Late Caledonian (Scandian) and Proto-Variscan (Acadian) orogenic events in Scotland

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Abstract

The later tectonic phases of the Caledonian Orogeny reflect the collision of Baltica and Laurentia. The result was the Scandian event in Silurian times, and the oblique docking of Eastern Avalonia with Scotland, generating deformation and metamorphism in the Southern Uplands. The exhumation of the Caledonide Orogen was then accompanied by sinistral transtensional faulting and emplacement of granitoid plutons. The Iapetus Ocean was finally closed, and subduction activity had migrated south to the Rheic Ocean by early Devonian times.
Continental rifting and deposition of the Lower Old Red Sandstone fluvial-lacustrine succession, accompanied by basaltic-andesitic volcanism, occurred across Scotland. Deposition commenced in the late Silurian and continued through to Emsian times, when it was interrupted by the short-lived, northward-directed Acadian event. The resultant deformation and folding, a product of sinistral transpression, were focussed along the major pre-existing faults and shear zones.

Evidence for Acadian transpressional movements along the Great Glen Fault (GGF) is found near Rosemarkie, where Moine psammites and semipelites are interleaved with Lewisianoid gneisses in a structural inlier. These lithologies are intruded by pink leucogranite veins that themselves show evidence of two phases of ductile deformation and folding. U-Pb monazite and zircon ages show that the leucogranites were emplaced at c. 399 Ma. Leucogranite intrusion and subsequent deformation are interpreted to have occurred during oblique extrusion of the inlier as an elongate ‘pip’, generated at a northwestward step-over that developed on the GGF during the Acadian Event. Crude strain estimates from the inlier suggest that around 30 km of sinistral displacement occurred on the GGF, and the inlier was uplifted by c. 15 km relative to the surrounding early Devonian rocks. Hence the inlier may formerly have been contiguous with the fault-bounded early Devonian Meall Fhuar-mhonaidh Outlier, now found adjacent to the GGF, 32 km farther south-west. The deformation of this Devonian outlier can also be attributed to Acadian transpression.

Acadian deformation and localised uplift were over by c. 393 Ma when Eifelian-Givetian sandstones and conglomerates were deposited on the exhumed Rosemarkie Inlier. Evidence from here and from farther south in the Midland Valley suggests that Devonian sedimentation overlapped the early stages of the Acadian Event in upper Emsian times. Thus, the transpressional event only lasted for a mere 6 Ma in northern Scotland. As the Acadian event related to Proto-Variscan plate-tectonic activity in the Rheic Ocean, it is deemed to mark the end of the Caledonian Orogeny.

Introduction

The term ‘Caledonian’, derived from the Latin for Scotland, was first used in a tectonic sense in 1888 by Eduard Suess (1831–1914) in the second volume of his book *Der Antlitz der Erde* (1888; Suess, 1906). He referred to Caledonian ‘pre-Devonian mountains’ extending from Norway through Scotland to Ireland and Wales. Suess recognised that tectonic events had both geographical limits and time-related frameworks but he lacked the evidence to define the age of deformation and metamorphism. Haug (1900) subsequently described the concept of orogeny as 'the process of mountain-building', and recognised four major orogenies in the European geological record: the Huronian (Precambrian), the Caledonian, the Hercynian and the Alpine.

During the 20th century the term Caledonian Orogeny was widely used, but with varied meanings. A recent appraisal of its use was given by McKerrow *et al*. (2000), who concluded that it should be restricted in a palaeogeographical sense to encompass the tectonic or orogenic phases that affected rocks within, or bordering, the Iapetus Ocean. McKerrow *et al*. commented on the diachronous nature of several of the constituent phases, and noted that the orogeny included several arc–arc and arc–continent collisions and related plate tectonic events. Thus, the Caledonian Orogeny in Scotland began with rift-drift transition at around 580–570 Ma, followed by the rapid formation of the Iapetus Ocean. The peak of tectonic activity occurred in Early to Mid-Ordovician times (*c.* 470Ma) and has been ascribed in the British Isles to a complex arc–continent collision and termed the Grampian Event.

Chew (this volume) has presented a synthesis of this event focussed on the evidence from the Irish Caledonides. Closure of the Iapetus Ocean to the south took place in the Wenlock (428–423 Ma) when oblique docking of the Eastern Avalonian microcontinent (England, Wales and southern parts of Ireland) with Scotland and the northern parts of Ireland occurred, generating the deformation and metamorphism of the Ordovician and Silurian largely turbiditic succession of the Southern Uplands (*see* Stone this volume). Hence, although oceanic tracts had disappeared from the palaeogeographic scene in Scotland by the Mid-Silurian and exhumation of the orogenic welt had commenced, later compressional stages of the Caledonian Orogeny were still in progress elsewhere. Between *c.* 440 Ma and 429 Ma the Northern Highlands and Outer Hebrides were affected by the Scandian Event that was responsible for the generation of the Moine Thrust Belt and related deformation. This tectonic event resulted from Baltica-Greenland continental collision farther north, demonstrating the diachronous and varied nature of Iapetus Ocean closure. In Mid-Silurian to Early Devonian times the Highlands were marked by the intrusion of abundant granitoid plutons, associated with subduction farther south, and accompanied by rapid uplift. Transcurrent movements, mainly sinistral, took place along the Great Glen Fault (GGF), and probably also along the Highland Boundary. A series of north-east-trending sinistral faults were also generated in the Grampian and Northern Highlands at this time, e.g. the Loch Tay, Ericht-Laidon and Strathconon faults.

The nature of the plate tectonic events directly responsible for the main tectonic phases of the Caledonian Orogeny has been the subject of much speculation based on many studies in the Grampian and Northern Highlands of Scotland, Shetland, the Irish Caledonides and the Southern Uplands. Sadly, the presently exposed evidence of such events is limited — unsurprising, given that subduction, faulting, uplift, exhumation and erosion all combine to either conceal or destroy it. Fortunately, evidence for indenting arcs, sutures, thrust belts and other structural events is better preserved in parts of Newfoundland, East Greenland and Norway, giving us a wider and more comprehensive picture of the Caledonian Orogeny. A general pattern of rapid but variable oceanic crust–microcontinent–continent convergence can been recognised, linked mainly to subduction outboard from the Laurentian margin, and ultimately the closure of the Iapetus Ocean. However, the detailed geometry, changing patterns of plate movements, palaeogeography and timing of these constituent events do still remain largely elusive. Following closure of the Iapetus Ocean and the Mid-Silurian Scandian Event in northern Scotland the main tectonic framework of Highland Scotland was broadly as it is today. Lateral fault movements later modified the relative positions of the tectonomorphic belts, but the tripartite division into the Grampian Highlands, the Northern Highlands and the Foreland was in place at the end of the Caledonian Orogeny (Fig. 1).

The Acadian Event occurred in Mid-Devonian times and was responsible for the main folding, cleavage formation and related metamorphism of the Cambrian, Ordovician and Silurian rocks in Wales, in the Lake District, and in south-west and south-east Ireland. These areas of deformed Palaeozoic successions have traditionally been regarded at parts of the Caledonides and indeed McKerrow *et al*. (2000) included the Acadian Event in the Caledonian Orogeny.

The type area for the Acadian Event is in the northern Appalachians where Western Avalonia collided with the Laurentian margin in the Early Devonian (between 419 Ma and 400Ma). Interestingly, no tectonic event has been detected in the coherent Devonian marine successions in Devon or in the Belgium Ardennes at this time. However, Woodcock *et al*. (2007) pointed out that Iapetus Ocean closure took place at least 20 Ma before the Acadian Event, which in England, Wales and Ireland is closely bracketed between 400 Ma and 390 Ma. The Acadian Event is attributed to northward movement of the Midlands microcraton that impinged onto the adjacent sedimentary basins. Woodcock *et al*. (2007) show clearly that these tectonic events linked to the development of the Rheic Ocean, and the formation and migration of the peri-Gondwanan microcontinents. Although there was overlap between the events on the Gondwanan margin of Iapetus and the early stages of development of the Rheic Ocean, they argued that the Acadian Event should be regarded as proto-Variscan rather than end Caledonian.

In this paper I will briefly describe the main structures related to the Scandian collision and the features generated during the subsequent Silurian–Devonian uplift and exhumation of the Caldonian Orogen — a time of widespread volcanism and emplacement of granitoid plutons, particularly in the Grampian Highlands. I will then show that Scotland, although distant from the main effects of the Acadian Event, did register its impact in both its Devonian stratigraphy and in the formation of localised structures. Deformation effects appear to have been focussed both along, and adjacent to, the main north-east-trending faults, namely the Southern Uplands, Highland Boundary and Great Glen faults. It will be argued that Acadian deformation resulted in the formation of the Rosemarkie Inlier, a lenticular body of Moine and Lewisianoid [*see below* under The Scandian Event 3] rocks adjacent to the GGF bordering the Inner Moray Firth; deformation of the early Devonian Meall Fhuar-mhonaidh Outlier farther south-west; and the formation of the Strathmore Syncline and Sidlaw Anticline in the northern part of the Midland Valley. Acadian deformation is generally reflected in the Old Red Sandstone fluviatile and lacustrine successions in Scotland by an unconformity that separates early Devonian conglomerates, sandstones and siltstones from the overlying mid-Devonian and late Devonian sandstones and siltstones. As such, this surface marks the end of the Caledonian Orogeny in Scotland.

The Scandian Event

The Scandian Event was generated when Baltica collided with Laurentia (East Greenland), closing the northern part of the Iapetus Ocean and creating the continent of Laurussia. Figure 2 shows palaoegeographical reconstructions by Cocks and Torsvik (2006) at 440 Ma and at 420 Ma. The palaeomagnetic evidence suggests that

between Cambrian and Mid-Silurian times Baltica effectively ‘pirouetted’ slowly 90° anticlockwise to collide with East Greenland, thus generating the extensive Scandian nappe stacks and related metamorphism that dominate the Greenland and Scandinavian Caledonides. It seems that Northwest Scotland was caught up at the southern end of this tectonic collision. As a consequence, deformed and metamorphosed Neoproterozoic rocks of the Moine Nappe were overthrust to the west-north-west for some 50–100 km over the older Foreland Lewisian gneisses and their Torridonian and Cambrian sedimentary cover, resulting in the formation of the Moine Thrust Belt.
The bedrock geology of Northwest Scotland comprises three major tectonic elements:

1. The Foreland, which consists of Archaean and Proterozoic gneisses, termed the Lewisian Gneiss Complex, overlain unconformably by a cover sequence of Torridonian and Cambrian–Ordovician sedimentary rocks. The orthogneisses were largely derived from felsic, mafic and ultramafic intrusive igneous protoliths. The Torridonian rocks are mostly fluviatile to lacustrine, red-brown arkosic sandstones with local conglomerates and minor siltstones and mudstones. They are late Mesoproterozoic and early Neoproterozoic in age and have not been metamorphosed. The overlying Cambro-Ordovician rocks comprise quartzites, in part with abundant worm burrow casts (‘pipe rock’), potash-rich shales with dolomitic beds, and dolostones and limestones. This shallow marine shelf sequence can be traced with only minor stratigraphical changes from the north Sutherland coast south-west to Skye, but is also found in Greenland, Baltica and parts of Newfoundland.
2. The Moine Thrust Belt (or Zone) that extends from Loch Eriboll south-south-west to the Sleat Peninsula of Skye. It forms a gently east-south-east-dipping structural succession of thrust and imbricated slices of the Foreland rocks, up to 11km wide, which in Assynt has been intruded by syenite plutons and abundant related minor intrusions. The thrust belt contains mylonitic rocks, found in its upper parts, but is characterised by its brittle deformation features. Major thrusts have transported different parts of the Foreland succession to the west-north-west with the older thrust nappes stacked above younger ones. The overall sequence of thrusting has juxtaposed earlier-formed nappes, spawned at deeper crustal levels, with those developed later at shallower crustal levels. Within the higher thrust sheets large-scale folds of the gneissose basement and sedimentary cover have been recognised, but more generally individual beds or sedimentary units have been stacked up and duplicated, commonly giving rise to an imbricate geometry (like tiles on a roof). The imbrication reflects the well-bedded and lithologically varied nature of the Cambro-Ordovician sequence and its response to the regional Scandian compression. In the southern part of the thrust belt thicker Torridonian units define large-scale recumbent folds and show evidence of greenschist facies metamorphism and local cleavage development.
3. The Moine Nappe lies in the hangingwall of the Moine Thrust (*sensu stricto*), a major dislocation within the Moine Thrust Belt that generally marks its eastern upper boundary. Within the Moine Nappe, which crops out over a large part of the Northern Highlands, are strongly deformed and metamorphosed metasedimentary rocks of the Moine Supergroup, originally deposited as fluviatile to lacustrine and marine sandstones, siltstones and mudstones. The Moine and Torridonian successions are lithologically and stratigraphically similar, and were deposited during the early Neoproterozoic. Both successions unconformably overlie Archaean basement orthogneisses with subsidiary metasedimentary enclaves, but those underlying the Moine rocks show lithological (more mafic and ultramafic intrusions) and isotopic

differences (general lack of Laxfordian reworking) to the Lewisian gneisses of the Foreland. Hence, they have been termed Lewisianoid to reflect their similar age and provenance but also to acknowledge they were formed at some distance from the Lewisian Gneiss Complex of the Foreland. The Moine and Torridonian successions exhibit similar detrital zircon age spectra and have been interpreted as lateral equivalents (Krabbendam *et al*., 2008). Following sedimentation and diagenesis the Moine succession was intruded by granite sheets and by dolerite dykes and sheets at around 870 Ma. Both the sedimentary succession and these early igneous rocks show evidence of an extended deformational and metamorphic history (Mendum *et al*. 2009). In places there is evidence of deformation and metamorphism relating to a Knoydartian orogenic event at *c.* 820–780 Ma and possible later metamorphism at *c.* 750–730 Ma. The succession was at least partially affected by the Grampian Event at *c.* 470–455 Ma and then again tectonically reworked during the Scandian Event at *c.* 440–429 Ma.

The Moine Thrust Belt (MTB) has excited interest since Lapworth's ground-breaking work on the east side of Loch Eriboll in north Sutherland in 1882–3. Lapworth rapidly showed that the Moine rocks had been carried westwards over the Cambro-Ordovician rocks and underlying gneisses by means of thrusts, thereby generating mylonites and other fault rocks. This work resolved a long-standing controversy as to the nature of the relationship between the unmetamorphosed Foreland sedimentary rocks and structurally overlying metamorphosed and foliated Moine rocks. Archibald Geikie, who in 1882 had been appointed Director General of the Geological Survey, was at first unconvinced by Lapworth's conclusions. However, from 1884 onwards he viewed geological mapping in the MTB as the key to understanding Highland geology. As a result, from 1883 to 1901 the Geological Survey mapped the belt in detail, work that was summarised in the Northwest Highlands memoir (Peach *et al*., 1907). The belt again became a focus for further studies in the 1970s and early 1980s with the recognition that it was a good place to work out the mechanics of thrusting and the complexities of its geometry (Elliot and Johnson, 1980; Butler, 1982; Coward, 1983; Butler, 2010).

It is not intended to provide a comprehensive account of the thrust belt here, but merely to focus on some of the more recent work carried out by the Geological Survey in Assynt and how that impinges on our understanding of its geological history.

The Traligill Transverse Zone

The geometry of the thrust belt is controlled by the number and magnitude of the basement Lewisian gneiss bodies that lie in the component thrust sheets and the thickness of the imbricated stacks of the various Cambro-Ordovician units. The relative abundance of basement gneiss sheets in Assynt has resulted in formation of the Assynt Culmination; here, the thrust belt reaches some 10–11 km in width and attains more than 2km in structural thickness. Figure 3 shows the component thrust sheets in this area. The culmination is transected by a west-north-west-trending sub-vertical zone of faults and thrusts that underlies Glen Dubh and the Traligill Valley, which Krabbendam and Leslie (2010) termed the Traligill Transverse Zone. This faulted zone extends west-north-west of the thrust belt in the Foreland Lewisian gneisses as the Loch Assynt Fault, which apparently links to the Stoer Shear Zone farther west-north-west. Krabbendam and Leslie showed that offset across the fault in the Foreland amounted to 1,200m sinistrally and 120m vertically (down to the north-east). In the higher Ben More Nappe the zone is manifest as the Bealach Traligill

Fault, which has only offset the nappe and the overlying Moine Thrust laterally by a few hundred metres. At lower structural levels the *en échelon* Gleann Dubh Fault has also displaced thrust features, implying *c.* 90m of lateral movement and 20m of downthrow to the north-east. Lower down in the thrust belt the Traligill Thrust forms a lateral ramp that here defines the north-east margin of a thick set of imbricated Durness group dolostones and limestones. This thrust dips moderately steeply to the south-south-west and strikes west-north-west, parallel to the main transport direction in the MTB.
Krabbendam and Leslie (2010) show that the Traligill Thrust is folded by the Droighinn Anticline, a major north-west-trending periclinal structure, which they interpret as generated by the stacking of later-formed imbricate slices beneath. The Droighinn Anticline can be traced south into the Breabag Dome. What is clear is that the thrust geometry changes markedly across this Traligill boundary. To the north-north-east the Glencoul Thrust Sheet and associated thrust nappes are composed of thick slabs of Lewisian gneisses and the imbricated and repeated occurrence of the overlying Cambrian quartzites (Eriboll Formation). In contrast, to the south-south-east the Stronchrubie–Breabag Thrust System consists of numerous individual thrust sheets formed in the Cambrian quartzites in its upper part, but is dominated by Cambro-Ordovician Durness Group dolostones and limestones in its lower part (Fig. 4). Krabbendam and Leslie (2010) showed that the faulting post-dated deposition of the Cambro-Ordovician sequence, but predated the formation of the thrust belt. The fault offsets and resultant steps in the geological template were relatively minor, but the effects on the development of the thrust belt geometry were significant. It is recognised that there are considerable lateral changes in the nature of the basement and cover along the exposed length of the MTB and that these are at least in part responsible for its variable geometry.

The Age of the Moine Thrust Belt

The presence of calc-alkaline igneous intrusions in Assynt has attracted the attention of petrologists and geochronologists for many years. Locally abundant sills, sheets and dykes and two syenite plutons, namely the Loch Borralan and Loch Ailsh plutons were intruded into the Assynt Culmination at or around the time of thrusting. The Loch Ailsh Pluton is locally foliated and was interpreted as being emplaced prior to the main brittle movements on the MTB. Its U–Pb zircon age of 439±4 Ma (Halliday *et al.*, 1987) was used to provide a maximum date for the main thrust movements. The Loch Borralan Pluton consists of an early phase of nepheline- and pseudoleucite-bearing syenites and a later phase of quartz syenite. Van Breemen *et al.* (1979a) obtained a bulk U–Pb zircon age of 430±4 Ma for emplacement of the pluton, which was considered to post-date movement on the MTB. Although most of the calc-alkaline intrusions lie within the MTB, the Canisp Porphyry, a porphyritic quartz-microsyenite that forms extensive sills, is found only in the Foreland succession, albeit very close to the mapped trace of the Sole Thrust. Hence its emplacement was assumed to predate brittle thrusting movements, particularly the latest phases that link to movements on the Sole Thrust. Goodenough *et al.* (2006) obtained a U–Pb zircon TIMS age of 437±5 Ma from the Canisp Porphyry. More recently Goodenough *et al.* (2011) have carried out further U–Pb zircon TIMS dating on these calc-alkaline intrusions and have reassessed their ages of emplacement (Fig. 5). Consequently, the Loch Ailsh Pluton is now dated at 430.6±0.3 Ma, and the early and later parts of the Loch Borralan Pluton are dated 431.1±1.2 Ma and 429.2±0.5 Ma, respectively.

The Canisp Porphyry gave an age of 430.4±0.4 Ma. This cluster of ages at *c*. 430 Ma, provides good control on the younger limits of thrust movements, but removes any constraint on their maximum age. Freeman *et al*. (1998) obtained Rb–Sr muscovite ages from mylonitic rocks of the MTB south of Assynt suggesting that movements continued until *c.* 408 Ma. Similarly, Dallmeyer *et al*. (2001) obtained Rb–Sr muscovite ages ranging from 427 Ma to 413 Ma from mylonitic rocks farther north in Sutherland. The Rb–Sr muscovite ages are at variance with those from Assynt suggesting that there may have been later localised reactivation of the MTB, and/or problems with interpretation of the isotopic data or systems.

Evidence for the Scandian Event in Moine rocks (Northern Highlands)

The Moine rocks in the southern part of the Northern Highlands can be structurally divided into a ‘Flat Belt’ in the east, a ‘Steep Belt’ in the centre and a more variable folded but overall gently dipping part in the west. The ‘Steep Belt’ consists mainly of Glenfinnan Group pelites, psammites and semipelites with amphibolitic mafic bodies locally common. It represents a zone of greater deformation with large- and small-scale refolding of earlier thrusts, folds and fabrics. At its eastern margin in Glen Dessarry the Moine rocks are intruded by the Glendessarry Syenite Pluton, which contains xenoliths of the Moine rocks, some of which show tight, early folds. The intrusion itself is tightly folded into a sheath-like synform and is foliated and lineated. The syenite was originally dated by van Breemen *et al*. (1979b) at 456±5 Ma (U–Pb zircon), but Goodenough *et al*. (2011) have revised this age to 447.9±2.9 Ma. This supports the idea that the late main folding in the ‘Steep Belt’, previously termed D3, may well relate to the Scandian Event.

In Sutherland several granite intrusions that lie within the Moine succession carry a penetrative foliation orientated near parallel to that of the adjacent Moine country rocks. These sheeted intrusions are locally discordant to earlier folds and fabrics but lie close to or within ductile thrust zones, notably the Naver, Swordly and Skinsdale thrusts, and have been interpreted as emplaced synchronous with westward thrusting. Kinny *et al*. (2003) obtained U–Pb SHRIMP zircon ages from the granites, ranging from 429±11 Ma (Strathnaver Granite) to 420±6 Ma (Klibreck Granite). Kocks *et al*. (2006) obtained a similar U–Pb TIMS monazite age of 426±2 Ma for intrusion of the Strath Halladale Granite. Thus, most of the ductile thrust zones in the Sutherland Moine rocks have been interpreted as being either of Scandian age or reactivating earlier formed thrusts during the Scandian Event. Goodenough *et al*. (2011) suggested that a re-interpetation of the data, which show evidence of Pb loss (particularly for the Klibreck Granite), would lead to revised ages closer to 430 Ma.

Mid- to Late Silurian faulting, uplift and granite plutonism

Closely following on the Scandian Event there is evidence for significant sinistral lateral movements on the GGF and other north-east-trending sinistral transcurrent faults in the Grampian and Northern Highlands. Emplacement of the Clunes Tonalite Pluton, dated at 428±2 Ma (U–Pb zircon TIMS), was interpreted as synchronous with sinistral lateral movements on the GGF (Stewart *et al*. 2001). Similarly the geometry of the Strontian and Foyers granitoid plutons, both of which lie adjacent to the GGF, is compatible with their emplacement coeval with lateral fault movements. North-east-trending faults are well developed across the Grampian Highlands with their formation also attributed to the Mid-Silurian, probably reflecting the major change in plate kinematics taking place farther south beneath the Southern Uplands.

Jacques and Reavy (1994) postulated that a series of lower crustal ductile shear zones developed at this time, providing pathways for the ascent of granitoid magmas that resulted in the widespread plutonism focussed at *c*. 425 Ma, particularly in the Grampian Highlands. The recent work of Neilson *et al*. (2009) on the Mid- to Late Silurian calc-akaline granitoid plutons and related dykes, sheets, lavas, etc of the south-west Grampian Highlands has clarified relationships between component bodies and their timing of emplacement. Neilson *et al*. (2009) presented revised U–Pb zircon TIMS ages from several of the intrusions in the Loch Etive — Glencoe–Ben Nevis region. They also used geochemical data from the intrusions and adjacent Lorn lavas to infer petrogenetic relationships. Figure 6 shows a summary of their revised ages for the major intrusions.

Neilson *et al*. concluded that that there was an evolving sequence of plutonism from 427 Ma to 407 Ma, accompanied by crustal uplift. Many of the lavas show geochemical affinities with the abundant but small-scale appinitic and lamprophyric intrusions. Neilson *et al*. proposed a model of slab break-off with a consequent uprise of hot 'dry' asthenosphere that melted enriched lithospheric mantle and thus formed repeated batches of appinite-lamprophyre magma (Fig. 7). Linked with partial melting of the lower crust, they suggested that this process resulted in the generation of the voluminous high Ba–Sr granitoid magmas. The Glencoe Caldera is one of the few remnants of a once more widespread volcanic province, typified by thick andesitic and dacitic lava flows. These large volcanic edifices have been uplifted and eroded and their roots intruded by the granitic plutons. Slab break-off may have resulted from either subduction resistance to the ingress of continental Avalonia to the south-east, or from south-westerly lateral propagation of slab detachment linked to the Scandian Baltica–Laurentia collision.

Devonian sedimentation

Outliers of Late Silurian to Early Devonian Old Red Sandstone (ORS) sedimentary and volcanic sequences are preserved in several parts of the Grampian and Northern Highlands, but more extensive successions are present in the north-west part of the Midland Valley of Scotland and in the Moray Firth–Caithness region. The sediments, mainly sands, gravels and silts, were deposited under fluviatile to lacustrine conditions in a desert environment. In many instances the sequences are non-fossiliferous, but in parts fish and arthropod fauna are present, and plant remains, spores and arthropod traces also occur (Trewin and Thirlwall 2002). Unquestionably, the jewel in the crown is the varied flora and fauna preserved in the Rhynie hot spring system, linked to local andesitic volcanism, dated by Parry *et al*. (2011) at 411.5±1.3 Ma (U–Pb zircon TIMS).

Although parts of the succession in the Stonehaven area are Late Silurian in age, most of the ORS sequences are Early Devonian (Lochovian to Emsian). Figure 8 shows the distribution of the groups within the Old Red Sandstone Supergroup in the Midland Valley and Figure 9 illustrates the component formations. Volcanic rocks, mostly andesite, basaltic andesite and basalt lavas with local agglomerate and tuff occur widely in the succession, notably in the Ochil and Sidlaw Hills. Volcanic clasts are also common in the conglomerates and sandstones of the Stonehaven and Dunnotar-Crawton groups. A dacitic welded tuff, the Lintrathen Tuff, occurs in Glen Isla, northwest of the Highland Boundary Fault. The tuff has been dated at 415.5±5.8 Ma (Rb–Sr, biotite; Thirlwall, 1988). This distinctive unit, locally up to 160m thick, has been correlated laterally with the Crawton Volcanic Formation that occurs widely in the Midland Valley succession southwest of Stonehaven (Fig. 9). As such it forms a chronostratigraphical unit within the succession and a link across the Highland Boundary Fault.

At higher stratigraphical levels in the Old Red Sandstone succession sandstone and mudstone formations are more common. The Cromlix Mudstone Formation is a widespread unit recognised across the Midland Valley. However, the uppermost Strathmore Group units are sandstone and locally conglomerate formations. The Gannochy Conglomerate Formation and Strathfinella Hill, Uamh Bheag and Bracklinn Falls conglomerate members all represent higher-energy deposits that lie adjacent to the Highland Boundary. In the Strathfinella Conglomerate Member (Teith Sandstone Formation) the cobbles are lithologically varied but include igneous and metamorphic clasts that can be matched to outcrops within the Grampian Highlands to the north-west. This suggests that derivation from an uplifted area of Dalradian rocks and granitic plutons northwest of the Highland Boundary Fault Zone, and deposition of local fanglomerate units in the marginal areas of the Midland Valley. These youngest rocks are Emsian in age.

In Ross and Cromarty and Caithness Early Devonian rocks are represented by the Struie Group in the Beauly-Dingwall region, and by the conglomerates, sandstones and mudstones found in the Golspie and Badbea basins and the Sarclet Inlier. The Struie Group has basal conglomerates and breccias, succeeded by *c.* 400m of olive-grey to black bituminous shales with impure limestones. The organic shales developed in a restricted lake environment and contain H_2S. Thus, they have a foetid odour and are the source of the sulphur ‘spa’ waters at Strathpeffer. Further Early Devonian lacustrine shale sequences lie offshore in restricted fault-bounded basins beneath the Mesozoic rocks of the Moray Firth (Marshall and Hewett 2003). These Lower ORS units are overlain by Mid-Devonian (Eifelian–Givetian) sandstones, siltstones and mudstones with fish beds, which form part of the wider Orcadian Basin lacustrine succession. In parts the Early and Mid-Devonian sequences are separated by an unconformity, but Rodgers *et al*. (1989) interpreted this break as only of local significance, viewing the succession as effectively continuous.

Some 30km south-west from Inverness and overlooking the Great Glen is the hill of Meall Fhuar-mhonaidh, formed of massive conglomerates that from part of the eponymous outlier of Early Devonian rocks that measures 15km long × 3km wide (Fig. 10). The *c.* 2km thick sequence consists of conglomerates, sandstones and siltstones and was mapped and described by Mykura and Owens (1983) (Fig. 11). Sedimentary features and the rapid facies variations suggested that the sediments were deposited rapidly in a small fault-bounded basin. Minor plant fossils and some spores from its upper parts imply that it is Late Emsian to Early Eifelian in age. At the north-east extremity of the inlier near the top of the stratigraphical sequence is a thick clast-supported, coarse-grained, breccio-conglomerate unit, termed the Craig Nay Conglomerate. Its origin was interpreted by Mykura and Owens as a proximal debris flow derived from the east. Angular clasts, commonly ranging in size up to 50cm, and rarely to 70cm, are abundant, and consist mainly of grey psammite and pink to orange leucogranite. Like the Early Devonian rocks farther north in Easter Ross, the sequence shows evidence of limited folding and thrusting (Underhill and Brodie, 1993).

The Rosemarkie Inlier

The Rosemarkie Inlier is a small fault-bounded lens of interleaved Moine psammites and semipelites and Lewisianoid felsic and mafic orthogneisses that lies adjacent to the GGF (*see* Fig. 10). It also contains amphibolitic mafic pods and numerous distinctive pink leucogranite veins and pods. Early Devonian sandstones and shaly mudstones lie in faulted contact with the basement rocks on the south-west side of the inlier, but both are unconformably overlain by Mid-Devonian sandstone and conglomerate (Fig. 12). The leucogranite veins are typically 0.3–1m thick but range from a few millimetres up to c. 5m thick. They range from concordant with the host gneisses and psammites to sub-parallel to the foliation, but show numerous examples of discordance, and in places lie at high angles to the banding. Both the Archaean and Proterozoic basement rocks, and the leucogranite veins, are strongly deformed and tightly folded, with three distinct fold phases affecting the veins (Rathbone and Harris, 1980). The related foliations are generally steeply dipping and a north-east-plunging rodding lineation is locally well developed. The leucogranite emplacement has been dated from igneous monazite at 397.6 ± 2.2 Ma, with acicular oscillatory zoned zircons giving a compatible concordant U–Pb TIMS age of 400.8±2.6 Ma (Mendum and Noble, 2010). Complex zoned zircons from two tonalitic basement gneisses gave concordant U–Pb LA-MC-ICP-MS ages between 2720 Ma and 2930 Ma, confirming the Archaean (Badcallian)origin of the gneisses. One of the gneisses sampled showed evidence of zircon growth and isotopic resetting at *c.* 1745 Ma, indicative of Laxfordian reworking.

Acadian transpression effects along the GGF

The presence of leucogranites is largely confined to the Rosemarkie Inlier; only minor examples are found in one or two other places along the GGF zone. The association of leucogranite veining with transcurrent faults and some large-scale mylonitic zones has been recorded in several parts of the world; in many examples lateral or oblique fault movement and generation of leucogranites seem to be coeval. At Rosemarkie, emplacement is interpreted to mark the onset of Acadian transpression and sinistral strike-slip movement on the GGF. Mendum and Noble (2010) argued that the Rosemarkie Inlier was extruded obliquely as an elongate ‘pip’, generated at a restraining bend in the GGF as the locus of fault movement migrated north-westward. They showed that the structural data from the inlier were compatible with a transpressive origin. The main foliation generally dips steeply to the south-east but dips do range to moderately eastward. The mean foliation pole lies some 10° clockwise from that of the GGF. The lineation, represented as prominent quartz rodding in the leucogranite, plunges moderately north-east (mean value 37° to 050°). Rathbone (1980) measured the shape of the deformed quartz aggregates in the leucogranite, and assuming they were roughly equant when the granite was emplaced, derived a prolate finite strain ellipsoid value of X:Y:Z = 18:2.5:1. Note that few directional indicators are present in the inlier, and those present indicate contrary senses of movement, probably reflecting the long and complex history of the fault zone. The inlier is unconformably overlain by Mid-Devonian conglomerates and sandstones, and if this prolate strain can be taken as representative of the Acadian deformation of the whole inlier, then an estimate the amount of translation and uplift can be obtained. Taking the inlier’s current dimensions (*c.* 2km wide) and restoring it to an unstrained state, suggests that a minimum of *c.* 29km of sinistral movement and *c.* 15km of uplift occurred during Acadian transpression (see Mendum and Noble, 2010 for details). The *c.* 15km of uplift would accord with the probable lower amphibolite grade metamorphic conditions implied by the fold structures and related biotite-bearing fabrics and mineralogy seen in the currently exposed outcrops. Interestingly, it would also place the interleaved Moine and Lewisianoid rocks approximately down dip from the outcrop of the Sgurr Beag Thrust around Garve and on the western flank of Ben Wyvis, where similar lithologies and relationships are exposed. Extrusion of the inlier is restricted realistically to a time period of *c.* 5 Ma (398–393Ma), placing limits on the rates of lateral and vertical movement on the GGF. These would be of the order of 6mm/year and 3mm/year, respectively, making Acadian transpression a tectonically rapid but localised event. Such values are in accord with published rates for fault movements in other parts of the world. Restoration of the sinistral lateral movement also places the Rosemarkie Inlier close to the north-east end of the Meall Fhuar-mhonaidh Outlier prior to Acadian lateral movements on the GGF. Hence the Craig Nay Conglomerate could be derived from erosion of the inlier, albeit overlapping its initial stages of extrusion (Fig. 13). This would imply that Acadian deformation was coeval with the final stages of deposition of the Old Red Sandstone sequence in the Meall Fhuar-mhonaidh Outlier with both occurring in the late Emsian, an age that agrees with the palaeontological evidence in the outlier and with leucogranite emplacement in the inlier.

The structure in the outlier, which lies 32km south-west of the Rosemarkie Inlier, is also compatible with Acadian transpression. Figure 11 shows the fold traces and interpreted thrusts mapped by Mykura and Owens (1983). They constructed cross-sections that showed how deformation was concentrated close to the trace of the GGF, with an overall shortening of *c.* 25% across the outlier. Small thrusts were mapped in the south-west part of the outlier. Although such structures may be of Mesozoic age their geometry defines a positive ‘flower’ structure compatible with Acadian transpression focussed on the GGF. Similar structures have been documented in Easter Ross where Underhill and Brodie (1993) showed from seismic and well data that the uppermost Mid-Devonian marker was folded and faulted linked to Permo-Carboniferous inversion related to movements on the Glaick-Polinturk Fault. Farther north they interpreted the Struie Thrust as a similar age structure but its geometry is also compatible with Acadian transpression. The waning of Acadian effects northward may well be reflected in the decreasing angular relationship between the Lower ORS and overlying Middle ORS. In Caithness the two successions become conformable.

The Cromarty Inlier is another fault-bounded kilometre-scale ‘pip’ that lies immediately north-east of the Rosemarkie Inlier, again adjacent to the GGF. It also consists of uplifted basement onlapped by Mid-Devonian conglomerates, but in this case composed mainly of Moine psammites with pegmatitic granite lenses and veins. Its occurrence may represent a further step-over of the GGF to the north-west, but with less uplift, thereby exposing rocks from higher structural levels than those at Rosemarkie. The Moine rocks are similar to those found in the main Northern Highland outcrop of the Loch Eil Group.

Evidence for Acadian deformation in the Midland Valley

The Midland Valley of Scotland is bounded on its north-west side by the Highland Boundary Fault Zone (HBFZ) and on its south-east side by the Southern Uplands Fault (SUF) (Fig. 14). Early Devonian rocks are folded and fractured and the age of deformation is constrained by the unconformably overlying Late Devonian sedimentary units. This Mid-Devonian (Acadian) deformation was apparently localised along the main terrane-bounding faults and resulted in the formation of major and intermediate-scale folds, most notably the Strathmore Syncline and Sidlaw Anticline. Note that fold tightness increases as the HBFZ is approached. Hence, the Strathmore Syncline, whose axial trace runs sub-parallel to the HBFZ (*see* Fig. 8), has a steep to sub-vertical north-western limb and a more gently dipping south-eastern limb. The related Sidlaw Anticline is an altogether more open structure. There is also evidence for Acadian lateral movement on the HBFZ in that the Linthrathen Tuff, which crops out north-west of the fault zone, is apparently displaced sinistrally by 34km, relative to the equivalent unit in the Midland Valley, the Crawton Volcanic Formation. As noted above, the latter stages of Lower ORS sedimentation overlapped relative vertical movements on the HBFZ, with the uplifted Highland area shedding coarse detritus into the Midland Valley ORS succession during the later part of the Emsian (*see* Fig. 9). Jones *et al*. (1997) demonstrated that formation of the Strathmore Syncline and Sidlaw Anticline was a consequence of Acadian transpression, focussed on the HBFZ. They assessed the overall bulk shortening as 10–15% and attributed most of this to vertical stretching with minor sinistral faulting accounting for the lateral stretching element.

Lower ORS sandstones, conglomerates, and andesitic and basaltic volcanic rocks also crop out in various inliers near the south-east margin of the Midland Valley (Smith, 1995) (*see* Fig. 14). Similar volcanic rocks in the Pentland Hills yield a Lochkovian age of *c*. 413 Ma (Thirlwall, 1988). The sequence reaches more than 2.5km thick locally in the Hagshaw Hills area, where it is deformed into kilometre-scale, asymmetrical anticlines and synclines. These folds form an *en échelon* array whose axes trend north-east to east-north-east, slightly oblique (clockwise) to the trace of the neighbouring SUF. Limited thrusting to the south-east is also recorded (Smith, 1995). Smith attributed this deformation to Mid-Devonian (Acadian) sinistral transpression, whose age is again constrained by the unconformably overlying Upper Devonian and Carboniferous strata. Floyd (1994) suggested that a Mid-Devonian sinistral offset of 12km along the SUF could explain the present disposition of the Ordovician (Caradoc) Tappins Group and Marchburn Formation in the area north of the Loch Doon Granite Pluton.

Acadian deformation — the regional picture

The type area for the Acadian Orogeny is in Nova Scotia, where it is attributed to the collision of the western Avalonian microcontinent with the eastern margin of Laurentia. It is one of a series of Lower Palaeozoic tectonic events that occurred as a result of the repeated accretion of continental crust and oceanic arcs to the Laurentian margin in Newfoundland, Nova Scotia and New England, and in the more south-western parts of the Appalachian chain (Murphy *et al*., 2011). These peri-Gondwanan terranes, which include Ganderia, Avalonia, Carolinia and Meguma, were detached from northern margin of Gondwana, starting in the Late Cambrian and Early Ordovician, when the Rheic Ocean began to open rapidly. Nance *et al*. (2010) contend that this rift-drift transition occurred coeval with the onset of major subduction on the north-west side of the Iapetus Ocean at *c.* 510 Ma. These narrow, lenticular and 'ribbon' microcontinental terranes tracked across the narrowing Iapetus Ocean to collide with the Laurentian margin in North America. Thus, together with older postulated peri-Laurentian microcontinental and oceanic arc terranes - e.g. the Dashwoods Terrane - were the main agents of deformation in the Caledonian Orogenic Belt in the Appalachians.

Such collisions gave rise to the Taconic (495–450 Ma), Salinic (442–425 Ma), Acadian (419–400 Ma) and Neoacadian (380–370 Ma) orogenic events (Murphy *et al*. 2011). Hence the distinction between the Caledonian and Variscan is blurred with closure of Iapetus completed by 425Ma. In the British Isles it is easier to make a distinction between events linked to the Iapetus Ocean and those linked to the Rheic Ocean. Caledonian orogenesis in Scotland largely resulted from the collision of Cambrian to Early Ordovician outboard arcs and possibly small microcontinental

fragments with the Laurentian margin generating the Grampian Event, but no peri-Gondwanan terranes were involved until the docking of Eastern Avalonia and consequent closure of the Iapetus Ocean at *c.* 423Ma. The only other tectonic agent was the Baltica–Laurentia collision that gave rise to the Scandian Event in northern Scotland, and in Greenland and Scandinavia. Significant post orogenic uplift occurred in Highland Scotland from *c.* 430 Ma accompanied by major grantic plutonism. Hence the Acadian effects were short lived, linked to proto-Variscan events that resulted from plate tectonic re-organisation in the Rheic Ocean.
In England and Wales the Acadian Event is bracketed between 400 Ma and 390 Ma and was responsible for the formation of the pervasive folding and related cleavages in the Ordovician and Silurian rocks of Wales and the Lake District (Woodcock *et al*. 2007). The event is generally attributed to northward movement of the Midland Platform or microcraton that generated compression in the adjacent sedimentary basins (*see* Fig. 14). The related short-lived northerly subduction gave rise to limited plutonism now manifest as granitic plutons in the Lake District and Southern Uplands. Deformation was orthogonal in Wales, from where Sherlock *et al*. (2003) obtained a ^{40}Ar/^{39}Ar muscovite age of 396±1.4 Ma from the main cleavage. Although deformation in Scotland was represented by localised sinistral transpression, in the Dingle Peninsula in the west of Ireland Acadian deformation of Early Devonian sedimentary rocks resulted from dextral transpression (Meere and Mulchrone, 2006). Details of the plate tectonic geometry and movements within and marginal to the Rheic Ocean to the south are unclear, but there seems little doubt that the Acadian Event in the British Isles was a product of such proto-Variscan activity. Woodcock *et al*. (2007) presented differing subduction models for the event, showing both northward and southward subduction as feasible mechanisms. However, all authors agree that Iapetan subduction had ceased by this time with only the remnants of the subducted plates still present at depth below the Iapetan Suture and adjacent areas. Farther north-east in Baltica there is evidence of an extended history of Devonian uplift and exhumation of the Western Gneiss region of Norway from at least 410 Ma to 370 Ma (Andersen, 1998; Johnston *et al*., 2007). Here, there is no sign of any Mid-Devonian compressional event. Instead, within the Caledonides are several large sinistral transtensional basins infilled with Devonian sandstones and conglomerates and underlain by major extensional dislocations (Osmundsen and Andersen, 2001). Dewey and Strachan (2003) argued that sinistral transtension prevailed during most of the Late Silurian and Early Devonian in the Caledonides of Scotland and Ireland, Baltica, Greenland and Svalbard (Spitzbergen).

Conclusions

The later phases of the Caledonian Orogeny in Scotland were strongly influenced by plate tectonic events either to the north, where Baltica collided with Laurentia, generating the Scandian Event, or to the south, related to Iapetan closure and the formation of the Southern Uplands. The effects of the Scandian Event are best seen in the Moine Thrust Belt and in parts of the Moine Nappe of the Northern Highlands. The Late Silurian and Early Devonian marked a *c.* 30 Ma period of orogenic uplift in the Northern Highlands and Grampian Highlands, accompanied by the emplacement of voluminous granitoid igneous intrusions. The more recent dating of plutons and related volcanic rocks, notably in the south-west Grampian Highlands, has provided good constraints on these processes. Uplift was accompanied by sinistral movements on the major terrane-bounding faults in the Highlands and by the generation of several subsidiary transcurrent faults. Fault movements were largely transtensional but there were times of localised transpression. The fluvial and lacustrine Early Devonian sedimentary sequences deposited in the Midland Valley and in smaller basins within the Highlands preserve a partial record of this exhumation and accompanying fault movements.

The Rosemarkie Inlier, situated adjacent to the Great Glen Fault (GGF) just north-west of Inverness, consists of Moine psammites and semipelites and Lewisianoid felsic and mafic gneisses, all intruded by abundant pink leucogranite veins. U–Pb TIMS data from monazites and zircons separated from leucogranite samples show that the veins were emplaced into the older basement rocks at *c.* 399 Ma (Mendum and Noble, 2010). The veins are discordant to the early planar fabrics and post-date Moine and Lewisianoid interleaving, but are strongly deformed and folded by three structural phases. Metamorphic assemblages and structural style are compatible with their formation at crustal depths of 12–15km. The inlier is overlain unconformably by mid-Devonian (Eifelian–Givetian) sandstones and conglomerates whose deposition commenced at *c.* 393 Ma; thus deformation and exhumation are restricted to a maximum time frame of only 6 Ma.

The structure of the Rosemarkie Inlier is dominated by a generally steep north-east-trending foliation, a moderately north-east-plunging lineation and strong constrictional strains (Rathbone, 1980). These features are compatible with its extrusion as an elongate 'pip' at a sharp restraining bend of the GGF resulting from sinistral transpression. The Rosemarkie and adjacent Cromarty inliers are thus interpreted as fault-bounded step-overs, formed when the locus of sinistral lateral movement on the GGF migrated onto sub-parallel faults farther to the north-west.

During the early Devonian (Emsian) the Rosemarkie Inlier may have been situated adjacent to the Meall Fuar-mhonaidh Outlier, now sited some 32km away to its south-west. The Lower ORS sequence in the outlier contains a highly proximal conglomerate unit at its north-east end, whose clasts match the main lithologies of the Rosemarkie Inlier. It is proposed that the final stages of Lower ORS sedimentation in the outlier overlapped with the initial exhumation of the inlier, dating the onset of significant lateral fault movement at *c.* 399 Ma. The 32km offset is broadly compatible with the strain values obtained from the deformed leucogranites and with the structural geometry of the inlier.

The mid-Devonian sinistral transpressional event identified at Rosemarkie is interpreted as part of the Acadian Event, here manifest as a short-lived, northward-directed compressional pulse occurring between 400 Ma and 390 Ma. This deformation was a consequence of the collision of an Armorican microcontinent, the Midlands microcraton, with other parts of Avalonia (Woodcock *et al*., 2007). In Scotland, deformation was focussed on the main terrane-bounding fault zones, namely the Southern Upland, Highland Boundary and Great Glen fault zones. It was generally partitioned into sinistral strike-slip movements and related orthogonal compression. Intensity of deformation was greatest adjacent to the fault zones and decreased with distance away from them. Deformation was preferentially taken up by the Lower ORS sequences in the nearby extensional basins. Positive flower structures were formed on the north-west side of the GGF in the Meall Fuar-mhonaidh Outlier and in the Lower ORS succession in Easter Ross. The Lower ORS–Middle ORS unconformity can be traced as far as Caithness, possibly reflecting the northward waning of the Acadian Event.

Mid-Devonian (Acadian) sinistral transpression marked a significant change in the kinematics of the GGF. Prior to this event in the late Silurian and early Devonian the fault appears to have been a planar structure and a focus for sinistral lateral movements, firstly in transpression (Stewart *et al*., 2001), but mainly in transtension (Dewey and Strachan, 2003). The end Caledonian uplift and formation of small-scale basins in the early Devonian altered the structural geometry, particularly in the Moray Firth area. Hence, when north-directed Acadian compression reached Highland Scotland, the GGF formed a restraining bend to facilitate the migration of lateral movement north-westward. This pattern of north-west fault migration was subsequently repeated in late Palaeozoic and Mesozoic times during transtensional and transpressional events, both sinistral and dextral.

The wider pattern of the Acadian Event shows it to be a major subduction-related orogenic collisional event in the north-eastern Appalachian Belt, but absent from Baltica and Greenland. In the British Isles it is patently a proto-Variscan event related to the Rheic Ocean rather than a Caledonian - i.e. Iapetan event. As such its onset marks the end of the Caledonian Orogeny.

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[figure captions]

Figure 1 Tectonic framework of the Caledonides in mainland Scotland and Ireland showing the main terrane-bounding faults and the Moine Thrust.

Figure 2 Palaeogeographical reconstructions illustrating the positions of the continents in the later phases of the Caledonian Orogeny at 440Ma and 420Ma; note that Avalonia includes Carolinia; areas affected by the Scandian Event that amalgamated Laurentia and Baltica into the continent of Laurussia are shown with a magenta dot ornament (modified after Cocks and Torsvik 2006).

Figure 3 Map showing the component thrust sheets of the Moine Thrust Belt in the Assynt Culmination.

Figure 4 Cross-section normal to the thrust-transport direction across the Bealach Traligill Fault showing the lateral variations in thrust geometry within the Moine Thrust Belt in Assynt (modified after Krabbendam and Leslie 2010).

Figure 5 Map of the syenite plutons in the southern part of the Assynt Culmination (Moine Thrust Belt) showing their ages of emplacement (modified after Goodenough et al. *2011).*

Figure 6 Map of the south-west part of the Grampian Highlands showing the plutons, dykes, other minor intrusions and related volcanic rocks; note that the Ben Nevis Dyke Swarm is omitted. Yellow boxes show recent U–Pb zircon ages; unshaded boxes show earlier published age data (from Neilson et al. *(2009).*

Figure 7 Schematic diagram illustrating a petrogenetic model for the formation of the Silurian granitoid putons of the Grampian Highlands. The model involves slab break-

off, consequent rise of hot asthenosphere and partial melting of the lithospheric mantle. This is followed by pluton formation and emplacement into the upper crust, all accompanied by faulting and uplift (from Neilson et al. *(2009).*

Figure 8 Map showing the distribution of the stratigraphical groups that make up the lower parts of the Old Red Sandstone Supergroup in the northern Midland Valley; the traces of the Strathmore Syncline and Sidlaw Anticline are also marked (modified after Browne et al. *2002).*

Figure 9 Fence diagram showing the component formations and members of the Late Silurian to Early Devonian parts of the ORS Supergroup in the northern Midland Valley (from Browne et al. *2002).*

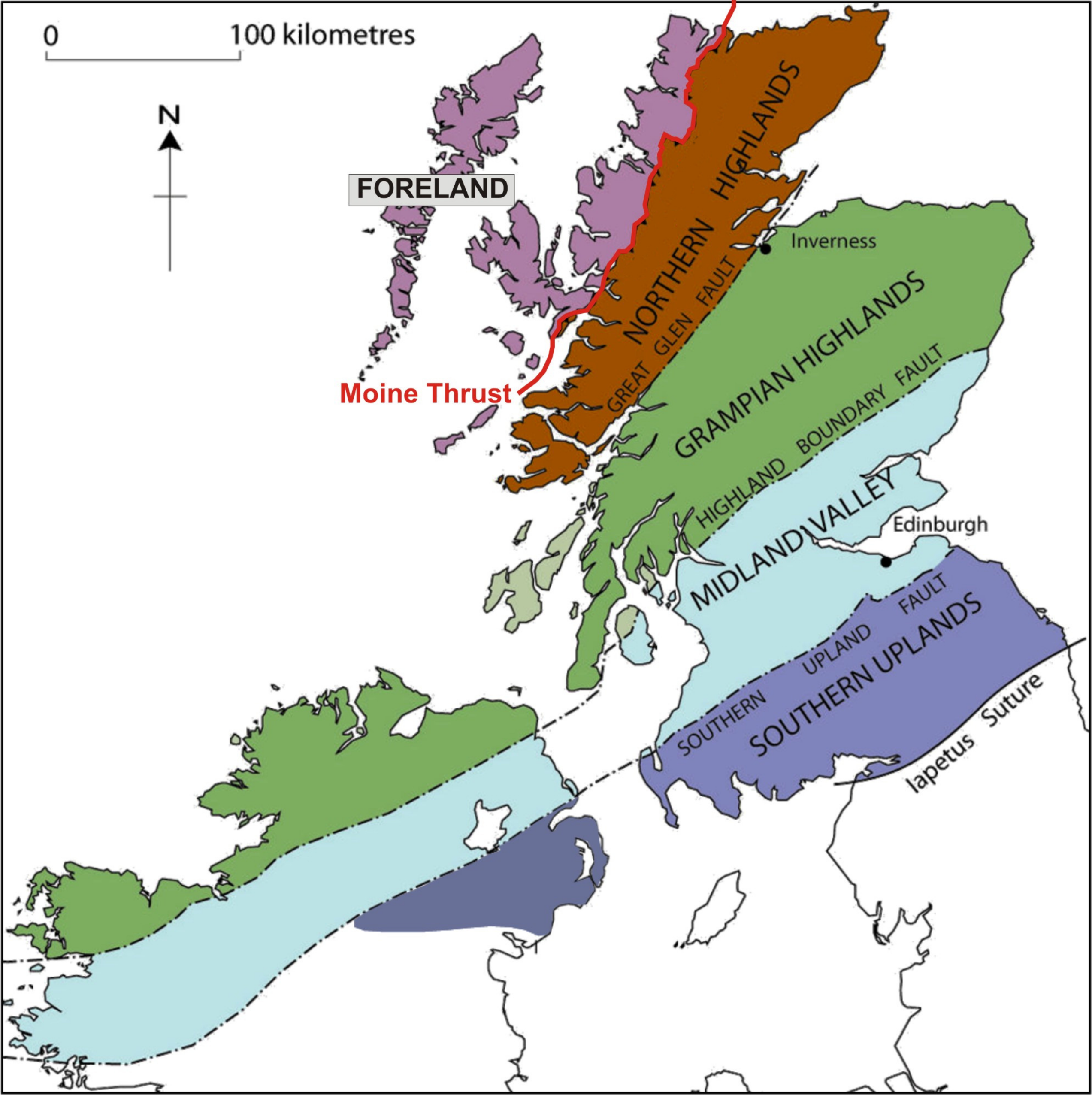
Figure 10 Map of the generalised geology of the area round Inverness showing the positions of the Rosemarkie and Cromarty inliers and the Meall Fhuar-mhonaidh Outlier (contains Ordnance Survey data © Crown Copyright and digital rights, 2012).

Figure 11 Geological map of the Early Devonian Meall Fhuar-mhonaidh Outlier showing the main lithological units and internal structure (modified after Mykura and Owens, 1983; contains Ordnance Survey data © Crown Copyright and digital rights, 2012).

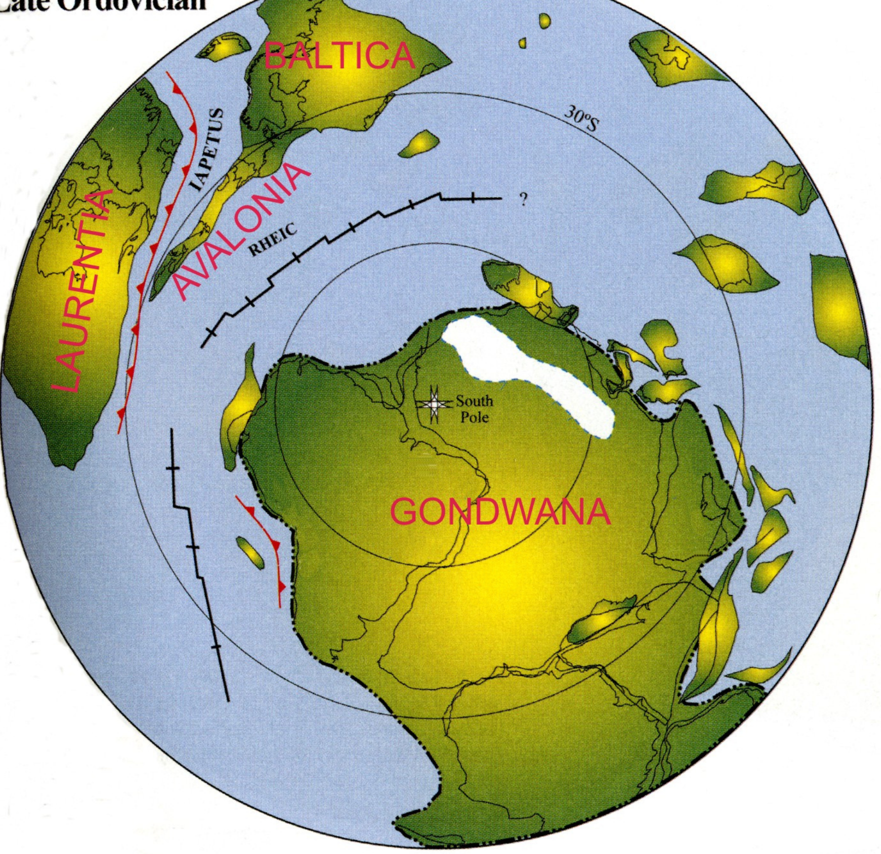
Figure 12 Diagrammatic cross-section through the Rosemarkie Inlier showing the main geological elements and their relationships to the bounding faults (scale is approximate).

Figure 13 Palaeogeographical reconstruction of the Lower ORS (Early Devonian) environments in Easter Ross and the northern part of the Great Glen. The present outcrops of Rosemarkie and Cromarty inliers and the Meall Fhuar-mhonaidh Outlier have been added. The red arrows signify sinistral Acadian movements. Note that a post-Devonian dextral transcurrent movement of 27km along the GGF has been reversed (see two positions of Inverness) (modified after Mykura and Owens, 1983).

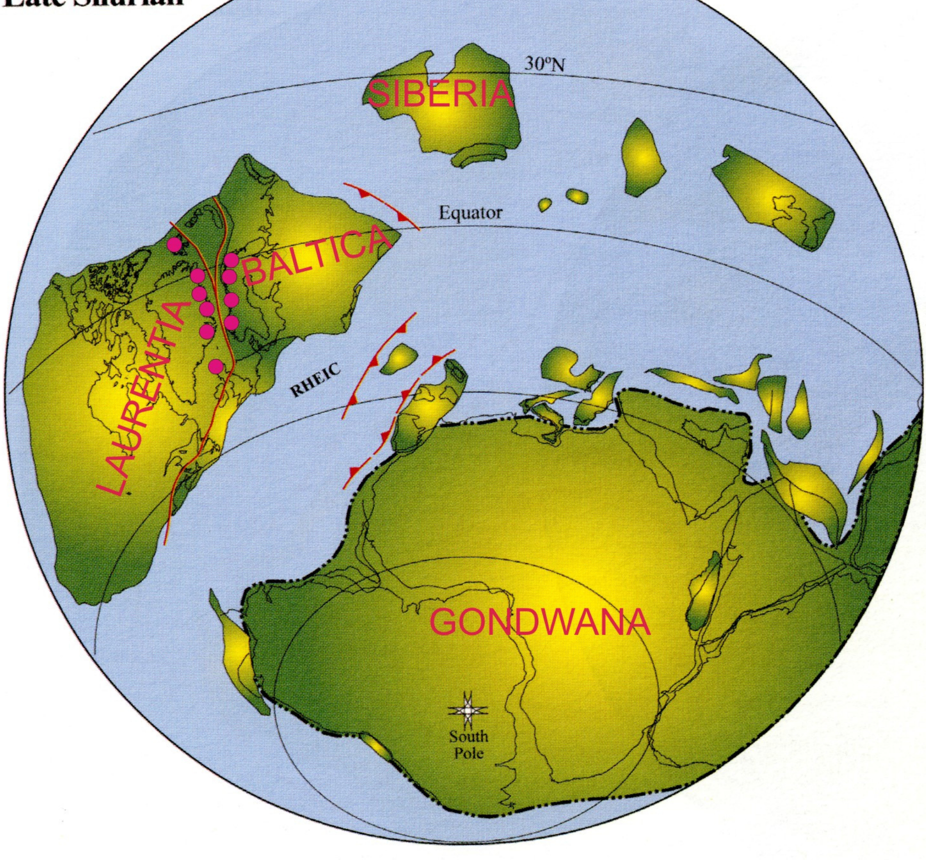
Figure 14 Acadian structures and related sedimentary and igneous features in the British Isles.

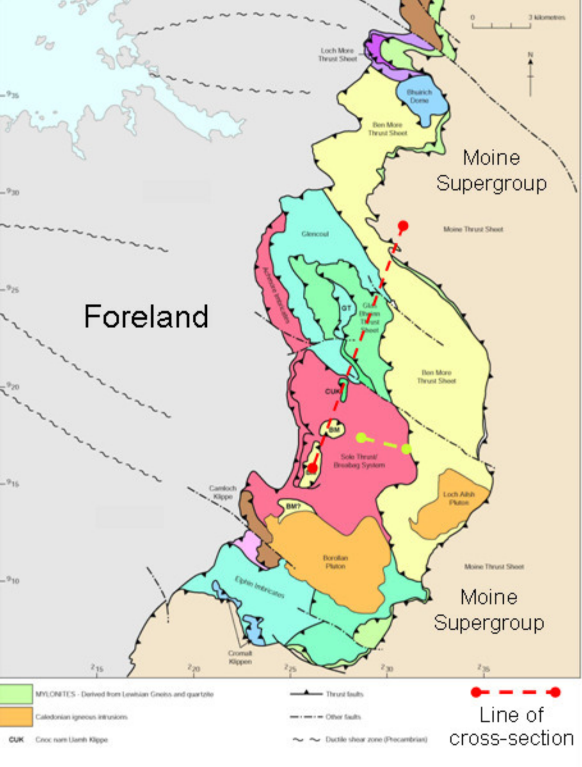

0
100 kilometres
N
FORELAND
NORTHERN HIGHLANDS
Inverness
GREAT GLEN FAULT
Moine Thrust
GRAMPIAN HIGHLANDS
HIGHLAND BOUNDARY FAULT
MIDLAND VALLEY
Edinburgh
SOUTHERN UPLAND FAULT
SOUTHERN UPLANDS
Iapetus Suture

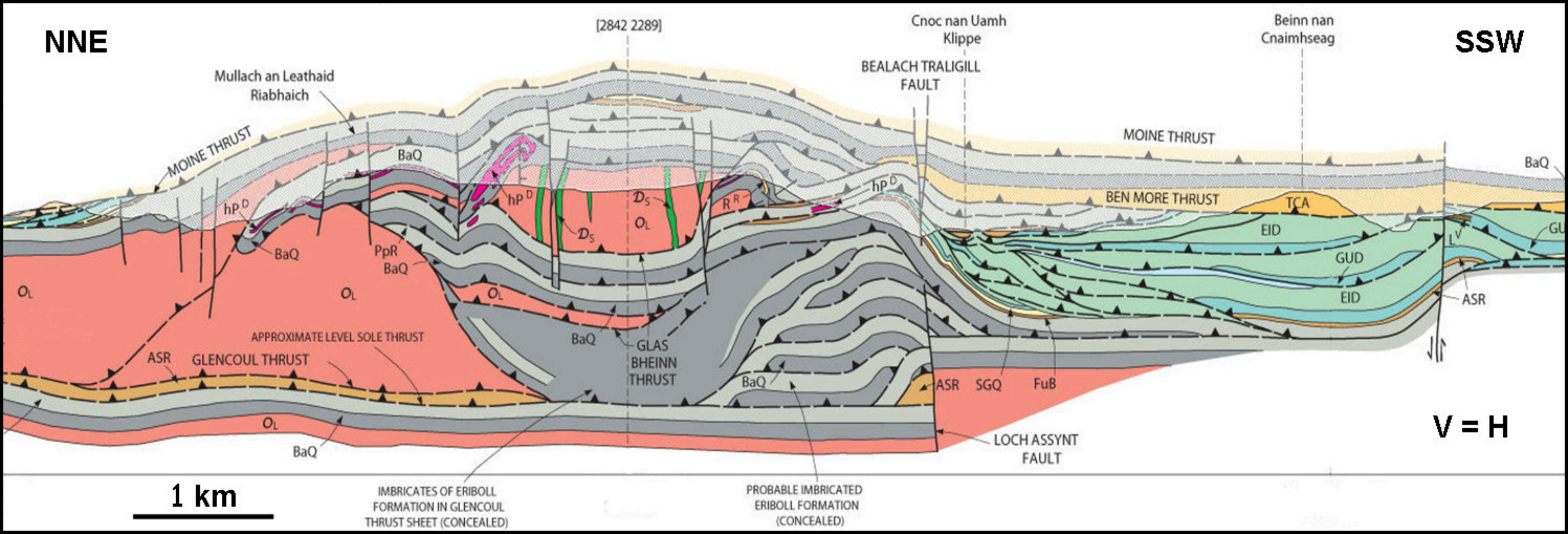
440 Ma
Late Ordovician

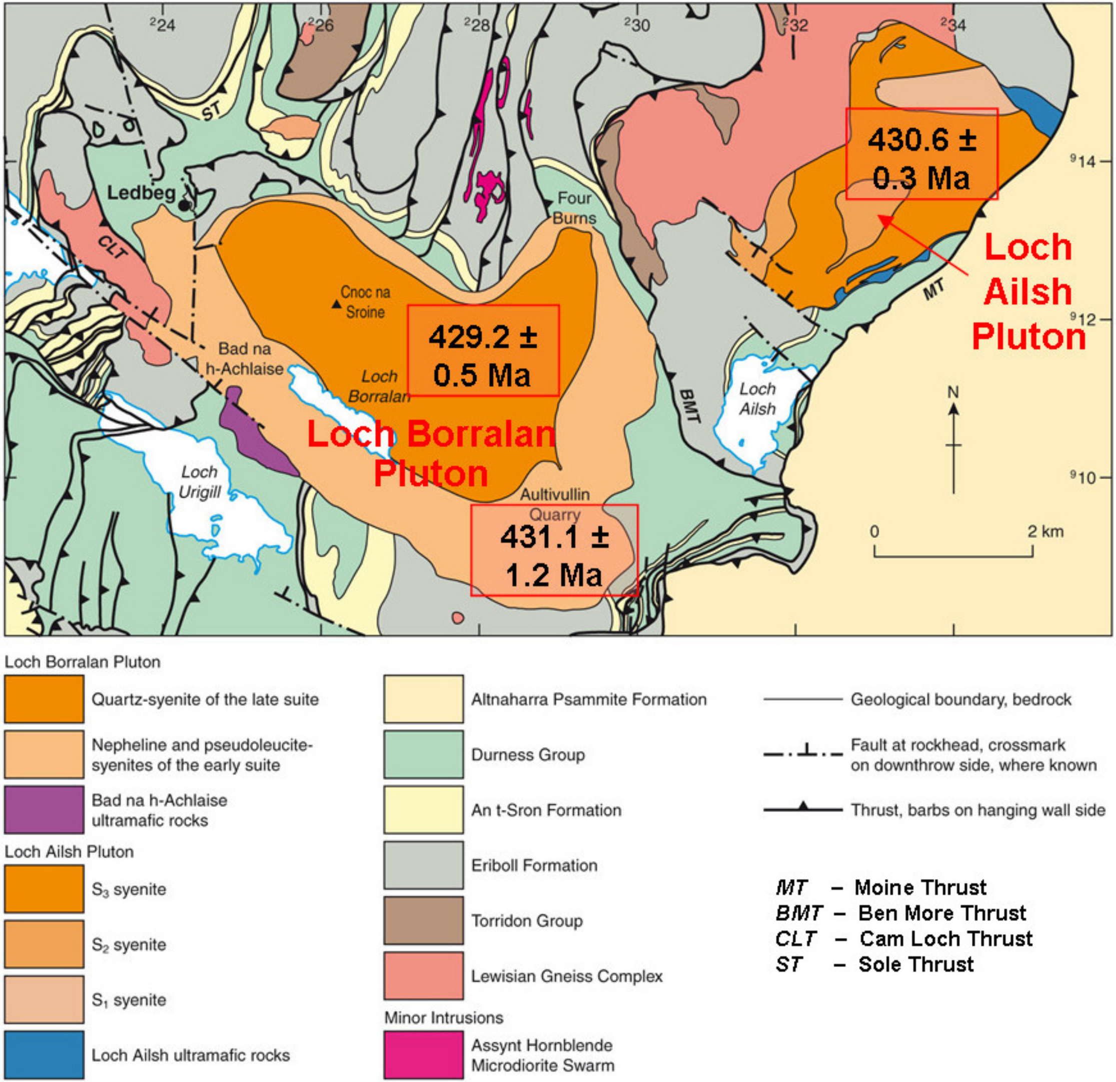


420 Ma
Late Silurian

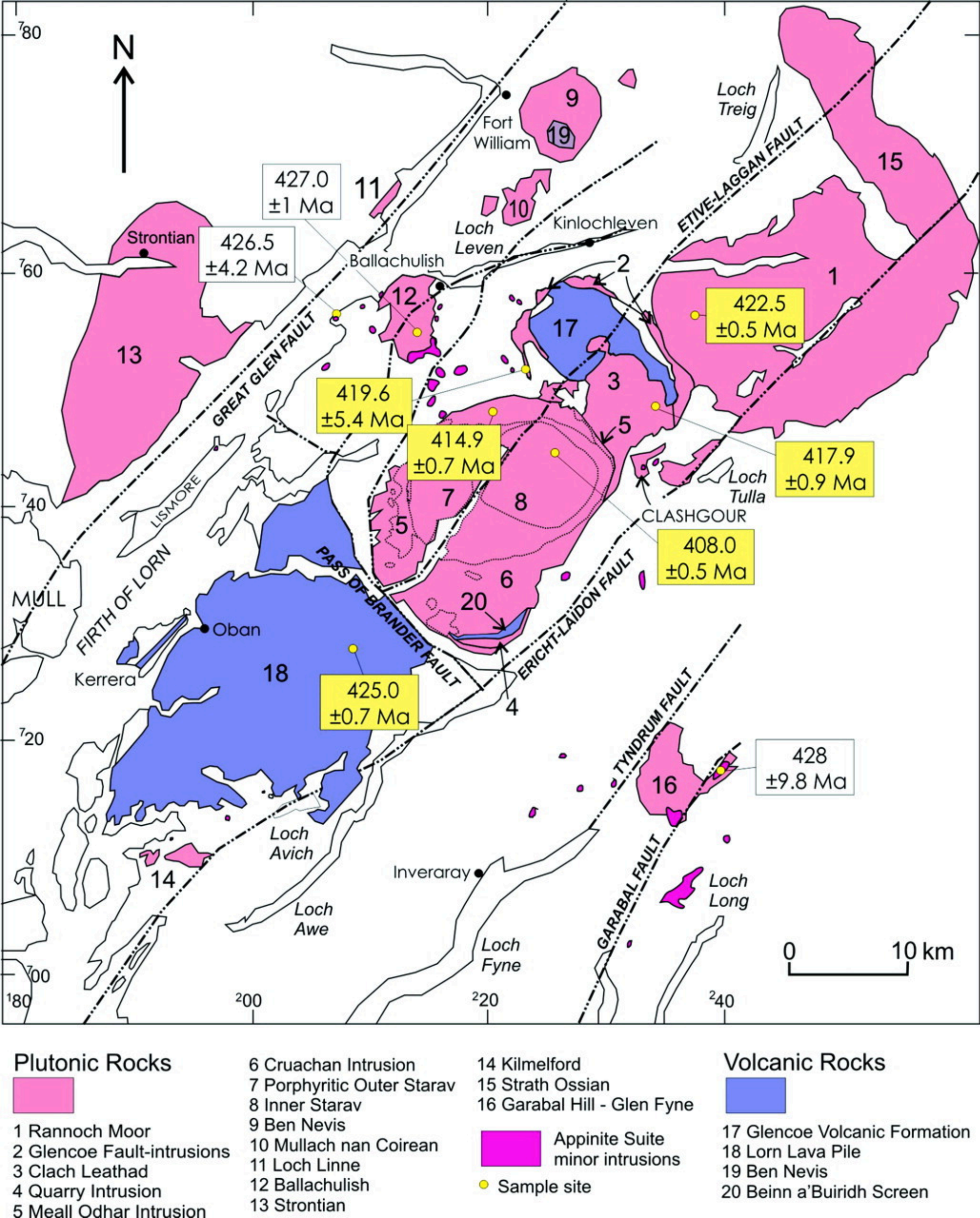



0
3 kilometres
N
Loch More Thrust Sheet
Ben More Thrust Sheet
Moine Supergroup
Moine Thrust Sheet
Glencoul
Foreland
GT
CUK
BM
Ben More Thrust Sheet
Camloch Klippe
BM?
Loch Ailsh Pluton
Borolan Pluton
Elphin Imbricates
Moine Thrust Sheet
Moine Supergroup
Cromalt Klippen
MYLONITES - Derived from Lewisian Gneiss and quartzite
Caledonian igneous intrusions
CUK Cnoc nam Uamh Klippe
Thrust faults
Other faults
Ductile shear zone (Precambrian)
Line of cross-section

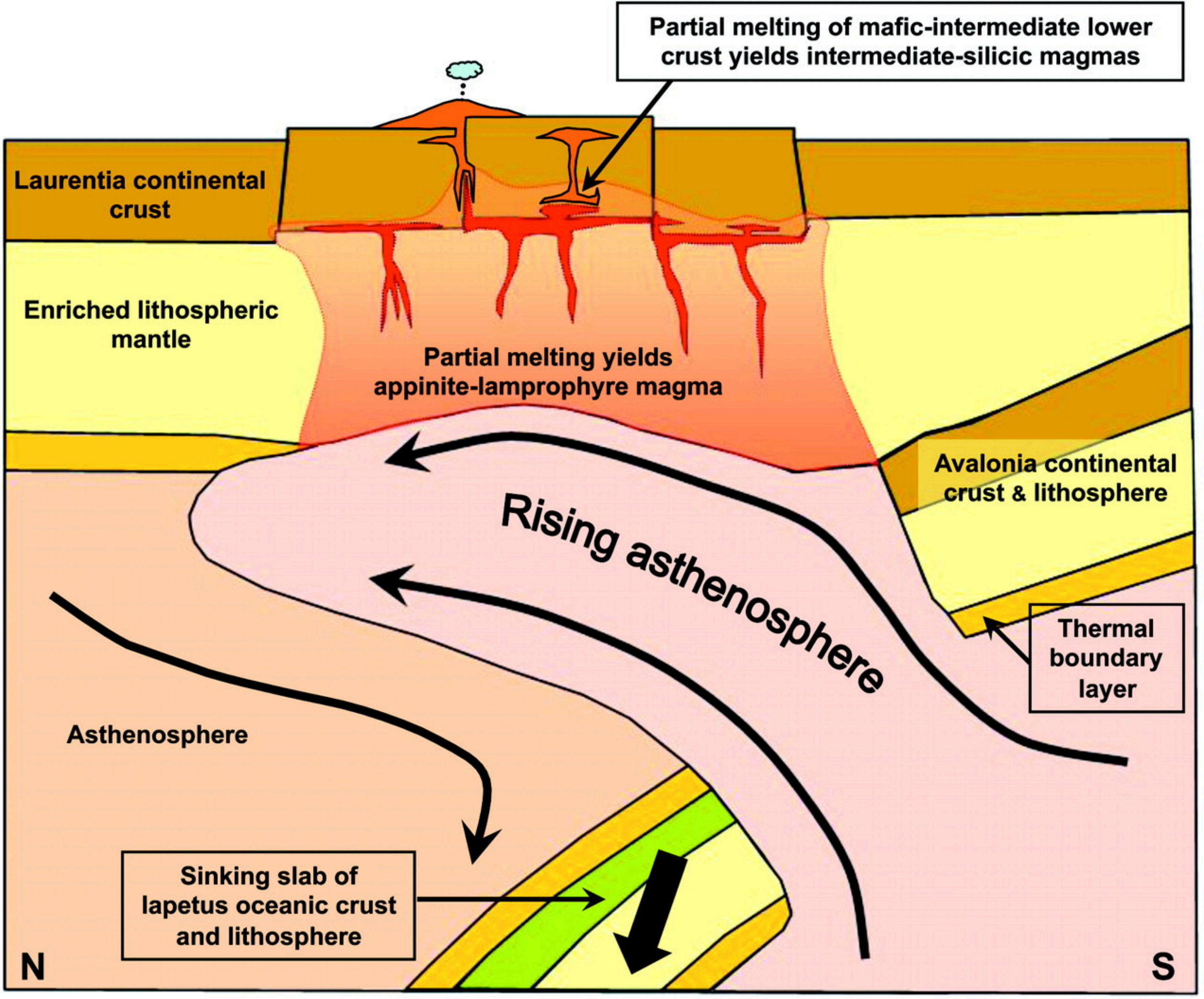

NNE
SSW
[2842 2289]
Cnoc nan Uamh
Klippe
Beinn nan
Cnaimhseag
BEALACH TRALIGILL
FAULT
Mullach an Leathaid
Riabhaich
MOINE THRUST
MOINE THRUST
BaQ
BEN MORE THRUST
TCA
EID
GUD
EID
ASR
OL
PpR
BaQ
GLAS
BHEINN
THRUST
APPROXIMATE LEVEL SOLE THRUST
GLENCOUL THRUST
ASR
SGQ
FuB
LOCH ASSYNT
FAULT
V = H
1 km
IMBRICATES OF ERIBOLL
FORMATION IN GLENCOUL
THRUST SHEET (CONCEALED)
PROBABLE IMBRICATED
ERIBOLL FORMATION
(CONCEALED)

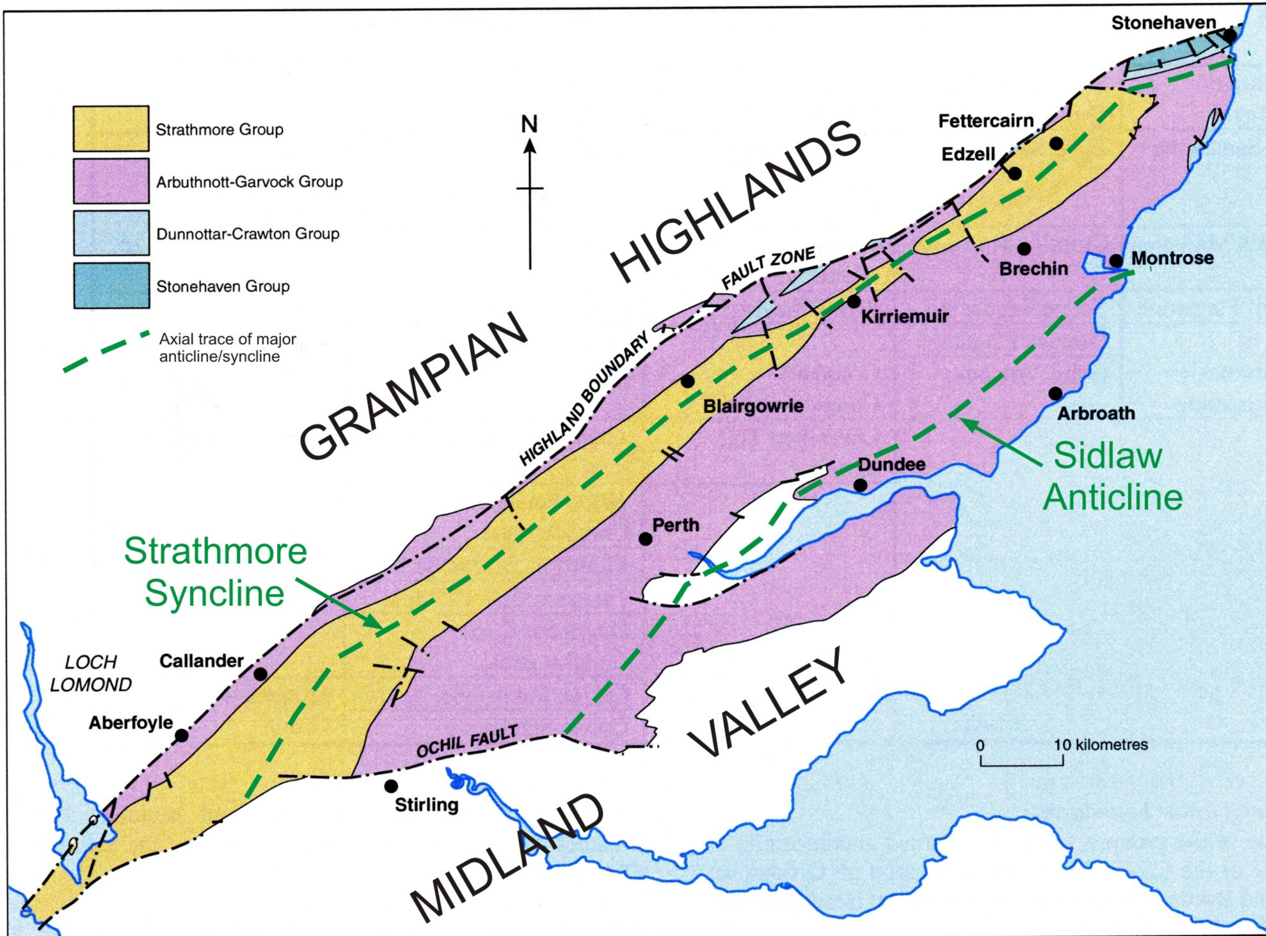


224
226
228
230
232
234
914
912
910
ST
Ledbeg
CLT
Cnoc na Sroine
Four Burns
Bad na h-Achlaise
Loch Borralan
429.2 ± 0.5 Ma
Loch Borralan Pluton
430.6 ± 0.3 Ma
Loch Ailsh Pluton
MT
BMT
Loch Ailsh
Loch Urigill
Aultivullin Quarry
431.1 ± 1.2 Ma
N
0
2 km
Loch Borralan Pluton
Quartz-syenite of the late suite
Nepheline and pseudoleucite-syenites of the early suite
Bad na h-Achlaise ultramafic rocks
Loch Ailsh Pluton
S3 syenite
S2 syenite
S1 syenite
Loch Ailsh ultramafic rocks
Altnaharra Psammite Formation
Durness Group
An t-Sron Formation
Eriboll Formation
Torridon Group
Lewisian Gneiss Complex
Minor Intrusions
Assynt Hornblende Microdiorite Swarm
Geological boundary, bedrock
Fault at rockhead, crossmark on downthrow side, where known
Thrust, barbs on hanging wall side
MT – Moine Thrust
BMT – Ben More Thrust
CLT – Cam Loch Thrust
ST – Sole Thrust

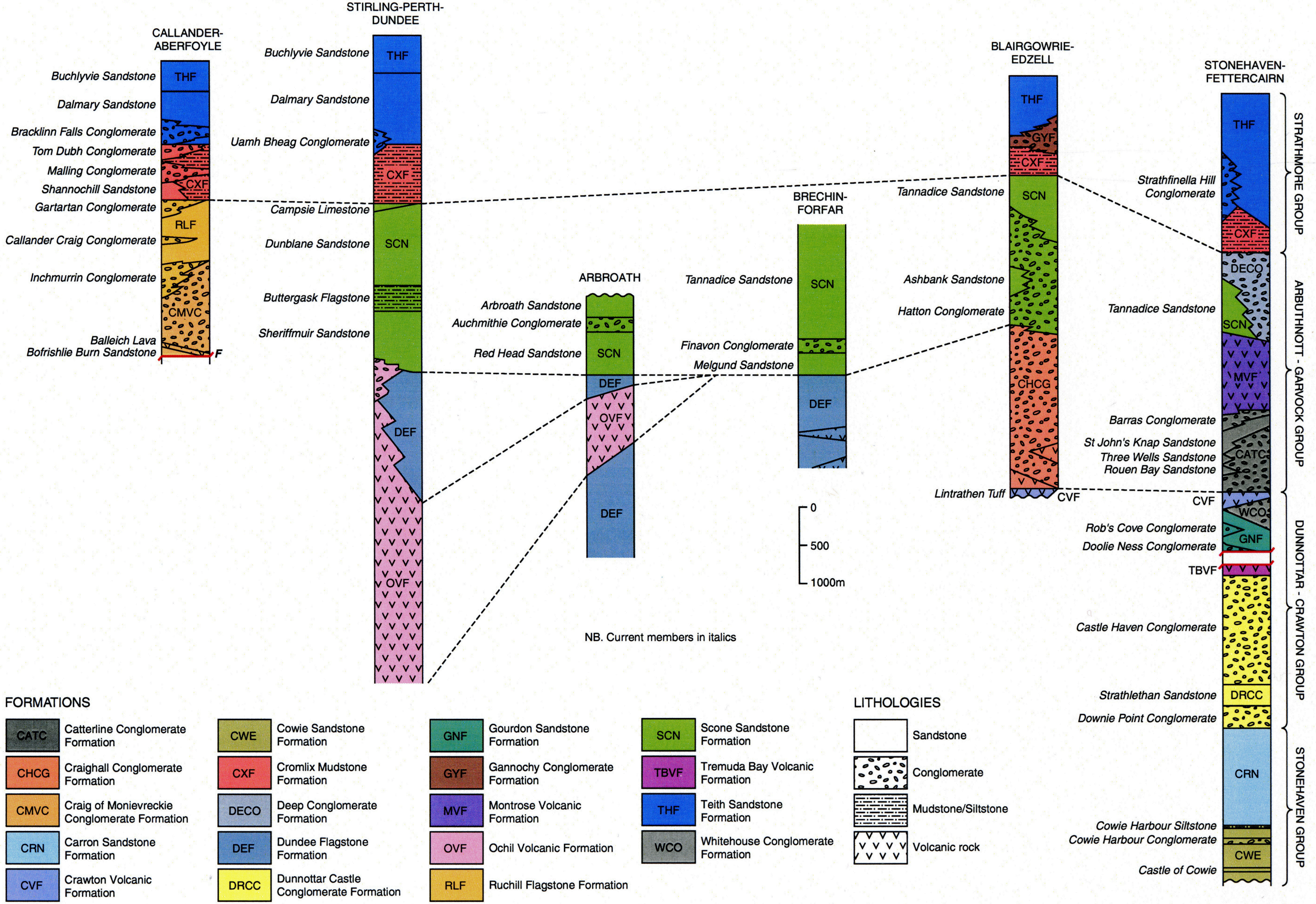


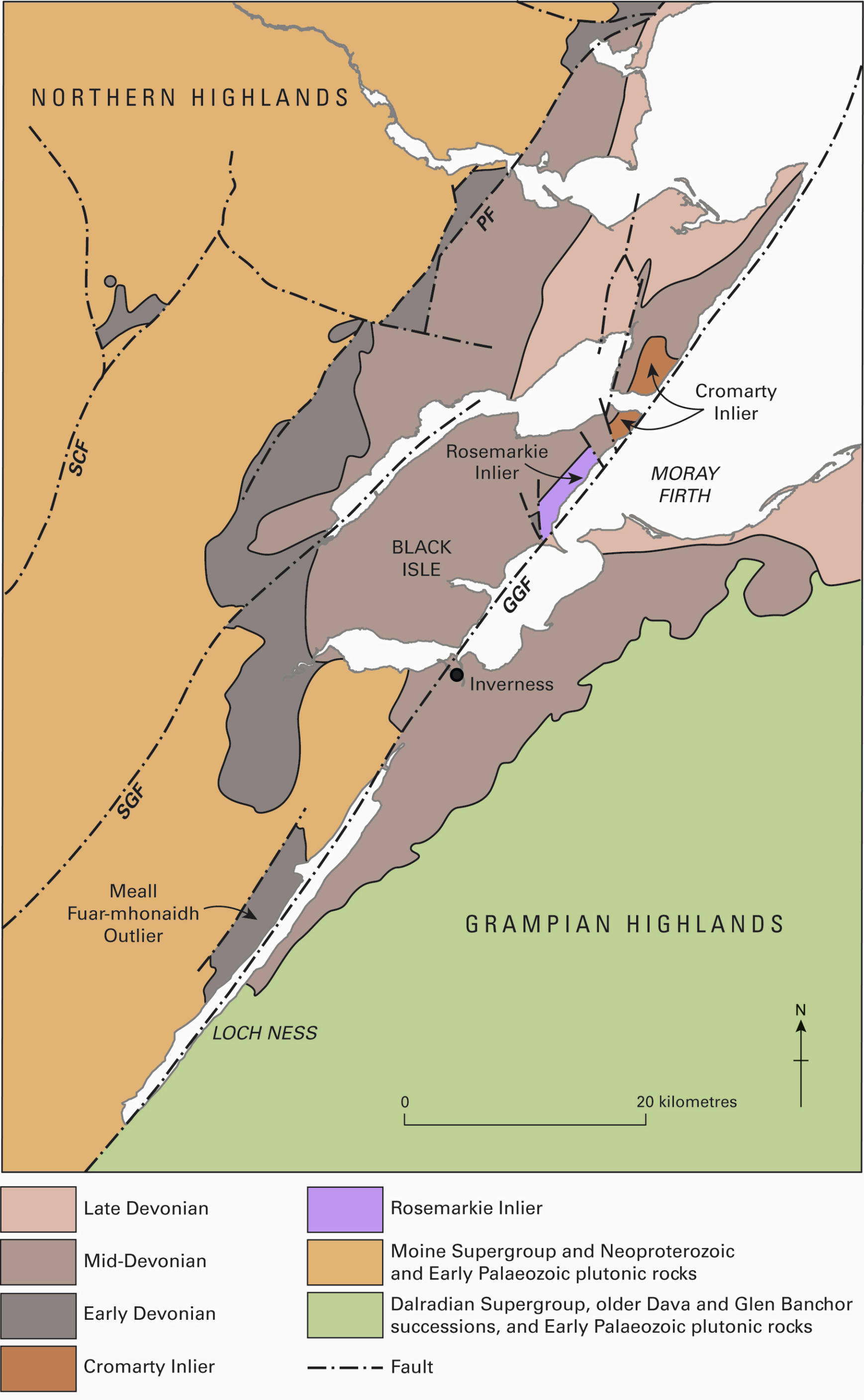
N
780
760
740
720
700
180
200
220
240
Fort William
9
19
Loch Treig
15
427.0 ±1 Ma
11
10
Strontian
426.5 ±4.2 Ma
Loch Leven
Kinlochleven
ETIVE-LAGGAN FAULT
Ballachulish
2
1
12
17
422.5 ±0.5 Ma
13
GREAT GLEN FAULT
419.6 ±5.4 Ma
3
414.9 ±0.7 Ma
5
417.9 ±0.9 Ma
Loch Tulla
LISMORE
7
8
CLASHGOUR
5
408.0 ±0.5 Ma
FIRTH OF LORN
PASS OF BRANDER FAULT
6
ERICHT-LAIDON FAULT
MULL
20
Oban
Kerrera
18
425.0 ±0.7 Ma
4
TYNDRUM FAULT
428 ±9.8 Ma
16
Loch Avich
14
Inveraray
GARABAL FAULT
Loch Long
Loch Awe
Loch Fyne
0
10 km
Plutonic Rocks
1 Rannoch Moor
2 Glencoe Fault-intrusions
3 Clach Leathad
4 Quarry Intrusion
5 Meall Odhar Intrusion
6 Cruachan Intrusion
7 Porphyritic Outer Starav
8 Inner Starav
9 Ben Nevis
10 Mullach nan Coirean
11 Loch Linne
12 Ballachulish
13 Strontian
14 Kilmelford
15 Strath Ossian
16 Garabal Hill - Glen Fyne
Appinite Suite minor intrusions
Sample site
Volcanic Rocks
17 Glencoe Volcanic Formation
18 Lorn Lava Pile
19 Ben Nevis
20 Beinn a'Buiridh Screen


Partial melting of mafic-intermediate lower crust yields intermediate-silicic magmas
Laurentia continental crust
Enriched lithospheric mantle
Partial melting yields appinite-lamprophyre magma
Avalonia continental crust & lithosphere
Rising asthenosphere
Thermal boundary layer
Asthenosphere
Sinking slab of Iapetus oceanic crust and lithosphere
N
S

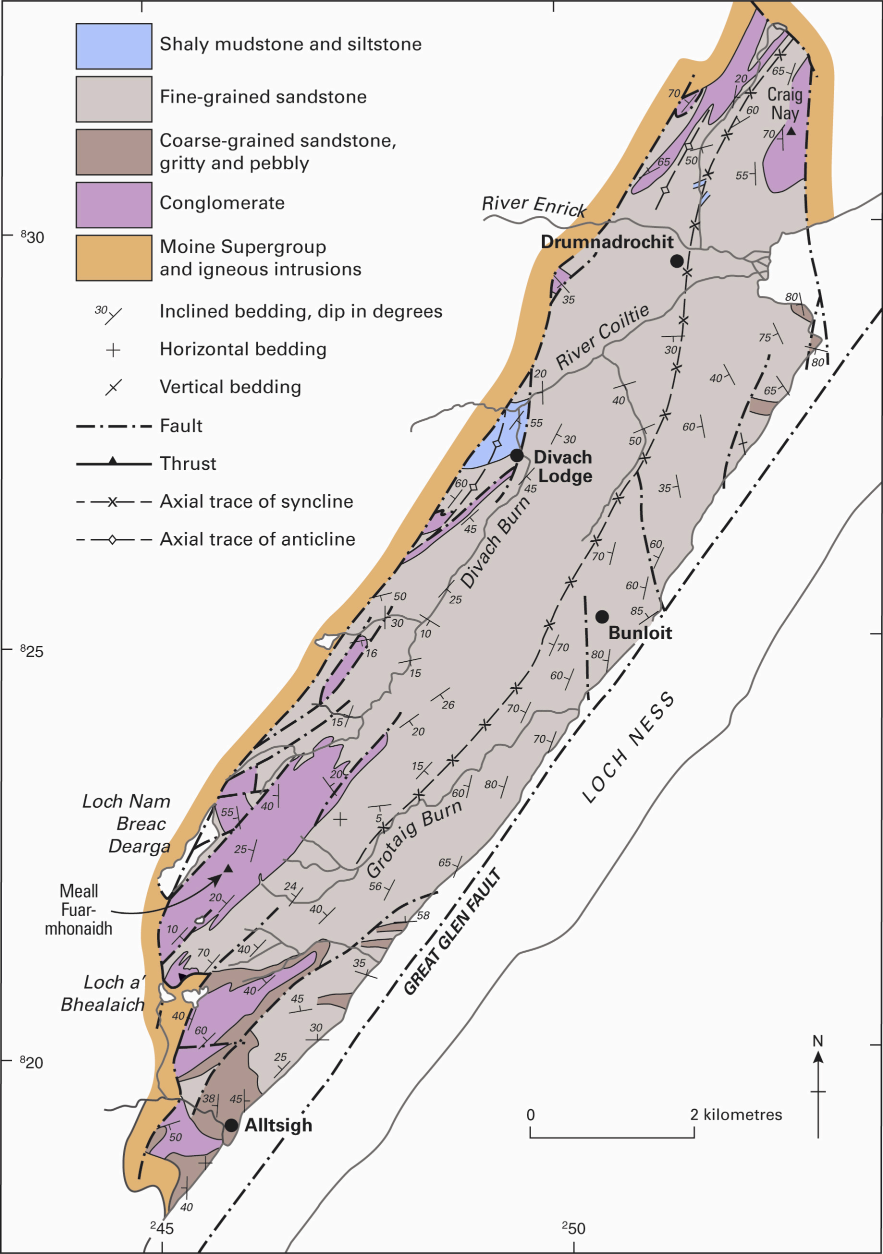


Strathmore Group
Arbuthnott-Garvock Group
Dunnottar-Crawton Group
Stonehaven Group
Axial trace of major anticline/syncline
N
GRAMPIAN HIGHLANDS
HIGHLAND BOUNDARY FAULT ZONE
MIDLAND VALLEY
OCHIL FAULT
LOCH LOMOND
Stonehaven
Fettercairn
Edzell
Brechin
Montrose
Kirriemuir
Blairgowrie
Arbroath
Dundee
Perth
Callander
Aberfoyle
Stirling
Strathmore Syncline
Sidlaw Anticline
0
10 kilometres

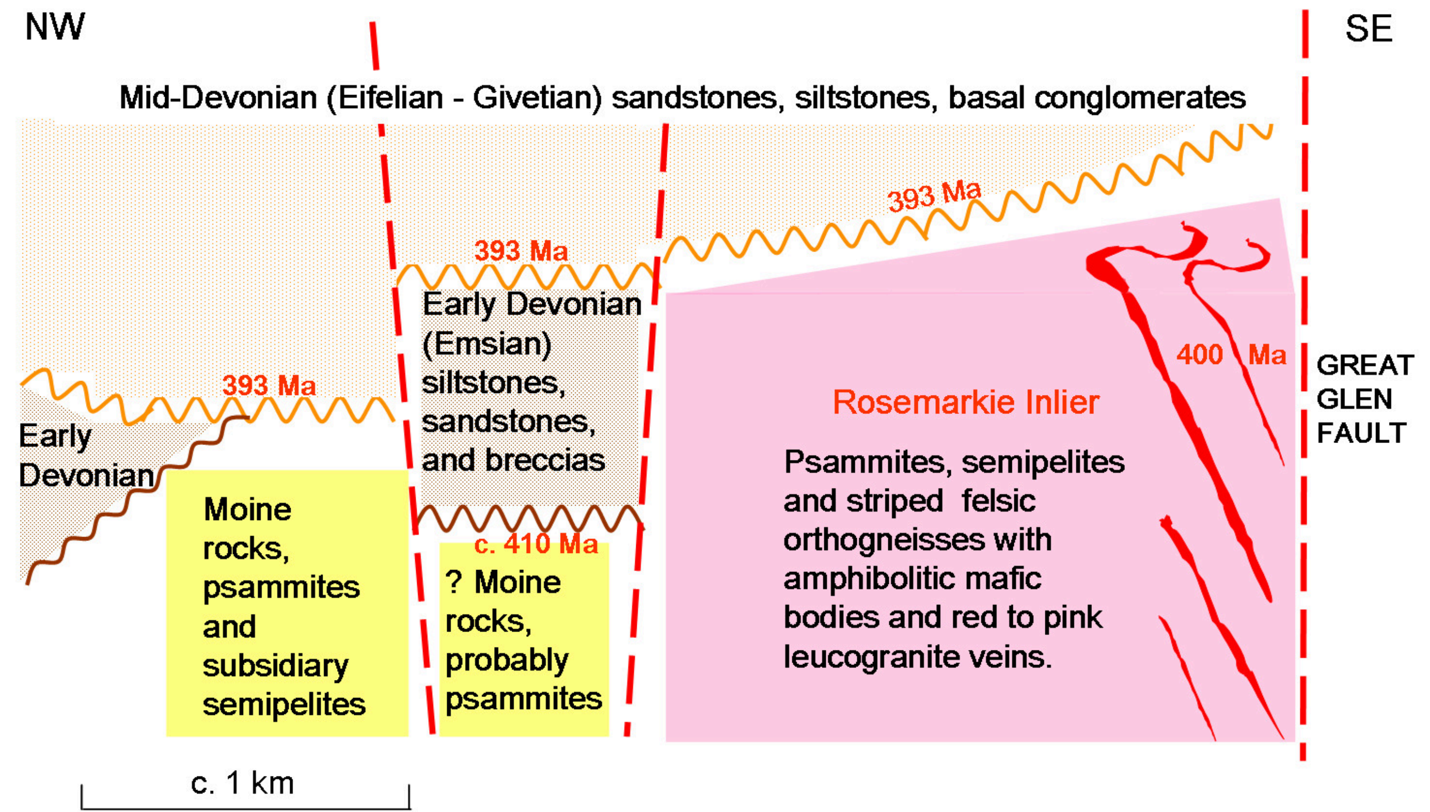

CALLANDER-ABERFOYLE
Buchlyvie Sandstone
Dalmary Sandstone
Bracklinn Falls Conglomerate
Tom Dubh Conglomerate
Malling Conglomerate
Shannochill Sandstone
Gartartan Conglomerate
Callander Craig Conglomerate
Inchmurrin Conglomerate
Balleich Lava
Bofrishlie Burn Sandstone
THF
CXF
RLF
CMVC
F
STIRLING-PERTH-DUNDEE
Buchlyvie Sandstone
Dalmary Sandstone
Uamh Bheag Conglomerate
Campsie Limestone
Dunblane Sandstone
Buttergask Flagstone
Sheriffmuir Sandstone
THF
CXF
SCN
DEF
OVF
ARBROATH
Arbroath Sandstone
Auchmithie Conglomerate
Red Head Sandstone
SCN
DEF
OVF
DEF
BRECHIN-FORFAR
Tannadice Sandstone
Finavon Conglomerate
Melgund Sandstone
SCN
DEF
0
500
1000m
BLAIRGOWRIE-EDZELL
Tannadice Sandstone
Ashbank Sandstone
Hatton Conglomerate
Lintrathen Tuff
THF
GYF
CXF
SCN
CHCG
CVF
STONEHAVEN-FETTERCAIRN
Strathfinella Hill Conglomerate
Tannadice Sandstone
Barras Conglomerate
St John's Knap Sandstone
Three Wells Sandstone
Rouen Bay Sandstone
CVF
Rob's Cove Conglomerate
Doolie Ness Conglomerate
TBVF
Castle Haven Conglomerate
Strathlethan Sandstone
Downie Point Conglomerate
Cowie Harbour Siltstone
Cowie Harbour Conglomerate
Castle of Cowie
THF
CXF
DECO
SCN
MVF
CATC
WCO
GNF
DRCC
CRN
CWE
STRATHMORE GROUP
ARBUTHNOTT - GARVOCK GROUP
DUNNOTTAR - CRAWTON GROUP
STONEHAVEN GROUP
NB. Current members in italics
FORMATIONS
CATC Catterline Conglomerate Formation
CHCG Craighall Conglomerate Formation
CMVC Craig of Monievreckie Conglomerate Formation
CRN Carron Sandstone Formation
CVF Crawton Volcanic Formation
CWE Cowie Sandstone Formation
CXF Cromlix Mudstone Formation
DECO Deep Conglomerate Formation
DEF Dundee Flagstone Formation
DRCC Dunnottar Castle Conglomerate Formation
GNF Gourdon Sandstone Formation
GYF Gannochy Conglomerate Formation
MVF Montrose Volcanic Formation
OVF Ochil Volcanic Formation
RLF Ruchill Flagstone Formation
SCN Scone Sandstone Formation
TBVF Tremuda Bay Volcanic Formation
THF Teith Sandstone Formation
WCO Whitehouse Conglomerate Formation
LITHOLOGIES
Sandstone
Conglomerate
Mudstone/Siltstone
Volcanic rock



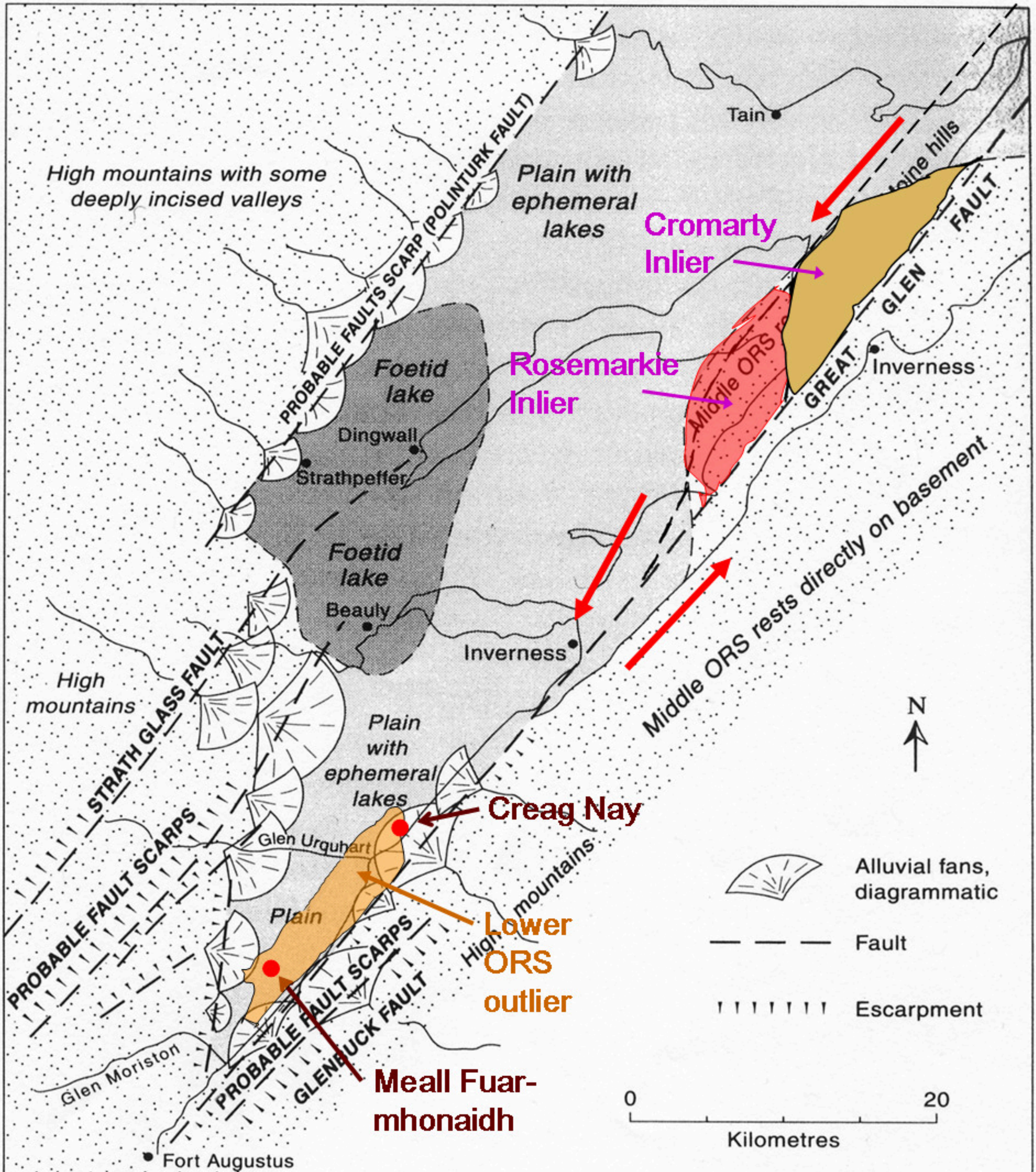
Abbreviations:
GGF - Great Glen Fault, ***PF*** - Polinturk Fault, ***SGF*** - Strath Glass Fault, ***SCF*** - Strathconon Fault

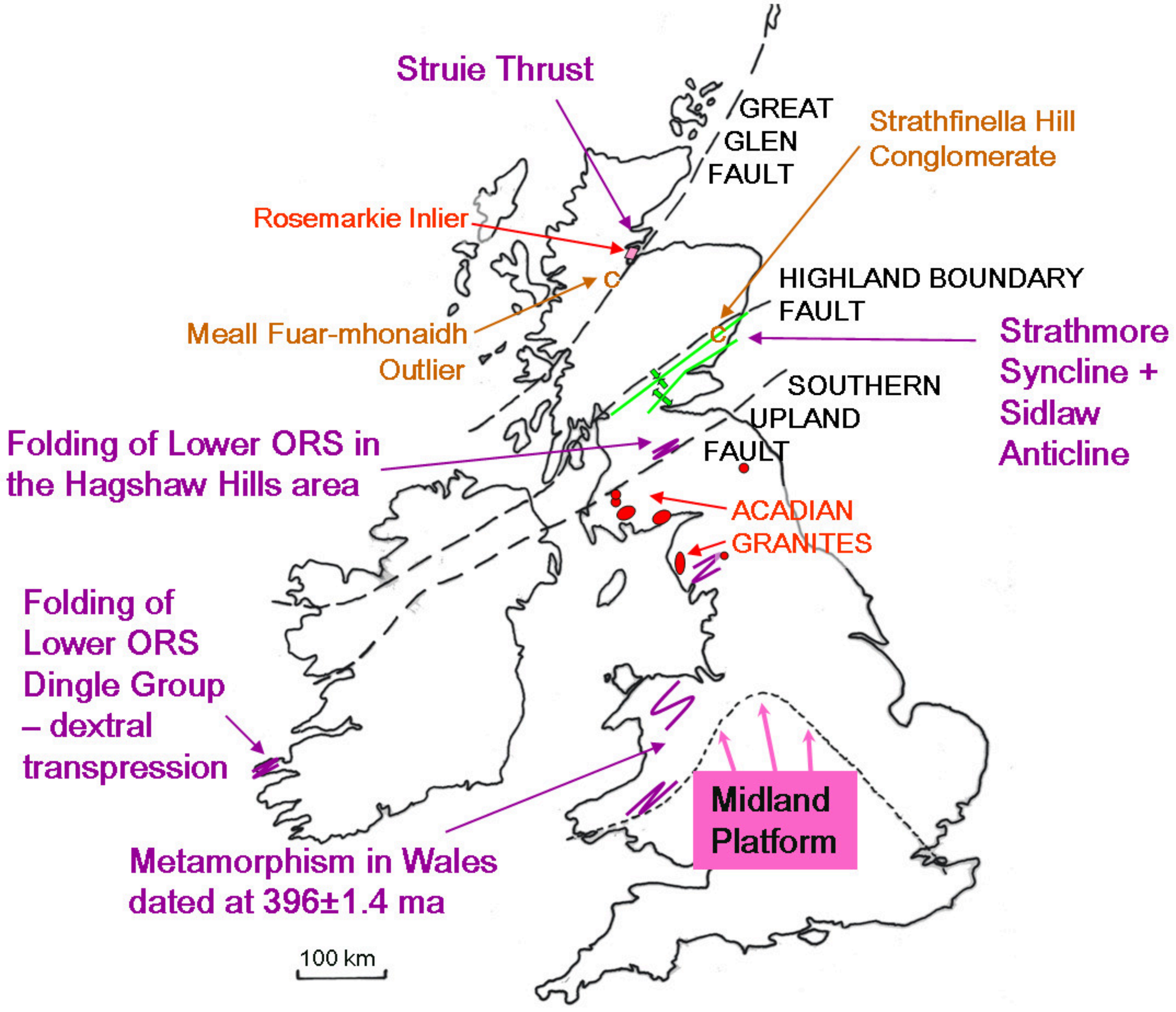


Shaly mudstone and siltstone
Fine-grained sandstone
Coarse-grained sandstone, gritty and pebbly
Conglomerate
Moine Supergroup and igneous intrusions
Inclined bedding, dip in degrees
Horizontal bedding
Vertical bedding
Fault
Thrust
Axial trace of syncline
Axial trace of anticline
Craig Nay
River Enrick
Drumnadrochit
River Coiltie
Divach Lodge
Divach Burn
Bunloit
LOCH NESS
Loch Nam Breac Dearga
Meall Fuar-mhonaidh
Grotaig Burn
GREAT GLEN FAULT
Loch a' Bhealaich
Alltsigh
0
2 kilometres
N
830
825
820
245
250



NW
SE
Mid-Devonian (Eifelian - Givetian) sandstones, siltstones, basal conglomerates
393 Ma
393 Ma
393 Ma
Early Devonian
Early Devonian (Emsian) siltstones, sandstones, and breccias
c. 410 Ma
Moine rocks, psammites and subsidiary semipelites
? Moine rocks, probably psammites
Rosemarkie Inlier
Psammites, semipelites and striped felsic orthogneisses with amphibolitic mafic bodies and red to pink leucogranite veins.
400 Ma
GREAT GLEN FAULT
c. 1 km


High mountains with some deeply incised valleys
PROBABLE FAULTS SCARP (POLINTURK FAULT)
Plain with ephemeral lakes
Tain
Cromarty Inlier
Foetid lake
Dingwall
Strathpeffer
Rosemarkie Inlier
Middle ORS
GREAT GLEN FAULT
Inverness
Foetid lake
Beauly
Inverness
High mountains
STRATH GLASS FAULT
Middle ORS rests directly on basement
Plain with ephemeral lakes
Creag Nay
Glen Urquhart
PROBABLE FAULT SCARPS
Plain
Lower ORS outlier
High mountains
PROBABLE FAULT SCARPS
GLENBUCK FAULT
Glen Moriston
Meall Fuar-mhonaidh
Fort Augustus
N
Alluvial fans, diagrammatic
Fault
Escarpment
0
20
Kilometres


Struie Thrust
GREAT
GLEN
FAULT
Strathfinella Hill
Conglomerate
Rosemarkie Inlier
C
HIGHLAND BOUNDARY
FAULT
Meall Fuar-mhonaidh
Outlier
C
Strathmore
Syncline +
Sidlaw
Anticline
SOUTHERN
UPLAND
FAULT
Folding of Lower ORS in
the Hagshaw Hills area
ACADIAN
GRANITES
Folding of
Lower ORS
Dingle Group
– dextral
transpression
Midland
Platform
Metamorphism in Wales
dated at 396±1.4 ma
100 km