2 Ben Vuirich

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2.1 Introduction

Ben Vuirich (2903 m) is a prominent feature in the Perthshire landscape, 13 km north-east of Pitlochry. It provides some excellent exposures of the deformed and foliated Ben Vuirich Granite Intrusion, which was emplaced before the main deformation and regional metamorphism that has affected the Appin Group country rocks. Its importance has therefore long been recognized as a target for radiometric dating to determine a minimum age for the Dalradian succession. More recently, with its radiometric age well established as 590 Ma, attention has turned to its field relationships, which reveal crucial evidence for the relative timing of structural events that have affected the granite and its host rocks.

The Ben Vuirich Granite is a member of the small, but geologically important, suite of pre-Caledonian intrusions that has commonly been referred to as the 'Older Granites' (e.g. Barrow *et al*., 1905). Such granites are uncommon but are scattered widely throughout both the Northern Highlands and the Grampian Highlands. Several smaller bodies occur near Ben Vuirich in Glen Tilt (e.g. within the *Gilbert's Bridge* GCR site). Recent radiometric dating has added several new intrusions to this suite, which is now recognized as representing a major 600 Ma magmatic event (Strachan *et al*., 2002; Kinny *et al*., 2003b). Hence any deductions regarding the structural relationships and timing of the Ben Vuirich intrusion have profound implications for the tectonic history of the whole Grampian Terrane.

The Ben Vuirich Granite Intrusion was first described by Barrow *et al.* (1905) and is included in the British Geological Survey's 1:50 000 Sheet 55E (Pitlochry, 1981). Research into the structural significance and age of the granite has aroused much controversy, which was generated initially by a large difference between the apparent ages given by early Rb-Sr (whole-rock) and U-Pb (zircon) dating methods (Giletti *et al*., 1961; Bell, 1968; Pankhurst and Pidgeon, 1976), and later by disagreement over structural correlations. A precise U-Pb age on abraded zircons from the Ben Vuirich Granite of 590 ± 2 Ma, obtained by Rogers *et al.* (1989), combined with the existing structural interpretation of Bradbury *et al.* (1976), was thought to show that the Dalradian block had been affected by both a Neoproterozoic orogeny (D1 and D2) and an Early Palaeozoic orogeny (D3 and D4). The 590 Ma age was subsequently confirmed by Pidgeon and Compston (1992) using the SHRIMP ion-microprobe. However, the structural interpretation was challenged by Tanner and Leslie (1994) who concluded that:

1. the foliation in the granite is correlated with S2 in the country rocks, and
2. the granite is pre-D2 in age and only post-dates a fabric which is possibly of regional D1 age.

The current dispute is between those workers who consider that the intrusion was most likely intruded, during a pre-orogenic rifting episode, into previously undeformed sedimentary rocks at *c.* 590 Ma (Soper and England, 1994; Tanner, 1996; Soper *et al.,* 1999; Tanner *et al.,* 2006) and those who favour emplacement into a sequence that had already been affected by a pre-590 Ma Neoproterozoic orogenic event (Rogers *et al*., 1989; Bluck and Dempster, 1997; Dempster *et al.,* 2002). In short, whether or not a pre-Grampian orogenic event has affected that part of the Dalradian Supergroup that lies below the base of the Southern Highland Group (dated at *c.* 600 Ma; Dempster *et al.,* 2002), the origin of the earliest fabric in the hornfels and xenoliths found at this GCR site is pivotal. Two critical localities, one within hornfels of the contact metamorphic aureole and the other featuring xenoliths within the marginal part of the granite, preserve evidence of the undeformed nature of the Dalradian host rocks immediately prior to the intrusion of the granite.

2.2 Description

The Ben Vuirich Granite Intrusion is a small (6 × 2 km) sheet-like body of pink or grey peraluminous monzogranite containing megacrysts of oligoclase and K-feldspar, up to 7 mm in length, together with quartz, muscovite, biotite, titanite, zircon and almandine-grossular garnet. It cuts poorly exposed metacarbonate rocks, quartzites, psammites, semipelites and pelites belonging to the Blair Atholl Subgroup of the Appin Group (Crane *et al*., 2002). The Dalradian country rocks have been affected by four phases of deformation (D1–D4), the first three of which comprise the Grampian Event. The granite was variably deformed during D2, resulting in NE-trending zones of strongly foliated rock transecting the main body of weakly foliated to granoblastic granite (Figure 6.4). The intrusion lies within the Tummel Steep Belt and is contained between two tectonic slides (ductile faults) of D2 age (Crane *et al*., 2002) (Figure 6.4). The Killiecrankie or Glen Loch Slide is inferred to follow the western margin of the intrusion, where metacarbonate rocks belonging to the Sron nan Dias Pelite and Limestone Formation strike towards this contact, and there is clear excision of part of the stratigraphical sequence. The Creag Uisge Slide to the east of the intrusion is seen locally as a prominent zone of mylonitic rock, and its position farther south is taken as the western margin of the Ben Lawers Schist.

The Ben Vuirich GCR site consists of two groups of exposures (localities A and B on (Figure 6.4)). An exposure of hornfels found at locality A on the north-west flank of the mountain is the only place in the whole Dalradian outcrop where rocks from the contact metamorphic aureole of one of the 'Older Granites' are exposed. At this locality, spotted hornfels have developed in finely banded semipelite typical of the Tulaichean Schist Formation (Crane *et al*., 2002, plate 4). At locality B on the north-east side of the body, xenoliths of locally-derived quartzose psammite, caught up in the granite magma before it was fully crystalline, preserve the lithological layering but show no sign of pre-intrusion minor folding. There, the granite locally cuts across bedding in the Tulaichean Schist Formation.

The main feature of the GCR site is the hornfels that occurs in metre-scale exposures and small patches of scree on the north-west side of the hill. The early workers reported hornfels-like rocks (Barrow *et al*., 1905; Pantin, 1961) but it was not until 1990 that the spotted hornfels was discovered at locality A, 750 m west-north-west of the summit of Ben Vuirich (Tanner and Leslie, 1994). Examination of the material in the screes shows that the hornfels grades from finely laminated, non-spotted rock to coarser grained, spotted hornfels that originally contained andalusite (of the chiastolite variety) and cordierite. The andalusite-bearing types are inferred to have come from the innermost parts of the aureole. Porphyroblasts of andalusite are now pseudomorphed by feathery intergrowths of kyanite and are identical to those found in the contact metamorphic aureole of the Carn Chuinneag intrusion, an 'Older Granite' in the Moine Supergroup rocks of Sutherland (Tanner, 1996). The largest and most abundant spots were originally of cordierite; they reached 2 cm across and grew across a pre-existing, fine-grained fabric. That fabric is still preserved within the pseudomorphs after cordierite, although the original mineral has been altered to an aggregate of minute flakes of biotite and muscovite, with small grains of almandine garnet 0.4–0.8 mm across (Figure 6.5) and less-obvious kyanite needles.

Petrological studies have shown that the original overall contact metamorphic assemblage, which contained cordierite ± andalusite, has been overprinted and converted to an equilibrium assemblage of muscovite + biotite + garnet + kyanite + plagioclase + quartz during the D2 regional metamorphism (Tanner and Leslie, 1994; Tanner, 1996). A scanning electron-microscope and electron-microprobe study of the small regional metamorphic D2 garnets has shown that they preserve an extremely unusual chemical zonation with, for example, Ca increasing from the core to the rim of the garnet (Ahmed-Said and Tanner, 2000).

At locality B, an irregular contact of the granite with quartzite and quartzose psammite is well exposed locally, with apophyses of granite cutting the country rock. Angular to sub-rounded xenoliths of country rock are common locally in the marginal facies of the granite; they commonly preserve a finely spaced alternation of light and dark layers, which on microscope examination is seen to be bedding with some mimetic growth of micas (Tanner and Leslie, 1994; Tanner, 1996; Tanner *et al.,* 2006). Along the contact farther to the south-west, schistose pelites containing garnet over 1 cm across are in direct contact with the granite.

2.3 Interpretation

Now that both the radiometric age for the granite intrusion of 590 Ma, and the D2 structural age of the main fabric that affects it, are generally accepted, the only contentious issue at present concerns the origin of the early fabric in the Ben

Vuirich hornfels. It is developed in rocks with a grain size of only 0.1–0.4 mm and, in all but the highest grade (andalusite-cordierite) hornfels, represents a very low-strain deformation (Figure 6.6). This fabric could have resulted from:

1. Neoproterozoic, pre-D1, tectonism;
2. D1 deformation at an early stage in the development of the Tay Nappe; or
3. Deformation of the country rocks synchronous with emplacement of the granite.

There are problems with both (1) and (2) above. If the fabric is of Neoproterozoic (pre-590 Ma) age, it would be absent from all rocks younger than the 600 Ma Tayvallich Lavas, and would necessitate the presence of a so-far undiscovered orogenic unconformity within the Argyll Group in Scotland. Alternatively, if the fabric is of D1 age, this would restrict D1 to 600–590 Ma and separate it by 120 Ma from D2 at 470 Ma. However, from work at Callander, Tanner (1995) has demonstrated that D1 in Southern Highland Group rocks of the Highland Border is post-515 Ma in age (see the *Keltie Water* GCR site report). As D1 and the D2 can be correlated between the Tummel Steep Belt, including the rocks around Ben Vuirich, and the Highland Border (Crane *et al*., 2002), and an orogenic unconformity has not been demonstrated in this ground, (1) is not a viable option. The most likely interpretation is that the early fabric is of *syn-emplacement* origin (Tanner, 1996). This conclusion was based on evidence that the pre-hornfels fabric increases in intensity toward the granite margin, and that microveinlets of granite are seen in thin section to have been deformed by the early fabric-forming event.

Further evidence of the nature of the pre-intrusion fabric is given by the xenoliths in the granite at locality B. The compositional layering in the population is randomly orientated, with some xenoliths exhibiting folds. However, it is clear that the S2 schistosity in the granite is axial planar to the folds in the xenoliths. In addition, long, thin blocks are parallel with, or at a small angle to, this external S2 fabric, whereas the shorter, more equidimensional, blocks contain folds. This situation is directly analogous to that described from the *Port Selma* GCR site (Treagus et al., 2013), where a population of clasts originally showing randomly orientated planar bedding, has been deformed. The result is that clasts with bedding initially at a low angle to the resultant cleavage plane are stretched and show boudinaged layers, whereas those with bedding initially at a high angle to the resultant cleavage are buckled internally. The conclusion to be drawn from the Ben Vuirich xenoliths is that the bedding laminations in these were all planar before the D2 deformation, and that the folds seen in some of them are the result of the D2 deformation of the internal foliation of the bedding in suitably orientated xenoliths.

An intriguing feature of the hornfelsed rocks at this GCR site is that they not only preserve a very fine-grained early fabric, but also show little sign of having been affected by the D2 deformation, despite the rocks to either side of them (granite intrusion and country rock, respectively) having been strongly deformed during D2. At that time, the country-rock pelites were being transformed into coarse-grained schists with garnets up to 2 cm across (see (Figure 6.4) for their distribution). The contact metamorphic assemblage may be used to give an estimate of the lithostatic pressure at which the assemblage crystallized, and hence the depth of emplacement of the granite. Comparison with published data on hornfelsed rocks gave an estimated pressure of 2–4 kbar, representing a depth of 7–14 km (Tanner, 1996). This conclusion is important when considering the origin and tectonic setting of the granite, and has been the cause of some debate (see Dempster *et al*., 2002). In addition, the chemical zonation patterns in D2 regional metamorphic garnets reported by Ahmed-Said and Tanner (2000) were interpreted by them to indicate that there was a marked increase in confining pressure as the garnets grew during D2, caused by the major crustal-thickening event that was taking place at the time.

It has been proposed that the granite was emplaced during extensional tectonism approximately synchronous with the eruption of the Tayvallich volcanic rocks (e.g. Soper, 1994), and 100 Ma before the Early Palaeozoic Grampian Event. This hypothesis involves neither a separate Neoproterozoic orogenic event, nor a splitting of the D1–D4 deformation episodes in the Grampian Terrane into two packages separated by a long, ill-defined time break. It is supported by the results of a recent geochemical study of the granite (Tanner *et al*., 2006). The granite samples have a restricted compositional range and occupy the within-plate granite field of Pearce *et al.* (1984), the A-type granitoid field (on Ga/Al plots) of Whalen *et al.* (1987), and lie wholly within the field for A_2-group granites, as defined by Eby (1992). Such granitoids are characteristically found in rift-related environments. The Ben Vuirich Granite is one of an increasing number of *c.* 600 Ma pre-Caledonian intrusions that are now being recognized throughout the Northern and Grampian highlands of Scotland (Strachan *et al*., 2002; Kinny *et al*., 2003b). These are regarded as being related to a swarm of diverse A-type magmatic bodies intruded at around 700–600 Ma which, in a Neoproterozoic reconstruction, can be traced across the Appalachian Fold Belt (Bingen *et al*., 1998; Tanner *et al*., 2006).

2.4 Conclusions

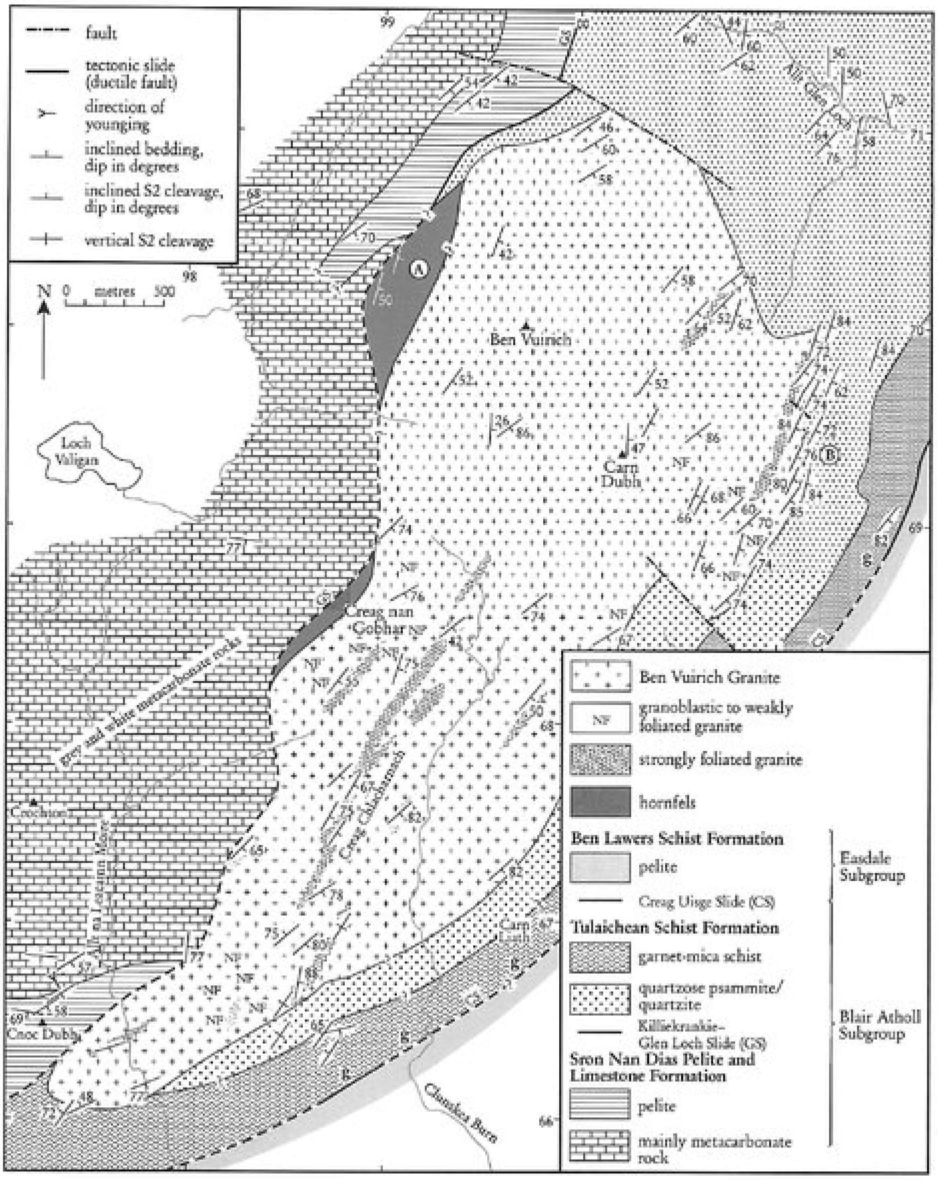
The Ben Vuirich Granite was one of the first members of an important suite of *c.* 600-million-year-old intrusions to be recognized and dated radiometrically. Members of this suite were intruded into the Neoproterozoic rocks of the Scottish Highlands before they were deformed during the Caledonian Orogeny. Hence the Ben Vuirich granite is of great national importance. Its radiometric age has been the subject of numerous investigations, initially to establish a minimum age for the Dalradian succession, and increasingly as a means of dating the early phases of Caledonian deformation.

The granite magma was intruded as a sheet-like body into a sequence of limestones, mudrocks, and quartzose sands belonging to the Appin Group. The heat that was released transformed the adjoining sedimentary rocks into a baked rock, or hornfels, of which only a small area remains and is currently exposed at ground level. Because of having been heated to *c.* 600°C, and losing much of their fluid during this process, the hornfelsed rocks became resistant to later deformation and hence much of their early history has been preserved intact. Their most significant feature is that minerals such as cordierite and andalusite, which grew in response to the heat, preserve a weak tectonic fabric within them. Unfortunately, it is not possible to be absolutely certain whether this fabric formed due to the forceful emplacement of the granite, or during an earlier, pre-Caledonian deformation event. However, it is clear that the granite was emplaced before the first deformation to affect the Dalradian Supergroup (D1). Fragments of the country rock that were torn off and encapsulated in the magma when it was emplaced, preserve significant evidence of the non-folded state of the rocks at that time.

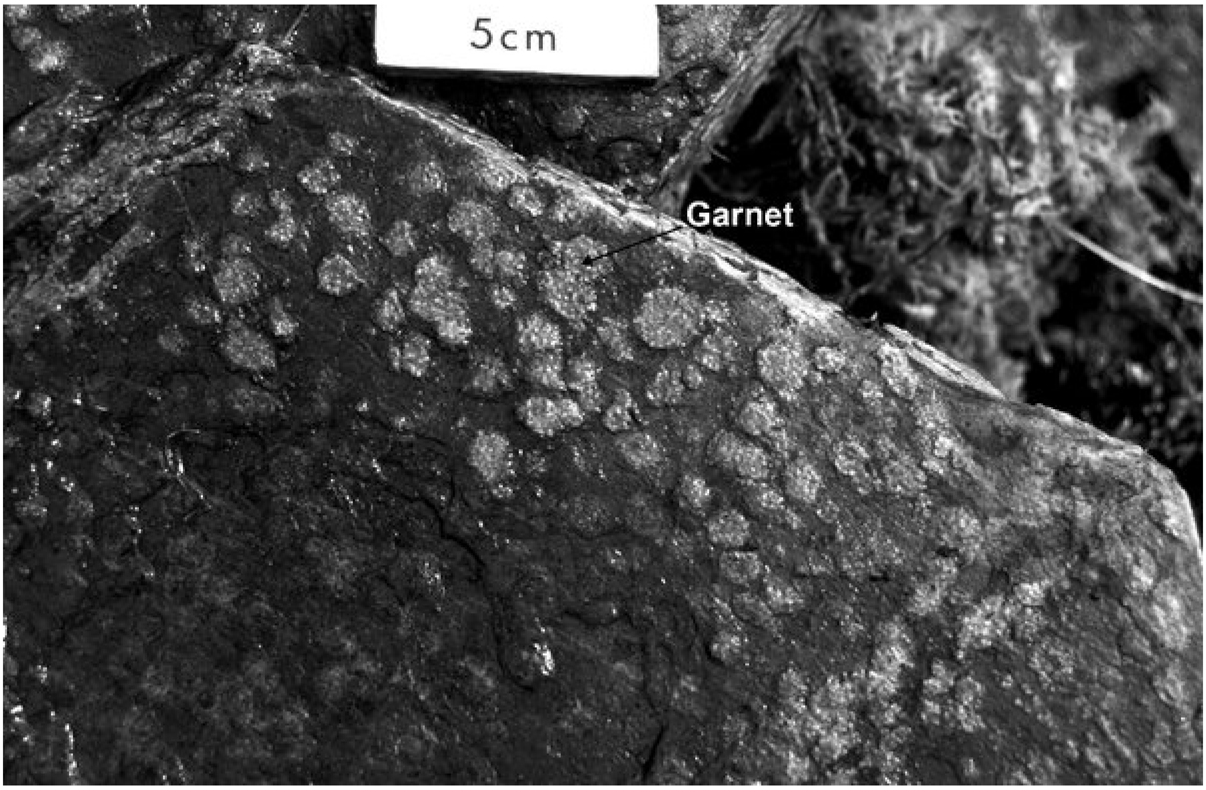
From a study of the mineralogy of the hornfels it has been concluded that the granite stopped rising and had crystallized fully at an estimated depth of 7–14 km beneath the surface of the Earth. The granite and enclosing country rocks were then strongly deformed, metamorphosed, and recrystallized, during the main progressive deformation (D2) and associated climax of regional metamorphism of the Grampian Event at about 470 million years ago. This process had a dramatic effect upon the mineralogy of the hornfels, as the low- to medium- pressure cordierite and andalusite were replaced by new high-pressure minerals such as kyanite and garnet that reflect the greatly increased depth of burial reached during the orogeny.

Geochemical and isotopic analyses of the Ben Vuirich Granite show that it has the chemical fingerprint characteristic of granites found in rifted portions of the Earth’s crust. This finding supports an earlier hypothesis that the granite formed in the same extensional tectonic setting that enabled the extrusion of the 600 Ma Tayvallich Lavas to take place (see the *West Tayvallich Peninsula* GCR site in Tanner et al., 2013a). The granite was possibly derived from partial melting of the Dalradian sedimentary rocks, or their basement, and belongs to a swarm of rift-related granitoids that originally stretched along the Caledonian orogenic belt from the Appalachians to Scotland and heralded the break-up of the supercontinent Rodinia. Hence its age and structural relationships have attracted considerable international interest.

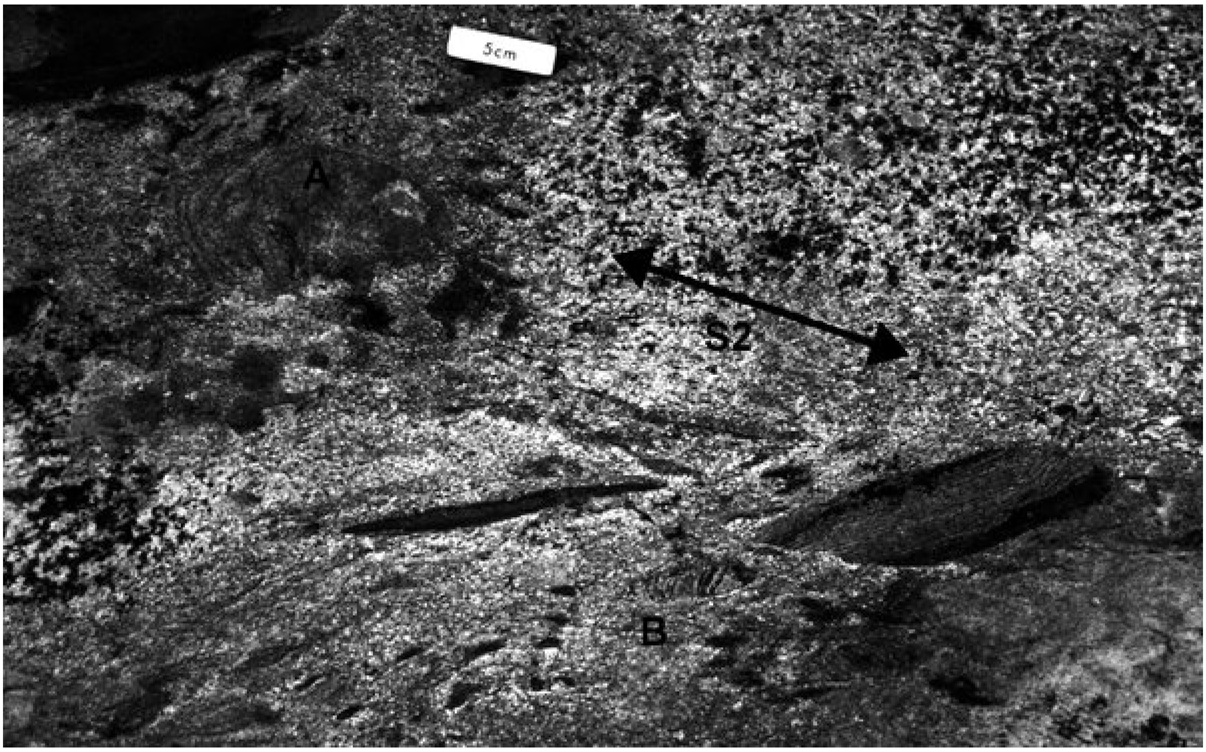
References



(Figure 6.4) Map of the Ben Vuirich Granite Intrusion and adjoining country rocks, showing the locations of the two groups of exposures (A and B) which comprise the GCR site. g exposure of pelitic schist with garnet over 2 cm across.



(Figure 6.5) Hornfels associated with the Ben Vuirich Granite, with centimetre-scale, altered porphryoblasts of contact metamorphic cordierite (pale grey), dotted with small garnets (white) that formed during the subsequent D2 regional metamorphism. (Locality A, (Figure 6.4)). (Photo: P.W.G. Tanner.)



(Figure 6.6) Xenoliths of banded quartzose psammite and pelite in the Ben Vuirich Granite at locality B, (Figure 6.4). See text for explanation. The scale is 5 cm long. (Photo: P.W.G. Tanner.)