Cromarty and Rosemarkie Inliers

[NH 808 688]–[NH 831 699], [NH 759 611]–[NH 768 621]

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Introduction

The Cromarty and Rosemarkie inliers comprise two contrasting 'windows' into Precambrian 'basement' rocks surrounded by Devonian Old Red Sandstone sedimentary rocks. These structural inliers occur north of Rosemarkie, and around the Sutors of Cromarty (Figure 6.51). They expose distinctive rocks with apparently complex tectonothermal histories that show affinities with both the Moine psammites and semipelites and the Lewisianoid gneisses to the north-west. The inliers lie adjacent to the Great Glen Fault, and are among the few localities that illustrate the ductile movement history of this fault system. The overall movement history of this fault system is increasingly well understood (see Smith and Watson, 1983; Harris, 1995; Stewart *et al.,* 1997, 1999). Sinistral movements dominate the Silurian and Devonian history of the fault, but a post-Devonian dextral offset of some 25–29 km largely accounts for the contrasting nature of the Devonian successions on either side of the Moray Firth and Great Glen (D.A. Rogers *et al.,* 1989).

The brief description of the inliers that followed the original survey by Hugh Miller in 1889 (in Horne, 1923) made little comment on the affinities of the metamorphic rocks, although Flett (in Horne, 1923) entertained the possibility that the amphibole-bearing rocks were part of a fault-bounded slice of Lewisian basement. Detailed work by Harris (1978), Rathbone (1980) and Rathbone and Harris (1980) showed that the inliers are lithologically dissimilar and have experienced different tectonometamorphic histories. The dominantly psammitic and semipelitic rocks of the Cromarty Inlier were tentatively attributed to the Glenfinnan Group. In contrast, in the Rosemarkie Inlier, Rathbone (1980) described the intercalation of Moine-like psammites and semipelites with amphibolites and finely striped hornblende-bearing felsic and mafic gneisses. Rathbone and Harris (1980) suggested that the striped hornblendic felsic and mafic gneisses were of Lewisianoid affinity. Most other Lewisianoid inliers in the Northern Highlands occur either as cores of major antiformal structures or as allochthonous sheets bounded by ductile shear-zones (Lambert and Poole, 1964; Rathbone and Harris, 1979; Barr *et al.,* 1986; Strachan and Holdsworth, 1988; Strachan *et al.,* 2002a). The Rosemarkie outcrop differs in that it lies well to the east and structurally above the nearest proven occurrence of allochthonous Lewisianoid rocks. There is no evidence for either an unconformable relationship or a discrete tectonic discontinuity between the Moine and probable Lewisianoid rocks within the inlier, although the rocks are highly strained (Rathbone and Harris, 1980).

Concordant and discordant leucogranite veins are common in the Rosemarkie Inlier and as they are tightly folded and strongly lineated, their intrusion appears to have occurred relatively early in the tectonometamorphic history of the inlier. A swarm of weakly deformed granite and pegmatite intrusions, probably of late Caledonian age, occurs within the Cromarty Inlier (Rathbone and Harris, 1980). Post-tectonic calc-alkaline appinitic microdiorite dykes are also present in the Cromarty Inlier.

The Mid-Devonian Kilmuir Conglomerate and Raddery Sandstone formations unconformably overlie the basement rocks on their north-western side (Fletcher *et al.,* 1996). In Rosemarkie Glen a small fault-bounded wedge of purple-brown siltstones, sandstones and locally breccia, interpreted to be of Early Devonian age, is exposed at the south-west end of the Rosemarkie Inlier (Figure 6.51).

Description

The GCR site covers two restricted areas of coastal outcrop along the cliffed north-western side of the Inner Moray Firth. The metamorphic rocks are best exposed on raised rock platforms around the high-water mark.

Cromarty Inlier

This site comprises a coastal section along part of the North Sutors on the north side of the entrance to the Cromarty Firth (Figure 6.51). Micaceous and siliceous psammites, interlayered with semipelite and pelite are the dominant lithology, but small lenticles of altered calc-silicate rock, up to 3 cm thick, are present (e.g. at [NH 8250 6906]). Bedding in the psammites ranges from 0.2 m to 0.7 m thick, with beds separated by thin mica-rich laminae. Sedimentary structures are not recorded. The semipelites are schistose with abundant garnet and muscovite porphyroblasts. Locally, small quartzofeldspathic segregations are wrapped by the main foliation. White mica porphyroblasts or aggregates are common, either as fine-grained 'shimmer' aggregate, or as large books of muscovite [NH 8169 6860]. In parts, the large muscovite books enclose small needles of fibrolitic sillimanite and rarely small ragged grains of kyanite. An example of strained bladed kyanite aggregates, armoured by muscovite, was found at Sutors of Cromarty [NH 8078 6630] (Rathbone and Harris, 1980).

Mafic layers and pods of dark-green amphibolite, up to 20 m thick, are abundant in the psammitic sequence. Most are concordant, but the large mafic body at [NH 8255 6904] is least locally discordant. A coarse-grained amphibolite cross-cuts a concordant sheet of schistose amphibolite at [NH 8325 7008]. The margins of the larger mafic masses are fine grained and schistose, but pass rapidly inwards into coarse-grained amphibolite. Metamorphic assemblages and textures predominate, although relict sub-ophitic textures are locally preserved [NH 8198 6869]. Thinner mafic bodies are generally schistose throughout. The amphibolites pre-date all but a possible primary deformational phase affecting the inlier.

The succession is folded by 'F3', minor- and intermediate-scale tight folds. In the southern part of the inlier F3 axial traces trend north-east, but swing east–west and north-west at the South Suitor Stacks [NH 812 670]. They remain NW-trending in the northern part of the inlier (Harris, 1978). The folds are strongly curvilinear with gently to moderately plunging axes, and do not show a consistent plunge direction or sense of asymmetry. A penetrative S3 axial-planar mica foliation is developed in most lithologies. Evidence for earlier deformations is confined to rare F1 isoclines, which are cut by the mafic intrusions and overprinted by the regional S2 foliation and a pervasive S2 foliation and related lineation, L2. Both the F2 and F3 structures are reworked by a later set of open to tight, NE-trending F4 folds.

Discordant, reddened, weakly deformed, quartz-feldspar pegmatite and leucogranite pods and veins pervade much of the Cromarty Inlier. Dyke-like intrusions of coarsely crystalline pegmatitic granite up to 3 m thick, are present (e.g. at [NH 8316 6996]). Pervasive late-tectonic 'granitization' of the metasedimentary rocks is well seen in cliff exposures between

NH 8093 6873 and [NH 8194 6868]. The boundaries of the in-situ 'replacement' are gradational over several metres. Psammitic rocks containing small K-feldspar porphyroblasts and granitic 'segregations', pass into foliated granite containing a 'ghost' layering, and finally into granite with mica-rich aggregates, schlieren, and included sheets of amphibolite. A 5 m-thick, compositionally zoned appinitic microdiorite dyke at [NH 8070 6884] cuts across psammite, semipelite and amphibolite, but is itself cut by late-stage brittle faults at [NH 8080 6885].

Rosemarkie Inlier

Rocks of the Rosemarkie Metamorphic Complex are well exposed along the coastal section northeastwards from below Learnie Farm to Ethie Shore (Figure 6.51). East of Learnie at [NH 755 610] thinly interlayered psammites and semipelites are intercalated with gneissose feldspathic psammites and other felsic gneisses. These generally Moine-like lithologies are interleaved with schistose amphibolite and layered hornblendic felsic gneisses. The overall strike of the lithological units trends north-east, slightly oblique to the coast throughout much of the site but complex fold patterns are present.

The 'Moine' lithologies are well seen close to the low-water mark between [NH 761 612] and [NH 767 619] and consist predominantly of psammites with subsidiary semipelites. The psammites are grey to pink-grey, flaggy, medium-to coarse-grained with partings picked out by pelitic laminae. Thin quartzofeldspathic lenticles impart a weakly gneissose appearance to the rocks. Small lenses of calc-silicate rock are locally present [NH 7517 6018]. Lenses of hornblendic felsic gneiss occur in a 20–45 m-wide zone in psammites in the south-west corner of the site. A schistose semipelite unit, up to 30 m thick, lies on the seaward side of the psammite-hornblendic felsic gneiss unit [NH 7618 6120]. The semipelite contains porphyroblasts of garnet and white mica aggregates, wrapped by the schistosity, which is defined by micaceous laminae, strained quartz and minor feldspar.

Amphibole-bearing lithologies occur throughout the site, but dominate in the north-east part of the section. Here they comprise thinly banded mafic and felsic gneiss (homblende-rich gneisses of Rathbone and Harris, 1980), whose contact with the metasedimentary rocks is sharp and locally folded [NH 7655 6155]. The layering in the gneisses reflects variations in the relative abundance of amphibole and quartz + feldspar and occurs on a scale ranging from a few millimetres up to approximately 1 m thick. The amphibolite layers contain some monomineralic hornblende laminae or pods [NH 7725 6275], but mostly comprise pale-green amphibole with quartz, feldspar, biotite and minor apatite, sphene and ilmenite. These are commonly gradational into the feldspar-rich layers with subordinate amphibole, normally replaced by biotite. Also present are small pods of serpentinized ultramafic rock [NH 7690 6211]. In the southern part of the site and to the east of the semipelite, a unit of finely striped pink felsic gneiss and intercalated schistose amphibolite (the mixed acid and hornblendic gneiss of Rathbone and Harris, 1980) forms exposures along the low-water mark (Figure 6.52). At Learnie Quarry [NH 752 613] and on Flower-burn foreshore [NH 7443 5895] larger bodies of amphibolite and/or metagabbro crop out in both the metasedimentary and amphibole-bearing gneissose lithologies (Highton in Fletcher *et al.,* 1996).

The disposition of the lithological units within the inlier is controlled by a set of NE-plunging folds, locally termed 'F3'. The principal planar fabric in all the rocks is composite (S1–S2) and normally lies parallel to the compositional layering, which in the metasedimentary rocks undoubtedly reflects bedding (SO). The earliest folds seen are tight to isoclinal, minor F2 folds of the layering and S1 schistosity, and commonly show curvilinear axes. A related intense mineral rodding lineation (L2) normally plunges moderately to gently to the north-east. F2 folds and fabrics are commonly refolded by the F3 fold structures (e.g. at [NH 7689 6111]). Minor F3 folds are close to tight, upright asymmetrical structures, whose axes also plunge gently to moderately to the north-east. A good example is seen at [NH 7673 6186]. In the semipelitic lithologies an axial-planar crenulation cleavage (S3) is developed in the F3 fold hinges. In the north-east part of the site, the D3 and earlier structures and associated fabrics show some minor re-orientation and are locally refolded by a later set of NE-trending F4 open folds, for example at [NH 767 617].

Numerous veins and sheets of red to salmon-pink microgranite and granitic pegmatite cut the metamorphic rocks in the inlier. The micro-granites are leucocratic and variably K-feldspar-phyric. They occur mainly as sharply bounded, steeply inclined intrusions that range in thickness from less than 1 cm up to 5 m. They are commonly concordant or subconcordant, but in several places they markedly cross-cut the layering in the psammites and striped mafic and felsic gneisses. They are folded by the F2 and F3 structures and even show excellent interference structures. Examples of folded veins and original or tectonically enhanced cross-cutting relationships are seen at [NH 767 617]. In places the veins show necking and locally they are boudinaged. In some instances the microgranite veins appear to post-date F2 folds but they carry a variably developed foliation and a strong quartz rodding lineation, both of apparent D2 age. On the long limbs of the upright F3 folds [NH 771 626] the intrusions are attenuated, and characterized by an L–S fabric, defined by orientated muscovite and biotite laths and quartz-feldspar ribbons. In the porphyritic microgranite the microcline phenocrysts form augen, which locally show asymmetrical quartz-feldspar tails. On the short limbs of these structures, the intrusions dip more gently and show a concomitant increase in thickness. These intrusions are themselves cross-cut by several younger granitic pegmatite intrusions that largely post-date the folding events, for example at [NH 767 617].

Minor cataclasite and pseudotachylite veining are present along the coastal outcrop of the Rosemarkie Metamorphic Complex, but the main late-stage brittle deformation features are steep to vertical brittle fractures and zones of brecciation that disrupt much of the outcrop (e.g. at [NH 7576 6088]). Most of the observed fault planes trend between north and NNW; only a few trend parallel to the nearby NE-trending Great Glen Fault. Mineralization is commonly associated with these fractures, which contain abundant pyrite, disseminated hematite and manganese. The Rosemarkie rocks are also cut by SE-dipping, low-angle faults, which exhibit both normal and reverse movements. A fine example of this is found at the nearby Cairds Cave [NH 7455 5954]. The age of movement on these structures is uncertain. An important phenomenon in the history of the Great Glen fracture system is found adjacent to the southeast corner of the site at [NH 7502 5992]. Here, irregular veins of breccia full of blue crocidolite ('blue asbestos'), accompanied by abundant carbonate and prehnite-rich veins, are present. The crocidolite also forms elongate braided masses at the margins of the carbonate veins. The veins both cut across, and are cut by, major and minor brittle deformational structures. These fenite occurrences are the products of late Caledonian alkali metasomatism and probably link to the other occurrences farther south-west (Deans *et al.,* 1971; Garson *et al.,* 1984). They may link to the appinitic bodies and Ach'uaine hybrids that formed small but widely occurring intrusions coeval with the intrusion of many of the granodiorite plutons in the Grampian and Northern Highlands at around 425 Ma.

Interpretation

The metamorphic rocks of the Rosemarkie and Cromarty inliers reveal a complex history of tectonometamorphic and igneous events. The status of the two inliers has yet to be fully established; published interpretations to date have focused mainly on their lithological and structural differences (Rathbone and Harris, 1980). The metasedimentary rocks of both inliers have lithological affinities with the Moine succession to the west and south-west of the Devonian cover sequence, and may correlate with the Loch Eil Group rocks (cf. May and Highton, 1997).

The Cromarty and Rosemarkie inliers have very different manifestations of granitic magmatism. The strong deformation of the abundant leucogranite intrusions at Rosemarkie shows that they were intruded early in the tectonic history of the inlier. Rathbone and Harris (1980) interpreted them as syn-D2, which accords with their overall structural relationships. Pink to red leucogranite veins are also found farther south-west along the Great Glen around Fort Augustus and in Ardgour (Stoker, 1983). In other parts of the world they are characteristic of large transpressional shear-zones, and leucogranite emplacement can be shown to be coeval with ductile lateral movements. Documented examples are the Red River Fault Zone that separates South China from Indochina (Leloup *et al.,* 1995), and the Karakoram fault zone in northern Ladakh (Searle *et al.,* 1998).

In contrast, the granitic rocks of the Cromarty Inlier are little deformed and are similar to other syn- to late-Caledonian granitic vein-complexes in the Highlands, such as those at Glenmoriston (May and Highton, 1997) and Glen Kyllachy (van Breemen and Piasecki, 1983). Areas of 'granitized' host rocks that pass into granite with restite fabrics are typical of such complexes. This feature is indicative of local assimilation during late-tectonic granite magmatism, rather than partial melting at high metamorphic grade (Rathbone and Harris, 1980). The cross-cutting form of most granite and pegmatite intrusions within the outcrop shows that the granitic melts were divorced from their source area.

The status of the amphibole-bearing lithologies within the Rosemarkie Inlier is also significant. Unequivocal metagabbro, amphibolite and schistose amphibolite of similar structural age are common to both the Rosemarkie (Highton in Fletcher *et al.,* 1996) and Cromarty inliers (Rathbone and Harris, 1980), and occur extensively in the Moine succession farther west (see Comrie GCR site report, this chapter). However, in the Rosemarkie GCR site, Rathbone and Harris (1980) noted the absence of garnet-bearing amphibolites, normally common in the early metabasic intrusions in the Moine succession. This led them to suggest that all amphibolite-bearing rocks here should be assigned to the Lewisianoid gneisses, even though in several instances the amphibolites intrude the dominantly psammitic host rock. The status of other amphibolite-bearing lithologies, such as the quartzofeldspathic gneisses with sparse hornblendic layers, is also questionable given the significant high strain in this part of the outcrop and the possible Neoproterozoic age for many of the basic meta-igneous rocks (Highton in Fletcher *et al.,* 1996). However, recent zircon U-Pb LA-MC-ICP-MS dating has shown that the striped mafic and felsic gneisses have a protolith age of between 2720 Ma and 2930 Ma, confirming their Lewisianoid identity (Mendum and Noble, in press).

The presence of the Lewisianoid rocks adjacent to the Great Glen Fault is critical to any interpretation of the tectonic history of the inliers, but its explanation is unclear. Harris (1995) interpreted the earliest ductile fold structures (F2) in the Rosemarkie Inlier as possibly formed during ductile transpression within the Great Glen Fault Zone, coeval with the main crustal shortening across the orogen. This implies significant early ductile displacement to juxtapose the Moine and Lewisianoid assemblages prior to regional tectonometamorphism. In view of recent age dating from both the Northern and Central Highlands (Noble *et al.,* 1996; Friend *et* ed., 1997), the Great Glen Fault might then represent a long-lived crustal structure dating back to the Neoproterozoic (Harris, 1995). However, work on the mylonites, cataclasites and breccias that mark the fault zone in the Fort Augustus to Loch Linnhe section to the south-west has shown that such features can be explained as a product of both sinistral ductile and later brittle displacements of late Caledonian age (Stewart *et al.,* 1997, 1999).

Recent dating of zircons and monazites from the microgranite veins and the adjacent striped hornblendic and felsic gneisses of the Rosemarkie Inlier has thrown some light on its tectonometamorphic history (Mendum and Noble, 2003, in press). U-Pb TIMS isotopic dating has shown that the leucocratic microgranites were intruded at *c.* 400 Ma, coeval with the mid-Devonian Acadian event. Microgranite intrusion and subsequent deformation ('D2', 'D3') and the rapid differential uplift of the Rosemarkie Inlier, are all interpreted as a product of sinistral transpressional movements along the Great Glen Fault. Lateral movements totalling 25–30 km and uplift of some 15 km are implied. Such movements must have been completed prior to deposition of the mid-Devonian succession in the Eifelian giving a maximum timespan of only some 6–7million years for the deformation and exhumation of the inlier. However, questions still remain as to the role of the D1 deformation, nature of the Moine–Lewisianoid relationships, age of the mafic intrusions, and pressure and temperature conditions accompanying the short-lived Acadian event.

The late history of the fault zone is entirely brittle, with lateral and vertical movements during the mid- to late Devonian. Fluid infiltration at this time is manifest in substantial carbonate veining, fluidized breccia dykes with carbonate matrices, fenitization and mineralization (Garson *et al.,* 1984). The fault system underwent dextral reactivation, firstly as a consequence of compression in late-Carboniferous–Permian times, and as an extensional structure during Permo–Triassic and late Jurassic rifting (Underhill and Brodie, 1993). It was also the site of Mid-Cretaceous to Neogene regional uplift.

Although the Rosemarkie Inlier coincides, in part, with a prominent aeromagnetic anomaly along the Great Glen Fault Zone, neither the Lewisianoid gneisses nor the metabasic rocks are thought to be the source of this anomaly. The source may reflect the presence of Early Proterozoic-age basement at shallow to mid-crustal levels adjacent to the fault zone (Rollin in Fletcher *et al.,* 1996).

Conclusions

The Rosemarkie and Cromarty Inliers GCR site presents a unique perspective of one of the most important fault structures within the Caledonian orogenic belt, the Great Glen Fault Zone. The site covers two separate 'basement' inliers situated immediately adjacent to the fault zone and surrounded by Mid-Devonian sandstones and conglomerates, which unconformably overlie the 'basement' rocks.

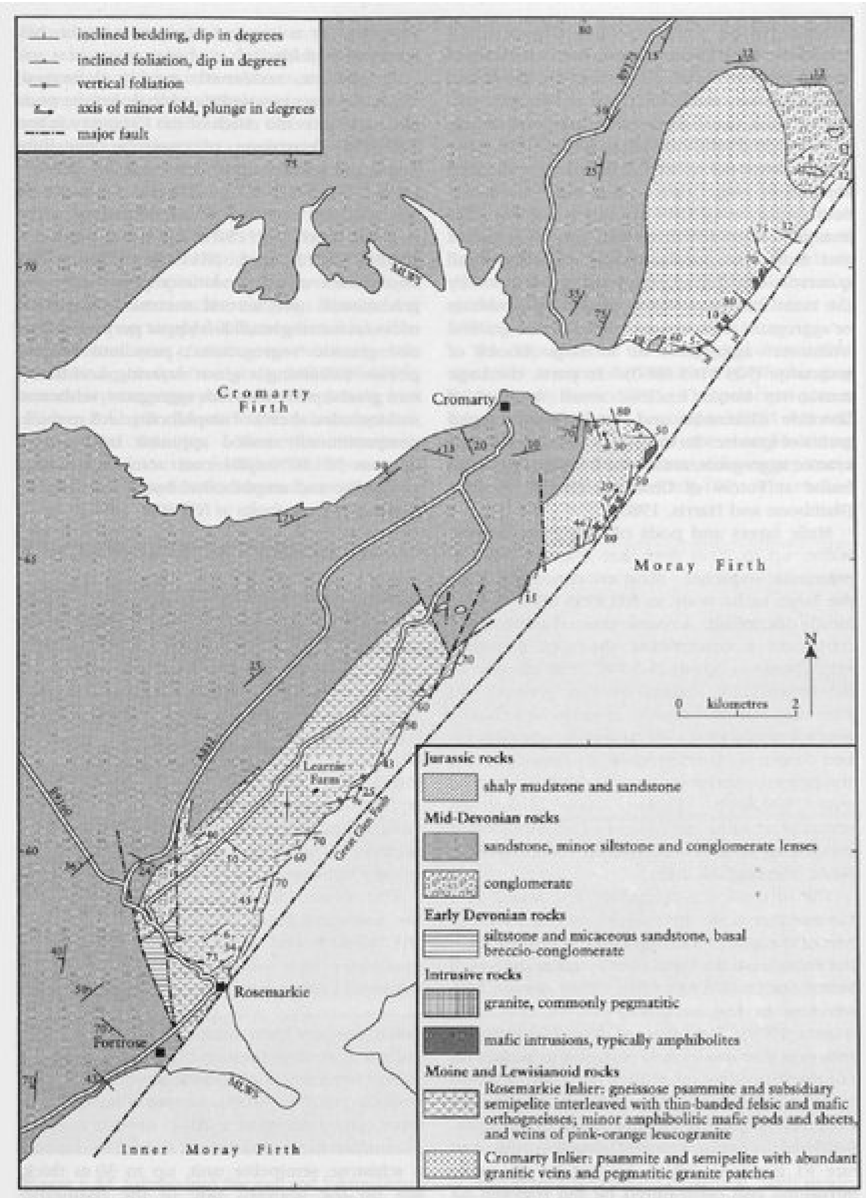
The two inliers are lithologically and tectonically different. In the Rosemarkie Inlier rocks of Lewisianoid affinity occur within the partially gneissose sequence of Moine psammites and semipelites. The Lewisianoid and Moine rocks show little evidence of either an original unconformable relationship, tight interfolding, or of obvious tectonic discontinuities. The rocks are highly deformed and show fine-scale inter-layering of the amphibolitic mafic and quartzofeldspathic rock-types. Amphibolitic mafic pods and sheets intrude both the Lewisanoid and Moine rocks. Abundant pink to red leucogranite veins intrude the interleaved Lewisianoid and Moine rocks; they post-date the first deformation episode, yet are tightly folded, lineated and strained during the main ductile deformation episodes (termed 'D2' and 'D3'). The leuco-granite veins, whose emplacement has been dated by U-Pb methods on zircon and monazite at *c.* 400 Ma, appear to have been emplaced at a very early stage of this deformation.

The Cromarty Inlier consists of psammites and semipelites with amphibolitic mafic pods and lenses. It exposes a fine example of a granitic vein-complex and its localized interaction with the host rocks. The emplacement age of the granitic material remains unknown but may be Late Silurian or Mid-Devonian. The aspects of the late brittle faulting and metasomatism along the Great Glen Fault Zone are also uniquely preserved here.

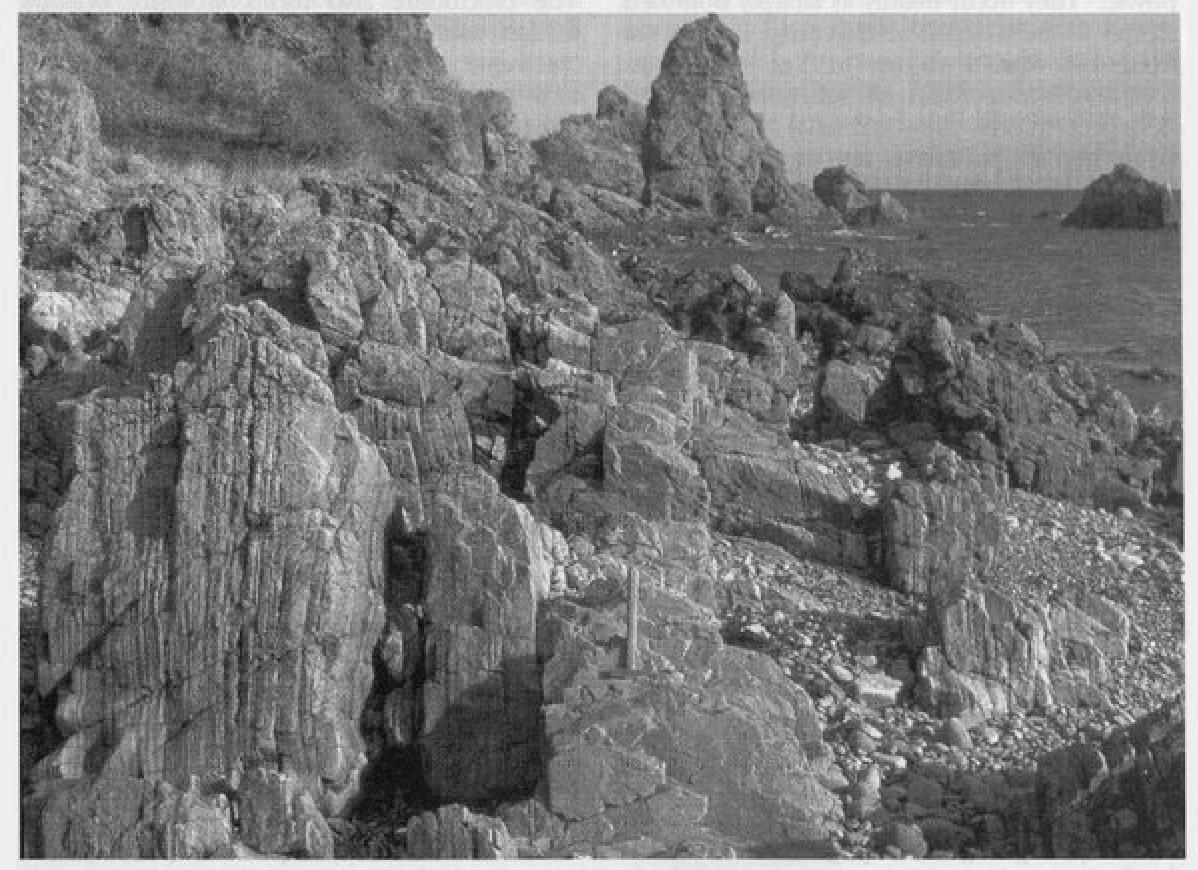
The formation of the inliers is attributed to deformation and exhumation resulting primarily from sinistral transpressional movements along the Great Glen Fault Zone during the Acadian event between *c.* 400 Ma and 393 Ma. The two inliers are interpreted as fault-bounded lenticular 'basement' pods that have been uplifted relative to the surrounding areas during this short-lived mid-Devonian compressional event. Interleaving of Lewisianoid and Moine rocks and the generation of an early bedding-parallel schistosity pre-date this deformation and uplift. These early events may be Neoproterozoic, Ordovician or Silurian in age. Subsequent to Devonian uplift both inliers have experienced fracturing, brecciation and some metasomatic activity.

The Cromarty and Rosemarkie Inliers GCR site is of international importance in that it provides crucial evidence of the tectonic development of Scotland during the Acadian event, which is lacking elsewhere. The site also presents an excellent opportunity to study the structural dynamics within a major zone of crustal shear and transcurrent faulting. The site remains suitable for further studies of the geological relationships and the relative timing of the intrusive, structural and metamorphic events.

References



(Figure 6.51) Geology of the Rosemarkie and Cromarty area. Compiled from British Geological Survey one-inch Sheet 94, Cromarty (Institute of Geological Sciences, 1973), 1:50 000 Sheet 84'W, Fortrose (British Geological Survey, 1997c), and Rathbone and Harris (1980).



(Figure 6.52) Salmon-pink lineated and foliated leucocratic microgranite vein cutting subvertical, thinly banded amphibolitic felsic Lewisianoid gneisses. The hammer is 37 cm long. Learnie shore [NH 7620 6124]. (Photo: J.R. Mendum, BGS No. P581260, reproduced with the permission of the Director, British Geological Survey, © NERC.)