the east of this garnet-bearing strip, across the Ballachulish Slide, is a garnet-absent interval occupied by the Appin Limestone/Phyllite and especially Ballachulish Slate lithologies, until further east garnet reappears simultaneously with the re-appearance of the Leven Schist. This unusual pattern, in particular the abrupt disappearance of garnet across the Ballachulish Slide, was a point of debate between Bailey (1923, and in Bailey & Mimic 1960) and Elles & Tilley (1930), and is the focus of Stop 2 of Day 1.

The Ballachulish Igneous Complex

The Ballachulish Igneous Complex is exposed over an area of ca. 7.5 x 4.5km: (Coloured Map (Map 1)). It consists of a zoned monzodiorite-quartz diorite envelope with flow- and deformation-foliation surrounding a core of variably porphyritic granite with hybrid margins (Weiss 1986: Weiss and Troll 1989). 'Note: the IUGS igneous rock classification scheme (Streckeisen, 1976) is used throughout I. To the SE of the complex is a small quartz diorite satellite intrusion probably related to the main intrusion. (Figure 3) shows two cross sections through the igneous complex.

The igneous complex is roughly cylindrical to a depth of about 4 km beneath the surface (Rabbel & Meissner, 1991), with the exception of two areas where the intrusion lies more shallowly beneath the surface (see (Figure 3)). In the SE, the igneous complex extends shallowly beneath the exposed metasedimentary rocks to join with the small satellite intrusion. On the western margin, quartz diorite partially intruded along the large quartzite anticline (Beinn Sgluich anticline), as shown on (Figure 2) and (Figure 3).

The monzodiorite occupies a roughly crescent-shaped area in the more southern and eastern parts of the intrusion. It is a greenish-grey, variably orthopyroxene bearing hornblende+biotite±augite rock, with an estimated emplacement temperature of ca. 1100 °C (Weiss & Troll, 1989). The quartz diorite forms the marginal northern, northwestern and southern parts of the diorite envelope. It is a grey, hornblende+biotite±augite quartz diorite with abundant metasedimentary, especially metapelitic, xenoliths and possibly cognate dioritic inclusions. Emplaced into the diorites is a central body of pink biotite±hornblende granite and granodiorite, with an estimated emplacement temperature of ca. 850 °C (Weiss & Troll, 1989). The lack of any change in the gravity pattern going horn the relatively dense diorites to the less dense granites suggests that the granite may grade into the diorite at relatively shallow depths. A small and late leucocratic granitic body near the centre of the granite is associated with sericitic alteration and weak Cu-Mo mineralisation. Microdiorite and rare rhyolite dykes cut both the igneous complex and host metasediments.

The contacts between the igneous complex and metasediments are generally sharp, discordant and steeply outward-dipping, and follow a variety of lithological and structural anisotropies. Along the eastern contact, hybrid granites enclose a large (750 m long) quartzite screen and numerous rafts of marbles, calsilicates and partially disaggregated pelitic sediments, whereas in the SE of the igneous complex, abundant metasedimentary rafts up to 250 m in length suggest disintegration of a metasedimentary roof zone by block stoping. These features, combined with the abundance of metasedimentary xenoliths in the quartz diorite, suggest that the present level of erosion is close to the roof zone of the intrusion (see (Figure 3)). Internal contact zones between different phases of the igneous complex range from sharp, well-defined contacts in the middle and eastern parts of the complex where the granites cut the monzodiorites, to hybrid transitional zones up to 500 m wide separating quartz diorites from the later granites. These hybrid transitional zones are interpreted as mixing zones (Weiss & Troll, 1989) between the two main phases of the complex and suggest that the granite was emplaced whilst the quartz diorite portion of the outer envelope was still partially molten.

The overall lack of deflections of bedding and absence of concentric tectonic fabrics in the marginal host rocks suggest there was no significant pushing aside or upward or downward flow of the host rocks to accommodate the volume of emplaced magma. Rather, the intrusive mechanism seems to have involved a combination of stoping, block faulting and roof displacement, possibly augmented by strike-slip movement on the Ballachulish Fault (Weiss & Troll, 1989).

Several small explosion-breccia pipes and mafic-ultramafic intrusions, collectively known as the Appinite Suite (Bowes & Wright 1967), occur around the margins of the Ballachulish Igneous Complex. These mafic intrusions include a number of sub-types (e.g. kentallenite) characterized by generally coarse grain size and consisting of variable proportions of olivine, augite, hornblende, biotite, plagioclase, K-feldspar and quartz. Geological relations (Bailey & Maufe 1960; Weiss & Troll, 1989) suggest that these were most likely emplaced shortly before the main intrusion. Zircon U-Pb ages of the appinites are within error of the ages of the main complex (Fraser et al. 2000).

Further details on the igneous complex are provided in Weiss & Troll (1989), Vol 1 et al. (1991) and Pattison & Harte (1997).

The Ballachulish Aureole

Metapelites

The intrusion of the igneous complex caused extensive contact metamorphism, with contact metamorphic mineral assemblages overprinting the regional mineral assemblages. The changes are often easily recognized in pelitic and semi-pelitic rocks, because they involve the widespread development of the low density Al-Fe-Mg mineral cordierite, rather than the high density Al-Fe-Mg mineral garnet of regional metamorphism. This difference testifies to the distinctly lower pressure conditions of contact metamorphism, and indicates that following regional metamorphism and prior to the intrusion of the Ballachulish Igneous Complex at 424 Ma the rocks underwent considerable uplift with erosion of the overlying rock pile. The depth of the present surface rocks has been estimated as 10±2 km (equivalent to 3.0 ± 0.5 kbar: Pattison, 1991; 1992). The temperature of the host rocks at the time of intrusion of the igneous complex is estimated to have been 250–300 °C (Pattison & Voll, 1991).

In the field the most obvious outermost effect of contact metamorphism is the appearance of cordierite as 'spots' in the regional pelitic schists (see below). Using this cordierite isograd as a guide, variations in width of the aureole are apparent (Coloured Map (Map 1)). The widest parts of the aureole, up to 1700 m on the cast and west flanks, incorporate large expanses of quartzite, whereas the narrowest parts of the aureole, <400 m, occur in pelitic host rocks adjacent to the most fractionated and therefore coolest parts of the quartz diorite envelope (e.g., NE corner). The quartzite is thought to have conducted heat outwards into the aureole more efficiently than the pelites (Buntebarth, 1991). To the SE of the main intrusion the aureole bulges outwards and surrounds the small quartz diorite satellite stock, consistent with other evidence indicating that the quartz diorite spread laterally outward beneath the metasedimentary rocks in this area.

Texturally, as one goes upgrade front the first appearance of cordierite `spots' towards the igneous contacts, the politic rocks undergo a gradual hut pronounced change from fine=grained schists and phyllites to tough cordierite rich hornfelses at the highest grades. Prograde sequences of contact metamorphic zones, separated by isograds, are particularly well developed in the pelitic and semi-pelitic rocks (Paulson, 1989; 1991; Pattison 1991; 1997) - see Coloured Map (Map 1) for isograds and high grade mineral occurrences. The sequence of contact metamorphic zones/isograds varies according to the hulk composition of the Nines and semi-pelites, and most particularly according to the presence or absence of graphite. Thus the mainly non-graphitic rocks of the Creran succession, Appin Phyllite and Leven Schist lithologies, show a different contact metamorphic sequence to the graphite-bearing rocks of the Ballachulish Slate lithology. The different sequence of mineral assemblages in the two types of pelites is largely ascribed to the effect of graphite on the metamorphic fluid composition (Pattison 1989; 1991). The difference is particularly seen in Zones III to V, where K-feldspar develops before andalusite in the graphite-free assemblages, but andalusite develops before K-feldspar in the graphite-bearing assemblages.

Listing of pelitic metamorphic zones and minerals. The graphite-free and graphite-bearing sequences are listed on the next two pages, and the petrogenetic grid of (Figure 4) shows the mineral reaction relations in P-T space. Abbreviations used in the zone listings, on (Figure 4) and (Figure 7), and the Coloured Map (Map 1) (Map 1) are as follows:

And — andalusite, Bt — biotite, Chl — chlorite, Crd — cordierite, Crn —corundum, Grt — garnet, — K feldspar, Ms — muscovite, Opx — orthopyroxene, Qtz — quartz, Sil — sillimanite, Spl — spinel.

Graphite-free sequence of metamorphic zones and isograds.

This is more widespread ('normal') sequence seen in pelitic rocks.

Zone/isograd	**Zonal assemblage/Isograd reaction (key minerals in bold italics)**	**Estimated temperature**
I (regional grade phyllites and schists)	MS+Qtz+***Chl***±Bt±Grt	
I/II isograds (reaction P1)	Ms+Chl+Qtz = Crd+Bt+H_2O (first development of Crd 'spots')	560° C
II	Ms+***Crd+Chl***+Bt+Qtz	
II/III Isograd	Loss of primary chlorite due to reaction P1	570° C
III	Ms+***Crd***+Bt+Qtz	
III/IVb isograds (reaction P2b)	Ms+Bt+Qtz= Crd+Kfs+H_2O (first development of K-Feldspar)	620° C
IVb	Ms+Crd+***Kfs***+Bt+Qtz	
IVb/V isograds (reaction P3)	Ms+Qtz= And+Kfs+H_2O (first development of andalusite)	640° C
Va	Crd+Bt+***And+Kfs***+Qtz±Sil. Loss of Ms in Qtz-bearing pelitic lithologies loss of Qtz in very aluminous pelitic lithologies sporadic development of sillimanite	
Va/Vb isograds (reaction P5)	Ms = Crn+Kfs+H_2O first development of corundum in Qtz-absent rocks only	670° C
Vb	***Crn***+Crd+Bt+And±Sil+Kfs (Qtz-absent lithologies only) Crd+Bt+***And+Sil+Kfs***+Qtz (Qtz-bearing lithologies only)	
Partial melting	Migmatitic features and quartzofeldspathic veins	670–720° C
Highest grade assemblage	***Grt±Opx*** in Qtz-bearing lithologies ***Spl*** in Qtz-absent lithologies	750–850° C

Graphite-bearing sequence of metamorphic zones and isograds

This is restricted to the Ballachulish Slate and Transition Series lithologies:

Zone/isograd	**Zonal assemblage/Isograd reaction (key minerals in bold italics)**	**Estimated temperature**

I and II	similar to graphite-free pelites	560° C
II/III Isograd	Loss of primary chlorite due to reaction P1	
III	Ms+***Crd***+Bt+Qtz	
III/IVa isograds	Ms+Crd=**And**+Bt+Qtz+H_2O	600° C
(reaction P2a)	(first development of andalusite)	
IVa	Ms+Crd+***And***+Bt+Qtz	
IVa/V isograds	Ms+ Qtz = And+Kfs+H_2O	625° C
(reaction P3)	(first development of K- feldspar)	
Va	Crd+Bt+***And+Kfs***+Qtz±Sil	
	Loss of Ms in Qtz-bearing pelitic lithologies; los of Qtz in very aluminous pelitic lithologies; sporadic development of sillimanite	
Va/Vb highest grades	Similar to graphite-free pelites	

Siliceous carbonates and quartzites

Metamorphic zones are also developed in the less abundant siliceous carbonates (Masch and Heuss-Aßbichler. 1991; Heuss-Aßbichler and Masch, 1991; Ferry, 1996a) and in the feldspathic quartzites (Buntebarth & Voll, 1991; Kroll et al.. 1991). The best exposure for siliceous carbonates is in Coire Giubhsachain on the NE flank of the igneous complex, where isograds can be mapped from middle-grade conditions up to the igneous contact (equivalent to Zones III-V in interbedded pelites) (see (Figure 5)). (Figure 6) shows an isobaric TXco2 diagram with the pertinent isograd reactions.

Siliceous carbonates are divided into two main sub-types: siliceous dolostones and siliceous limestones. In siliceous dolostones, the sequence of metamorphic zones observed in the aureole involves the development of talc (Tlc) (reaction C9; 480°C), forsteritic olivine (Fo) (reaction C9; 620° C). isobaric invariant assemblage Fo+Di+Trem+Cal+Dol (CIII; 640 °C), spinel (Spl) (reaction C16; 670 °C), and periclase (Per) (reaction C15; ca. 760°C). With the exception of the talc isograds, all these isograds are developed in Coire Giubhsachain (Figure 5). Lack of exposure makes location of the incoming of tremolite in the aureole uncertain. In siliceous limestones, the sequence of metamorphic zones observed in Coire Giubhsachain involves the development of diopside (Di) (reaction C6; 570° C) and wollastonite (Wo) (reaction C14; 670 °C). Temperature estimates obtained independently from the interbedded siliceous carbonates and metapelites in Coire Giubhsachain are in excellent agreement.

Adjacent to the igneous contacts, especially along the ridge west of Coire Giubhsachain, layered calcsilicate rocks formed from impure limestones occur interleaved with semipelitic rocks and marbles and contain a wide range of mineral assemblages. Particularly striking are massive sheets, sometimes complexly folded, of medium- and coarse-grained rocks rich in grossular (Gros)±vesuvianite(Ves)±epidote (Ep).

In the feldspathic quartzites, as the contact is approached, recrystallization and coarsening of elastic quartz occurs (Bunteharth & Voll, 1991), and elastic feldspar grains develop a high temperature structural state (Kroll et al.. 1991). Locally, the feldspathic quartzite rocks show microtextural features suggestive of anatexis (Flolness & Clemens. 1999).

Cause and duration of contact metamorphism

Geological and petrological considerations. combined with thermal modelling by Buntebarth (1991), suggests that the contact metamorphism was mainly caused by the intrusion of the diorite phase (emplacement temperature 1000-1100 °C. The later and cooler granite (emplacement temperature ca. 850 °C), which intruded when the quartz diorite was still molten, had little effect on the thermal structure of the aureole. The duration of the contact metamorphic event, for temperatures raised above conditions of the cordierite isograd (ca. 550 °C), was approximately up to 500,000 years; whereas rocks were hot enough to be partially molten (temperatures above ca. 660 °C) for up to 270,000 years. The maximum temperature at the contact is estimated to have been 750–800 °C, in excellent agreement with the phase equilibrium constraints.

The rate of heating of the aureole rocks was faster close to the igneous contacts than farther out in the aureole. The heat (and therefore isograds) radiated outwards from the igneous contacts and dissipated with both distance and time ((Figure 12) of Pattison & Harte, 1997). The isograd positions now seen in the field, are believed to correspond with the farthest distance from the contact which reached the temperature corresponding to the isograd reaction concerned (e.g., 640 °C for the reaction P3 andalusite+K-feldspar (Zone IV/V) isograd). The different isograds were thus established in the rocks at different times, with the higher temperature isograds having been frozen into the rocks before the lower temperature isograds. Using the isograds on the cast flank of the aureole as an example, the thermal modelling suggests that the andalusite+K-feldspar isograd (reaction P3) was frozen into the rocks ca. 500 m from the contact after about 120,000 years; whereas cordierite+K-feldspar isograd (reaction P2b; ca. 600 m from the contact) and cordierite isograd (reaction P1: ca. 1100 m) were frozen into the rocks after 135,000 and 200,000 years, respectively (see (Figure 12) of Pattison & Harte, 1997).

Fluid movement in the aureole

Stable isotope systematics of the igneous rocks, combined with the evidence of limited exchange of stable isotopes between igneous and aureole rocks, suggest that the intrusion of the Ballachulish Complex did not lead to exchange with meteoric water or to the development of a large scale hydrothermal circulation system (Hoernes et al., 1991; Harte et al., 1991b). On the east flank of the aureole (Coire Giubhsachain), localized metasomatic reactions in pelites and siliceous carbonates (Ferry, 1996a) indicate that fluid infiltration during contact metamorphism was generally limited rather than extensive, and channelled rather than pervasive. The greatest amount of fluid infiltration appears to have been focused in the inner contact zone, with the most probable fluid source being deeper-level pelitic rocks undergoing dehydration, although a magmatic component close to the contacts may also have been important locally (Ferry, 1996a). On the west flank, extensive partial melting in the 400m-wide Chaotic Zone indicates widespread, although possibly not voluminous, infiltration of magmatically-derived fluid from the quartz diorite into the immediately overlying Lovett Schist semipelites (Pattison & Harte, 1988: Linklater et al.. 1994).

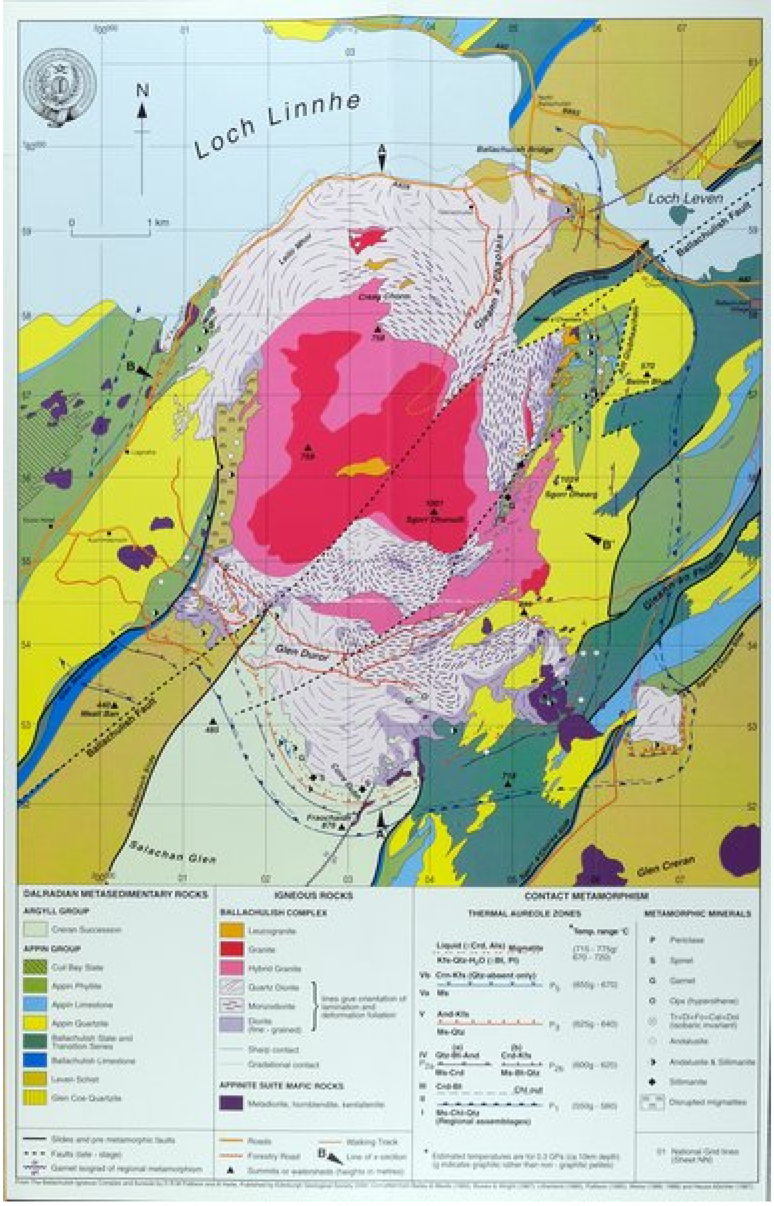
The mineralogical assemblage evidence on fluid flow probably underestimates the overall fluid flow, owing to the potentially large amount of fluids that may have been channelled along fractures rather than pervading the metasediments. These fluid conduits are probably partly preserved as a variety of types and sizes of veins, especially quartz veins, in all rock types but most noticeably in the quartzites. Variable, fluid infiltration following the thermal peak is indicated by a variety of retrograde minerals in pelitic hornfelses and siliceous carbonates.

The limited extent of fluid movement at Ballachulish contrasts with the situation in some higher level (< 2km) intrusions. such as in the Tertiary igneous province of the Scottish Hebrides. where depletion in 18O revealed the formation of an extensive hydrothermal circulation system involving meteoric water (Taylor & Forester, 1971). The contrast may he explained by the greater depth (ca. 10 km.) of intrusion and metamorphism exposed at Ballachulish, this depth most likely being below that at which a network of fluid-filled cracks open to the surface can exist and thereby facilitate substantial fluid circulation by convection Harte el al., 1991b).

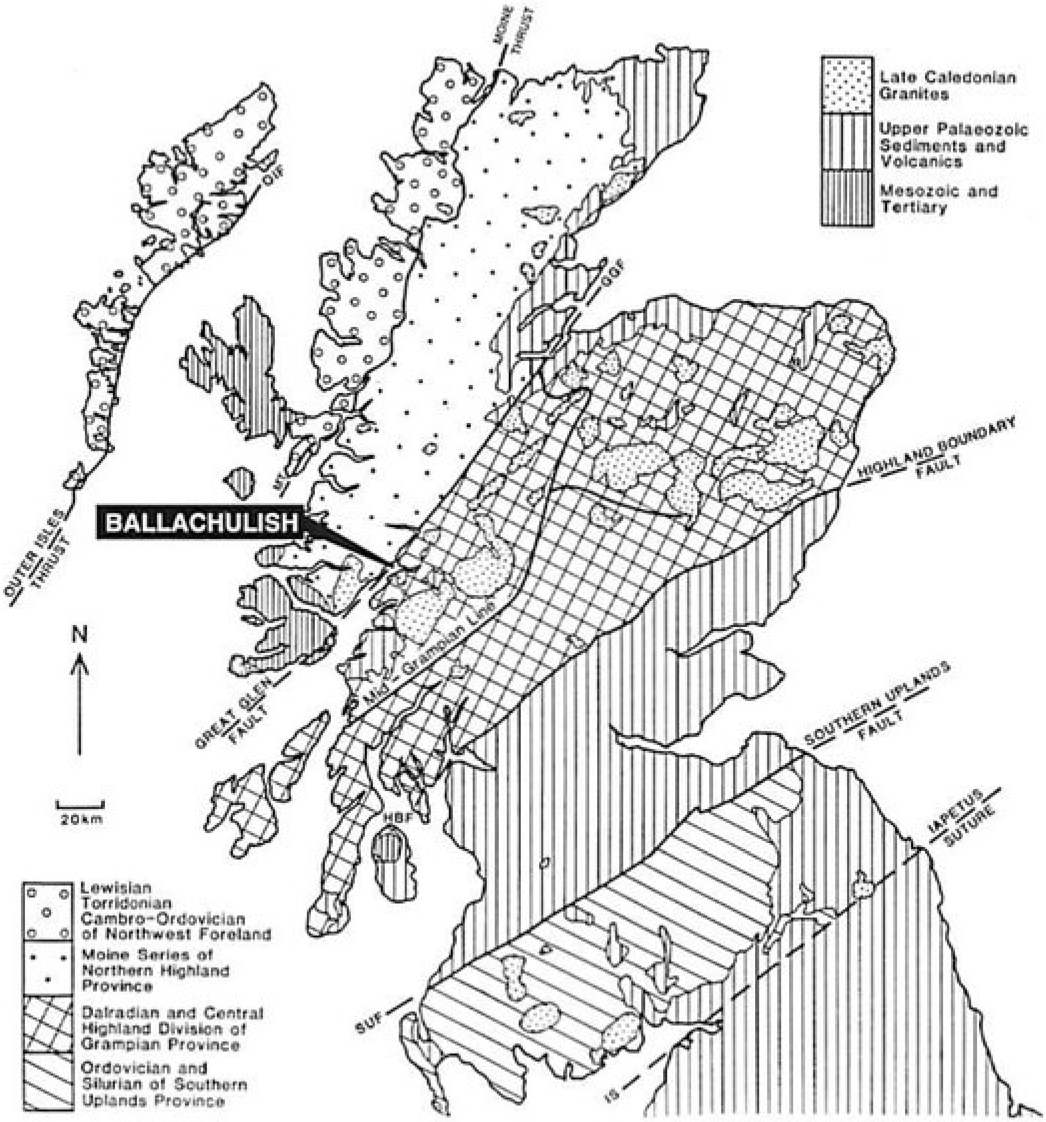
For further information and references on the contact metamorphism and fluid history, see Volt et al. (1991), Ferry (1996a) and Pattison & Harte (1997).

Illustrations of exposures and rocks in the literature

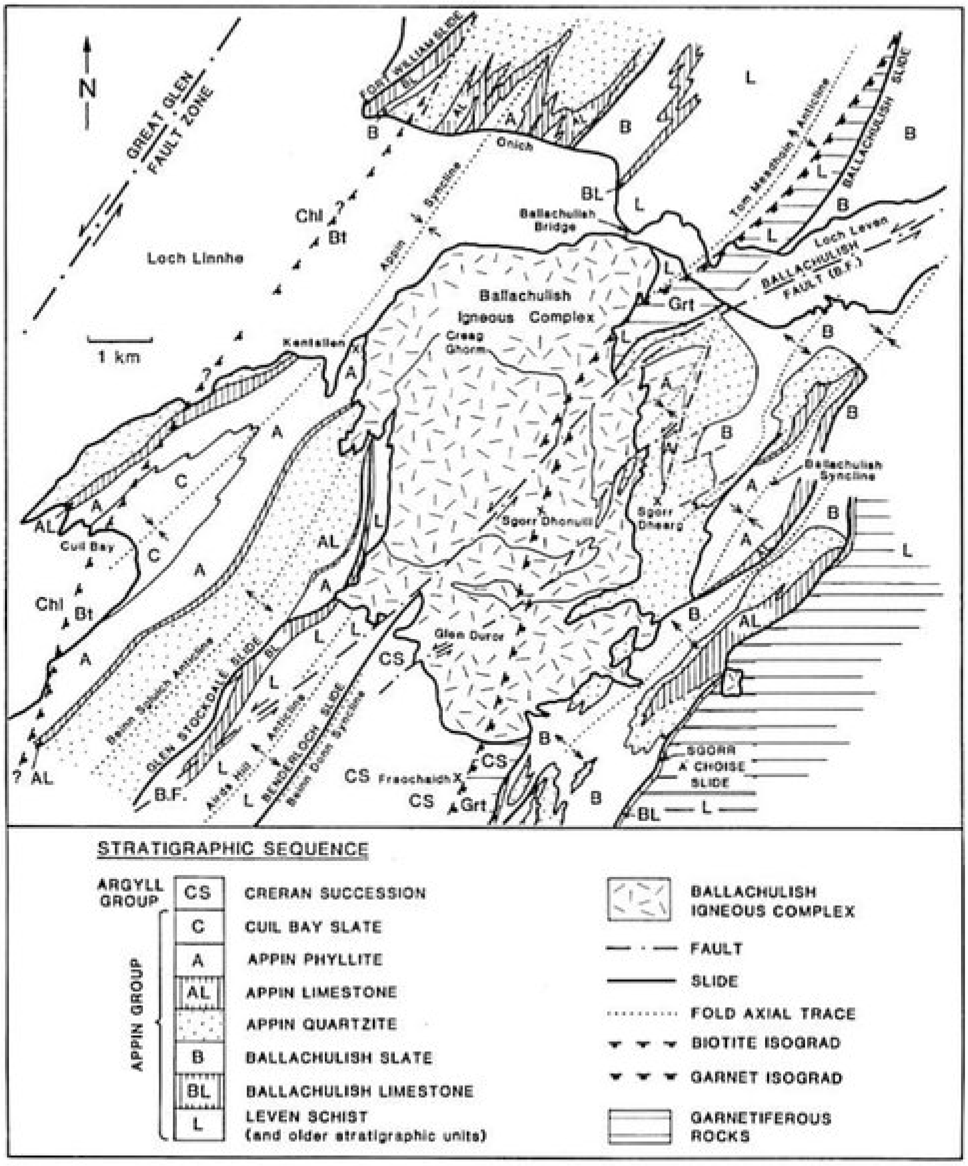
Photographs and drawings of outcrop and thin section features of the igneous complex and aureole may be found in the following references: Pattison & Harte (1988; migmatitic features, including colour pictures of stained samples); Weiss & Troll (1989; igneous textures). Voll et al. (1991; see articles on general geology, igneous complex, metapelitic hornfelses, migmatites, metacarbonates and quartzites); Paulson (1992; thin section pictures of andalusite±sillimanite bearing metapelites); Ferry (1996a: thin section pictures of siliceous carbonates); and Holness & Clemens (1999; thin section pictures of melting features in Appin feldspathic quartzites).



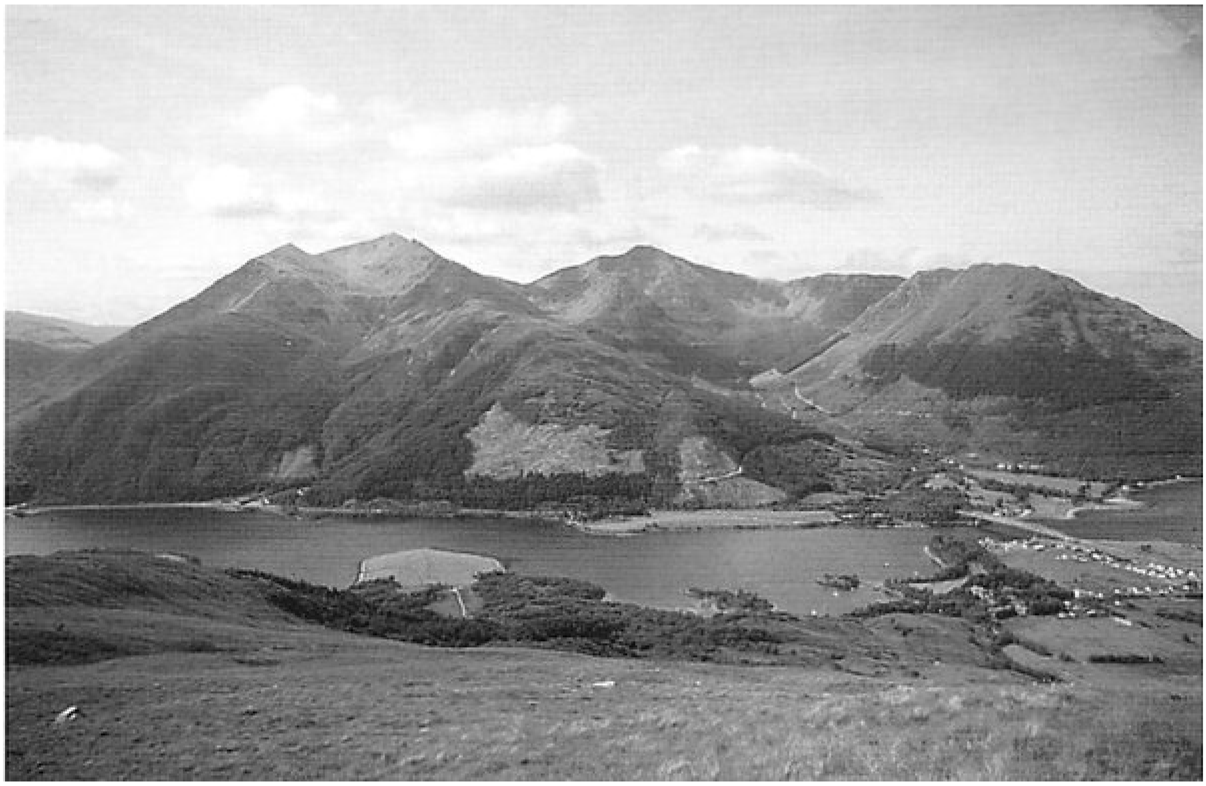
(Map 1) Geological map of the Ballachulish Igneous Complex and aureole. (map in endpocket).



(Figure 1) Outline map of major geological provinces in Scotland, and the distribution of Caledonian igneous complexes ('granites'); with location of the Ballachulish area.

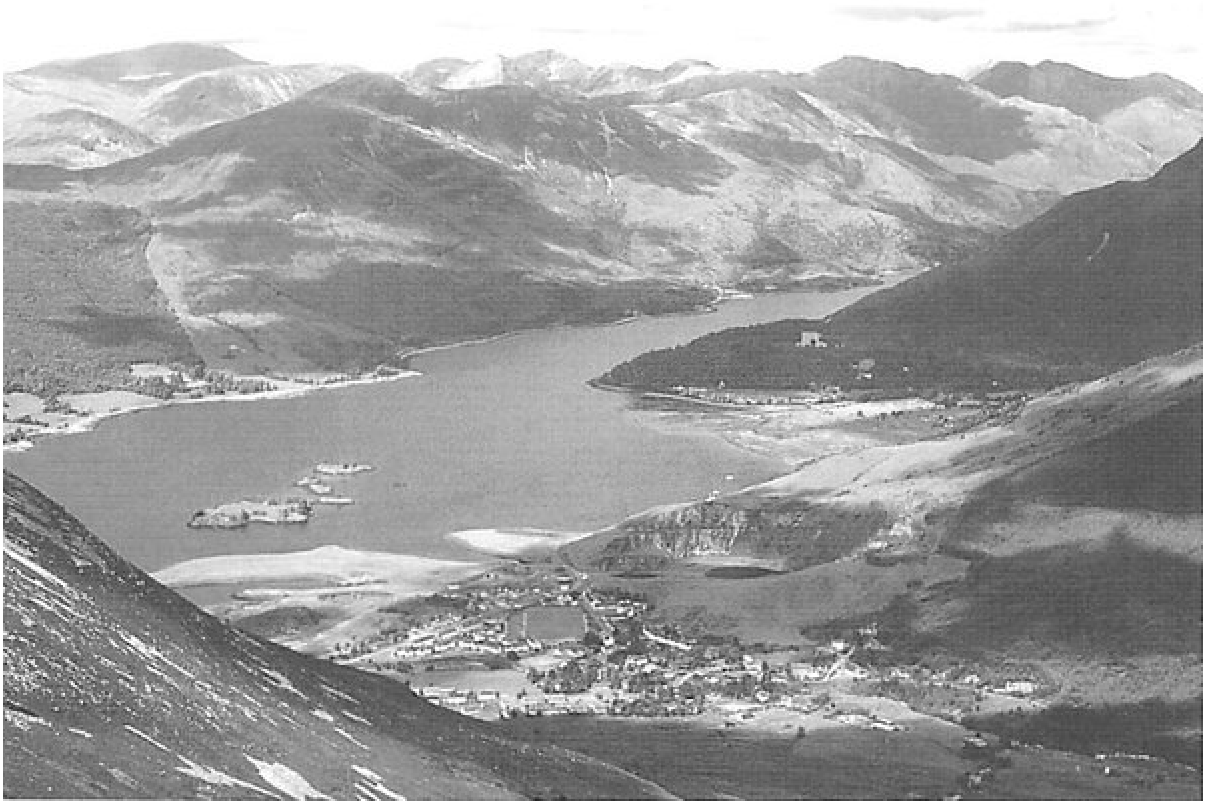


(Figure 2) Outline of lithostratigraphic units and major regional structures around the Ballachulish Igneous Complex. The position of the garnet isograd of regional metamorphism. Which formed prior to intrusion of the complex, is extrapolated across the area of the complex. From Pattison & Harte (1997).

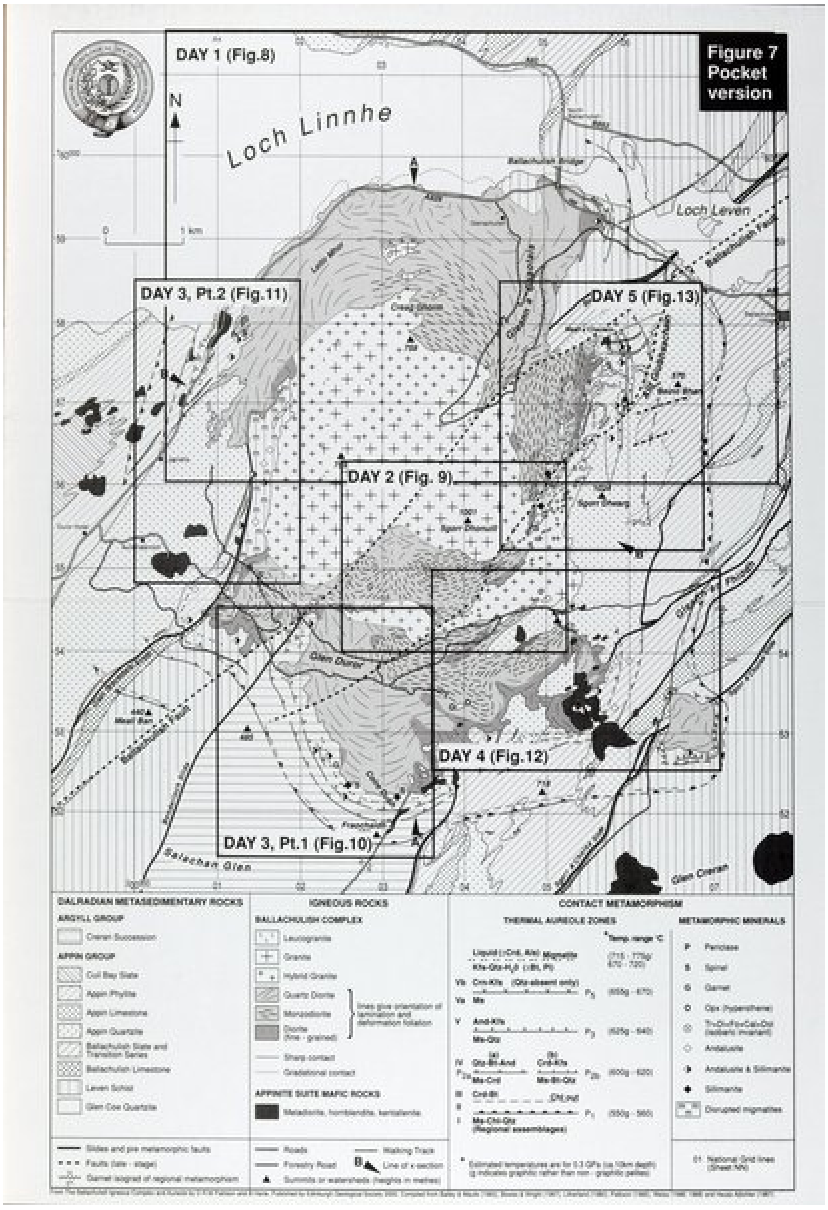


(Photo 1) (Frontispiece). Overview of the Ballachulish Igneous Complex and Aureole from Tom Meadhoin ridge, looking SW.

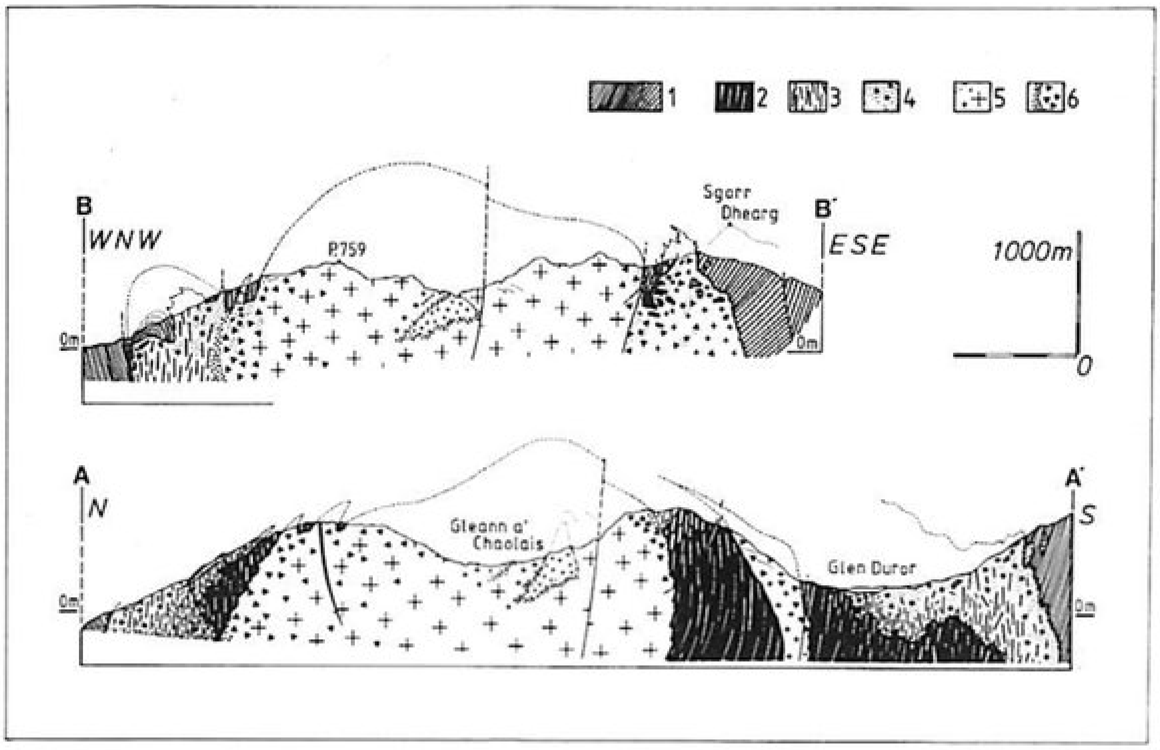
(Photo 2) View to SW from the summit of Sgorr Dhearg looking across Loch Linnhe



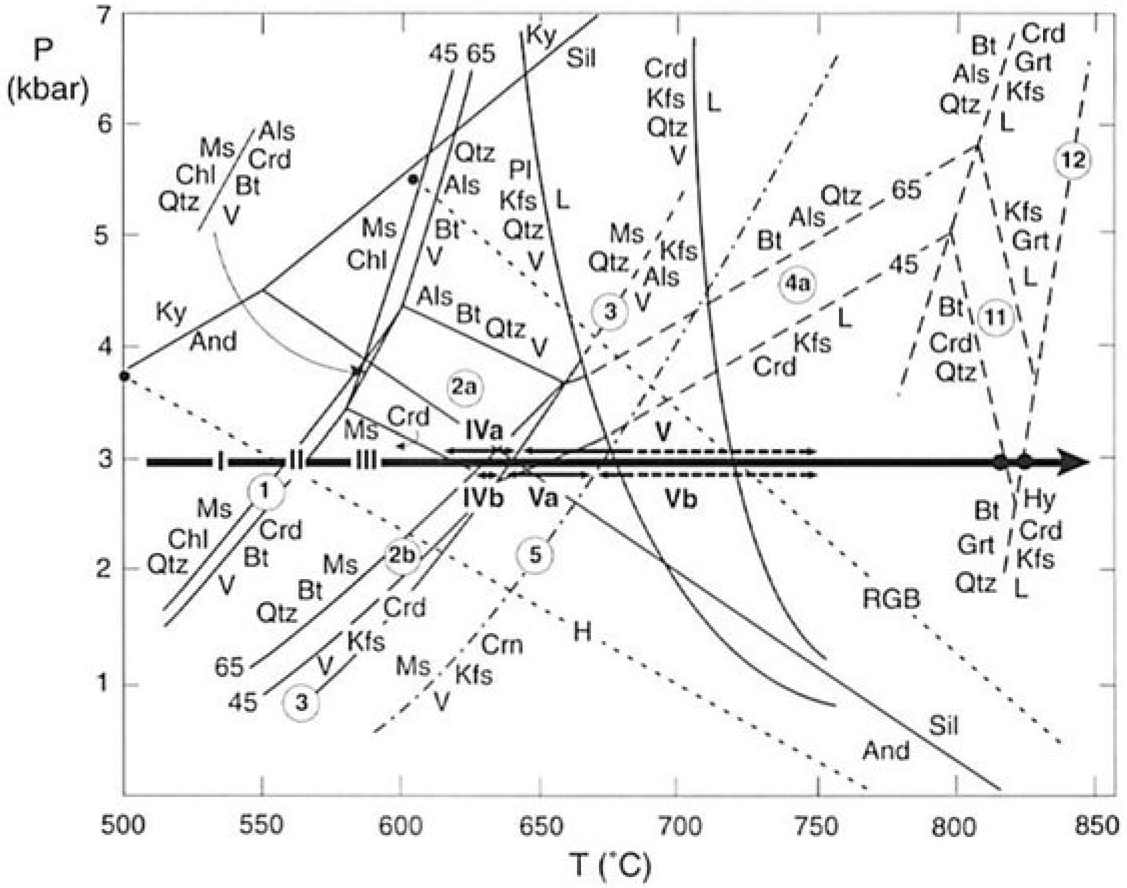
(Photo 3) View from Beinn Man looking NE to the town of Ballachulish and Loch Leven.



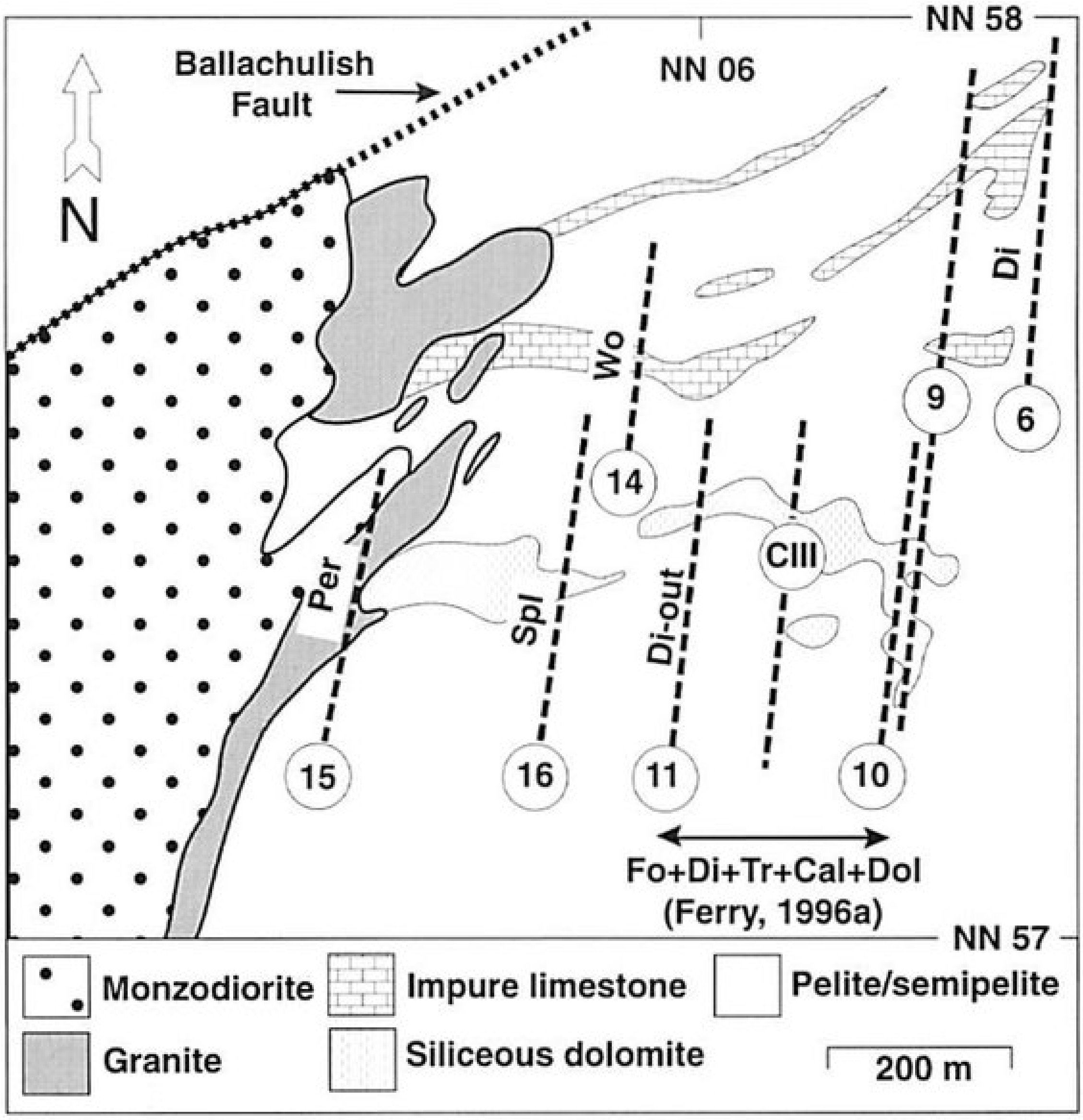
(Figure 7) Outline of area for field excursions. Geological map showing location of field stops for Day 1 (see (Figure 7) for key to geological map).



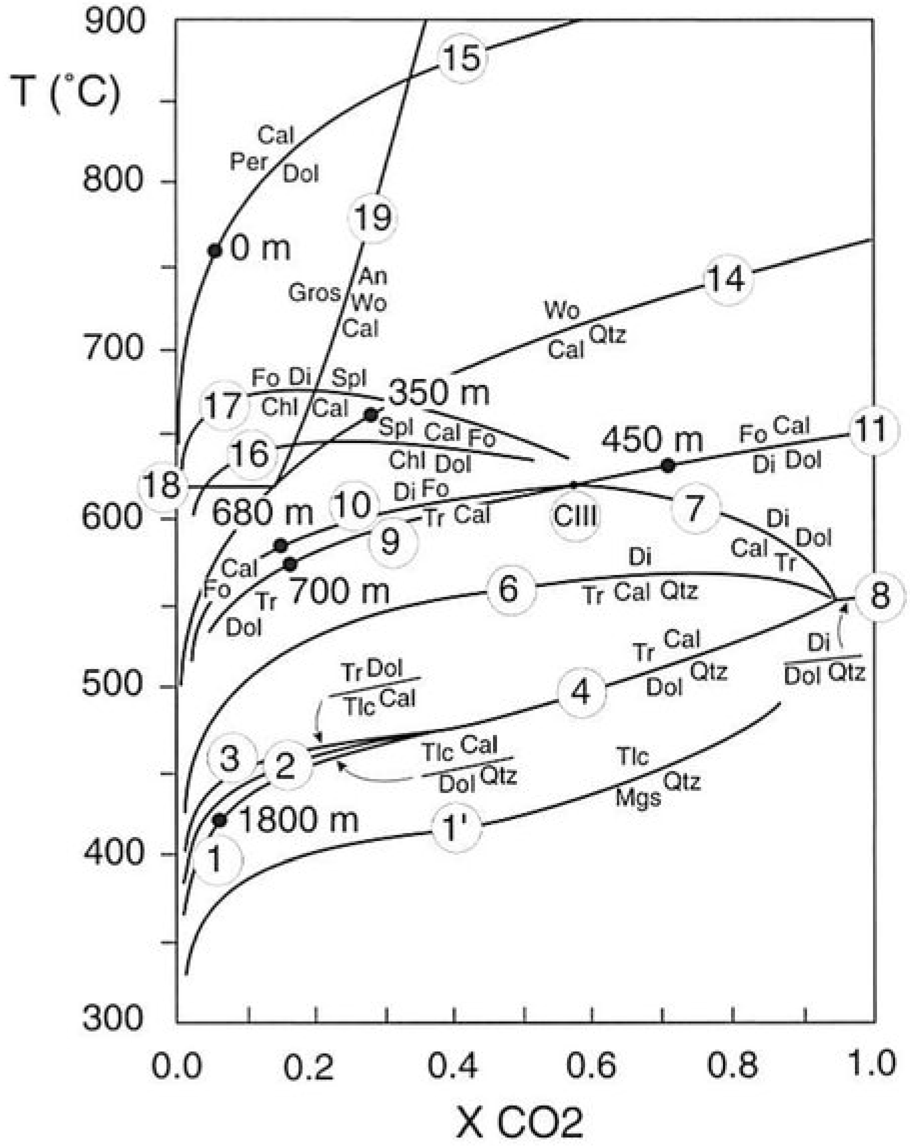
(Figure 3) Geological cross-sections through the igneous complex (see section lines on Coloured Map (Map 1) and (Figure 7)), from Weiss (1986) and Troll and Weiss (1991). 1 - metasediments. Lined patient indicates pelites and semipelites; lined pattern with dots represents quartzites. Squiggly lines indicate migmatitic rocks. The orientation of the lines gives the attitude of the bedding projected into the cross section. 2 - monzodiorites, showing flow- and deformation foliation. 3 - quartz diorites, showing alignment of metasedimentaty xenoliths. 4 - fine grained diorites with xenoliths. 5 - granites. The flue crossed ornament in the centre represents leucogranite, and the bounding stippled margin represents a gradational contact with the main granite. 6 - hybrid transition zones between granite and quartz diorite. The dotted line labelled '..Sgorr Dhearg' represents the projected topographic expression of this peak which occurs about 300 m N of the line of section.



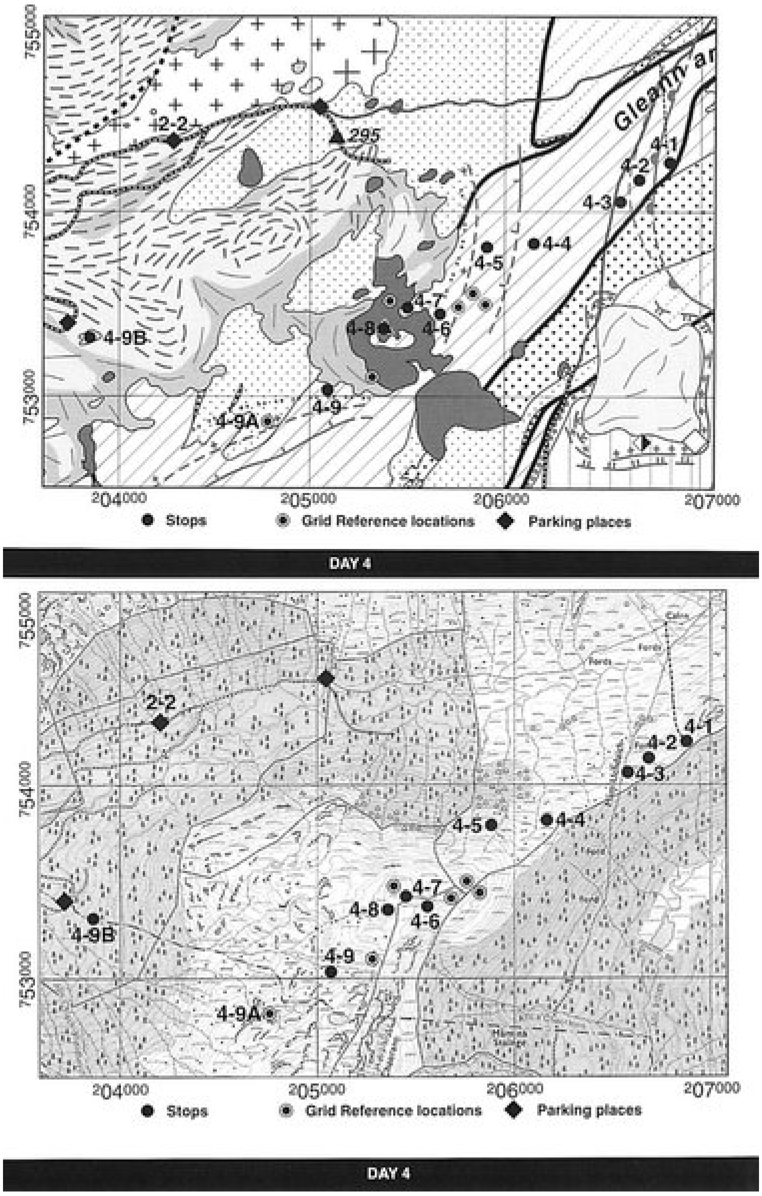
(Figure 4) Pressure-temperature grid of reactions in the chemical system K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O for typical mineral compositions in quartz-bearing pelitic rocks from Ballachulish (Pattison Harte, 1997). Dehydration reactions below the initial melting reaction (Pl+Kfs+Qtz+H_2O = L) are shown in solid lines. Higher grade reactions up-temperature of the initial melting reaction are shown in dashed lines. Als = andalusite or sillimanite. V = hydrous vapour, The short dashed line numbered 3 is the metastable extension of Ms+Qtz = Als+Kfs+V The dot-dashed reaction 5, Ms=Crn+Kfs+V, only occurs in quartz-absent rocks. The And=Sil curve is from Pattison (1992). H - And=Sil curve and triple point of Holdaway (1971); RGB - And=Sil curve and triple point of Richardson et al. (1969). Roman numerals - contact metamorphic zones referred to in the text. Zone IV comprises two different assemblages IVa and IVb that occur at the same grade in rocks of different composition. In quartz-absent rocks, Zone V can be divided into lower grade (Va) and higher grade (Vb) subzones based on the presence of muscovite (Va) and corundum (Vb), respectively. Reaction numbering in Arabic numerals follows the text except that the ‘P’ prefix is omitted. Isopleths are of (100× Mg/(Mg+Fe)) in cordierite.



(Figure 5) Isograds in carbonate rocks from the Coire Giubhsachain syncline, northeast flank of igneous complex (Paulson & 1997; modified from Masch and Heuss-Aßbichler 1991 and Ferry, 1996a). Numbering of isograds is the same as in the text (with 'C' prefix omitted). Circled numbers and symbols 9, 10, CIII, 15 and 16 refer to assemblages and isograds observed in siliceous dolostones, wheras circled numbers 6 and 14 are for isograds in impure limestone.



(Figure 6) Isobaric T-X_{CO2}, diagram (3 kbar) for selected equilibria in the chemical system CaO-MgO-SiO_2-Al_2O_3-H_2O-CO_2, showing numbered reactions discussed in the text (Pattison & Harte, 1997: modified from Masch and Heuss-Aßbichler 1991). All reactions except C18 involve H_2O and/or CO_2. The unlabelled reactions are: Tlc + Cal + Qtz = Tr + CO_2 + H_2O. 18. Gros + Qtz = An + Wo (phases on the right hand side of the reaction are on the high-temperature side)



(Figure 12) (a) Geological map showing location of field stops for Day 4 (see (Figure 7) for key to geological map) (b) Corresponding topographic map showing location of field stops for Day 4 (reproduced with permission by the Ordnance Survey).