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# Summary of Moine Geology

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## Introduction

The Moine Supergroup is a sequence of Precambrian metasedimentary rocks that outcrops in the Northern Highlands of Scotland (Figure S.1). These rocks, also known informally as 'the Moine', have excited the interest of geologists for well over a hundred years since the pioneering studies of the Geological Survey in the late 1800s. The Moine represents classic ground in the history of structural geology, because it is here that some of the first and most influential studies were carried out on the nature of basement-cover relationships and polyphase fold patterns within an orogenic belt. The Moine Thrust Zone that bounds the Moine to the northwest is one of the best known and most accessible examples worldwide of basement-involved thrusting along the margin of an orogenic belt. Since the first edition of this fieldguide was published, there have been many advances in the understanding of the Moine. These are principally the result of the integration of structural and metamorphic studies with modern isotopic dating techniques, the systematic remapping of selected areas by academic groups in collaboration with the British Geological Survey, and the refinement of Neoproterozoic and Lower Palaeozoic plate reconstructions. Nevertheless, despite the considerable amount of research that has been carried out on the Moine in recent years, various aspects of its geological evolution as well as the nature of its relationship with other Precambrian rock units in the region are still controversial matters that continue to attract geologists to the Scottish Highlands. The aim of this new edition of the fieldguide is to present an updated view of Moine geology as a series of excursions through classic as well as hitherto less well known ground. These excursions are designed to be intelligible and interesting to the casual or amateur visitor, or undergraduate field parties, whilst still providing sufficient detail for the professional enthusiast. Short itineraries are suggested for all excursions, for those with limited time. The summary that now follows is intended as a brief statement of the current understanding of Moine geology; those who require more detail are referred to the syntheses provided by Holdsworth *et al.* (1994), Strachan *et al.* (2002, 2010), and Mendum *et al.* (2009).

## Geological background

The Moine Supergroup of the Northern Highlands of Scotland is a sequence of Neoproterozoic metasedimentary rocks that was involved in the Ordovician-Silurian Caledonian Orogeny. The Moine rocks comprise thick formations of psammites, semi-pelites and pelites, as well as striped or banded units characterized by rapid alternations of lithologies. Sedimentary structures are often present in areas of low tectonic strain and provide the evidence on which the original way up of local successions can be established. Caledonian deformation and metamorphism has long been recognized within the Moine, but in recent years significant isotopic evidence has accumulated suggesting that these rocks were also affected by Precambrian orogenesis at c.820-730 Ma.

The Moine rocks are separated from the Hebridean foreland to the NW by the Moine Thrust Zone (Figure S.1). The oldest component of the foreland is the Archaean-Palaeoproterozoic Lewisian Gneiss Complex (Park *et al.*, 2002; Kinny *et al.*, 2005 and references therein). These basement rocks are overlain unconformably by Proterozoic Torridonian sedimentary rocks (Stewart, 2002) that are in turn overstepped by a Cambrian-Ordovician shelf sequence of quartz arenites, limestones and dolomites (Swett, 1969; Park *et al.*, 2002). Within the Moine Thrust Zone, the cover and basement rocks are imbricated, folded and stacked up in a complex sequence of thrusts (e.g. Peach *et al.*, 1907; Elliott & Johnson, 1980). The Moine rocks rest on the roof thrust to this belt, the Moine Thrust. The Moine Supergroup is limited to the southeast by the Great Glen Fault Zone (Figure S.1). Possible equivalents of the Moine in the Central Highlands are represented by the Badenoch Group (formerly the Dava and Glen Banchor successions, Smith *et al.*, 1999). These are of generally higher metamorphic grade and greater structural complexity than the overlying metasedimentary rocks of the mid- to late-Neoproterozoic Dalradian Supergroup, although the inferred unconformity between the two has been largely obscured by tectonism.

Various suites of igneous intrusions cut the Moine, including pre- to synmetamorphic amphibolites, granites and pegmatites that were emplaced during the Neoproterozoic, and Caledonian granite plutons and minor intrusions (Stephenson *et al.*, 1999). The Moine is overlain unconformably by Lower Devonian Old Red Sandstone rocks (Figure S.1) and is cut by regional basic dyke swarms of Permo-Carboniferous and Tertiary age. Table S.1 summarizes the timing of the main geological events in the Northern Highlands.

Table S.1	Summary of the Caledonian and pre-Caledonian history of the Moine rocks of the Northern Highlands of Scotland. Timing based on isotopic dates quoted in the text.
430-390 Ma	Emplacement of the 'Newer Granite' suite and sinistral displacements along the Great Glen fault system.
435-425 Ma	Scandian orogenic event – mid to low amphibolite facies metamorphism, widespread ductile thrusting and folding, culminating in development of the Moine Thrust Zone.
470-460 Ma	Grampian orogenic event – mid to upper amphibolite facies metamorphism and deformation of the eastern Moines above Sgurr Beag and Naver thrusts.
600-590 Ma	Intrusion of augen granites (e.g. Inchbae) during continental rifting and development of the Iapetus Ocean.
820-725 Ma	Knoydartian orogenic event(s) – garnet grade metamorphism, isoclinal folding, intrusion of pegmatites, early displacement on the Sgurr Beag Thrust.
870 Ma	Intrusion of amphibolites and the granitic protoliths of the West Highland Granitic Gneiss – during an orogenic event or during crustal extension and development of the Moine sedimentary basin?
1000-870(?) Ma	Deposition of Moine sediments.

## Age and tectonic setting of Moine sedimentation

The Moine Supergroup is unfossiliferous and its age is constrained only by isotopic data. Detrital zircon grains obtained from Moine rocks, as well as inherited zircons within migmatites and granites that were formed by the melting of Moine sources, have given ages that mostly range between c.1800 and c.1000 Ma (Friend *et al.*, 1997, 2003; Kinny *et al.*, 1999; Cawood *et al.*, 2004, 2007; Kirkland *et al.*, 2008). The Moine rocks were therefore probably derived in part from the erosion of the c.1.1-1.0 Ga Grenville orogenic belt that formed during the assembly of the super-continent Rodinia (see Fig. S.2)a, as well as other basement sources located along the eastern margin of Laurentia. A lower limit for Moine sedimentation is provided by ages of c.870 Ma for igneous rocks that intrude the supergroup (see below). Moine sedimentation is therefore constrained to the period between about 1000 and 870 Ma. The general consensus is that the Moine sedimentary basin was located within the Rodinia supercontinent, near to the junction between three major continental blocks, Laurentia, Baltica and Amazonia ((Figure S.2)a; Dalziel & Soper, 2001; Friend *et al.*, 2003; Cawood *et al.*, 2004; see, however, Cawood *et al.*, 2010). The Moine rocks may have been deposited in an aborted zone of crustal extension and rifting that developed along the eastern margin of Laurentia at the same time as various crustal blocks separated from west Laurentia to form the Pacific Ocean (Dalziel & Soper, 2001).

## Regional framework

The regional framework that has been developed arises in part from the recognition of regional ductile thrusts, principally the Sgurr Beag and Naver thrusts (Figure S.1). This enabled the Moine to be considered in terms of a series of thrust nappes, each with a distinctive lithostratigraphy and structural sequence (Tanner *et al.*, 1970; Barr *et al.* 1986; Holdsworth *et al.*, 1994). In addition, refinement of local Moine successions within thrust nappes resulted in part from the identification of inliers of Archaean orthogneisses that are thought to represent fragments of the basement upon which the Moine sediments were deposited (e.g. Flett, 1905; Peach *et al.*, 1907, 1910; Read, 1931; Ramsay, 1958; Holdsworth,

1989a).

The basement inliers consistently lie at the lowest structural levels in local successions where the effects of thrusting and/or folding are removed (e.g. Richey & Kennedy, 1939; Ramsay & Spring, 1962; Holdsworth, 1989a). In the Glenelg and Fannich areas, as well as Sutherland, many basement inliers lie in the cores of isoclinal folds (Excursions 6, 9, 10 and 13), whereas others are carried as allochthonous slices along Caledonian ductile thrusts, notably the Sgurr Beag Thrust (Excursions 5 and 8). Marbles and pelites within some inliers (e.g. Loch Shin inlier, Excursion 10) appear to be integral parts of the basement rather than infolds or tectonic slices of Moine lithologies. Although ductile deformation has mainly obliterated any sedimentary or structural discordance across the basement-Moine contacts, the present consensus is that the relationship is one of basement and cover (e.g. Peach *et al.*, 1910; Ramsay, 1958; Holdsworth, 1989a). Correlation of the basement inliers with the Lewisian Gneiss Complex of the Caledonian foreland has been generally accepted on the basis of lithological and geochemical similarities (e.g. Ramsay, 1958; Winchester & Lambert, 1970; Rathbone & Harris, 1979; Moorhouse & Moorhouse, 1988; Strachan & Holdsworth, 1988). U-Pb zircon dating of some basement inliers has yielded late Archaean protolith ages similar to those of the Lewisian Gneiss Complex (Friend *et al.*, 2008). Sm-Nd and U-Pb mineral ages of c.1100-1000 Ma obtained from the eclogite-bearing eastern Glenelg inlier (Excursion 7; Sanders *et al.*, 1984; Brewer *et al.*, 2003) imply that at least some of the basement inliers were reworked during the Grenville orogeny.

## Tectonostratigraphy of the Moine Supergroup

The Moine rocks of West Inverness-shire comprise three lithostratigraphic units – the Morar, Glenfinnan and Loch Eil groups ((Figure S.1); Holdsworth *et al.*, 1987, 1994; Roberts *et al.*, 1987). Although the Morar and Glenfinnan groups are thought on the mainland to be separated by the Sgurr Beag Thrust, stratigraphic passage between the two has been proposed on the Ross of Mull (Holdsworth *et al.*, 1987, Excursion 1). The boundary between the Glenfinnan and Loch Eil groups is also transitional (Roberts & Harris, 1983; Roberts *et al.*, 1984, Excursion 4). The Morar Group stratigraphy in its type area is dominated by a tripartite psammite-pelite-psammite succession that is up to 5km thick (Figure S.3); Richey & Kennedy, 1939; Ramsay & Spring, 1962; Johnstone *et al.*, 1969; Brown *et al.* 1970). A discontinuous basal pelite comprises a tectonic melange of Moine semi-pelite and retrogressed gneisses derived from the underlying basement that occupies the core of an early isoclinal fold. The Knoydart Thrust (Figure S.3) is the only structure that disrupts the sequence significantly, although a common succession is recognized in its foot-wall and hanging-wall. The thick psammites within the Morar Group are commonly weakly strained and therefore preserve sedimentary structures (Excursions 1 and 3). The Glenfinnan Group mainly comprises striped units of thinly interbanded psammites, semi-pelites, quartzites and pelites, together with thick pelitic formations ((Figure S.3); Excursion 3). Tectonic strain is commonly high and sedimentary structures are therefore rare. Estimates of original thickness vary from 1-4km (Holdsworth *et al.*, 1994). Allochthonous slices of basement present along the trace of the Sgurr Beag Thrust north of Loch Houran are assumed to lie at the stratigraphical base of the Glenfinnan Group. The Loch Eil Group (Excursions 2 and 5) is a monotonous sequence of psammites, although local quartzite and striped formations are recognized in the type area ((Figure S.3); Stoker, 1983; Strachan, 1985). Sedimentary structures are locally common and the succession may be up to 5km thick. Outliers of the Loch Eil Group occur as synformal infolds within the Glenfinnan Group, and migmatitic gneisses adjacent to the Great Glen Fault probably represent upfolds of the Glenfinnan Group (Figure S.1).

Following recognition that the Sgurr Beag Thrust can be traced at least as far north as the Dornoch Firth ((Figure S.1); Wilson & Shepherd, 1979; Kelley & Powell, 1985; Strachan & Holdsworth, 1988, Excursion 10), the type Moine succession has been extended into Ross-shire. Further north, there seems little doubt that the psammite-dominated succession of western Sutherland equates with the Morar Group ((Figure S.1); Holdsworth *et al.*, 1994). Further east, however, correlations are less certain because the Sgurr Beag Thrust cannot be linked unambiguously with any of the major ductile thrusts recognised in central and east Sutherland (Friend *et al.*, 2003; Kocks *et al.*, 2006). The Sgurr Beag Thrust has been conventionally linked with the Naver/Swordly thrust system (e.g. Soper & Barber, 1982; Butler & Coward, 1984; Barr *et al.*, 1986; Strachan & Holdsworth, 1988). However, there are significant differences between the metamorphic history of the Loch Coire migmatites that occur above the Naver Thrust in Sutherland and the Glenfinnan Group rocks above the Sgurr Beag Thrust south of the Dornoch Firth. It is possible that the Skinsdale Thrust in SE Sutherland (Figure S.1) is a more plausible correlative of the Sgurr Beag Thrust (Kocks *et al.*, 2006).

Sedimentological studies of parts of the Moine Supergroup are possible in areas of low strain. However, the interpretation of Precambrian sandstone-dominated sequences is difficult because they contain none of the fossils that might, for example, distinguish between marine and non-marine sequences. Glendinning (1988) interpreted the Upper Morar Psammite between the Ross of Mull and Mallaig as a predominantly tidal shelf deposit (Excursion 3). Complex sand waves, bipolar cross-bedding and gravel lag deposits were thought to compare closely with those found in modern shelf environments. A shallow marine environment is also indicated for the Loch Eil Group in its type area by bipolar cross-bedding, wave ripples and possible lenticular and flaser bedding (Strachan 1986). In contrast, recent analysis of the Morar Group psammities of west Sutherland suggests that they represent fluvial deposits that may correlate with the Applecross Formation of the Torridon Group on the Caledonian foreland (Krabbendam *et al.*, 2008). Similarly, the Upper Morar Psammite of Ardnamurchan has been reinterpreted as an alluvial braidplain deposit (Bonsor & Prave, 2008). Further work is clearly necessary to resolve the depositional environments and basin evolution of the Moine Supergroup. It seems likely that the great thickness of Moine sediments must have accumulated in a basin formed by crustal extension, and both localized rifts (Soper *et al.*, 1998) and larger-scale basins (Cawood *et al.*, 2004) have been proposed.

## Regional metamorphism

Metamorphic grade within the Moine is often difficult to establish because of the aluminium-poor nature of pelitic rocks that has inhibited the formation of Barrovian index minerals. Metamorphic grade has therefore been in part defined in terms of mineral assemblages in calc-silicates that have been correlated with Barrovian metamorphic facies (Kennedy, 1949; Johnstone *et al.*, 1969; Winchester, 1974; Tanner, 1976; Powell *et al.*, 1981; Fettes *et al.*, 1985). Metamorphic grade within the Morar Group increases rapidly from the greenschist facies in the west, through the epidote-amphibolite facies and into a broad belt of low amphibolite facies metamorphism where rare kyanite appears in pelites and calc-silicates show hornblende  $\pm$  plagioclase assemblages. A central area of high-grade rocks occupies a narrow NNE-trending belt, broadly corresponding to the outcrops of the migmatitic rocks of the Glenfinnan Group and the Loch Coire migmatites in Sutherland. These contain hornblende  $\pm$  pyroxene  $\pm$  bytownite assemblages in calcsilicates. The western margin of the high-grade belt is broadly coincident with the Sgurr Beag and Naver thrusts, consistent with field evidence that migmatization preceded ductile displacements along both structures (Powell *et al.*, 1981; Strachan & Holdsworth, 1988). The eastward decrease in grade into the low amphibolite facies of the Loch Eil Group is probably the result of the late folding of gently-dipping isograds into a broad regional synform, because high-grade Glenfinnan-type migmatites re-emerge locally adjacent to the Great Glen. The apparent simplicity of the regional metamorphic zonation is, however, illusory since the implication of isotopic studies is that it is composite and polymetamorphic (see below).

## Early (c.870 Ma) igneous activity in the Moine Supergroup

The West Highland Granitic Gneiss (Johnstone 1975) is a series of separate bodies that mainly outcrop close to the boundary between the Glenfinnan and Loch Eil groups between Strontian and Glen Doe ((Figure S.1); Excursions 2, 4 and 5). Other bodies occur to the east within the Loch Eil Group. Barr *et al.* (1985) interpreted the granite gneisses as magmatic intrusions that were formed by anatexis of Moine rocks at a deeper structural level. Dating of zircons has shown that the granitic protolith of the Ardgour body, and its enclosed segregation pegmatites, formed at  $873 \pm 7$  Ma (Friend *et al.*, 1997). A similar age of  $870 \pm 30$  Ma has been obtained for the igneous protolith of the Fort Augustus granitic gneiss (Rogers *et al.*, 2001).

Sill-like metabasic bodies are common within the Glenfinnan and Loch Eil groups but rare in the Morar Group except in west Sutherland (e.g. Moorhouse & Moorhouse, 1979; Smith, 1979; Roberts & Harris, 1983; Winchester & Floyd, 1983; Winchester, 1984; Rock *et al.*, 1985; Strachan, 1985; Holdsworth, 1989a; Millar, 1999). They also cut members of the West Highland Granite Gneiss (Excursions 2 and 5). Most are foliated amphibolites or hornblende schists, although metagabbros with relict igneous textures are present locally. The metabasic intrusions display a tholeiitic chemistry comparable with modern mid-ocean ridge basalts. Although it is clear that the metabasic rocks were not emplaced within an oceanic setting *sensu stricto*, since the host Moine rocks were apparently deposited on Archaean basement, the chemistry is also consistent with intrusion into continental crust that had been thinned during extension. It therefore seems likely that these early metabasic bodies were intruded during crustal extension and development of the Moine

sedimentary basin(s). A U-Pb zircon age of  $873 \pm 6$  Ma obtained from a metagabbro at Glen Doe (Millar, 1999) is thought to date its magmatic crystallization and it is assumed that the rest of the suite is of broadly the same age.

Barr *et al.* (1985) argued that the West Highland Granite Gneiss was syn-orogenic and formed during regional migmatization and  $D_1$  isoclinal folding of the Moine rocks. In contrast, Soper & Harris (1997), Millar (1999) and Dalziel & Soper (2001) have suggested that the granitic protolith of the gneiss was formed during crustal extension, formation of the Moine sedimentary basin and emplacement of the regional metabasic suite. Ryan & Soper (2001) envisage that the metabasic intrusions provided sufficient heat to locally melt both the underlying basement and Moine sediments to produce granitic melts that migrated up through the sedimentary pile to their present location. However, in the absence of reliable pressure-temperature data to constrain the conditions of melting, the origin of the granitic protoliths, the age of their gneissification, and hence the nature of the c.870 Ma tectonothermal event remain equivocal.

## **Evidence for Neoproterozoic Knoydartian orogenic activity at c.820-730 Ma**

Rather firmer evidence exists for younger orogenic events in the period c.820-725 Ma. The first indications that the Moine rocks were metamorphosed during the Precambrian were provided by the Rb-Sr dating of muscovites from deformed pegmatites within the Morar Group (Giletti *et al.*, 1961). Ages of 750-690 Ma were interpreted as the likely age of pegmatite segregation during an early high-grade metamorphic event that was later termed the Knoydartian (Bowes, 1968) or Morarian (Lambert 1969) orogeny. Further isotopic dating of these pegmatites and others has yielded Rb-Sr muscovite and U-Pb zircon and monazite ages of c.830-730 Ma (van Breemen *et al.*, 1974, 1978; Piasecki & van Breemen, 1983; Powell *et al.*, 1983; Piasecki, 1984; Rogers *et al.*, 1998). The Loch Eilt pegmatite (Excursion 3) is a classic example of one of these deformed early intrusions. Much debate has focused on the tectonic significance of these pegmatites. Their field relations with host Moine rocks are commonly difficult to evaluate because of the high degree of superimposed Caledonian strain and metamorphic recrystallization (Powell *et al.*, 1983). An alternative interpretation is that the pegmatites are entirely pre-tectonic and were produced during crustal extension and episodic melting of the Moine sedimentary pile (Soper & Anderton, 1984; Soper & Harris, 1997; Dalziel & Soper, 2001), thus challenging the very existence of a Precambrian orogenic event. Recent studies that have linked modern geochronological techniques and pressure-temperature data have provided firmer evidence for Neoproterozoic orogenesis. Sm-Nd ages of c.820-790 Ma obtained from post-  $D_1$  garnets in the Morar Group date early prograde metamorphism during crustal thickening (Vance *et al.*, 1998; Cutts *et al.*, 2009). In Inverness-shire, this event is thought to have been associated with nappe-scale interleaving of Moine rocks and the basement rocks of Glenelg and Morar (Excursions 3 and 6; Ramsay, 1958; Powell, 1974). A U-Pb age of  $737 \pm 5$  Ma has been obtained from prograde titanites that developed after initial displacement along the Sgurr Beag Thrust in the Loch Eilt area of west Inverness-shire (Excursion 3; Tanner & Evans, 2003). Similar U-Pb ages of c.730-725 Ma are recorded by zircons and monazites that formed during high-grade metamorphism of the Moine rocks in Glen Urquhart ((Figure S.1); Cutts *et al.*, 2010). Hyslop (1992) has confirmed that most of the early pegmatites formed *in situ* in zones of high strain and melt generation during metamorphism at garnet grade and higher. Further complexity is provided by Storey *et al.* (2004) who have obtained a U-Pb age of  $669 \pm 31$  Ma from syn-kinematic titanites within a contractional shear zone in the Glenelg area (Excursion 7). It therefore seems possible that the Moine rocks were affected by a number of orogenic events in the mid-Neoproterozoic. The term 'Knoydartian' is probably best employed with reference to this overall period of orogenic activity rather than to any individual phase.

The present consensus is that the earliest prograde metamorphic events and associated foliations and isoclinal folds within the Moine are likely to be of Precambrian age. The tectonic setting of Knoydartian orogenic events is presently uncertain. The lack of any Neoproterozoic calc-alkaline igneous rocks within the Moine means that it is unlikely that orogenic activity occurred near to an active plate margin. Neoproterozoic plate reconstructions mostly depict the continents in close proximity (Figure S.2)a and there is little scope in the segment of Rodinia where Scotland is thought to have been located for the opening and closure of large ocean basins. Cawood *et al.* (2004) have suggested that Knoydartian orogenic activity resulted from the episodic closure of a Moine intracratonic basin, perhaps driven by far-field stresses arising from terrane accretion on the periphery of Rodinia.

## **Late Neoproterozoic magmatism**

The Moine rocks of Ross-shire and East Sutherland were intruded by granites during the late Neoproterozoic. These include the Carn Chuinneag-Inchbae granite within the Morar Group of Ross-shire (Figure S.1) and minor granite sheets within the East Sutherland Moine. These have yielded U-Pb zircon ages of  $594 \pm 11$  Ma (Inchbae granite, Oliver *et al.*, 2008) and  $599 \pm 9$  Ma and  $588 \pm 8$  Ma (East Sutherland granites, Kinny *et al.*, 2003a). The preservation within the contact aureole of the Carn Chuinneag granite of delicate sedimentary structures appears to rule out a pervasive pre-granite deformation in the Morar Group country rocks (Peach *et al.*, 1912; Soper & Harris, 1997). The Carn Chuinneag-Inchbae granite is thus presumed to lie within an area of low Knoydartian strain. Contemporaneous magmatism in the Dalradian Supergroup, and in the Appalachians and the Norwegian Caledonides, has been attributed to the break-up of Rodinia and development of the Iapetus Ocean (Fig S.2)a and (Fig S.2)b; Bingen *et al.*, 1998). In this context, the late Neoproterozoic granites in Northern Scotland probably resulted from processes related to continental rifting (Kinny *et al.*, 2003a).

## **Ordovician (Grampian) structures and metamorphism**

Following the breakup of Rodinia in the late Neoproterozoic, the Iapetus Ocean widened through the Cambrian and into the early Ordovician (Figure S.2)b and c; Cocks & Torsvik, 2002). The Moine is thought to have been located on the margin of Laurentia and during the Cambrian and early Ordovician was probably overlain unconformably by shelf sediments that passed southeastwards into deep marine turbidite basins of the Upper Dalradian (Anderton, 1985). Sedimentation was halted in the early to mid-Ordovician by the Grampian orogenic event (Lambert & McKerrow, 1976; Soper *et al.*, 1999). A possible model for the Grampian orogenic event in Scotland and Ireland involves the collision of the Laurentian continental margin with an intra-oceanic subduction zone and a volcanic arc that developed during closure of Iapetus (Figure S.2)c and (Figure S.4). This is thought to have resulted in overthrusting of the Laurentian margin by an exotic ophiolite nappe and regional deformation and metamorphism of the Dalradian and Moine rocks (Dewey & Shackleton, 1984; Dewey & Ryan, 1990). Remnants of this nappe may be represented by the ophiolitic rocks exposed on the island of Unst in Shetland and intermittently along the Highland Boundary Fault.

Various lines of evidence indicate that the eastern Moine was affected by Grampian deformation and metamorphism. In Sutherland, formation of the Loch Coire migmatite complex and its associated N-S-trending lineations and isoclinal folds has been dated at c.470-460 Ma (U-Pb zircon; Kinny *et al.*, 1999; Kocks *et al.*, 2006). Relict garnet-pyroxene assemblages preserved within metabasic sheets in the Naver Nappe are thought to result from the same high-grade Grampian metamorphic event (Friend *et al.*, 2000, Excursion 13). In Inverness-shire U-Pb titanite and monazite ages of c.470 Ma record Grampian metamorphism in this part of the Moine (Rogers *et al.*, 2001; Cutts *et al.*, 2010). Recumbent, tight to isoclinal folds that are curvilinear about a N-S mineral lineation are widespread in the Glenfinnan and Loch Eil groups and probably represent the effects of the Grampian event in the eastern Moine (Rogers *et al.*, 2001, Excursion 4). These folds predate intrusion of the Glen Dessary syenite at  $456 \pm 5$  Ma (van Breemen *et al.*, 1979a; Roberts *et al.*, 1984). U-Pb monazite ages of  $455 \pm 3$  Ma obtained from the Ardgour Granitic Gneiss and its host Moine psammites at Glenfinnan provide additional evidence for Grampian metamorphism (Aftalion & van Breemen, 1980). A major concentration of variably deformed pegmatites within the Glenfinnan Group in Inverness-shire and Ross-shire is also arguably late Grampian in age as two members of the suite have yielded Rb-Sr and U-Pb mineral ages of c.455-445 Ma (van Breemen *et al.* 1974). As yet, there is no isotopic evidence that the Morar Group was affected by Grampian metamorphism. One solution to this conundrum is that a western 'front' to Grampian orogenic activity is buried beneath younger ductile thrusts ((Figure S.5); Dallmeyer *et al.*, 2001).

## **Silurian (Scandian) deformation and metamorphism**

It is believed that following the Grampian orogenic event, continued closure of the Iapetus Ocean was achieved by a reversal in the polarity of subduction and the development of the Southern Uplands accretionary prism ((Figure S.4); Dewey & Ryan, 1990). The final orogenic events in the Scottish Highlands are the result of the oblique collision in the Silurian of three continental blocks, Laurentia, Baltica and Avalonia (Fig S.2)d-f; Soper & Hutton, 1984; Pickering *et al.*, 1988; Soper *et al.*, 1992). Baltica is thought to have collided with the segment of the Laurentian margin that incorporated the Northern Highlands, to result in the Scandian orogenic event (Figure S.5); Coward, 1990; Dewey & Mange, 1999; Dallmeyer *et al.*, 2001; Dewey & Strachan, 2003; Kinny *et al.*, 2003b). This resulted in regionally significant

metamorphism and ductile thrusting and folding of the Moine, culminating in development of the Moine Thrust Zone.

The best place to study the early stages of Scandian thrust-related deformation is Sutherland where the effects of later upright folding are minimal (Excursions 10 and 13). Within the Morar Group and lowermost parts of the Loch Coire migmatites, widespread tight to isoclinal folding of the Moine accompanied NW-directed ductile displacements along the Swordly, Naver and Ben Hope thrusts (Strachan & Holdsworth, 1988; Holdsworth, 1989a; Holdsworth *et al.*, 2001a). The syn-kinematic growth of garnet and hornblende shows that deformation occurred within the amphibolite facies (Strachan & Holdsworth, 1988; Holdsworth, 1989a; Holdsworth *et al.*, 2001a). Above the Swordly Thrust, the intensity of Scandian deformation dies out and reworking of the Loch Coire migmatites is apparently restricted to the Skinsdale Thrust (Kocks *et al.*, 2006). Syn-kinematic granite sheets in the vicinity of the Naver Thrust have yielded U-Pb zircon ages of c.435-420 Ma (Kinny *et al.*, 2003b; Excursion 10). Further east, late stages of displacement along the Skinsdale Thrust were accompanied by intrusion of the Strath Halladale Granite at  $426 \pm 2$  Ma (U-Pb monazite, Kocks *et al.*, 2006). This phase of thrust-related deformation was responsible for the major interleaving of Moine rocks with basement gneisses in Sutherland. Within the Morar Group, many inliers occupy the cores of major sheath folds; thin allochthonous slices of highly strained basement lie along the Ben Hope, Naver and Swordly thrusts (Holdsworth, 1989a). The folding of ductile thrusts by folds developed in their footwalls demonstrates that thrust-related deformation propagated towards the foreland.

Extensive tracts of the Morar Group in Ross-shire as far south as Loch Duich are dominated by NW-trending lineations and associated tight to isoclinal folds that are geometrically and kinematically identical to those described above from west Sutherland (Kinny *et al.*, 2003b). There may have been significant displacement along the Sgurr Beag Thrust during the Scandian event. The total displacement along the thrust is unknown, but likely to be at least tens of kilometres and conceivably > 100km (Powell *et al.*, 1981). However, a wholly Caledonian age for the Sgurr Beag Thrust has been questioned by Tanner & Evans (2003) who argue that in west Inverness-shire it is fundamentally a Knoydartian structure.

Subsequent tight upright folding along NNE-trending axes resulted in the formation of the Northern Highland Steep Belt (Excursions 3, 4 and 5). Outliers of the Loch Eil Group occur within the steep belt along the axial trace of a major curvilinear synform (Roberts *et al.*, 1984, 1987). These folds gradually become less intense northwards and in Ross-shire they deform NW-trending thrust-related lineations that are correlated with the Scandian structures identified in west Sutherland (Kinny *et al.*, 2003b). This implies that the steep belt folds are most probably of Scandian age.

## Moine Thrust Zone

The Moine Thrust Zone is the westernmost and youngest of the system of Scandian thrusts on the mainland of Northern Scotland. The thrust zone at Loch Eriboll and Durness (Excursions 11 and 12) is historically important ground in structural geology as it is here the existence of large-scale thrusts was first demonstrated by Lapworth (1883, 1885). In a classic publication, Peach *et al.* (1907) recognized that the Moine rocks had been displaced along the Moine Thrust at a low angle to the WNW across the Hebridean foreland. Between the Moine Thrust and the undeformed foreland lay a 'belt of complication', up to 11km-wide, within which cover and basement rocks were interleaved by folding and thrusting: this is the Moine Thrust Zone. Peach *et al.* (1907) recognized major, low-angle thrusts, that delimited nappes within the thrust belt, and also families of small-scale thrusts or reverse faults that repeated the stratigraphy many times over in a series of imbricate slices. These faults generally rooted down onto one of the major thrusts.

Structurally above the Moine Thrust is an extensive belt of mylonites, best exposed at Loch Eriboll and Durness (Excursions 11 and 12). These formed from the intense ductile shear and recrystallization of Moine rocks, associated slices of Lewisian(oid) basement, and Cambrian quartzites at temperatures of c.350-400°C (Holdsworth *et al.*, 2007). In the Morar Group of Sutherland, the regional Scandian lineation is parallel with the main mineral and stretching lineation within the mylonite belt (Soper & Brown, 1971; Soper & Wilkinson, 1975; Holdsworth *et al.*, 2006, 2007). This suggests that the internal ductile thrusting and folding of the Morar Group is linked kinematically with development of the mylonite belt during the same Scandian event. Within the underlying Moine Thrust Zone, slices of Lewisian, Torridonian and Cambrian units are limited by sharp, brittle thrusts that lack much mylonite. This part of the thrust zone clearly developed at higher crustal levels than the mylonite belt, and the Cambrian-Ordovician rocks record peak temperatures of only

about 275°C (Johnson *et al.*, 1985). Notable examples of major overturned and recumbent folds occur within the thrust zone in the Assynt region and between Loch Carron and Skye. Structural analysis has shown that the thrusts generally developed in a foreland-propagating sequence, with successively younger and lower thrusts transporting older and higher thrusts to the WNW in 'piggyback' fashion (Elliott & Johnson, 1980; McClay & Coward, 1981; Butler, 1982, 2009). This is complicated in some areas by later, low-angle 'out-of-sequence' faults that cut through previously thrust and folded strata. Such structures may either be late thrusts or extensional faults that developed due to gravitational instability of the evolving thrust zone (Coward, 1985; Holdsworth *et al.*, 2006).

Isotopic dating of recrystallized micas within Moine mylonites suggests that thrusting occurred at c.435-430 Ma (Johnson *et al.*, 1985; Kelley, 1988; Freeman *et al.*, 1998; Dallmeyer *et al.*, 2001). This is consistent with the U-Pb zircon age of  $430 \pm 4$  Ma obtained from the syn-tectonic Loch Borralan syenite complex within the thrust zone in the Assynt area (van Breemen *et al.*, 1979b). Isotopic ages as young as c.408 Ma obtained from some mylonites suggest that at least locally thrusting continued into the Early Devonian (Freeman *et al.*, 1998). Minimum displacements across the thrust zone are c.50-80km (Elliott & Johnson, 1980; Butler, 1982; Butler & Coward, 1984). It is difficult to assess the displacement on the Moine Thrust itself, but its association with a thick mylonite belt suggests a minimum offset of several tens of kilometres. A total minimum displacement for the Moine Thrust Zone of c.100km is therefore likely.

Deep seismic reflection profiling carried out in the Pentland Firth was designed to determine the sub-surface profile of the Moine and Outer Isles thrusts (hence the acronym MOIST). Brewer & Smythe (1984) identified several mid-crustal, east-dipping reflectors, either of which could represent the down-dip continuation of the Moine Thrust. It is difficult, however, to reconcile either solution with Butler & Coward's (1984) interpretation that the Cambrian-Ordovician foreland succession originally extended c.54 km to the ESE. This implies that the Moine Thrust must follow a shallow trajectory (c.3°) within the upper crust over this distance before any steep ramp occurs. The geometry and deep structure of the margin of the Caledonian orogen is thus still problematical.

## Late Caledonian strike-slip faulting and plutonism

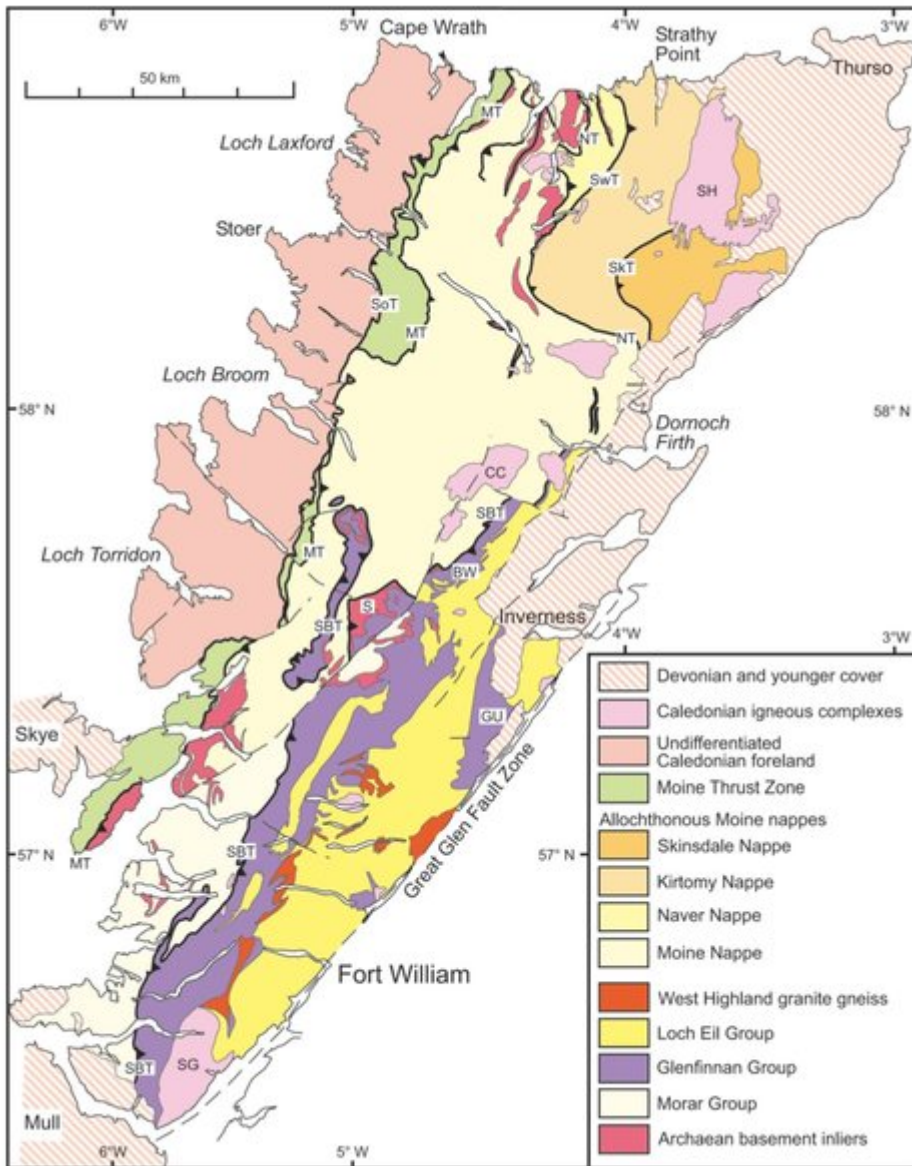
The main phase of Scandian ductile thrusting and folding was followed by sinistral strike-slip displacements along the Great Glen Fault and associated structures (Figure S.1). The development of these faults most likely occurred during the terminal stages of the oblique collision between Laurentia, Baltica and Avalonia in the late Silurian to Early Devonian ((Figure S.2)f; Soper *et al.*, 1992; Dewey & Strachan, 2003). The final stages of the Caledonian orogeny in Scotland were also marked by a major phase of subduction-related plutonism, to form the 'Newer Granite' suite (e.g. Read, 1961; Stephens & Halliday, 1984; Watson, 1984; Soper, 1986; Thirlwall, 1988; Stephenson *et al.*, 1999; Oliver, 2001; Atherton & Ghani, 2002). The emplacement mechanisms of many intrusions were structurally controlled. As indicated above, some granites were emplaced during Scandian thrusting. However, the main phase of plutonism accompanied displacements along strike-slip faults that appear to have acted as ascent pathways for magmas (Jacques & Reavy, 1994). The Great Glen Fault (e.g. Kennedy, 1946; Smith & Watson, 1983) has been linked with the Walls Boundary Fault in Shetland (Flinn, 1961; McBride, 1994) and to the southwest with the Loch Gruinart-Leannan Fault in Islay and Ireland (Pitcher *et al.*, 1964; Alsop, 1992). Seismic reflection studies show that it is coincident with a subvertical structure that extends to at least 40km depth (Hall *et al.*, 1984). Mantle-derived, late Caledonian lamprophyre dykes appear to have different isotopic signatures either side of the fault, suggesting that it has some expression in the upper mantle (Canning *et al.*, 1996, 1998). On the Scottish mainland, the Great Glen Fault comprises a c.3km-wide belt of fracturing and intense cataclasis of Moine and Dalradian protoliths (Stewart *et al.*, 1997, 1999, 2000; Excursion 14). Kinematic indicators demonstrate a consistent sinistral sense of displacement with a minor southeasterly component of downthrow. Related minor faults in the Northern Highlands include the Strathconon Fault, and possibly also the Strath Glass and Helmsdale faults, all of which trend NE, subparallel to the Great Glen Fault. A subordinate set of NW-trending faults, such as the Strath Fleet Fault, may represent anti-Reidel shears to the main Great Glen fault system.

Caledonian sinistral displacements along the Great Glen fault system probably occurred between c.430 Ma and c.400-390 Ma (Stewart *et al.*, 1999). Evidence for Silurian displacement is indicated by the U-Pb zircon ages of structurally controlled plutons located along or adjacent to major faults. These include the Clunes Tonalite ( $428 \pm 2$  Ma, Stewart *et al.*, 2001), the Strontian Granite ( $425 \pm 3$  Ma, Rogers & Dunning, 1991) and the Ratagain pluton ( $425 \pm 3$  Ma,

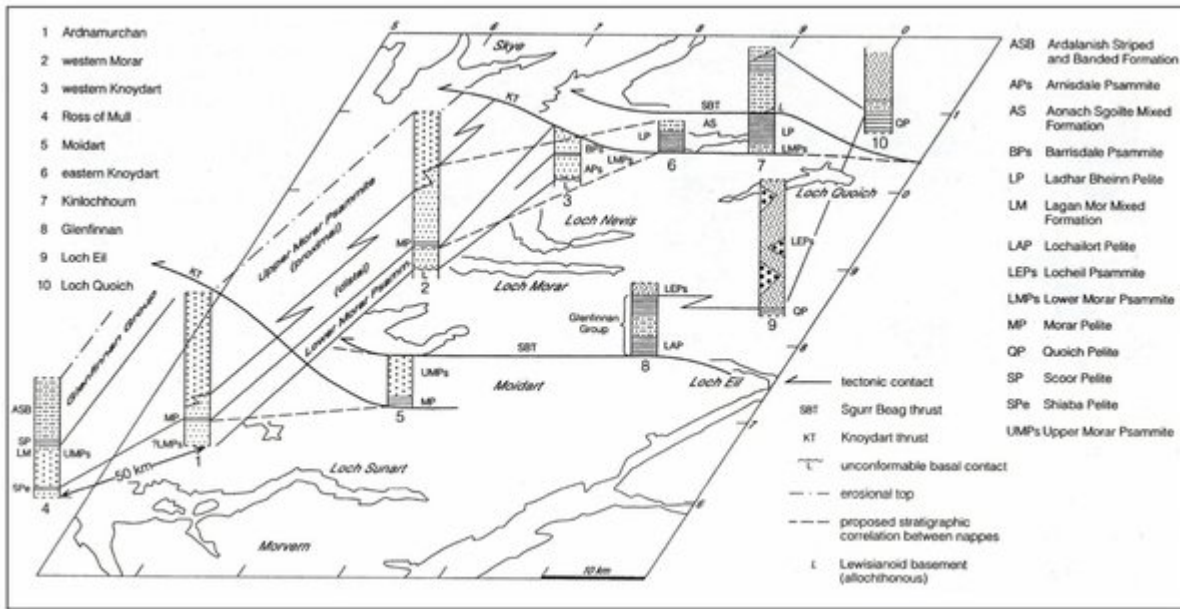


Rogers & Dunning, 1991; Hutton & McErlean, 1991). A lower age limit of c.400-390 Ma is indicated by the low strain nature of Old Red Sandstone (latest Emsian?) sedimentary rocks within the fault zone. These are relatively undeformed compared with the metamorphic basement, and the deformation fabrics described above clearly predate Old Red Sandstone deposition (Stewart *et al.*, 1999, see also Mykura, 1982; Stoker, 1982). The magnitude of early sinistral displacement along the Great Glen Fault has been controversial because there is no unambiguous correlation of pre-Devonian features across the fault. The general consensus has been that sinistral displacements are unlikely to have exceeded 200-300 km, consistent with the available palaeomagnetic evidence (Briden *et al.*, 1984). A rather larger displacement of c.500-700km is implied, however, by tectonic reconstructions that place the Northern Highlands opposite Baltica during the Scandian collision (Dewey & Strachan, 2003; Kinny *et al.*, 2003b).

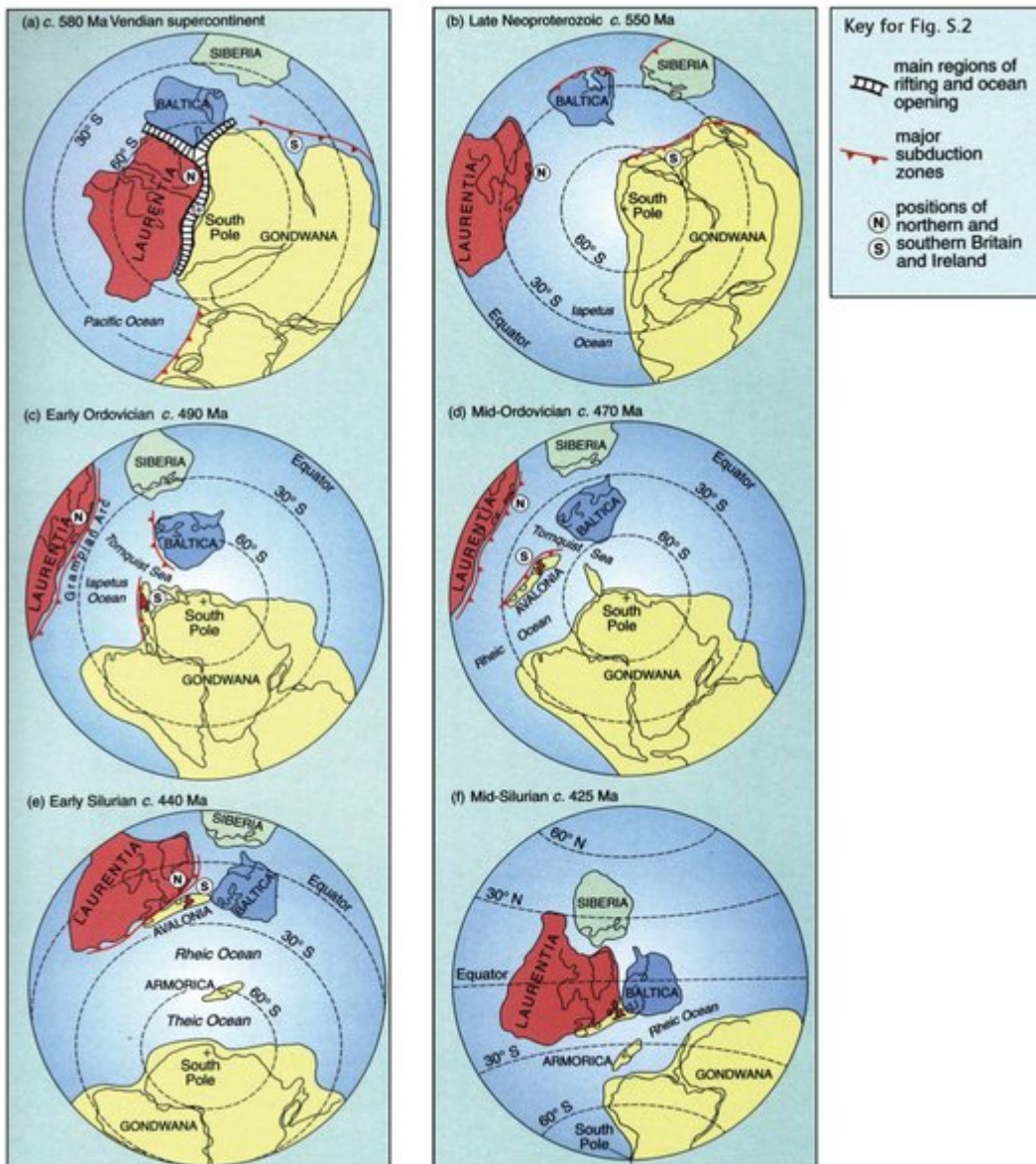
## References



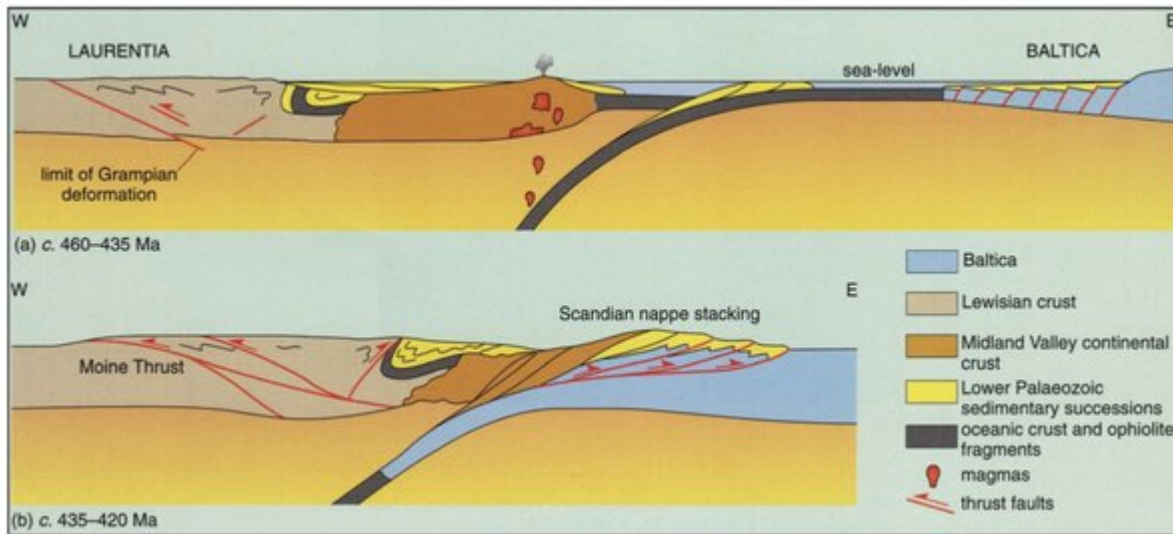
Geological map of the Northern Highlands of Scotland. Abbreviations as follows: MT = Moine Thrust; NT = Naver Thrust; SwT = Swordly Thrust; SkT = Skinsdale Thrust; SoT = Sole Thrust; SH = Strath Halladale Granite; CC = Carn Chuinneag-Inchbae Granite; GU = Glen Urquhart; S = Scardroy; SBT = Sgurr Beag Thrust; BW = Ben Wyvis; SG = Strontian Granite



A fence diagram, viewed from the south, of different stratigraphic columns within the southern Moine (from Soper et al., 1998). Vertical exaggeration x2.5. Dots represent psammitic lithologies of varying proximity, but coarse dots in column 9 signify quartzite. Close fine dots are Loch Eil Group psammities. Lines represent pelite or semi-pelite (undistinguished). Dot-dash ornament represents striped and banded pelitic, semi-pelitic and psammitic units.



Generalized reconstructions of the positions of the main continents from the late Neoproterozoic to late Silurian times (from Open University, 2003). The configuration of Laurentia, Baltica and Gondwana depicted here in S.2a remained stable throughout the Neoproterozoic from the formation of the supercontinent Rodinia to the rifting at c.600 Ma which led to the formation of the Iapetus Ocean.



A simplified tectonic model for the Scandian phase of the Caledonian orogeny at c.435-424 Ma in Northern Scotland (from Open University, 2003). A. Development of an active margin in post-Grampian times by westwards subduction of the northern arm of Iapetus beneath Laurentia. B. Underthrusting of Baltica beneath Laurentia and the development of both E- and W-directed thrust systems. In the Northern Scotland sector of the collision zone, this culminated in the Moine Thrust. This was followed by strike-slip displacement along the Great Glen Fault (omitted here for clarity) that brought the Northern Highlands to its present position relative to the Grampian Highlands which was unaffected by Scandian phase deformation and metamorphism.