

Chapter 1: Scotland's geology: evolution, crustal structure, and societal relevance

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Scotland has a remarkably varied geology (Fig. 1.1). Onshore exposures combined with offshore data incorporate rock units that together represent all the major slices of geological time from three billion years ago up to the Quaternary. In the first section of this introduction to the 5th edition of “The Geology of Scotland”, we present a summary of the geological framework and its evolution as evidenced from the onshore rocks and offshore borehole cores and seismic data. We present this evolution in terms of dynamic earth processes and highlight major global geological events. In the second section, we draw together various independent lines of research to reveal the heterogeneous nature and ancient pedigree of the crust beneath Scotland, its current state of stress and implications for earthquake risk and fault reactivation. In the final section, in a change from previous editions, we present Scotland's geological resources in the context of their relevance to society and to the underpinning of climate change mitigation and transition towards Net Zero.

Whilst we have drawn on the other contributions to this volume, the views expressed here are those of the authors. Twenty years on, the ‘significant differences of opinion’ expressed in the introduction to the 4th edition have diminished in many areas. This is in part due to improved geochronological age constraints leading to a wider consensus, combined with a decline in the volume of research and fieldwork as geology in UK academia has been progressively subsumed into a wider environmental research portfolio.

The geological evolution of Scotland: a synopsis

It is increasingly recognised that the Earth's geological evolution is governed by the supercontinent cycle which has profound implications for crustal development, mountain building processes, oceanic circulation patterns, long-term climate change and the evolution of life (Nance *et al.* 2013 and references therein). Scotland has had the ‘geological good fortune’ to be located close to the edges of major continental masses and plate boundaries for a substantial part of its geological record. It therefore contains evidence for subduction zones, volcanic arcs and mountain building, all arising from periods of ocean closure and plate collision, as well as continental rifts, sedimentary basins and volcanic centres formed during supercontinent breakup and ocean opening. Rock units from all the main periods of geological time are present in Scotland. None the less, the geological record is not complete: major unconformities represent significant gaps in time. Furthermore, the palaeontological record is interrupted by global-scale extinction events, although not all are preserved in the sedimentary strata of Scotland. This complex geological history was developed against a backdrop of the gradual movement of the continents across different climatic zones and major environmental

change as the Earth evolved through cycles of 'greenhouse' and 'icehouse' events. The evidence for these events is preserved in many of the sedimentary successions and palaeontological records documented in this volume. In the interests of readability in the following section we have kept references to a minimum and readers are directed to the appropriate chapters for supporting references and figures.

The broad geological and tectonic framework. A satellite view (Fig 1.2) shows the principal geological faults that transect the crust of Scotland and subdivide its pre-Devonian geology into different segments or crustal blocks. In the far northwest, the Moine Thrust is a low-angle reverse fault, whereas the Great Glen, Highland Boundary and Southern Upland faults are steep structures at surface. The Great Glen and Highland Boundary faults are readily visible and form important topographic features, although arguably one of the most important crustal boundaries, the Iapetus Suture, is entirely obscured by younger sedimentary successions. Since the early 1990s (Bluck *et al.* 1992), these faults have been used to divide the geology of Scotland into a series of 'terranes'. The term 'terrane' was developed from studies in western North America where, during the Mesozoic and Cenozoic, blocks of crust of typically oceanic affinities had been juxtaposed against the Laurentian craton during accretion at a subduction zone followed by strike-slip faulting. This resulted in complex collages of fault-bounded blocks with contrasting geology which were often difficult to reconstruct into a pre-deformational template (Coney *et al.* 1980). Such fault-bound blocks were termed 'terranes'. In Scotland, many workers suggested that during pre-Devonian times there had been significant (100s of km) of strike-slip displacement along the Great Glen, Highland Boundary and Southern Uplands faults which strengthened the comparison with western North America. However, since the publication of the 4th edition of this volume the pendulum of scientific thought has tended to swing back towards viewing these terranes as presenting a relatively coherent geological picture. Some of the bounding faults may be less important than thought previously. Nevertheless, the terrane concept remains a useful framework for describing Scotland's geology and we continue to refer to the Hebridean, Northern Highland, Grampian, Midland Valley, and Southern Upland 'terranes' (Fig 1.2).

The approach taken in this overview is to divide the geological history of Scotland into regionally significant events (Fig. 1.3). Some are periods of sedimentation and basin development during crustal extension whereas others accompanied plate collision and crustal shortening, metamorphism and igneous activity.

Formation of the Archean-Paleoproterozoic crystalline basement: the Lewisian and Rhinns complexes. In northwest Scotland, the Hebridean terrane is underlain by the oldest rocks in the British Isles, the Lewisian Gneiss Complex, which records a protracted geological evolution between c. 3100 and 1600 Ma – approximately one-third of the elapsed age of the Earth. Similar age basement rocks occur in the Northern Highland terrane, and on the islands of Islay and Colonsay in the Grampian terrane (Fig. 1.2). Their geological record is fragmentary but together they form the crystalline basement to sedimentary successions that were deposited at least 600 million years later.

The Lewisian Gneiss Complex is dominated by felsic orthogneisses with subordinate mafic and ultramafic lithologies. It is cut by major shear zones and the extent to which these delineate terranes of contrasting geology has been vigorously debated over the last 20 years (Chapter 3). The felsic orthogneisses form a tonalite-trondhjemite-granodiorite (TTG) suite similar to those that dominate Archaean cratons worldwide. The geological setting in which their igneous protoliths developed between c. 3100 and 2700 Ma is uncertain as the nature of Archaean tectonic processes is still debated. Did plate tectonics operate through the Archaean or did it not develop until the Paleoproterozoic or perhaps even later? Irrespective of tectonic setting, these igneous rocks were affected by high-grade metamorphism at 2700 (Badcallian) and 2500 (Inverian) Ma and intruded by the 'Scourie' dolerite dykes between c. 2418 and 2375 Ma. The development of magmatic arcs at c. 1900–1850 Ma is recorded in the Loch Maree Group of mainland NW Scotland, the South Harris Igneous Complex in the

Outer Hebrides, and the Rhinns Complex of Islay and Colonsay. Widespread Laxfordian metamorphism and deformation affected most parts of the gneiss complex between c. 1790 and 1670 Ma. A northern limit to the Laxfordian event probably lies just north of mainland Scotland since it does not appear to have affected the Archean basement rocks of NW Shetland and offshore to the west.

The geological events outlined above have counterparts in related parts of the cratons of the North Atlantic region, such as South-East Greenland and Fennoscandia. In the Neoproterozoic these cratons may have formed part of a Kenorland supercontinent (Williams *et al.* 1991). The igneous protoliths to the Lewisian Gneiss Complex could have evolved above a subduction zone along the periphery of the supercontinent, and mafic dyke swarms such as the Scourie dykes, may have heralded supercontinent breakup in the early Paleoproterozoic. The magmatic arcs within the Lewisian Gneiss Complex are thought to lie along sutures that formed in the final collisional amalgamation during the Laxfordian event. Similar-aged collisional events recorded in adjacent cratons correspond to the assembly of the supercontinent Columbia (or Nuna) by late Paleoproterozoic times (Chapter 3, Fig 1.4a).

Late Mesoproterozoic to early Neoproterozoic sedimentation and orogeny: the ‘Torridonian’ and ‘Moine’ successions. On the Hebridean terrane, the Lewisian Gneiss Complex is overlain unconformably by ‘Torridonian’ continental sedimentary rocks (Chapter 4). The Torridonian rocks comprise two separate successions. The older Stoer Group was deposited at c. 1200 Ma. It includes the distinctive Stac Fada Member within which have been discovered shocked quartz and zircon grains leading to its interpretation as a meteorite impact deposit, although the location of the impact site is unknown. The Stoer Group was tilted before deposition of the unconformably overlying Sleat and Torridon groups at c. 1000 Ma. The Torridon Group forms much of the spectacular mountain scenery along the western seaboard of northern Scotland. The lowermost Diabaig Formation infills an irregular palaeotopography and contains exceptionally well preserved eucaryotic fossils. The overlying Applecross and Aultbea formations have been used over the last 10 years to model fluvial style and processes in a pre-vegetation landscape. Palaeocurrents flowed eastward (present reference frame) carrying detritus derived from the Lewisian Gneiss Complex and more distal basement rocks in NE Canada. Broadly correlative successions are exposed on the islands of Iona and Skye.

East of the Moine Thrust, the Northern Highland terrane is largely underlain by ‘Moine’ metasedimentary rocks and correlative units are exposed in the Grampian terrane (Badenoch Group) and Shetland. Inliers of Archean–Paleoproterozoic ‘Lewisianoid’ orthogneisses are thought to represent the substrate on which the Moine rocks were deposited in a range of fluvial, deltaic and marine environments. It has been long known that the Moine rocks were intruded by mafic and felsic igneous rocks and segregation pegmatites during the Neoproterozoic. The significance of this was strongly debated in the late 1990s to early 2000s but more recent isotopic dating and petrological studies provide evidence for two periods of crustal thickening and amphibolite-facies metamorphism: the Renlandian orogeny (950–920 Ma) and the Knoydartian orogeny (840–725 Ma). The westerly Morar Group and its correlatives in Shetland are thought to have been deposited between c. 1000–950 Ma and then affected by the Renlandian orogeny. The easterly Glenfinnan, Loch Eil, and Badenoch groups appear to represent a younger succession that was deposited c. 900–840 Ma. All three groups were then affected by Knoydartian orogenesis at 840–780 Ma and 740–725 Ma.

Much historical debate has centred around potential linkages between the Torridonian and Moine successions. Recent reassessment of similarities in sedimentary facies, palaeocurrent directions and detrital zircon populations have led to correlation of the Torridon and Morar groups and equivalent units within a ‘Wester Ross Supergroup’, with the corollary that the Moine Thrust does not separate fundamentally different rock units (Chapter 4). These are interpreted to have been deposited in the foreland of the Grenville orogen which resulted from the collision of Amazonia with combined Laurentia and Baltica, a key event in assembly of the Rodinia supercontinent (Fig 1.4b). Sediments were dispersed towards the Asgard Sea and the Valhalla accretionary orogen that had developed

along eastern Laurentia (Fig 1.4b). The Renlandian and Knoydartian orogenic events are interpreted as separate periods of tectonic activity within this orogen, perhaps driven by flat-slab subduction or terrane accretion. Between these two orogenic events, the Glenfinnan, Loch Eil and Badenoch groups were deposited in a successor basin, strata now grouped as the 'Loch Ness Supergroup'.

Late Tonian to early Ordovician sedimentation: from Rodinia to Iapetus. The next major geological event spans >200 million years and is represented by successions which were deposited between the late Tonian and the early Ordovician which have only been affected by Caledonian orogenesis (see below). The thickest and most extensive of these successions is the Dalradian Supergroup of the Grampian terrane in Scotland and Ireland (Chapter 5). The lower Glenshirra, Grampian and Appin groups pass upwards from alluvial fan-fluvial deposits into marine turbidites and then into a siliclastic-carbonate shallow-marine to shoreline succession. The mainly siliciclastic Argyll Group records alternating periods of marine basin deepening and shallowing, followed by mafic submarine volcanism at c. 600 Ma and accumulation of the deep-water sedimentary rocks of the Southern Highland and Trossachs groups.

The age of the base of the Dalradian Supergroup and hence its total duration is poorly constrained. The long-standing view is that Dalradian sedimentation was initiated in rift basins which formed after 725 Ma, the youngest of the Knoydartian orogenic events in the Northern Highland terrane. Alternatively, the Glenshirra, Grampian and Appin groups could represent the flysch-molasse succession of a foreland basin that developed in response to Knoydartian orogenesis then active in the Northern Highland terrane (Chapter 5). The Argyll, Southern Highland and Trossachs groups might then represent the main record of continental extension and breakup of Rodinia and formation of the Iapetus Ocean. It is widely accepted that Dalradian deposition overlapped the period of extreme global climatic fluctuations known as 'Snowball Earth' (Kirschvink 1992). There has been considerable progress over the past 20 years in calibrating the Dalradian succession against globally recognized glacial events (Chapter 5). The Port Askaig Tillite Formation at the base of the Argyll Group has long been correlated with the Sturtian glacial event which may have been diachronous between c. 716 and 660 Ma. The base of the unit on Islay has been proposed as a candidate for a Tonian-Cryogenian GSSP (Global Boundary Stratigraphic Section and Point) (Fairchild *et al.* 2018). A prominent negative carbon isotope excursion in the middle of the Argyll Group is thought to correspond to the c. 640-635 Ma Marinoan glaciation, and the Macduff and Loch na Cille 'boulder beds' within the Southern Highland Group have been correlated with the c. 583-582 Ma Gaskiers glaciation.

The Southern Highland Group is now viewed as stratigraphically continuous with the Trossachs Group, a thin succession of deep-water sedimentary rocks of early Cambrian to Ordovician age that occurs as small, isolated outcrops along the Highland Boundary Fault. The tectono-stratigraphic affinity of this rock unit has been controversial, but the current consensus is that it should be included within the Dalradian Supergroup. The broadly time-equivalent Ardvreck and Durness groups of the Hebridean terrane (Fig 1.3a) unconformably overlie the Lewisian Gneiss Complex and Torridonian successions. The Ardvreck Group is dominated by quartz arenites and passes upwards into the carbonates of the Durness Group, together recording a broadly transgressive succession that records c. 50 million years of shallow marine to shelf sedimentation.

Cambrian strata worldwide are known for recording the remarkable 'explosion of life'. The Pipe Rock Member (Ardvreck Group) contains a diverse trace fossil record but is commonly known for the abundant *Skolithos* burrows; body fossils are relatively sparse within the Scottish successions. Olenellid trilobites are found within the Fucoïd Beds Member of the Ardvreck Group and approximately time equivalent strata of the Trossachs Group. The Durness Group contains a sparse fauna of trilobites, brachiopods, cephalopods and gastropods. The trilobites within these successions are of considerable historical importance as they were recognized over 100 years ago as being similar to North American (Laurentian) trilobites (Peach 1913). The differences between these and

contemporaneous trilobite genera of Baltica and Gondwana provided key early evidence for the existence of the Iapetus Ocean (Fortey 1992; Cocks & Torsvik 2002). The deposition of these Scottish successions on the margin of Laurentia in part overlapped supercontinent breakup in the Ediacaran to create the Iapetus Ocean (Fig. 1.5a). Igneous activity at c. 600–580 Ma related to extension and continental breakup includes the eruption of mafic volcanics at the top of the Argyll Group and emplacement of the Ben Vuirich and Carn Chuinneag granite plutons in the Grampian and Northern Highland terranes respectively. Thermal subsidence through the late Ediacaran to early Ordovician coupled with a global sea-level rise resulted in the deep-water character of the Southern Highland and Trossachs groups. This passive margin is assumed to have gradually widened so there was sedimentary continuity across the Northern Highland terrane between the Ardvreck, Durness and Trossachs groups, although no trace of any linking succession remains due to subsequent erosion.

Closure of the Iapetus Ocean and the Caledonian orogeny. Palaeomagnetic evidence indicates that the Iapetus Ocean had started to close by the late Cambrian. The final closure of the ocean resulted from the collision of Laurentia, Baltica and the Gondwana-derived microcontinent Avalonia (Figs. 1.5b & c) to form the Caledonian mountain belt. However, the ‘Caledonian orogeny’ was not one simple plate collision but a series of tectonic events or orogenic phases (Chapter 6), each one of which may be referred to in the scientific literature as an ‘orogeny’. As is the case with many ancient orogens, the geological record is fragmentary because of various events and processes, including thrusting, strike-slip faulting, and deep erosion prior to the deposition of unconformably overlying cover sequences.

Evidence for a Late Cambrian(?) to Early Ordovician Midland Valley plate margin. Ocean closure requires the development of subduction zones, and typically results in the emplacement of calc-alkaline igneous rocks in magmatic arcs in overlying plates. The extensive Devonian and Carboniferous sedimentary-volcanic cover of the Midland Valley terrane is thought to overlie a late Cambrian to early Ordovician plate margin which likely comprised a series of magmatic arcs and marginal basins. These are collectively referred to as the ‘Midland Valley terrane’. Geophysical and other evidence suggests that this terrane extends at depth northwards and southwards beneath the Grampian and Southern Uplands terranes respectively, and hence is wider than its surface outcrop between the Highland Boundary and Southern Uplands faults.

The evidence for calc-alkaline magmatism in the Midland Valley terrane is partly based on the composition of locally derived detritus within Middle Ordovician sedimentary rocks of Girvan and the Southern Uplands terrane. Arc-related rocks of the Midland Valley terrane also extend northeastwards along strike under the North Sea. Submerged arc-type basement east of the Shetland Islands is the likely source of Cambrian to Early Ordovician granitic rocks present as clasts within the Funzie Conglomerate in NE Shetland. The southern Scotland successions include boulders of felsic plutonic rocks, one of which has yielded a U–Pb monazite age of 474 ± 2 Ma. Xenoliths of granulite facies meta-igneous rocks within Carboniferous igneous rocks in the Midland Valley were thought to indicate the presence of Grenville (c. 1.2–1.0 Ga) continental basement at depth. However, these xenoliths are now known to have Upper Ordovician and Devonian protolith ages with no sign of older crustal inheritance. Although the presence of continental basement at depth cannot be ruled out, the current presumption is that Midland Valley arc magmatism was largely developed on oceanic crust, analogous (albeit somewhat younger) to the late Cambrian to early Ordovician Lough Nafoe arc along strike in western Ireland (Chew *et al.* 2007).

In SW Scotland, the Ballantrae Complex mainly comprises igneous rocks that originated as components of Iapetus oceanic crust and mantle, some of which have yielded protolith ages as old as c. 500 Ma. Volcanogenic sequences are dominated by basaltic pillow lavas that were erupted in diverse tectonic settings including within-plate oceanic islands, supra-subduction island arcs and oceanic (back-arc?) spreading centres. Interpretation of this complex is difficult as it includes evidence for at least one suture, and the contacts between its various components are faulted. However, the

Ballantrae Complex provides insights into the types of marginal basins and associated arcs that developed outboard of Laurentia in the late Cambrian to early Ordovician.

Early to Mid-Ordovician ophiolite obduction, Grampian orogenesis and arc-continent collision. In NE Shetland (Unst) and the SW Highlands (Bute), Dalradian rocks are overlain by tectonically emplaced ultramafic and/or mafic igneous rocks. These are considered to represent ophiolites, which are slices of oceanic lithosphere. Their chemistry is consistent with formation in a supra-subduction zone, fore-arc setting (hence the term 'SSZ-ophiolite'). The most likely mechanism for their emplacement involves under-thrusting of continental lithosphere at a subduction zone. It is therefore believed that a subduction zone dipped southeastwards beneath the Midland Valley terrane, and that the arrival here of the edge of Laurentia (Fig. 1.5b) initiated northwest-directed ophiolite obduction (Chapter 6). The Shetland and Bute ophiolites are underlain by a metamorphic sole, a tectonized slice of the subducting oceanic plate that was welded onto the base of the ophiolite during obduction. Isotopic data from these sheared basaltic rocks indicate that obduction occurred at c. 490–482 Ma. At Stonehaven in NE Scotland, MORB-type basaltic rocks adjacent to the Highland Boundary Fault may represent a different type of ophiolite that was formed near a mid-ocean spreading ridge. The presence of a metamorphic sole within the Ballantrae Complex indicates ophiolite obduction along the south side of the Midland Valley terrane.

The progressive convergence of Laurentia with the Midland Valley terrane is thought to have driven regional folding and metamorphism of the Dalradian rocks and the Loch Ness Supergroup in the Northern Highland terrane. This major tectonic event is the 'Grampian orogeny' or the 'Grampian orogenic event'. Isotopic ages obtained from metamorphic garnets are c. 475–460 Ma. Barrovian metamorphism in the Grampian terrane increases in grade from greenschist facies in the SW Highlands to amphibolite facies in the Central Highlands where 10–12 kilobar pressure estimates indicate significant crustal thickening. By contrast, in NE Scotland, the metamorphism is of low-P-T Buchan type and heat may have been advected from syn-tectonic calc-alkaline gabbro plutons which could also have driven crustal melting and formation of late-tectonic S-type plutons. Grampian deformation was finished by c. 457 Ma, the age of the youngest post-tectonic pluton.

Significant debate centres around the polarity of subduction during the Grampian orogeny and a mechanism to account for the large-scale divergent fold-facing observed within the Dalradian rocks, in particular the regional-scale SE-facing Tay Nappe, as well as syn-tectonic mafic magmatism (Chapter 6). In one end-member interpretation: 1) subduction was southeasterly directed throughout the orogeny and early NW-vergent to upright folds were modified by extensional collapse of the obducted ophiolite sheet and 'retrocharriage' to verge SE, and 2) the syn-tectonic gabbros, which have a calc-alkaline chemistry, were derived from the sub-arc asthenosphere during progressive underthrusting of the Laurentian margin. Alternatively: 1) early SE-directed subduction and SSZ-ophiolite obduction was followed by 'subduction flip' to form a new subduction zone that dipped northwest underneath Laurentia and drove folding and metamorphism of the Dalradian rocks, 2) the syn-tectonic gabbros resulted from subduction of a mid-ocean ridge, and 3) development of the Tay Nappe in part resulted from broadly westward underthrusting of the Midland Valley terrane beneath the Dalradian.

Mid-Ordovician to mid Silurian active margin geology of the southern Midland Valley and Southern Uplands. Irrespective of the debate outlined above, there is general agreement that subduction between the Grampian and Midland Valley terranes terminated when they collided, and that this was followed by initiation of a NW-dipping subduction zone along the southern margin of the latter (Fig. 1.5c). Within the southern Midland Valley, the mid to late Ordovician sedimentary rocks of the Girvan area mainly comprise clastic sedimentary rocks that were deposited in fluvio-deltaic and marine environments. These are thought to have accumulated in a fore-arc basin that was located near an active volcanic arc in the northern part of the Midland Valley terrane. By mid-Silurian times, small transtensional basins had formed more widely along the southern margin of the terrane. These

commence with deep-marine strata and terminate with continental fluvial facies, the transition between marine to continental spanning the Llandovery–Wenlock boundary.

Critical evidence for NW-directed subduction underneath the Midland Valley comes from the Ordovician and Silurian black shales and sandstone turbidites of the Southern Uplands terrane (Chapter 7). The black shales are interpreted as representing deep marine background sedimentation and the sandstone turbidites as submarine fans. They occur in NW-dipping tectonic slices bounded by steep reverse faults. Within each slice, the stratigraphy youngs to the northwest, although in an apparent paradox the gross stratigraphy youngs to the southeast. The region is interpreted as an imbricate thrust belt; the bounding faults are regarded as thrusts that were subsequently rotated into their present orientation. The established tectonic model is that the thrust belt represents an accretionary prism, and that the sedimentary rocks were detached from a descending oceanic plate and progressively accreted underneath similar thrust-bound slices. An alternative model that argued for a back-arc basin setting was based on the presence of detritus thought to have been derived from a contemporaneous outboard arc. However, this detritus has yielded only Neoproterozoic U-Pb zircon ages, suggesting that it was derived from a detached fragment of Avalonia within the Iapetus Ocean.

The Ordovician-Silurian rocks of the Southern Uplands are of international importance for studies of stratigraphy and global climate change. The stratigraphic type section for the Ordovician-Silurian boundary is at Dob's Linn in the Scottish Borders. The Ordovician black shales below this boundary contain important evidence for the nature of the Late Ordovician global mass extinction event which wiped out an estimated 85% of all marine species. A long-held view was that this was related to glaciation. However, recent geochemical studies from various localities around the world, including Dob's Linn, instead suggest that it resulted from a major volcanic episode which in turn led to global warming and anoxia of ocean waters (Bond & Grasby 2020).

Detrital mineral studies from the Ordovician and Silurian rocks of the Midland Valley and Southern Uplands indicate that sediment was in part derived from the erosion of Dalradian rocks of the Grampian terrane. The ages of Precambrian detrital zircons are comparable with those found in the Dalradian rocks, and hence are at least second cycle. Early Ordovician detrital zircons are c. 475 Ma in age and probably derived from a local magmatic arc within the Midland Valley terrane. Detrital garnet within the Southern Uplands is compositionally similar to, and the same age as, Barrovian garnet within the Dalradian rocks. ^{40}Ar – ^{39}Ar detrital muscovite ages from the Southern Upland terrane also coincide with K–Ar and Rb–Sr muscovite ages from the Grampian terrane. These similarities suggest that a river system sourced in the Grampian terrane transported detritus southwards into the Midland Valley basins and thence into the Southern Uplands accretionary prism.

Late Ordovician to early Devonian Scandian orogenesis and closure of the Iapetus Ocean.

Palaeomagnetic and faunal evidence indicates that the Iapetus Ocean had closed by the late Silurian (c. 420 Ma; Fig. 1.5d). The sinistrally oblique collision of Laurentia with Avalonia and Baltica resulted in widespread orogenesis which in Norway is referred to the 'Scandian' event. This term is often used to encompass similar age events in Scotland although the effects here vary considerably (Chapter 8). The Avalonia-Laurentia collision resulted in northward thrusting of the Southern Uplands accretionary prism onto the Midland Valley terrane, and sinistral displacements along the Moniaive shear zone and the Southern Uplands Fault, but there is no evidence for any associated regional metamorphism nor any deformation other than weak folding in the Midland Valley and Grampian terranes.

In the Northern Highland terrane (NHT), the Moine Thrust Zone represents the western limit of the Caledonides. Structurally above and to the east, NW-directed ductile thrusting resulted in peak P-T conditions of 8–9 kilobars and 700°C and was followed by upright folding to form the Northern Highland Steep Belt. At the time of the 4th edition of this volume, ductile thrusting was dated at c. 435–425 Ma but based on sparse isotopic constraints. Subsequently, c. 450–445 Ma Lu-Hf and Sm-Nd garnet ages have been reported from the NHT and attributed to a 'Grampian II' accretion event.

Alternatively, they may date the *onset* of a protracted Scandian continental collision (Chapter 8) as it is now known that outboard segments of a hyper-extended Baltican margin collided with Laurentia at *c.* 450 Ma (Jakob *et al.* 2019). If the segment of the Laurentian margin that included the NHT was affected by that early collision, late orogenic sinistral displacement along the Great Glen Fault could have juxtaposed the NHT and the Grampian terrane in approximately their present relative positions. This could therefore account for the differences in the intensity of the Scandian event across the Great Glen Fault (see however Searle 2021 for a different view).

Magmatic rocks of the Late Caledonian igneous province were emplaced during the Silurian and Early-Mid Devonian in all the main geological regions of Scotland. They include volcanic sequences, major granitoid plutons and a wide variety of minor intrusions. The broad chemistry is consistent with formation above a NW-dipping subduction zone, and the Midland Valley lavas in particular are directly comparable to some modern arc volcanics. There is continued debate as to the relative contributions of mantle and crust to melts and the role of slab detachment at the end of the orogeny. Subduction is believed to have been ongoing into the early Devonian, and so slab detachment might only account for the formation of the youngest plutons in the Southern Uplands.

Devonian (Old Red Sandstone) to Carboniferous sedimentation, igneous activity and the Variscan orogeny. The collision of Laurentia, Baltica and Avalonia formed the landmass of Laurussia, informally known as the 'Old Red Sandstone Continent' (Fig. 1.5e). In Scotland, Scandian deformation and metamorphism was followed by uplift and erosion, and development of extensional half-graben basins within which accumulated continental 'Old Red Sandstone' (ORS) successions deposited in a range of alluvial fan, fluvial and lacustrine environments (Chapter 9). Local volcanic occurrences are linked to the waning Late Caledonian Igneous Province. Although most of the ORS successions are of Devonian age, the oldest, in the Midland Valley and the Oban/Lorne area, are of late Silurian age. During the Devonian, Scotland was located in the southern hemisphere and drifted from 30°S to 20°S (Figs. 1.5e). There is abundant evidence for arid climatic conditions, including evaporites, calcretes, aeolian sandstones and arid lakes with desiccation cracked surfaces. Both the Great Glen and the Highland Boundary faults were active as sinistrally transpressive structures during late Emsian to Eifelian times, possibly the far-field effects of the Acadian orogeny which resulted in a widespread Middle Devonian unconformity further south in England and Wales.

With better knowledge of the ages of the various Scottish ORS successions, it has become clear that the formal Lower, Middle and Upper subdivisions employed in previous editions of this book are outdated. Hence the ORS successions are here described in the context of two independent depocentres, namely the Orcadian Basin between Shetland and the Moray Firth, and the Midland Valley Basin (also including outliers in Argyll, the Tweed Basin and the North Sea south of the Highland Boundary Fault). The Achanarras fish bed level is the major stratigraphic tie across the Orcadian Basin, containing the most diverse and best preserved fish assemblage within a permanent lake system. Since the 4th edition of this book, it has been correlated with the latest Eifelian Kačák Event, a global eustatic sea level rise which inundated some intracontinental basins thus permitting the migration of fish fauna into the lakes of the Orcadian Basin. The ORS Rhynie Chert is internationally famous as it is the Earth's only known terrestrial lagerstätte. It preserves a complete ecosystem developed near to a hot spring and includes microbes, algae, plants, fungi, and arthropods in life position.

Since the 4th edition of this book, there have also been significant advances in the definition of the ORS-Carboniferous boundary. It was previously thought that the upper part of the Upper ORS was Early Carboniferous in age and that the Devonian-Carboniferous boundary was at an undefined position in the Kinnesswood Formation of the Midland Valley. However, recent palaeontological discoveries reassign all the Upper ORS into the Devonian.

The Devonian-Carboniferous boundary corresponds approximately to a calcrete horizon that represents a major period of aridity and the final cycle of the Late Devonian glaciation. A global mass

extinction event in the Late Devonian has been attributed to major volcanic activity, although the effect on fossil genera was less intense than all of the other “Big 5” Phanerozoic extinction events (Bond & Wignall 2014). This was followed by warming and the termination of glaciation. A global sea level rise resulted in the change which is clearly evident in Scotland from ORS continental deposits to the grey mudstones and dolostones of the lower Carboniferous successions.

The Carboniferous successions of the Midland Valley, the borderlands of southern Scotland, and parts of the Forth Approaches and Outer Moray Firth were deposited during the northward migration of Scotland over a period of 60 million years from low latitude wet equatorial climates to seasonal and drier climates of the northern hemisphere. The rocks are dominated by cyclical successions of mudstone, siltstone, sandstone, coal and/or limestone that were deposited in fluvio-deltaic, lacustrine and shallow-marine environments and record the interplay of varying tectonic, magmatic, sea-level, sediment supply and climatic controls (Chapter 10).

The global spread of forests has given the Mississippian strata renewed palaeontological significance. It had long been known that tetrapods had evolved in aquatic environments in the Late Devonian and by late Visean times had adapted to terrestrial environments. However, fossil tetrapods had only rarely been identified in Tournaisian to mid-Visean strata and hence the details of their environmental diversification were unknown. This apparent gap in the fossil record was known as ‘Romer’s Gap’ (Chapter 10). Since the 4th edition of this volume, discoveries of fossil tetrapods have raised the international significance of the Ballagan Formation in Scotland. Currently, it is one of only two places worldwide where Tournaisian tetrapods have been reported, and nine of the dozen sites worldwide that have yielded Visean tetrapods are also in Scotland. These newly discovered fossils have helped closed ‘Romer’s Gap’ and improved our understanding of the emergence and diversification of tetrapod life on land.

Volcanism renewed in Visean times after a 40–50 million year period of quiescence and continued into the mid-Permian. This magmatism was of intraplate character, associated magmas were of mildly alkaline composition and erupted as large shield volcanos, fissure fed lavas and pyroclastic deposits. The volcanic products include the Arthur’s Seat volcano in Edinburgh and the Clyde Plateau and Garleton Hills volcanic fields. By late Visean times, magmas had evolved to more primitive, silica-poor, alkalic types and these continued to be emplaced into the Permian, except for a brief phase of intrusion of voluminous tholeiitic basalts as dykes and sills across Scotland and northern England. The reasons for the changes in magma type and why the locus of magmatism moved southwards into northern England during Permian times are currently unclear.

Carboniferous sedimentation and basin evolution in Scotland were strongly influenced by interactions between the continental masses of Laurentia, Baltica and Gondwana in the foreland of the Variscan orogen during the final stages of formation of Pangea (Fig. 1.5f). The late Devonian to early Carboniferous northward convergence of Gondwana with Laurentia is thought to have resulted in lateral expulsion of Baltica and reactivation of Caledonide faults. Early Carboniferous sedimentary basins developed under a regime of sinistral transtension. This was followed in mid- to late Carboniferous times by westward ‘reinsertion’ of Baltica during the Uralian orogeny, to result in dextral transpression across the Highlands, Midland Valley and northern England. Dextral displacements occurred along the Walls Boundary, Great Glen and Highland Boundary faults, and fold tightening and fault inversion affected the Carboniferous successions of the Midland Valley and southern Scotland. A widespread late Carboniferous unconformity exists above folded Upper Coal Measure formations.

Permian to Triassic sedimentation and magmatism in the interior of Pangea. Permian and Triassic rocks only have limited onshore outcrop but are widely present offshore. The oldest Permian (formerly ‘New Red Sandstone’) strata rest unconformably on late Carboniferous and older rocks, and the depositional break represents a gap of c. 30 million years. The gently undulating nature of the sub-

Permian unconformity is thought to reflect the long period of post-Variscan erosion. The Permian and Triassic sedimentary basins of Scotland were located well within the interior of Pangaea (Fig. 1.5g) and together they record approximately 70 million years of mainly terrestrial sedimentation interrupted only by a late Permian marine incursion. Climatic conditions were semi-arid to arid, reflecting the northward drift of this sector of Pangaea through the northern hemisphere desert belt (Chapter 11).

Sedimentation commenced in the late Permian in depocentres that varied from broad basins (e.g. Moray Firth and North Sea) to small N–S-trending half graben (e.g. southern Scotland, West of Shetland), although the latter did not contribute significantly to regional subsidence. Onshore exposures on the south side of the Moray Firth are representative of basin margins and dominated by alluvial fan and coarse fluvial deposits. In contrast, the basin interiors which occur offshore in the North Sea are characterised by aeolian dune sandstones (Rotliegend Group) and occasional sabkha lakes. Within the southern Scotland rift basins, the onshore components are aeolian sandstones and alluvial fan deposits. Late Permian vertebrate fauna and reptile trackways are well known in the Elgin area and Dumfries. Intraplate igneous activity continued from the Carboniferous, with dyke swarms and sills extending from the Midland Valley to Caithness and Orkney and offshore with subaerial volcanic trachyandesites in the northern North Sea. Towards the end of the Permian, oceanic waters flooded the North Sea basins and deposited the cyclic successions of carbonates and evaporites of the Zechstein Group.

The end of the Permian is known globally for the most significant mass extinction event in Earth history with the loss of c. 90% of species in the oceans and c. 70% of species on land. The general consensus is that this was caused by a massive injection of CO₂ into the atmosphere from large volcanic eruptions (such as the Siberian traps) that triggered global warming and ocean acidification. However, traces of this event are not forthcoming in the continental successions that were deposited across much of Pangea, including Scotland. The transition from the Permian to the Early Triassic in Scotland is marked by the onset of active rifting and development of graben and half graben structures: the early stages of the break-up of Pangaea. Many of these structures likely resulted from the reactivation of NE–SW- to N–S-trending Caledonian faults. The basins west of Scotland and Shetland contain >4 km of Permo-Triassic sediments, comprising conglomeratic alluvial fan and floodplain deposits with coarse-grained fluvial and playa lake facies in more basinal areas. In the Moray Firth and North Sea basins, Late Permian marine and coastal evaporitic successions were replaced by Triassic playa lakes with local aeolian deposits. The overlying Triassic rocks are dominated by sandstones that record the progradation and retrogradation of fluvial systems that were transporting large volumes of detritus derived from the landmasses of Scotland, Greenland and Fennoscandia. The predominance of fluvial strata in the Triassic successions overall suggests a wetter climate across Scotland with larger and more integrated river systems. A global rise in sea-level led to the onset of shallow marine sedimentation in southern and western offshore areas by the end Triassic (Rhaetian).

Jurassic sedimentation and development of the North Sea, Hebridean and NW Atlantic basins. The main basins that were established in the Permo-Triassic continued to accumulate sediment through Jurassic times under a wetter and more temperate climate as Scotland moved northwards to approximately 37°N (Fig. 1.5h). The regional tectonic framework was dominated by crustal extension with normal faulting associated with North Sea rifting and predominantly strike-slip faulting in the Rockall-Shetland-Faroe troughs associated with the early stages of the later opening of the Atlantic. Although rifting commenced in the Triassic, formation of the main graben and rift basin elements in the North Sea was controlled by crustal extension across palaeoplate boundaries in the underlying basement (see below) combined with a rising lithospheric plume that triggered uplift of the Central North Sea during Toarcian to Aalenian times (Chapter 12). Uplift and erosion of Lower Jurassic and Triassic sediment resulted in the widespread Mid-Cimmerian unconformity, while in the centre of the dome basic volcanism developed during the Bathonian and early Callovian. In the Hebrides Basin contemporaneous basin subsidence and hinterland rejuvenation correlate in age with the

unconformity suggesting that the two tectonic events were linked. Subsequent collapse and subsidence in the three main rift arms in the North Sea occurred at varying rates during the Middle and Late Jurassic. As the dome deflated and volcanism ceased, renewed subsidence and transgression of Late Callovian to Early Kimmeridgian strata became widespread.

Outcrops of Jurassic strata in the Western Isles (e.g. Skye, Mull), and around the Moray Firth represent the margins of basins that have their main depocentres offshore. A Scottish landmass was generally emergent as were the Shetland and Hebrides platforms. Onshore around the Moray Firth, Triassic continental deposits were reworked into Hettangian fluvial and lagoonal deposits and fully marine conditions were established by the Sinemurian. Considerable thickness variations in the Lower Jurassic marine deposits of Skye suggest contemporaneous faulting and sedimentation. Further offshore, the sediments record the transition from fluvial and alluvial Triassic deposits into shallow marine sands and offshore muds of the Lower Jurassic. In the late Lower Jurassic (Toarcian) a major perturbation of the carbon cycle is recorded by a Global Oceanic Anoxic Event and in the Hebrides Basin is evidenced by condensed sequences of mudstone and ironstone.

The onshore and offshore Middle Jurassic sedimentary successions described in Chapter 12 each display considerable variations in facies. The Bajocian strata of SW Skye were deposited in a high-energy tidal setting, in contrast to the younger Bathonian Great Estuarine Group of the Hebrides which is characterised by a variety of fluvial, lacustrine, lagoonal and restricted marine facies. Major new discoveries of vertebrate fossils on Isles of Skye and Eigg including dinosaur bones and trackways have significantly improved our understanding of the nature of the Jurassic ecosystem at this time. In particular, the sediments on Eigg preserves partial and near-complete skeletons of many precursors to modern animal groups including, salamanders, lizards and mammals (see Topic Box in Chapter 12). Within the North Sea, the Brent Delta System was deposited in the Viking Graben and marine and coastal sandstone facies surround the central North Sea dome. A major marine transgression in the Callovian resulted in a rapid transition to deep water open marine conditions as recorded in both the offshore and onshore successions. This coincided with the onset of rapid extension and basin deepening in the northern North Sea. By Kimmeridgian times there was widespread deposition of the organic-rich marine muds which provide the main source for Scotland's hydrocarbons. Active rifting at this time is indicated by fault-controlled sedimentation along the margins of land areas. The well known Helmsdale Boulder Beds and associated deposits were eroded off an active submarine fault scarp that controlled the northwest margin of the Inner Moray Firth basin. Oxfordian to Kimmeridgian deep water marine shales are also seen in the Hebridean basins and to the west of the Outer Hebrides platform in proto-Atlantic basins. Whilst the Jurassic-Cretaceous boundary has yet to be formally defined globally, in Scotland it varies from an erosional unconformity in the North Sea to a disconformity in other regions recording a more passive overstep onto Jurassic strata.

Cretaceous marine transgression and Atlantic rifting: Cretaceous rocks are widely distributed in offshore basins west, north and east of mainland Scotland, where they reach several kilometres in thickness (Chapter 13). In contrast, onshore outcrops are thin and dispersed although they were probably once much more extensive and covered much of Scotland. Sedimentation through the Cretaceous period reflects the interplay between changes in sea level and tectonics in response to the closure of the Tethys Ocean and opening of the Atlantic Ocean (Fig. 1.5i). Rising sea levels brought shorelines onto basin highs and the Scottish mainland. Significant advances in understanding have come from new data from the Faroe-Shetland and Rockall basins which demonstrate the controlling influence of strike-slip faulting along the Atlantic margin. Furthermore, recent syntheses of well exploration data and seismic profiling from the Faeroe-Shetland basin divide the Cretaceous into two megasequences, separated by a 'Mid' Cretaceous Unconformity (MCU) located at the Turonian-Coniacian boundary. This has been recognised in the North Sea basins (as the Early Campanian Unconformity) as well as onshore on Mull and in Northern Ireland, and thus it provides a critical regional marker horizon. This major stratigraphic break is thought to be related to inversion tectonics

affecting offshore basins in NW Europe and which also resulted in major changes in oceanic current circulation patterns.

During the Early Cretaceous (Megasequence 1: Berriasian to Turonian), the Scottish mainland was low-lying but largely above sea-level. In situ onshore Lower Cretaceous rocks are limited to small exposures in NE Scotland interpreted as remnants of a former shoreline system that formed around the Moray Firth. Offshore, the oldest rocks of Megasequence 1 rest on the Base Cretaceous Unconformity, infilling remnant Jurassic topography with mudstones and sandy turbidites. Basin sedimentation continued with accommodation space filled with calcareous mudstone, thin argillaceous limestone and sandstone with sandy conglomerates on or near highs and deep water clastics in basins to the west of Scotland. The Late Aptian turbidite sands sealed by the shales of the Chalk Group are key reservoirs and targets for CO₂ sequestration. A significant intra-Early Cretaceous marker bed is the Cenomanian-Turonian boundary Black Band succession (equivalent to the global Plenus Marl Oceanic Anoxic Event II). This possibly corresponds to a global sea-level rise and provides a key correlation horizon across many inshore and offshore basins. It is recognised onshore in the Inner Hebrides by the change from the Morvern Greensand Formation to the Lochaline White Sandstone Formation.

Late Cretaceous rocks (*Megasequence 2: Santonian to Maastrichtian*) were deposited in aerobic, open shelf settings during a period of global sea level rise. This coincided with active rifting and increased subsidence, particularly west of Scotland where basin development became extensive along the Atlantic rift zone. Most of Scotland was likely submerged under the 'chalk seas' and hence contributed little sediment to offshore basins. Despite the likely extensive onshore successions, little now remains visible as much is either obscured by Paleogene lavas or was removed during later uplift erosion and glaciation. Active rifting and salt diapirism led to the shedding of sediment from structural highs to be redeposited as high porosity reservoir rocks.

Paleogene sedimentation and igneous activity during North Atlantic spreading. Plate reorganisation and the impact of the Icelandic plume on the base of the lithosphere to generate Atlantic oceanic spreading and uplift produced a regional landmass extending across all of Scotland, Ireland and north and west England. During the Paleocene, Scotland was located at c. 47°N and subject to deep tropical weathering which along with subsequent erosion has removed any evidence for the Cretaceous-Paleogene (K-Pg) boundary at c. 66 Ma. This is unfortunate as it corresponds to the 5th and final geological mass extinction event in Earth history which has been linked to eruption of the Deccan basalts in India as well as the Chicxulub meteorite impact in Mexico. Post-extinction biosphere-geosphere recovery as indicated by carbon and oxygen isotope studies reveals a major faunal diversification above the K-Pg boundary with changes in marine calcareous nanofossils.

Globally, the Paleocene-Eocene boundary records a thermal maximum and a change in ocean isotopic composition. As Scotland moved away from the spreading ridge (Fig. 1.5j) it formed a new passive continental margin with intense chemical weathering producing high sedimentation rates and development of large sediment fan systems that prograded both westwards into the Hatton Basin and eastwards into the Moray Firth and North Sea basins (Chapter 14). During the Eocene, volcanic activity extended northwards into Faroe-Shetland and extensive ash fall gave rise to the Balder Tuff, a key marker horizon in the North Sea. By Mid to Late Eocene times, environments changed from deep water with a stratified water column to more shallow oxygenated environments.

The early Oligocene witnessed an abrupt change from greenhouse to icehouse conditions which has been linked to changes in oceanic circulation with opening of seaways and the build-up of Antarctic ice. In the Faroe-Shetland area, small, disconnected basins evolved into the single channel seen today

and uplift of Fennoscandia shed sediment into the North Sea. The waxing and waning of ice caps has been linked to eustasy and transgressive-regressive cycles of sedimentation. By Late Oligocene times, compression in the Faroe-Shetland area created inversion structures and deposition of deep-water sediment. Cooling continued into the Neogene with large ice sheets in the Northern Hemisphere which initially formed in Scotland during the Mid-Miocene although rapid cooling did not occur until the Pliocene. In the Faroe-Shetland region, pre-glacial sedimentation continued to be dominated by deep water circulation with contourites and extensive sheet-like deposits. In the Central North Sea, southerly derived deltaic muds were fed by European river systems, in contrast to more sand-dominated systems in the north derived from the Orkney platform. Continued uplift and tilting of the Scottish landmass and ongoing subsidence during the Pliocene saw offshore progradation of sediment wedges along the western continental shelf with gravels and ice rafted clays being deposited onshore in NE Scotland. The classic geology of Scotland's west coast islands and offshore reveals that this landmass was intruded by a series of large volcanic centres (Skye, Rum, Mull, Arran and Ardnamurchan) that rest on an erosion surface and sediments of Jurassic and Late Cretaceous age (Chapter 15). The eruptive centres, collectively termed the Hebridean Igneous Province, are characterised by fissure eruptions and dyke swarms producing thick lava sequences of transitional to tholeiitic basalts and trachytes with evidence of hydromagmatic activity including breccias, hyaloclastites, and pillow lavas with volcanic ash deposited offshore in distant compartmentalised rift basins. Activity was relatively short lived (60–55 Ma) with volcanic activity located along Mesozoic rifts and older inherited structures. Offshore sediment from the Scottish landmass was increasingly shed south eastwards into the North Sea and westwards into the Faroe-Shetland basin. On the western continental shelf, the interplay between changing sea level and tectonic subsidence led to complex patterns of basin fill with shelf edge siliciclastic sediments deposited in deltaic and shallow marine environments and recycled offshore into deep water turbidite environments.

Quaternary glaciations, sea level change and paleoenvironmental reconstruction: Although progressive cooling of the Earth's climate had commenced in Eocene times (55 Ma) it was not until the Pleistocene (2.5 Ma) and extending into the Holocene (c. 11,000 years ago) that a major period of glacial activity or ice age affected the northern hemisphere. This ice age represents the final episode in Scotland's geological history and produced the classic glacial landforms and onshore sediment record of the Quaternary period. A change in orbitally-forced climate patterns to longer and colder phases is thought to have occurred around 780 ka. As the British-Irish Ice Sheet waxed and waned Scotland experienced repeated cycles of glacial and interglacial activity that combined to shape the present day landscape and coastline and also deposited significant accumulations of sediment in offshore basins (Chapter 16). Since the 4th edition our understanding of the onshore glacial record has radically improved through the application of new dating techniques including Optically Stimulated Luminescence (OSL), cosmogenic-nuclide surface exposure and research into bedrock-ice interactions and the influence of groundwater. Offshore, new data from high resolution seismic, multibeam echosounder and bathymetric surveys combined with borehole data from offshore infrastructure (pipelines and windfarms) have significantly added detail to patterns of ice streaming (tunnel valleys) and ice sheet margins. The combination of these new onshore and offshore records now permit a more detailed picture of migrating ice divides, ice dispersal centres and sediment depocentres tied to global events recorded in the Greenland Ice Core.

During Palaeocene–Miocene times thick laterite tropical soils probably covered much of Scotland. Weathering and subsequent erosion by repeated glaciations redeposited most of these soils offshore leaving behind a series of elevated peneplane surfaces. The ages of these surfaces are not well

understood and many are an integration of processes over time. What is clear is that the inherited pre-glacial landscape was dominated by a N–S-trending drainage divide that formed in response to Paleogene and Neogene uplift in the west with eastward tilting of the Scottish landmass. Onshore, the earliest known remnants of pre-Devensian deposits are preserved locally *in situ* in the Buchan lowlands of NE Scotland and in Orkney and Shetland and the Hebrides. Elsewhere around the Scottish coast, rafted shelly tills indicate ice streaming onshore from the east with rare erratic blocks derived from Scandinavia. Offshore, early-mid Pleistocene shelf margin to deep water turbidite and contourite deposits are overlain by deltaic and shallow marine sediment fan, the latter fed by ice streams indicating ice advance into western North Sea at c. 2.5 Ma and with expansion of the Fennoscandian ice sheet into the Central North Sea at 1.87 Ma. Ice did not cover Shetland until 1.1 Ma although debate continues as to whether this was a separate ice cap or a result of ice streaming. The early to mid-Pleistocene boundary (780 ka) then marked a significant change in climate regime with glacial activity moving from small mountain-field ice streams to widespread coverage by colder ice-sheets.

By the time of the last glacial maximum at 29–22 ka, ice flows and ice divides had formed by interaction with terminating glaciers of the British-Irish and Fennoscandian ice sheets. In open low ground, multiple tills and subglacial channels and bedrock gouging indicate switching of fast ice streams and contrast with more confined lobate and slower streams in mountain areas. Key ice streams on the continental shelf record phases of rapid advance and retreat with iceberg calving. Local readvances occurred at 19–18 ka (Scottish) and 15.3 ka (Wester Ross). During recessional phases, ice streams became topographically constrained and the presence of woolly rhinoceros bones and reindeer antlers indicate that during Mid-Devensian times areas north of Glasgow and in Ayrshire were ice free. The last glacial-interglacial transition at 16.5–16.0 ka is indicated by the thinning and retreat of ice sheets to reveal mountain nunataks and formation of ice dammed lakes around glacier margins with distinctive landforms (drumlins, eskers and kame fields).

By 14.7 ka the continuing northward migration of the North Atlantic Polar Front and the establishment of thermohaline circulation in the NE Atlantic to produce warmer climates is well documented with an extensive bio- and litho-stratigraphical dataset for Scotland that is correlated with Icelandic tephra. Divided into the Windermere and Loch Lomond stadials, site specific pollen stratigraphies and invertebrate assemblages have been used to infer vegetational zones and palaeotemperature varying from 10–15°C between stadial to interstadial. The release of ice dammed lakes, as evidenced by the ‘Parallel Roads’ in Glen Roy, and a rise in sea levels led to the incursion of marine waters in major estuary settings (e.g. the Clyde) and overstepping of glaciomarine sediments onto onshore deposits. The Loch Lomond (or Dryas) stadial marked a temporary return to colder temperatures and glacial advance at 12–11 ka. Studies of landforms now indicate a more extensive ice cover than previously thought.

Finally, the Holocene epoch (11.7 ka to present day) is marked by continued warming and establishment of oceanic warm water circulation that gave rise to a climate similar to present day. Detailed vegetational and peat bog studies record transgressive changes linked to latitude and altitude with major landscape readjustment via rock slides and landslides in upland terrains. With most of Scotland forested by 6 ka the so called ‘Little Ice age’ at 5 ka again saw climate cooling with the possibility of re-establishment of small mountain glaciers in the Scottish Highlands. In the early Holocene the rate of sea level rise was greater than uplift and then it progressively declined as recorded by the connection and isolation of basins and lochs. This was not a steady decline but interspersed with pulses of global meltwater as major Laurentian pro-glacial lakes drained and raised

global sea levels. Tsunami deposits recognised around the Scottish coastline are related to the submarine Storegga slide on the Norwegian continental shelf.

The nature of Scotland's crust

Today, Scotland sits on the NW margin of the Eurasian plate on stable intra-plate lithosphere that is >1000 km from active plate margins and therefore has relatively low levels of earthquake activity. As a result of ancient plate collision, post-orogenic uplift, post-Carboniferous extension and North Atlantic plate spreading Scotland's lithosphere (i.e. crust and uppermost mantle) are the end products of a complex history and interpreted to preserve a fossil anisotropic signature that includes features that formed hundreds of millions of years ago. Key events in the geological evolution outlined above are described in greater detail elsewhere in this volume. However, unravelling the nature of this crust is problematic with critical basement-cover relationships and major tectonic structures rarely visible; many of the largest-scale features are only clearly exposed in the crystalline basement north-west of the Great Glen Fault. Elsewhere, understanding of the deeper levels in Scotland's crust is essentially derived from remote methods including: analysis and modelling of deep seismic reflection and refraction line data, passive seismological methods, monitoring of earthquakes and quarry blasts and regional geophysical (gravity and magnetic) data. In addition, petrological studies of the episodes of magma emplacement in Scotland, and of the mantle and crustal xenoliths sampled and returned to near-surface levels by those magmas, provide direct sampling of the underlying crust.

Whilst regional gravity and magnetic maps enable interpretations of the shape and form of Scotland's crust, the onshore fault map of Scotland (Fig 1.6) reveals a landscape transected by numerous regional-scale faults and their related fracture networks dominated by NW–SE trends. This section describes the contribution these data and interpretations have made to our understanding to the nature of Scotland's crust and how they can be integrated into a series of interpretative cross-sections (see below).

Regional gravity and magnetics: Regional geophysical data (principally gravity and magnetic field data) provide an integrated view of the cumulative effects of the physical properties of crustal features including sedimentary basins, intrusions and structural discontinuities. Lateral and vertical variations in density and magnetization often occur at contacts and can be used to estimate basin thicknesses, the shapes of igneous intrusions and bulk compositional changes across major fault structures (Trewin & Rollin 2002). However, any resolution of crustal thickness (i.e., depth to the Moho from these data), is hindered in Scotland by a generally thick crust containing significant volumes of granitic material, modified by post-Mesozoic uplift along major faults.

The Bouguer gravity anomaly map (Fig. 1.7a) reveals a general decrease in values from south-western to northern and north-eastern Scotland but is interrupted by two major onshore anomalies. In north-east Scotland and east of the Portsoy Shear Zone, the Buchan region is characterized by a positive gravity signature indicating a shallower (or possibly different) basement to that seen underlying the wider Grampian terrane. In this region, the late-Grampian Buchan Anticline and the voluminous gabbroic intrusions that supplied the heat for the classic Buchan metamorphism (see Chapter 6) have been proposed as indicating crustal thinning and asthenospheric upwelling as part of the early Ordovician Grampian orogenic deformation (Johnson *et al.* 2015). NW of Inverness, the Lairg gravity low has been related to thrusting and the Oykel Transverse Zone (Leslie *et al.* 2010) and more recently interpreted speculatively as a buried impact crater (Simms & Ernstson 2019). Individual features visible on the aeromagnetic anomaly map (Fig. 1.7b) are dominated by granitic intrusions and Paleogene igneous centres and dyke swarms. A positive linear feature associated with the Great Glen Fault (Trewin & Rollin 2002) is suggested to indicate that movement along the fault zone has brought magnetic rocks of unknown age to within 1 km of the surface on both walls of the fault trace.

Crustal stress and fault activation: Earthquakes represent brittle failure in the crust and are controlled by a range of factors including, geothermal gradient, mineral composition and the presence of fluids which together influence the depth to the ductile-brittle transition. Imposed on this is the regional rock stress and strain rate, triggering the largest earthquakes at depths of <20 km under Scotland. However, determining the relationship between seismic events and movements on specific geological structures is often difficult with only a small number of events providing convincing focal mechanism solutions (Fig. 1.8).

The world's first purpose built inverted pendulum seismometer was installed in Comrie in 1840, after the 'Great Earthquake' of 1839 that was felt across much of Scotland. Situated some 2 km north of the surface trace of the Highland Boundary Fault, Comrie has recorded more earthquakes than anywhere else in Scotland, living up to its name of the 'shakey town'. The UK seismic network, managed by BGS, was first established in the Midland Valley in 1967 (Crampin *et al.* 1970) in part to record events related to coal mining. Damaging earthquakes across Scotland are fortunately relatively rare and the present seismic network has 56 stations capable of detecting any earthquake of magnitude > 2.5 ML (Fig. 1.9a). Since 1970, the primary data on earthquake activity have been released in an annual bulletin by BGS. Using this database, recent estimates of earthquake activity rate suggest up to eight earthquakes with a magnitude of 2.0 or above occur in Scotland every year (Baptie *et al.* 2016). Apart from events recorded in the vicinity of Comrie, other notable historical large earthquakes (>4.5 ML) occurred at Inverness, Kintail, Arran and Oban (Musson 1996).

The distribution of Scotland's earthquakes (Fig. 1.9b) and the BGS earthquake catalogue reveal the Western Highlands of Scotland to be one of the more active seismic areas in the UK. The 2017 4.0 ML Moidart earthquake (Fig. 1.8) was one of the largest in Scotland for almost two decades and was widely felt along the west coast (Baptie *et al.* 2017). Focal mechanism solutions indicate that seismicity in NW Scotland is characterised by N–S compression and E–W tension which results in strike-slip movements along SW–NE or NW–SE fault planes. The distribution of earthquakes coincides in part with the thickest ice cover and its removal during the Quaternary (Chapter 16) but, as the focal mechanisms resolve to show predominantly strike-slip faulting with a horizontal principal stress direction, glacio-isostatic rebound cannot be the principal driving force (Musson 1996). Baptie *et al.* (2017) proposed that earthquake activity in Scotland is driven largely by reactivation of major fault systems in response to forces associated with first-order plate motions, rather than by deformation associated with glacio-isostatic recovery.

Borehole breakout data are widely used to resolve the state of *in situ* stress on the crust. The technique is applied to data typically obtained from hydrocarbon and geothermal resource exploration, or from studies into radioactive waste disposal (e.g., at Dounreay). These datasets record stress-related borehole deformation during drilling. Such data are critical to investigations of fracture mechanics as it impacts the sustainability of unconventional energy resources, groundwater aquifers, hydropower infrastructure and geothermal energy (Chapter 17). However, borehole breakout data for onshore UK are relatively sparse with offshore data confined to hydrocarbon wells in the North Sea (Evans & Brereton 1990; Cowgill *et al.* 1993; Williams *et al.* 2016). Recent summaries of these data (Fellgett *et al.* 2017), considered in the context of the regional stress map of Great Britain and Ireland (Kingdon *et al.* 2022) and combined with earthquake focal mechanism data (n=474), confirm that oblique or strike-slip movements are predicted across major fault structures and across all major depositional basins in Scotland. Overall, a broadly E–W extensional stress regime now prevails with the principal stress horizontal (sH compression) displaying a gradual clockwise change in trend from $152^{\circ} \pm 12^{\circ}$ N in southern Scotland to a more N–S orientation in the north (Fig. 1.8) (Baptie 2010), consistent with mean horizontal stress orientations across the wider European plate (Heidbach *et al.* 2018).

The prevailing (N)NW–(S)SE orientation for sH is modified by glacial rebound where the normal stress induced along the axis of uplift is dependent upon the degree of curvature in response to the dynamic load (Baptie 2010). Widespread evidence from slope failures, ground ruptures, displaced Quaternary features and slumping of seabed sediments suggests that there was an increase in seismic activity across the main Scottish glacial ice centres during the Younger Dryas and Holocene deglaciations in response to differential ice loading and unloading and relative sea level change (Ringrose 1989; Fenton 1991; Firth & Stewart 2000). Based on post-glacial sea level indicators (Shennan *et al.* 2006) glacial rebound has since slowed to current low levels with uplift rates of around 2 mm yr⁻¹ in northern Britain.

In terms of fault re-activation (or capability), a modern regional stress field with a subhorizontal maximum compressive stress acting in a north–south direction would favour existing (Caledonide-trending) steeply dipping NE–SW-striking faults to now be re-activated in a sinistral manner (Fig. 1.8), for example, as in the Kintail and Aberfoyle earthquake data (Assumpção, 1981; Ottemöller & Thomas, 2007). Alternatively, if moderately-dipping they could be activated by a sub-vertical maximum compressive stress resulting from post-glacial rebound. These alternatives remain poorly resolved in the current data and, in the absence of any focal mechanisms or data on major faults such as the Great Glen or Southern Upland faults, the neotectonic slip direction remains uncertain. The evidence for fault reactivation during deglaciation is speculative (Fig. 1.10). One of the best chronologically controlled examples is the detached screes on the Beinn na Leac Fault on the SE side of the Isle of Raasay (Smith *et al.* 2021).

Evidence from active source and passive seismology: Initial knowledge of the deep crustal structure came from active source seismic exploration methods. In the UK these included arrays of mainly deep marine large-scale reflection and refraction experiments (DRUM, MOIST, WINCH), (Fig. 1.11) that were pioneered in the 1980s and 90s by the British Institutions Reflection Profiling Syndicate (BIRPS), (Blundell *et al.* 1985; Smythe *et al.* 1982; Snyder & Flack 1990; Klemperer & Hobbs 1992). Onshore, crustal structure is constrained by fewer profiles, the main one being the lithospheric seismic profile in Britain (LISPB), a N–S profile through Scotland and northern England (Bamford *et al.* 1978; Barton 1992) and the Caledonian Suture Seismic Project (CSSP), an E–W profile along the Iapetus Suture line (Bott *et al.* 1985). These and subsequent studies (see below) are in general agreement that the crust essentially comprises 3 main layers. An unreflective upper layer 1 extending down to c. 10 km depths is interpreted to represent strong brittle upper crust. This is underlain by a weak anisotropic more ductile layer 2 representing the lower crust with a reflective base indicating the possible position of the Moho at depths of 20–30 km. Beneath this, layer 3 is unreflective and interpreted as relatively strong upper mantle material.

Recent teleseismic P and S-wave receiver function analysis confirms a mean crustal thickness of c. 28 km beneath Scotland (Di Leo *et al.* 2009; Licciardi *et al.* 2020; Bonadio *et al.* 2021), with thinner and more complex older lithosphere to the NW and a depth to Moho c. 22 km thickening southwards to >30 km at the Highland Boundary Fault and to >36 km under the Midland Valley of Scotland. Local earthquake tomography based on a UK dataset of continuous seismic monitoring over 30 years has also been used by Luckett & Baptie (2015) to create 3D models of seismic velocity. These models, ground-truthed with quarry blast data from the Midland Valley and Glensanda Quarry, produce crustal images broadly in agreement with the reflection and refraction data.

Offshore, under the central and northern North Sea, repeated extension has thinned the crust to <25 km (Chadwick & Pharaoh 1998). Here, whilst the structure and nature of the uppermost crust is well constrained by extensive hydrocarbon exploration data, the deeper crust is poorly understood with only a small number of deep seismic reflection/refraction profiles shot over the past decades. More recent geophysical investigations into the nature of rift geometries and heterogeneities in the underlying crustal features (Lyngsie & Thybo 2017; Crowder *et al.* 2021) have begun to unravel the

nature of the Baltica-Avalonia-Laurentian palaeoplate boundaries (Fig. 1.12) and their potential influence on rift evolution and geometries. Relatively thin crust (13–18 km) underlies the Central and Viking graben and contrasts with thicker crust (25–30 km) on either side. The contrast between symmetrical rifting in the Viking Graben compared to asymmetrical rifting in the Central Graben has been attributed to the latter being located above a triple plate junction (Crowder *et al.* 2021).

In many of the onshore studies there is a strong spatial correlation of linear discontinuities in the velocity models with NE–SW-trending Caledonide structures, with the Great Glen and Highland Boundary faults in particular interpreted to be lithospheric in scale and associated with a thickening of the lower crustal anisotropic layer. There is dispute, however, over whether the Moho in fact is displaced across either structure (McBride 1995). Active source and passive source data (Ascencio *et al.* 2003) and shear wave splitting studies (Bastow *et al.* 2007) support the hypothesis that Scotland's crust preserves fossil lithospheric structure unaffected by Palaeogene rifting and plume dynamics and is supported by an increase in crustal thickness of 4.5 km from E to W across the Moine Thrust (Di Leo *et al.* 2009).

These datasets and their interpretations notwithstanding, the characterisation of anisotropy of the continental lithosphere velocity structure beneath Scotland remains the subject of considerable debate. The presence of multiple reflectors in layers 1 and 2 that derive from the alignment of minerals, fluid or melt in crust and mantle may represent older strain remnants from Caledonian collision and late Palaeozoic–Mesozoic extension, or alternatively lithospheric-thinning and underplating with basaltic magma, related to the opening of the Atlantic Ocean and development of the Icelandic plume (Knapp 2003).

Evidence from xenolith suites: Xenoliths and xenocrysts (typically <30 mm in size) have been recorded from 70 localities across all Scottish terranes (Fig. 1.12) with concentrations particularly in the Midland Valley and northwest of the Great Glen - Walls Boundary Fault (Fig. 1.2). Although widely scattered these point sources record a marked provinciality to the lateral chemical heterogeneity of the lower crust and lithospheric mantle under Scotland.

With one exception in the Outer Hebrides, all samples have been found in volcanic plugs and dykes of Carboniferous to Permian age. These include mantle-derived peridotites, pyroxenitic xenoliths from base of the crust and others from lower crustal granulite-facies meta-igneous rocks; (Upton *et al.* 2011; Badenszki *et al.* 2019). Metagabbroic, dioritic and anorthositic xenoliths (mafic granulites) are widely distributed and interpreted to represent plagioclase-clinopyroxene cumulates derived from magmas that underwent fractional crystallization and assimilation processes in the lower crust. Across the Midland Valley Carboniferous age alkali-basalt volcanic plugs and dykes contain xenoliths and xenocrysts of both upper mantle and lower crustal origin of mid to upper Ordovician age (Badenszki *et al.* 2019; Chapter 10) including, probable mantle peridotites and garnet pyroxenites, shallow mantle or deep crustal garnet pyroxenites, and megacrysts.

Collectively these xenoliths indicate a complex tectonomagmatic lcrust and upper mantle history in broad agreement with the seismic data with decreasing age and increasing thickness from the ancient Hebridean terrane in the northwest to the Southern Uplands (Menzies & Halliday 1988; Upton *et al.* 2011). Geochemical signatures also indicate a decrease in enrichment (metasomatism) in lithospheric mantle from the older to the younger terranes with greater isotopic homogeneity in xenoliths sampling the younger terranes.

Upper crustal scale cross sections: The Peterhead, Skye, Mull and Islay cross-sections included here (Fig. 1.13a-d) are part of a suite of mainly onshore sections compiled by BGS. The lines of section are shown in Fig. 1.1; they extend to a nominal depth of 15 km at 1:625 000-scale, each with a vertical exaggeration of x2. The sections depict a non-unique regional-scale interpretation based on a

consideration of all data mentioned above in addition to: published BGS geological mapping and other published literature; interpretations of geophysical data including earthquake, seismic survey, and natural field data; data derived from underground mining and infrastructure development (tunnels, pipelines etc.) in those limited areas where such exists onshore. These cross-sections, along with the similarly-styled cross-section included with the BGS 1:625 000 scale geological map (Bedrock Geology UK North, BGS 2007) also support the geological accounts in the succeeding chapters 3 to 15.

A brief summary of the geological relationships depicted in these cross-sections is provided below, with particular emphasis given to the regional-scale faults recognized in Scotland e.g., the Great Glen, Highland Boundary, and Southern Upland faults and which are now accepted to record a long-lived history of repeated displacements.

Basement: The crystalline basement beneath the Scottish terranes is presumed mainly to be of Laurentian affinity, contrasting with Avalonian basement beneath Northern England and parts of the Southern Uplands. In the NW Highlands, Archean–Proterozoic basement rocks (e.g. of the Lewisian Complex) are exposed at the surface principally in the footwall of the Moine Thrust Belt, but also as slices within the regional-scale imbricate stack distributed within the thrust hanging wall (Skye and Peterhead sections). Magnetic Paleoproterozoic Rhinnian basement is exposed on Islay (Islay section) but may also occur at relatively shallow depths along, and below on either side of, the trace of the GGF, possibly as part of a slab translated on a deeper continuation of the Moine Thrust (Skye section). The specific nature of the crystalline basement underlying the Dalradian rocks of the Grampian terrane is uncertain and often cited as ‘Lewisianoid’ in nature (Mull and Peterhead sections). The southern Grampian terrane is likely underlain at relatively shallow depths (Barton 1992), by ‘basement’ rocks of uncertain affinity that were being driven beneath the developing Tay Nappe in the Lower Ordovician (Mull and Skye sections, and see also Chapter 6). In part, this basement is likely to be composed of Lower Ordovician volcanic arc rocks (and any substrate) comparable to the Tyrone Volcanic arc in N Ireland (Chew *et al.* 2008). Separate blocks of Paleozoic magmatic and Proterozoic crystalline basement rocks are shown on each section beneath the Midland Valley of Scotland, Southern Uplands, and Northern England. The detailed character of the rocks making up these blocks is uncertain and individual structures are not shown. The definitive location and nature of any structure now representing the former Iapetus Suture is not definitively imaged.

Grampian-Scandian structures: The WNW-vergent polyphase deformation and fold and thrust structures of the Northern Highlands terrane (Grampian and Scandian, Chapters 6 and 8) are most evident on the Skye and Peterhead sections. The former depicts the superimposed folding and refolded geometry of the regional-scale thrusts, including the Sgurr Beag Thrust. To the south of the Great Glen Fault, the sections illustrate the divergent geometry and polyphase Grampian deformation affecting the Dalradian Supergroup. The regional-scale change in major fold-facing takes place across the axis of the composite Loch Awe Syncline structure (Mull and Islay sections, and see Chapter 6, Fig. 6.10). Major folds in Islay, Appin, and in the north-west Grampian Highlands face up to the north-west whereas the major folds in the Southern Grampian Highlands, including the Tay Nappe, essentially face (S)SE. The downward-facing Aberfoyle Anticline structure is portrayed on the Skye section, representing the hinge zone of the Tay Nappe now rotated across the hinge of the Highland Border Downbend fold (see discussion in Leslie 2023, Chapter 6 this volume). Slivers of Ordovician strata (both lowermost Ordovician Dalradian Trossachs Group strata and the Highland Border Ophiolite (Tanner 2013a, b), are entrained within the damage zone associated with the Highland Boundary Fault (Mull and Skye sections). The distinctive nature of the Buchan Block and north-east Scotland, and of its western boundary – the Portsoy-Duchray Hill Lineament including the Portsoy and Keith shear zones – is captured in the Peterhead section.

Major faults: The Great Glen Fault (GGF; Figs. 1.1 & 1.4) forms an integral part of an array or system of regional-scale, steeply-dipping and generally NE–SW-trending, apparently sinistral strike-slip fault

structures that transect the Grampian and Northern Highland terranes (Fig.1.6). The Great Glen Fault is known to have experienced a protracted history of movement, responding to changing stress regimes from the Caledonian (Ordovician–Silurian), throughout the Late Paleozoic, into the Mesozoic development of the Moray Firth region, and continuing in the Paleogene as the northern Atlantic Ocean opened. In detail, and following on from the dominant sinistral strike-slip regime active during later Caledonian Siluro-Devonian events (Stewart *et al.* 1999; 2001; Mendum & Noble, 2010), the GGF is known to have experienced: extension during the Devonian (Séranne, 1992); dextral displacement in the latest Carboniferous to Early Permian (Speight & Mitchell, 1979); transtensional opening and expansion across the Moray Firth–Pentland Firth region from the Permian and through the Mesozoic (Underhill & Brodie, 1993; Roberts & Holdsworth, 1999; Dichiarante *et al.* 2016); and dextral oblique wrench in the Paleocene–Eocene as Atlantic Ocean opening progressed (Holgate, 1969; Watts *et al.* 2007).

Near Fort Augustus, Kemp *et al.* (2019) show that the Sronlairig Fault (a NE–SW-trending splay of the Great Glen Fault, British Geological Survey, 1995) contains evidence for two episodes of active growth of movement-related authigenic clay-rich fault gouge fillings. A series of Illite Age Analysis plots produced mean ages of 296 ± 7 Ma (Late Carboniferous–Early Permian) for the oldest and 145 ± 7 Ma (Late Jurassic–Early Cretaceous) for the youngest. These demonstrate the longevity of faulting in post-Caledonian times where other isotopic evidence for younger tectonic overprints is only recently beginning to emerge. The record of repeated displacements is to be expected to be the case for most, if not all, of the faults of Caledonian heritage identified across the Scottish Highlands.

The Highland Boundary Fault is also a long-lived structure. It represents the boundary between Laurentia (Grampian terrane) and the accreted Midland Valley terrane but would most likely have become a discrete mappable feature towards the end of Grampian deformation and metamorphism (Chapter 6), in part accommodating uplift of the metamorphic rocks in its north-western wall (Dempster *et al.* 1995). Reverse (or thrust) movement is likely to have been accommodated across this important structure at various times through the Silurian and Devonian, with the (Acadian) Strathmore Syncline developed in its footwall region. McKay *et al.* (2020) reported Carboniferous fossil fragments within clay-rich fault gouge from within the fault core at Stonehaven, fabrics preserved in that gouge clearly demonstrating Carboniferous (–Permian?) opening and dextral translation on the HBF. It is very likely that that Southern Upland Fault was similarly active at repeated intervals in the geological record.

The Skye, Mull and Islay cross-sections demonstrate the comparatively simpler architecture and undulating stratigraphy of the Midland Valley terrane, albeit transected by NW–SE-trending faults which, like the similarly-aligned structures in the Scottish Highlands, probably accommodated significant amounts of lateral slip, both dextral and sinistral at differing times in the geological record. Carboniferous and Devonian strata rest on Silurian and Ordovician strata, overlying a variety of late Ordovician crystalline and magmatic basement rocks (Badenzski *et al.* 2019) for which no definitive architecture can be determined (e.g., Hall *et al.* 1984; Barton 1992). The largest-scale folding of Upper Paleozoic strata occurs in the north-east of the Midland Valley, expressed as the Strathmore Syncline/Ochil Anticline structures, but pronounced and localized folding is spatially associated with many of the sub-vertical oblique-slip faults cutting Upper Palaeozoic strata in the Midland Valley, demonstrating a clear relationship between broadly contemporaneous fold and fault structures that were being generated within the regional-scale stress regimes active at this time (Chapter 10).

The Southern Upland Fault separates the Paleozoic geology of the Midland Valley terrane from the accretionary complex of the Southern Uplands terrane; like the HBF, the SUF is presumed to have been active at various times throughout the Paleozoic at least. These NW–SE-trending sections illustrate a steeply dipping discontinuity for the SUF that likely extends to the base of these sections. To the south-east of the SUF, the various fault-bounded tracts of Ordovician and Silurian strata are

arranged within an accretionary complex that demonstrates the contradictory and long-recognized stratigraphical younging pattern, i.e., right-way-up, broadly NW-dipping strata that young, overall, to the south-east. The major part of the accretionary complex is thought to lie above a sub-horizontal boundary (decollement?) separating the accreted Lower Paleozoic strata from crystalline basement rocks beneath. The exact nature of this boundary is uncertain; a south-vergent detachment (thrust?) is possible. By late Silurian times, the accretionary complex was increasingly affected by sinistral strike-slip movements expressed along the major tract-bounding faults e.g., the Orlock Bridge Fault, and especially within the Moniaive Shear Zone. The overall geometry of Southern Upland geology suggests formation of a transpressional positive flower structure that significantly modified the earlier accretionary architecture with rocks thrust both south, and perhaps less so, to the north (Pyet Thrust, see discussion in Chapter 7) in the hanging wall of any older subduction-related structure. On these sections, Devonian and Carboniferous strata overstep the Lower Palaeozoic accretionary complex in the southern parts of the Southern Uplands and along the Scottish border with Northern England. Significantly greater accommodation space was developed in the Carboniferous fault-bound Solway Basin in the south-west (Islay and Mull sections) than along strike to the north-east where a more gently onlapping overstep relationship is seen on the northern flank of the Northumberland Trough (Skye section).

Nearshore basins: Mesozoic relationships in the Little Minch and North Minch basins that overlie the Lewisian Complex rocks of the Outer Hebrides and the Northwest Highlands foreland to the Moine Thrust Belt are shown on the Peterhead, Skye, and Mull sections. Oligocene strata occupy the Inner Hebrides Trough offshore west of Islay (Islay section) and the Islay-Donegal Platform. The older Outer Hebrides Fault Zone and the Outer Hebrides thrust that floors the fault zone are cut by the Mesozoic Minch Fault.

Plutons: Caledonian (Ordovician and late Silurian–Devonian) granitic to dioritic plutons are a conspicuous component of the geological map of Scotland and are depicted on these sections (but see also the section accompanying the 1:625 000 scale Bedrock Geology map, UK North, BGS 2007). Their sub-surface shapes are not constrained in detail; they are typically modelled as either broadly teardrop-shaped or more globular bodies with a floor at or around 10 km depth below the present land surface. Badenzski *et al.* (2019) have shown that zircons of the same age as these Siluro-Devonian Caledonian granites are enclosed within xenoliths entrained in Carboniferous intrusions in the MVT, indicating that a source for these mineral grains must also occur in the MVT sub-surface. Paleogene felsic and mafic plutons of the Mull Central Complex and mafic plutons of the Skye Central Complex (Cuillin Centre gabbros) are represented as broadly cylindrical bodies rising from beneath the section profiles.

Geology and societal relevance

In 2015 the Scottish Government was one of the first countries to adopt the UN Sustainable Development Goals (SDGs) requiring national governments to report on progress towards delivering on a series of 17 goals up to 2030 (Fig. 1.14). The SDG framework is therefore a key driver for government policy (Scottish Government 2020) and is intimately linked to the global agendas of the Climate Change (Paris Agreement (COP21)) and Disaster Risk Reduction (Sendai 2015). As described by Gill & Smith (2021), geology and geosciences have a role to play in helping achieve many of these goals including among others, responsible consumption, climate action, economic growth, clean energy, sustainable cities and environmental protection. Combined with adaption to climate change society is now witnessing a fundamental shift in policy and in particular with regard to the future role of hydrocarbons in energy and industry as we transition to a Net Zero world.

Against this backdrop and in a departure from previous editions the final three chapters in this volume describe Scotland's geological resources and consider their application to current Scottish

Government policy, regulation and mitigation of climate change. In this context the accumulated geological research, data and advice may be collectively described as capital assets that provide ‘geosystem services’ (Gray 2011; Van Ree & Beukering 2016; Chapter 19) which together underpin and sustain Scotland’s economic development, the energy transition and enable solutions to the environmental impacts of climate change. As an introduction to the content of these ‘geosystem services’ the final chapters are summarised below under two broad headings: those relating to climate change and the environment and geodiversity, and those to security of supply and development. This is illustrated in Fig. 1.15 which shows the linkages between geology and some of the key active policy and regulatory instruments of Government in 2023. Looking forward, whilst individual policies may change in response to political drivers and public opinion, the fundamental environmental and societal aspects of resource management, energy supply and climate change will remain with us for decades to come.

Geology and climate change

The current state of Scotland’s climate is one of gradual change to warmer summers and wetter winters with, increasing periods of drought, reduced snowfall and an increase in storm and high intensity rainfall events combined with a rising sea level (Adaptation Scotland 2021).

The Climate Change (Scotland) Act of 2009 as amended by The Climate Change (Emission Reduction Targets) (Scotland) Act 2019 aims to deliver on the 2015 Paris Agreement and ambitiously end Scotland’s contribution to climate change by 2045. Delivering on these Acts requires a multidisciplinary approach that addresses the environmental and socio-economic impacts on both the natural and human systems (SNIFFER 2021). Whilst the geological record of past climate change events is well known and is described in various chapters in this volume, the focus in these final chapters is on resource and adaptation.

Geological knowledge underpins adaptation in several key sectors including transport, business and industrial process, residential and public buildings, energy and water supply, landfill and waste management, change in landscape character and land use and tourism. Issues related to resilience and a sense of place and addressing flood risk, water supply, and landscape change are considered in Chapter 18. Landslides triggered by high intensity rainfall events increasingly impact upon built infrastructure, landfill and soil erosion. In urban settings particularly in the Central Belt of Scotland, geological input to the design of resilient cities (Smith & Bricker 2021) will involve ‘blue-green’ city approaches with sustainable urban drainage systems (SUDS) and perhaps underground water storage to ensure uninterrupted water supply, and access to cool circulating air. A good example is the British Geological Survey’s Clyde Urban Super Project (British Geological Survey 2022). This long standing project focusses on the integration, renewal and communication of subsurface and surface data relevant to urban development, the environment, human health, planning and policy.

Scotland’s groundwater aquifers and springs are essential to underpin not only agriculture and maintaining river flows but also industry including bottled water, distilling and brewing, quarrying and hydropower. Under climate change scenarios that include decreasing winter snowmelt and increasing summer drought, the risk of future water shortages is expected to increase. The distribution of Scotland’s aquifers and regulatory monitoring is described in Chapter 17. To manage future impacts an assessment of and research into groundwater supply including the extent, nature and interconnectivity of key aquifers in the Devonian, Carboniferous and Triassic sediments and fracture controlled flow in older rocks is needed. Water quality and the environmental impact of rising groundwater levels post-coal mining, particularly across the Central Belt are also of concern and requires long term monitoring and safety management.

Encompassing numerous islands, Scotland has the second longest coastline in Europe and its variety is a consequence of geology and the legacy of past sea-level change (Hansom *et al.* 2017). UK Climate

data and projections indicate that the average sea-level around the UK has risen by approximately 1.4 mm/year from the start of the 20th century (UKCP18; Palmer *et al.* 2018). Although estimates in projected global sea-level rise are generally lower for Scotland, depending on global warming and ice-melt, the average sea-level for Scotland by 2100, relative to the 1981–2010 mean sea-level, could rise between 0.3 and 0.9 m (Horsburgh *et al.* 2020) (Fig. 1.16) placing infrastructure and natural capital assets at risk (CREW 2021; Rennie *et al.* 2021).

This will result in fundamental changes to coastal geomorphology and consequential greater impacts on the softer, more erodible sedimentary, glacial and Holocene deposits of the east coast in contrast to the more resistant basement and igneous lithologies of the west coast. Depth to resistant bedrock is recognised as an important factor in assessing erodibility with rising sea level (Hansom *et al.* 2017). The Dynamic Coast National overview 2021 categorises approximately 21% of Scotland's coastline as soft or erodible comprising sand dune, machair, salt marsh and estuary flats (Fig. 1.17) (Rennie *et al.* 2021). About 46% of these features are now affected by increased storminess and rising sea level and coastal defence and shoreline management plans are required to effect a managed retreat.

Tied into this are the wider impacts on historical, geodiversity and biodiversity localities not only of scientific value but also sites of aesthetic, cultural, spiritual, recreational or touristic value. Climate change and changes of land-use lead to loss of visibility, interruption or loss of access, physical damage and destruction, and the interruption and arrest of dynamic processes (e.g. in coastal and river environments). In this context, key geology and fossil sites could be affected, for example, Siccar Point, the Helmsdale Boulder Bed and dinosaur discoveries on Skye and Eigg (Fig. 1.18). In Chapter 19, MacFadyen (2023) outlines a site based conservation approach with a combination of national instruments and designations and community-led initiatives, guided by NatureScot.

Geology and security of supply

External factors such as climate change, a pandemic or armed conflict impact global economic trade to create risk in the supply chain of goods and services. Thus, security of supply applies not only to energy and water but also crucially to minerals and metals required for modern technologies and the clean energy transition. Increasing risk and the decarbonising agenda are now providing stimuli for reassessment and research into Scotland's natural resources and their potential contribution to understanding of geological processes and future exploration strategies.

As Scotland transitions from dependence on high carbon fuels including, coal, oil and gas to low carbon (clean) alternatives and renewables, the focal point of subsurface geology is moving increasingly from extraction to injection. To achieve carbon reduction targets whilst maintaining the supply, albeit declining, of oil and gas will require carbon mitigation strategies with the geodisposal of CO₂ and complementary energy storage in reservoirs and aquifers to balance the intermittency of renewable energy.

The geology of Scotland's coal and hydrocarbon resources will continue to play a role in this transition. As described in Chapter 17 the large volumes of legacy data and modelling generated by surveys, mining and drilling across the Midland Valley and offshore can now be repurposed to inform alternative exploration strategies and resource assessment for compressed air and hydrogen storage onshore and injection of dense CO₂ offshore. These techniques require detailed understanding of the reservoir architecture, the flow of displaced water and brines, and the impact of drilling and fracking on the local subsurface environment. In the Central Belt of Scotland the reservoir properties and suitability of Carboniferous sedimentary rocks offer opportunities not only for shallow geothermal but also in the deeper unmined parts of the coalfields for coal bed methane and shale gas that could be utilised as test sites for hydrogen production. Offshore hydrocarbon production is expected to continue to ensure security of supply of oil and gas to manage the transition, with limited new fields

in exploration frontiers (e.g. Cambo, west of Shetland) and identification of depleted oil fields as potential CO₂ injection targets (Chapters 12 & 17).

Whilst there is a great variety to Scotland's mineral endowment, no world class deposits have been located. In Chapter 17 barite, silica sand are noted as key commodities along with aggregate for local use but what has changed is Scotland's and the UK's requirement for critical materials. Whilst these will be largely met from the global market requiring an understanding of the cyclical nature of the economy, Scotland's geology also provides a natural laboratory for research into the tectonic settings and genesis of formation. An example is described which focusses on gold-bearing ore fluids and highlighting recent research on the Cononish deposit. The minerals review in Chapter 17 concludes by identifying the potential for further research and exploration of six deposit types across Scotland.

Finally, the rise of clean power and renewables also highlight the potential for geothermal and hydropower to contribute to a mixed low carbon economy approach. In this respect understanding and communicating the nature of the geology and fracture systems is key to de-risking infrastructure design and construction.

Summary

During the past two decades there have been significant advances in our understanding of Scotland's geology both onshore and offshore. These confirm that Scotland, despite its modest size contains many world class exposures and continues to make fundamental and internationally recognised contributions to geoscience across a wide range of topics including orogenic processes, evolution of failed rifts, emplacement histories of plutonic complexes, palaeontology and the evolution of life, and long-term and recent climate change. Many key sites are designated as SSSIs and two as IUGS sites of geological heritage. Together they underpin the UNESCO-accredited Northwest Highlands and Shetlands geoparks and continue to be studied by academic researchers, students and geological societies.

Looking forward, whilst the application of high-precision mineral dating in combination with detailed petrological and field studies over the last two decades has resolved some of the problems and controversies identified in the 4th edition of this volume, others remain and are highlighted in the various chapters that follow this overview. The application of geological data and its effective communication for risk assessment and to inform investment in major infrastructure development will be important in the decades to come. In particular, the energy transition will require the continued re-purposing of offshore reservoir data to assess suitability for long-term CO₂ storage, the realisation of full-scale test sites and the reliability of reservoir seals over time. Onshore, the BGS UKGEOS project is a major onshore monitoring of resource extraction and storage project that will contribute to our understanding of storage options for heat, hydrogen and the re-use of mine waters. A more detailed assessment of deep geothermal potential is long overdue and would require major investment in deep drilling. Regional airborne geophysical surveys and increasing use of drone-mounted sensors will underpin growth in urban geology studies, environmental characterisation and groundwater aquifer performance and sub-surface flow in a changing climate regime.

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Figure captions

Fig. 1.1: Simplified geological map of Scotland, derived and modified from the BGS 1:625 000 scale 'Bedrock Geology UK North Map' (BGS 2007). Selected major faults are shown, more detailed representations of elements of the figured geology here is provided in diagrams included in the appropriate succeeding chapters, and with reference to the BGS 1: 625 000 map (BGS 2007). Lines of the crustal-scale, vertical cross-section profiles (A–D) presented in Fig. 1.12 are superimposed. All map-face labels are expanded in the map legend; J(K) highlights the presence of important outcrops of Cretaceous strata (along with Jurassic strata) that are too small to represent at this scale. Source: Contains BGS GEOLOGY 50K Data © UKRI and Ordnance Data © Crown Copyright and database rights 2020. Graphic design and generation of this figure by Craig Woodward. BGS © UKRI.

Fig. 1.2: NextMap topo image of Scotland with geological terranes, major faults and places mentioned in the text. Source: Contains BGS GEOLOGY 50K Data © UKRI. Hill shading using NEXTMap Britain elevation data from Intermap Technologies. BGS © UKRI.

Fig. 1.3a: Table of onshore geological events in the terranes of Scotland. Source: Modified and updated after Trewin & Rollin (2002). © Geological Society of London.

Fig. 1.3b: Table of geological events in the offshore sedimentary basins of Scotland from Devonian to Quaternary Periods. Timescale as for Fig. 1.3a. BGS © UKRI.

Fig. 1.4: Palaeogeographic reconstructions at a) 1780Ma, showing the selected continental blocks and the supercontinent Nuna, bordered to the west by a subduction zone, and b) 990Ma, showing relevant parts of the supercontinent Rodinia, with the Grenvillian-Sveconorwegian collisional orogen in red. Note also in green the external accretionary orogen that developed around the periphery of this sector of the supercontinent following its amalgamation. In both, the letter 'S' shows the approximate position of the Archean-Paleoproterozoic basement of Scotland. Abbreviations: Am, Amazonia; Au, Australia; Ba, Baltica; I, India; La, Laurentia; NC, North China; Si, Siberia; WA, West Africa. Source: Reproduced with permission from Holdsworth *et al.* (2012).

Fig. 1.5: Palaeogeographic reconstructions at selected time intervals of Scotland's geological journey Source: Reproduced with permission from Holdsworth *et al.* (2012).

Fig. 1.6: Simplified fault map of Scotland. Faults identified in the 1:625 000 scale BGS geological map and database. The fault network pattern overall is consistent with late-Caledonian (Siluro-Devonian) sinistral transpression. Source: Contains BGS GEOLOGY 625K Data © UKRI and Ordnance Data © Crown Copyright and database rights 2020. Hillshading using NEXTMap Britain elevation data from Intermap Technologies. BGS © UKRI.

Fig. 1.7: Shaded relief image of (a) gravity anomaly map and (b) aeromagnetic anomaly map for Scotland. B, Buchan; L, Lairg. Based on BGS 1997; 1998. Source: Contains BGS GEOPHYSICAL 625K Data © UKRI and Ordnance Data © Crown Copyright and database rights 2020. BGS © UKRI.

Fig. 1.8: Focal mechanisms available for earthquakes in Scotland. The blue and white areas show the compressional and dilational quadrants and the lines between the quadrants show the strike and dip of the two possible fault planes. The axes of the maximum and minimum compression are indicated by the blue and white squares respectively. The black dots show the location of the earthquakes. The blue lines show the orientation of the maximum horizontal compressive stress (s_H) taken from the smoothed stress orientations published in the World Stress map (Heidbach *et al.* 2016). Source: After Baptie (2010), contains BGS GEOPHYSICAL Data © UKRI and Ordnance Data © Crown Copyright and database rights 2020. Hillshading using NEXTMap Britain elevation data from Intermap Technologies, stress orientation data Creative Commons Licence BY 4.0. BGS © UKRI.

Fig. 1.9: (a) The BGS seismic network in 2023, (b) Distribution of earthquakes in Scotland. Source: contains BGS GEOPHYSICAL Data and Ordnance Data © Crown Copyright and database rights 2020. Hillshading using NEXTMap Britain elevation data from Intermap Technologies. BGS © UKRI.

Fig. 1.10: Map of the locations of inferred focal mechanisms of mapped lineaments inferred as fault surface ruptures. The blue and white areas show the compressional and dilational quadrants and the lines between the quadrants show the strike and dip of the two possible fault planes. Source: modified after Main *et al.* (1999), contains Ordnance Data © Crown Copyright and database rights 2020. Hillshading using NEXTMap Britain elevation data from Intermap Technologies, fault data copyright Oxford University Press, Open Access. BGS © UKRI.

Fig. 1.11: Map showing the principal terranes boundaries with selected deep seismic reflection and refraction profiles (red lines) after Barton (1992), blue stars representing xenolith localities across Scotland after Upton *et al.* (2011) and probabilistic Moho depth surface reconstruction (blue lines) after Licciardi *et al.* (2020). Contours of Moho depth are in km. Source: contains BGS GEOLOGICAL 625k Data and Ordnance Data © Crown Copyright and database rights 2020. Hillshading using NEXTMap Britain elevation data from Intermap Technologies. BGS © UKRI.

Fig. 1.12: Tectonic model for the Laurentia–Avalonia–Baltica sutures in the North Sea. Source: Modified after Lyngsø & Thybo (2007). BGS © UKRI.

Fig. 1.13: Upper crustal-scale geological vertical cross-section profiles: A1, A2 - Peterhead; B1, B2, B3 - Skye; C1, C2 - Mull; D1, D2 - Islay; part of a suite of mainly onshore sections compiled for BGS by one of the chapter authors (AGL). These profiles are intended to support the geological accounts of the succeeding chapters 3–15; their geology is summarised here in the accompanying text. Each profile is constructed to a nominal depth of 15 km, with vertical exaggeration $\times 2$, and fitted to the linework of the BGS 1:625 000 scale 'Bedrock Geology UK North Map' (BGS 2007), consistent with the similarly-styled cross-section included with the BGS 1:625 000 scale geological map (BGS 2007). Lines of section are shown in the figure inset, and are also superimposed on the geological map of Fig. 1.1. For each cross-section, the principal lithostratigraphical units and igneous plutons are shown, along with key tectonic discontinuities (faults and thrusts); intrusive dyke swarms are omitted for clarity. Younging directions are symbolised for the Lower Palaeozoic strata of the Southern Uplands in the Mull and Islay profiles. GGF, Great Glen Fault; LAS, Loch Awe Syncline; OHFZ, Outer Hebrides Fault Zone; OHT, Outer Hebrides Thrust; SKT, Loch Skerrols Thrust. All polygon labels are expanded in the figure legend. Source: contains BGS GEOLOGICAL 625k Data. BGS © UKRI.

Fig. 1.14: Summary of Scotland's geology and the SDG's. Source: Modified after Scottish Government 2020a, contains BGS GEOLOGICAL 625k Data. BGS © UKRI.

Fig. 1.15: Table of climate change adaptation and security of supply techniques and relationship of Scotland's geology and to current (2023) policy and regulation. Source: BGS © UKRI.

Fig. 1.16: Example of projected relative sea level rise scenarios from UKCP18 under three representative concentration (5%, 50% & 95%) pathways projected forward to 2100 for Montrose. Actual mean sea level record plotted in black. Source: Reproduced with permission from Dynamic coast.com.

Fig. 1.17: Distribution of Hard & Mixed, Soft and Artificial coastlines in Scotland, by coastal cell (Source: NCCA) From : Hansom *et al.* (2017) Dynamic Coast - National Coastal Change Assessment: National Overview, CRW2014/2. Source: Reproduced with permission from Dynamic coast.com.

Fig. 1.18: Limb bone of a probable Stegosaur found on beach on the Isle of Eigg. Source: Photo image reproduced with permission © Elsa Panciroli

Chapter 1: Figures

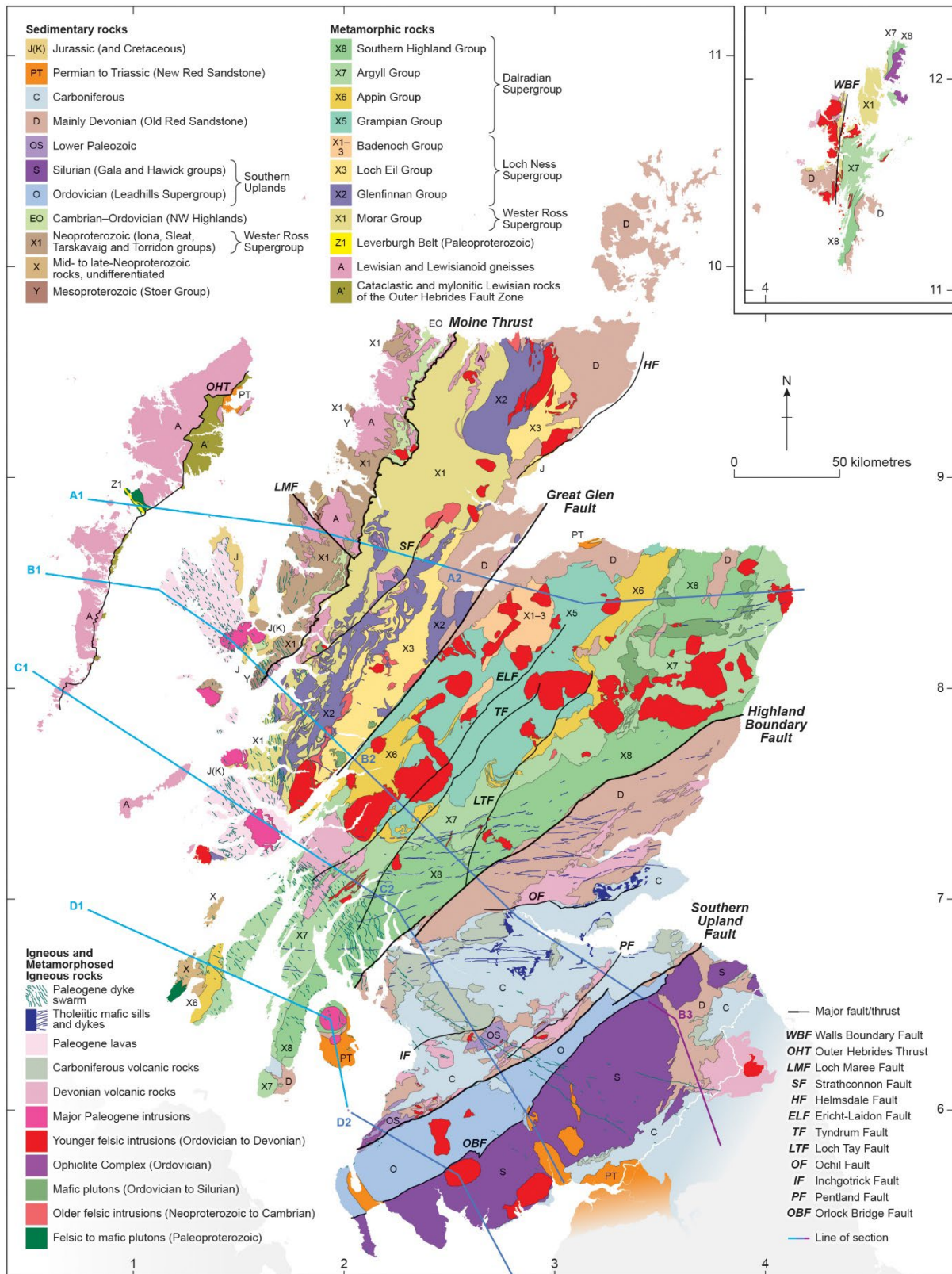
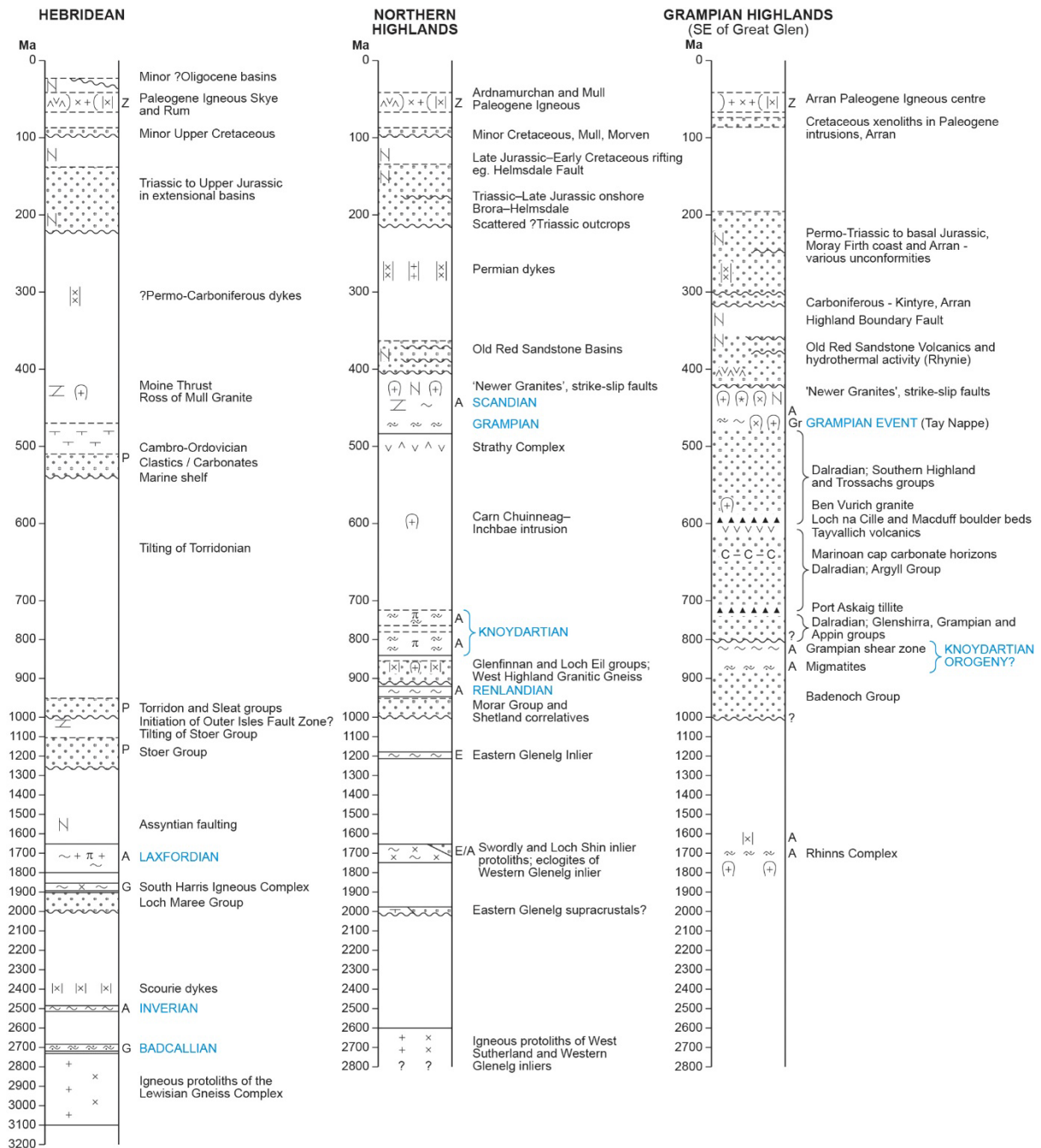


Fig. 1.1



Fig. 1.2:



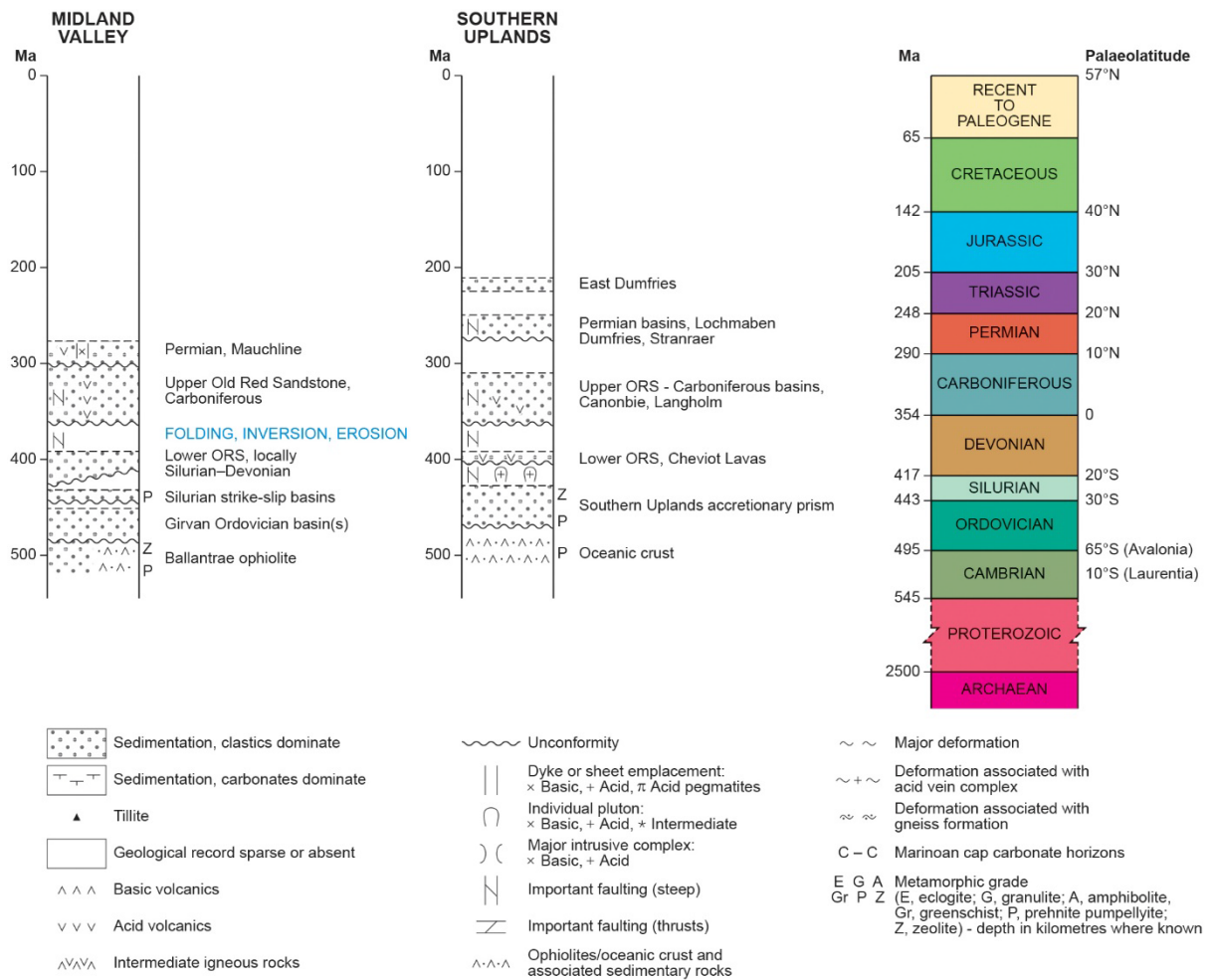


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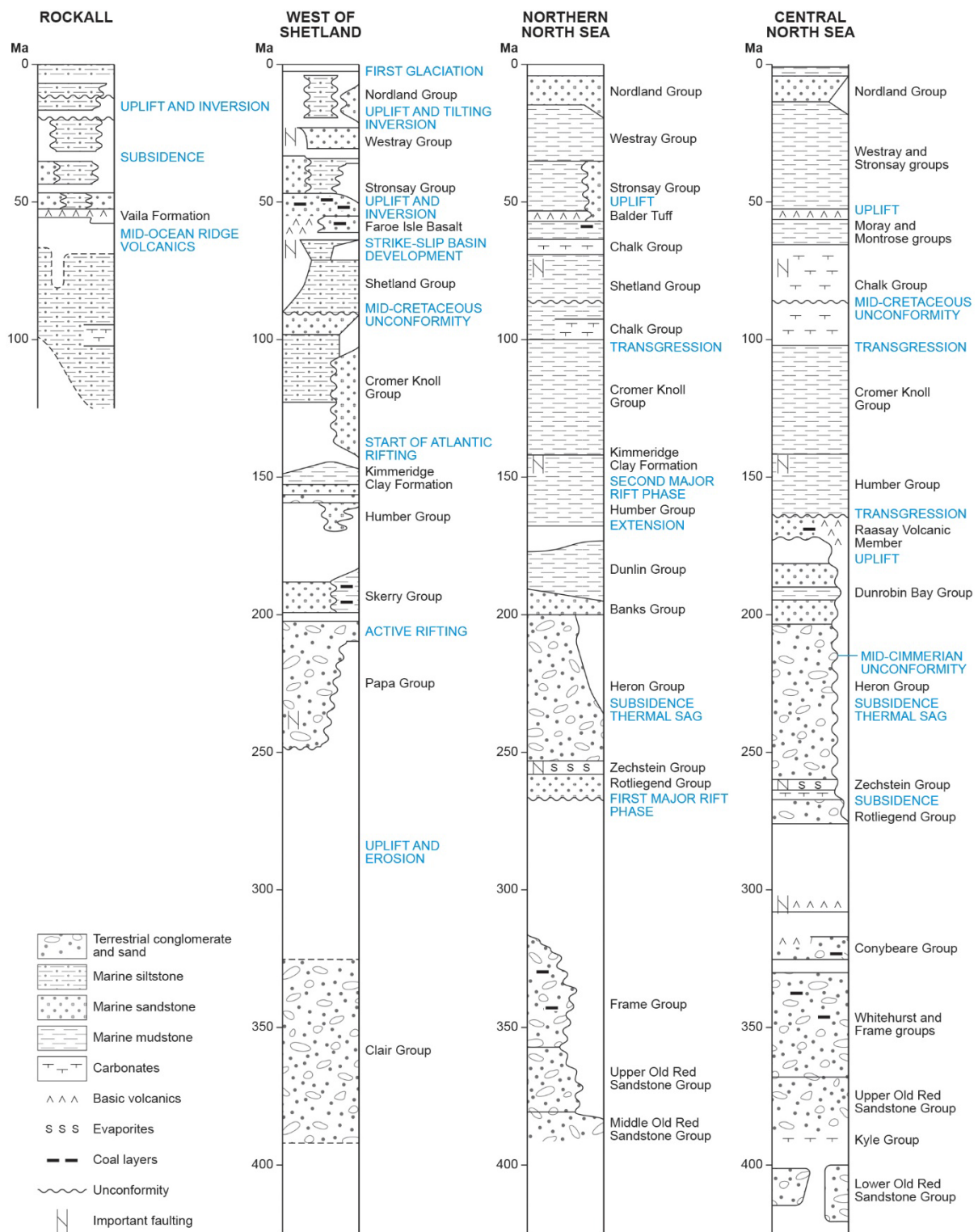


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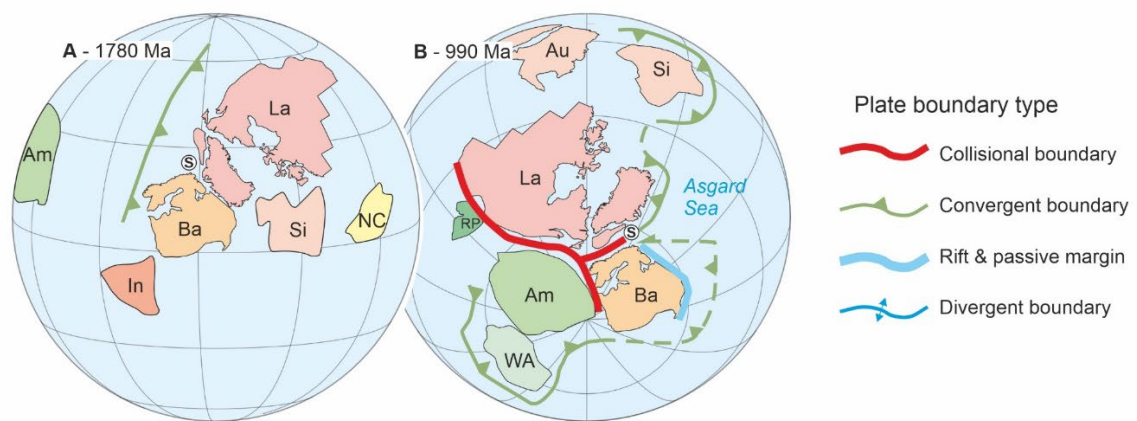
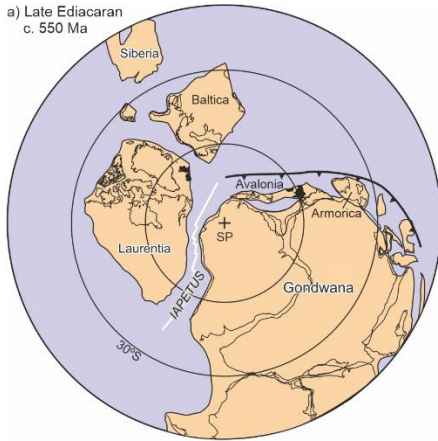
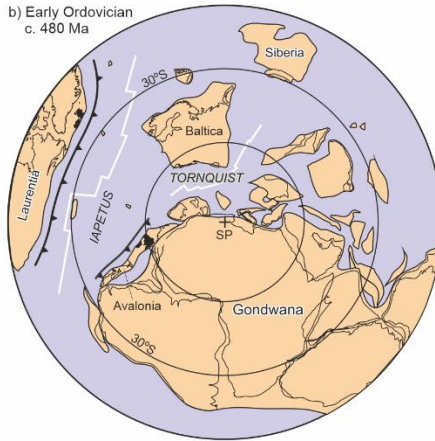


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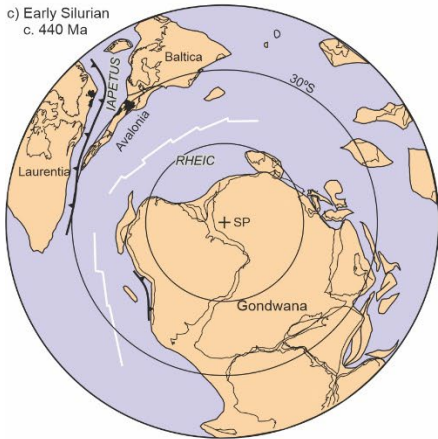
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c. 550 Ma



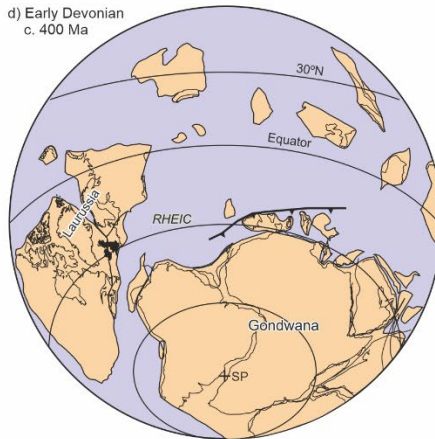
b) Early Ordovician
c. 480 Ma



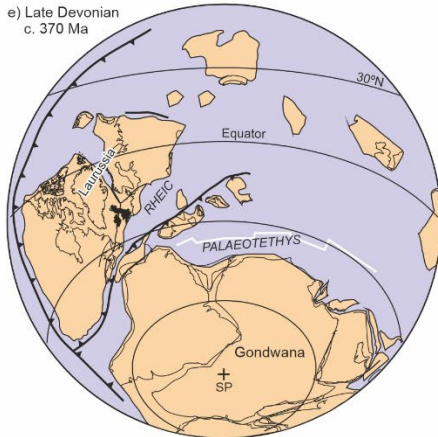
c) Early Silurian
c. 440 Ma



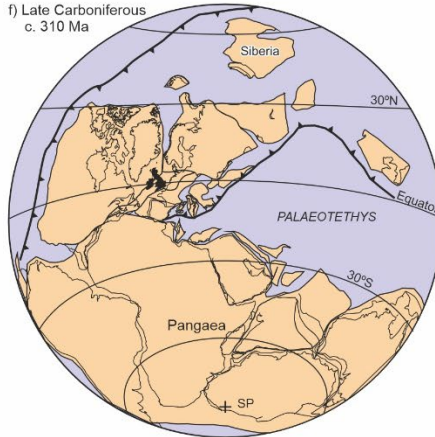
d) Early Devonian
c. 400 Ma



e) Late Devonian
c. 370 Ma



f) Late Carboniferous
c. 310 Ma



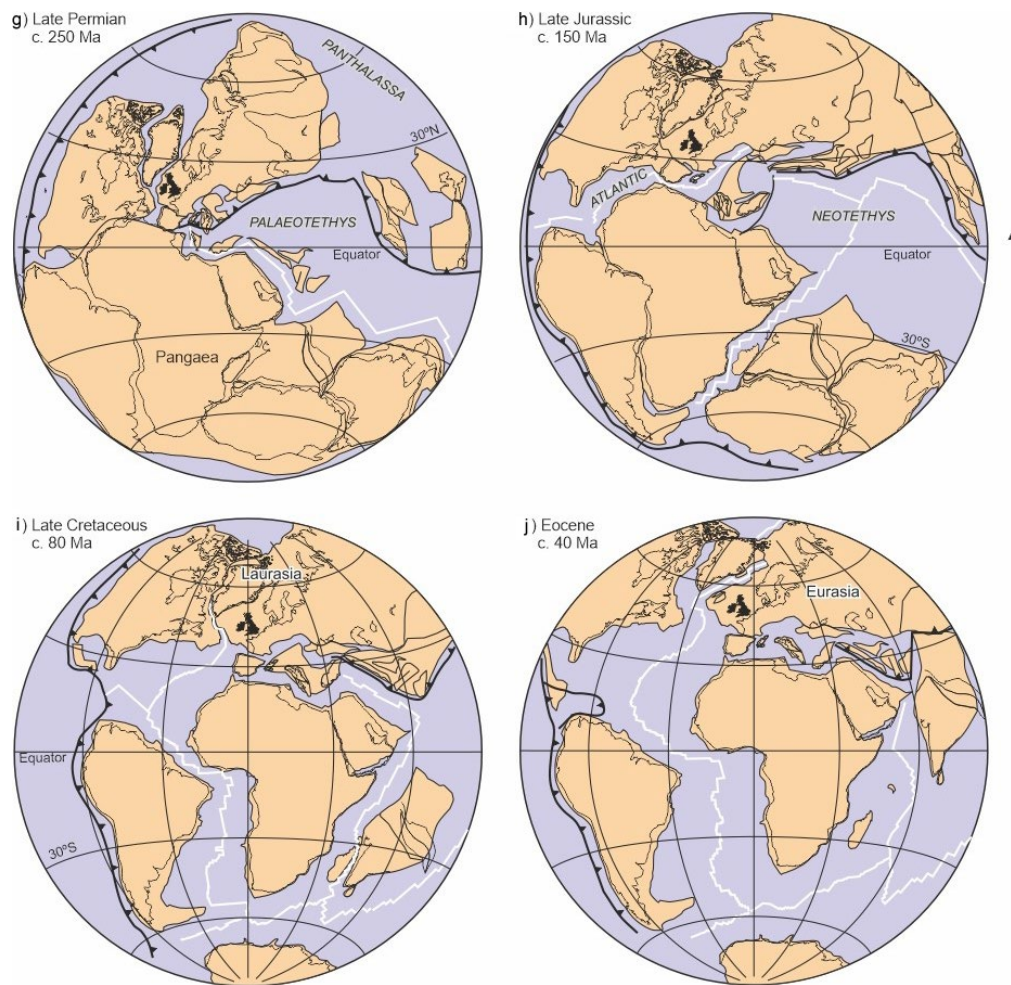


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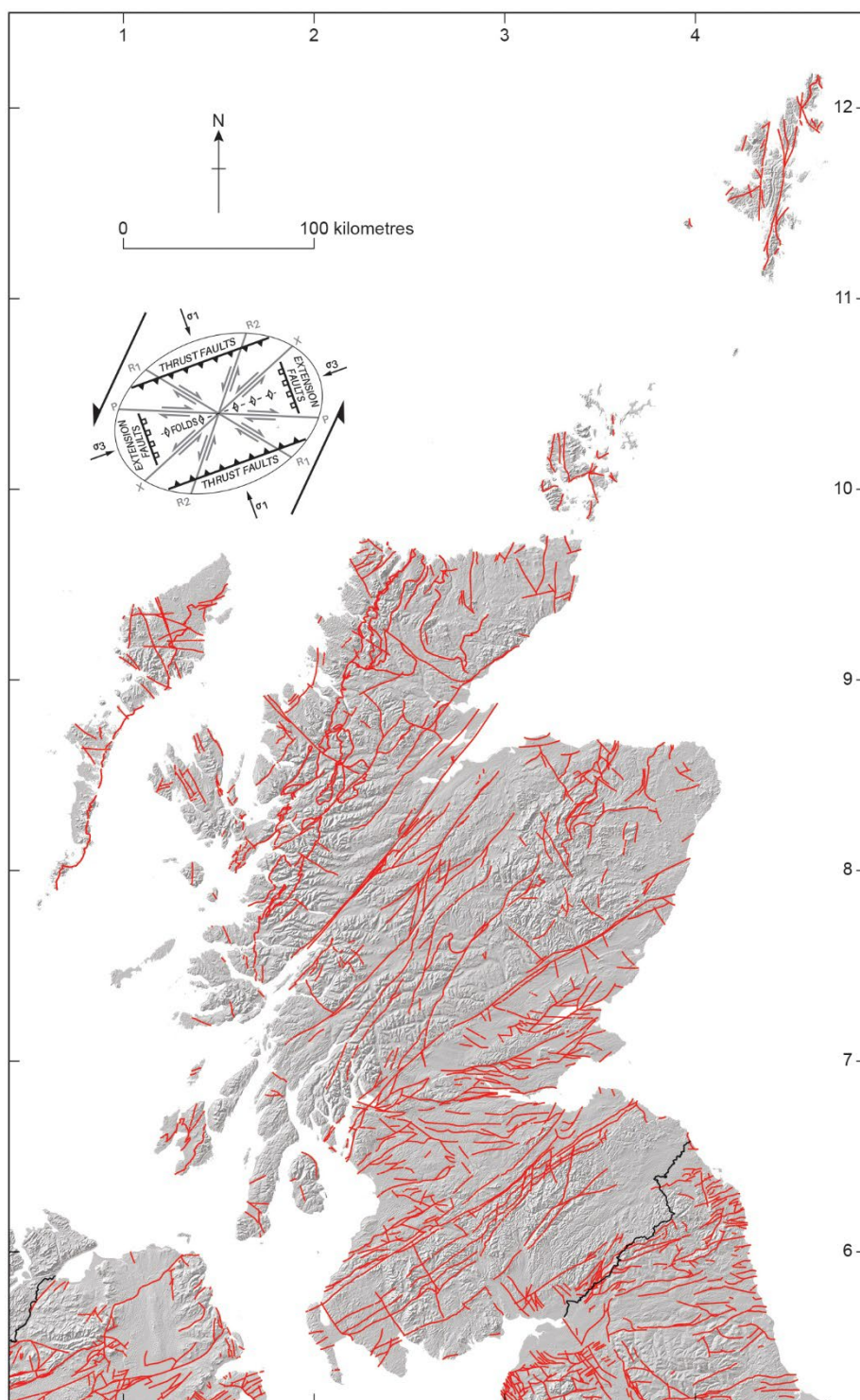
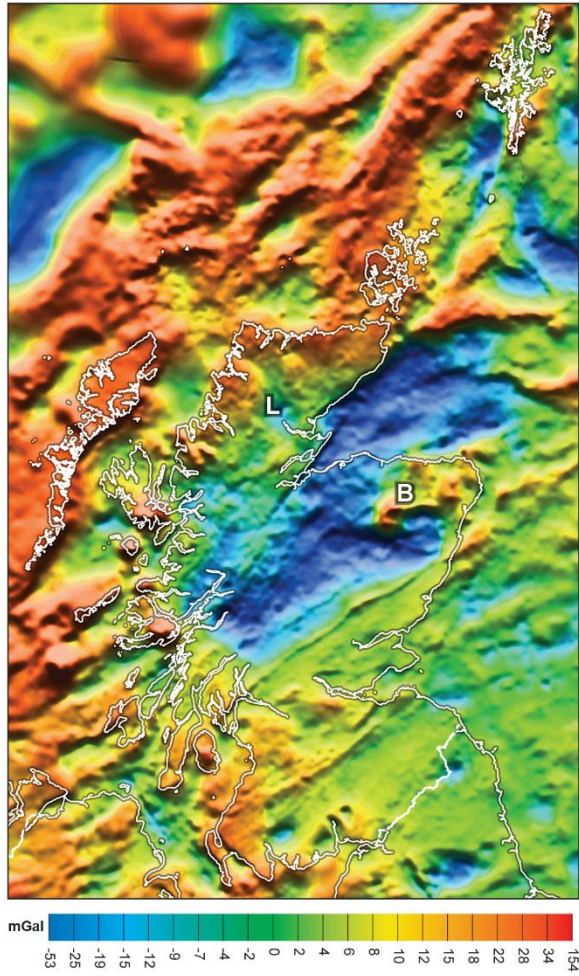


Fig. 1.6:

A Colour shaded-relief gravity anomaly map



B Colour shaded-relief magnetic anomaly map

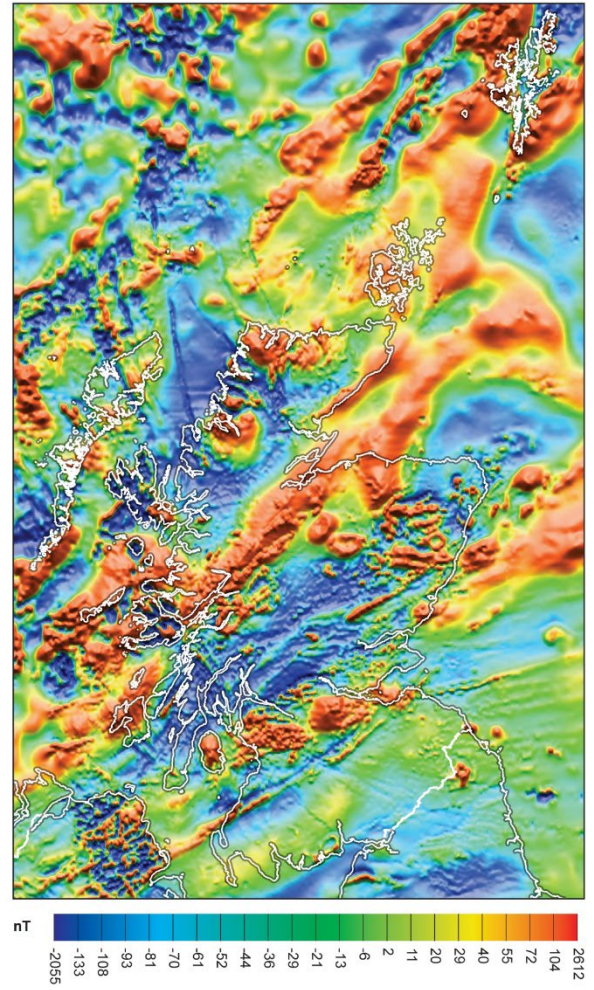


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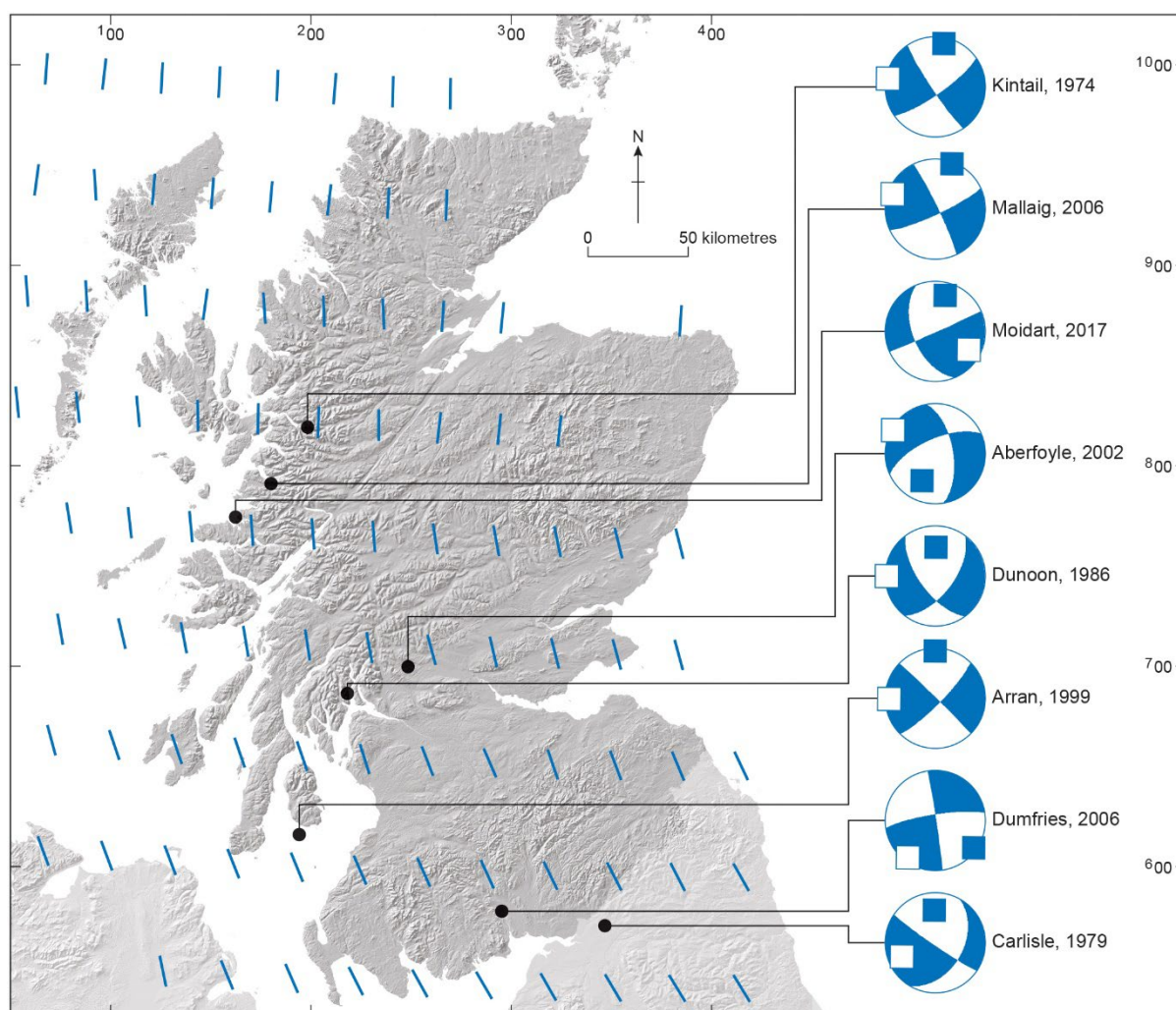


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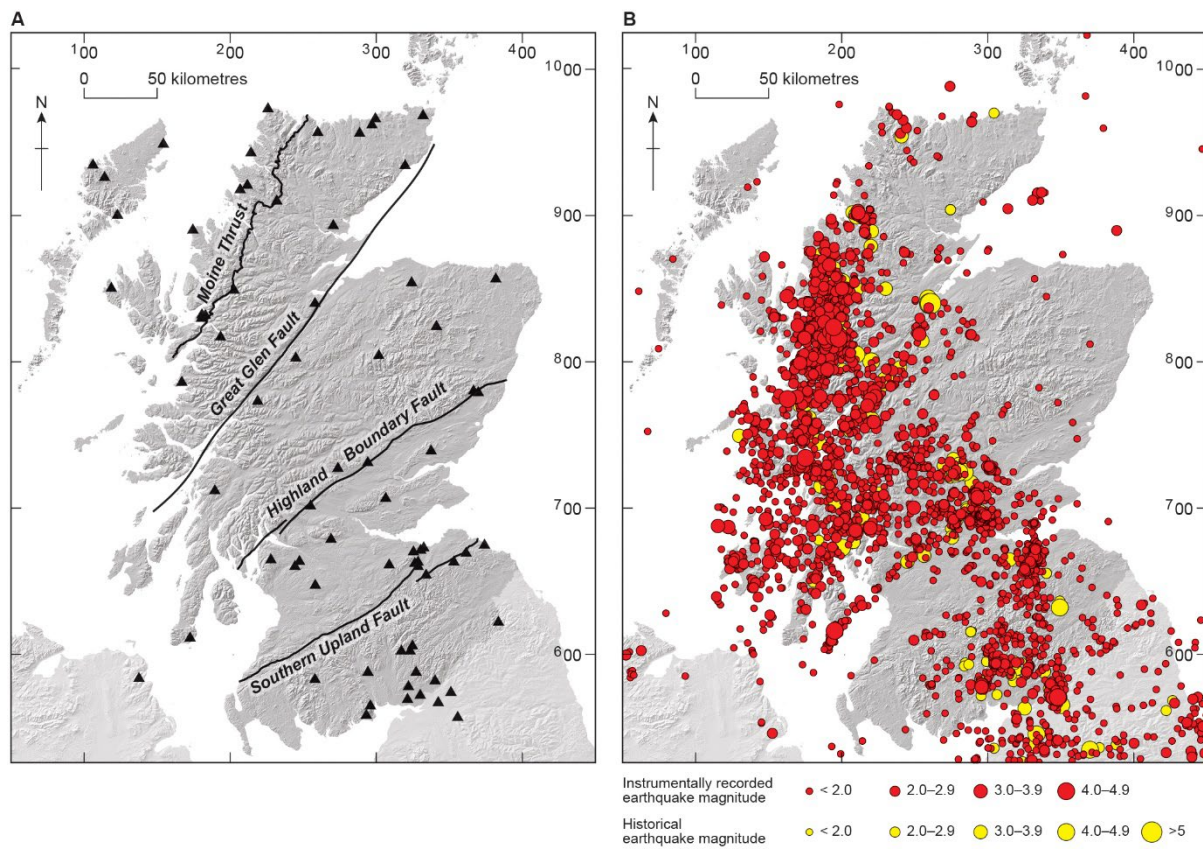


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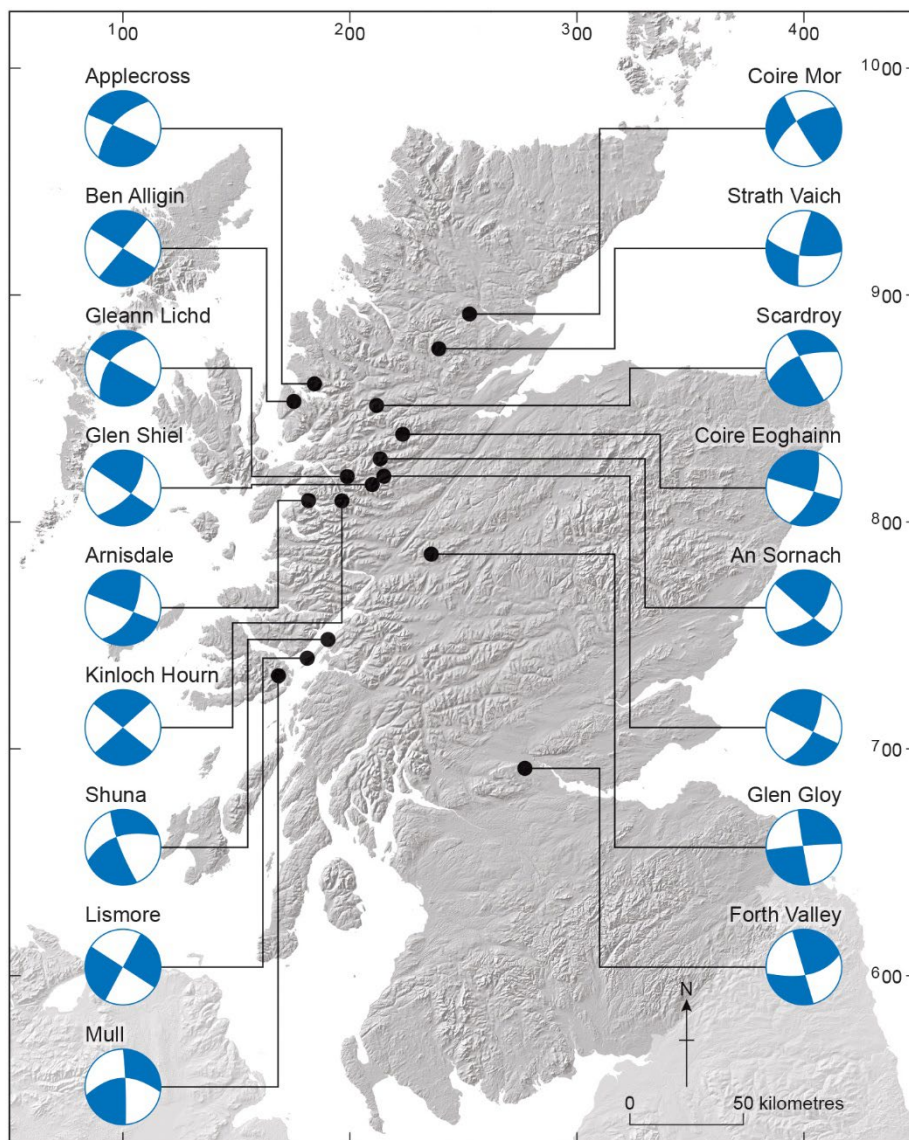


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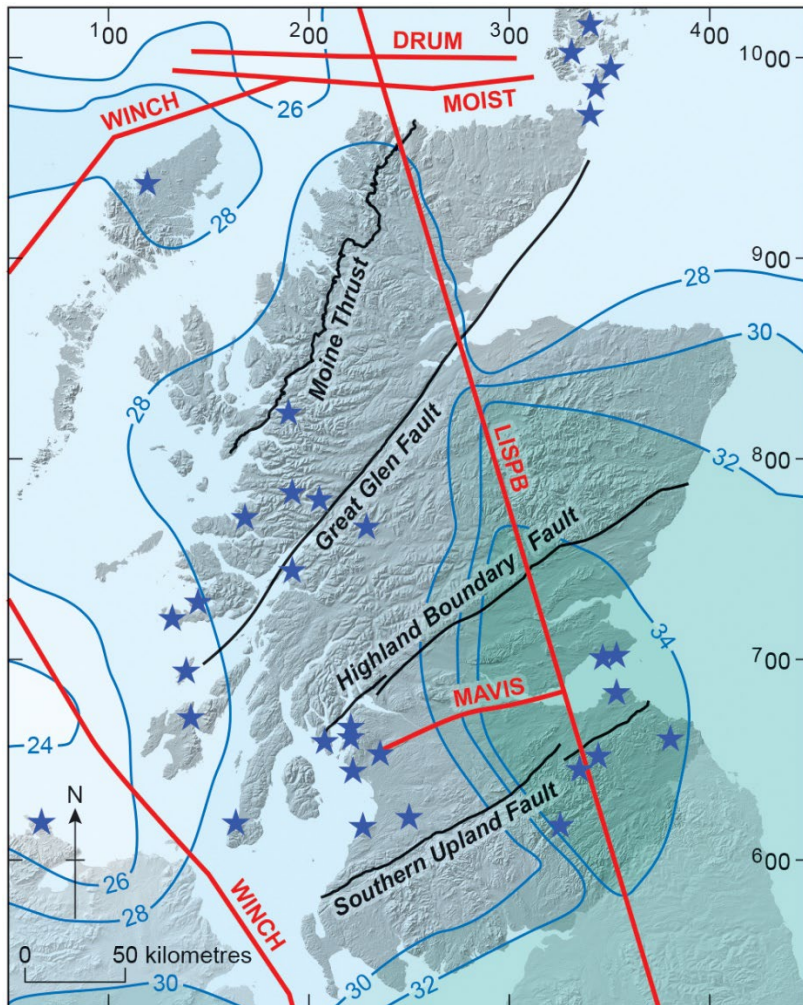
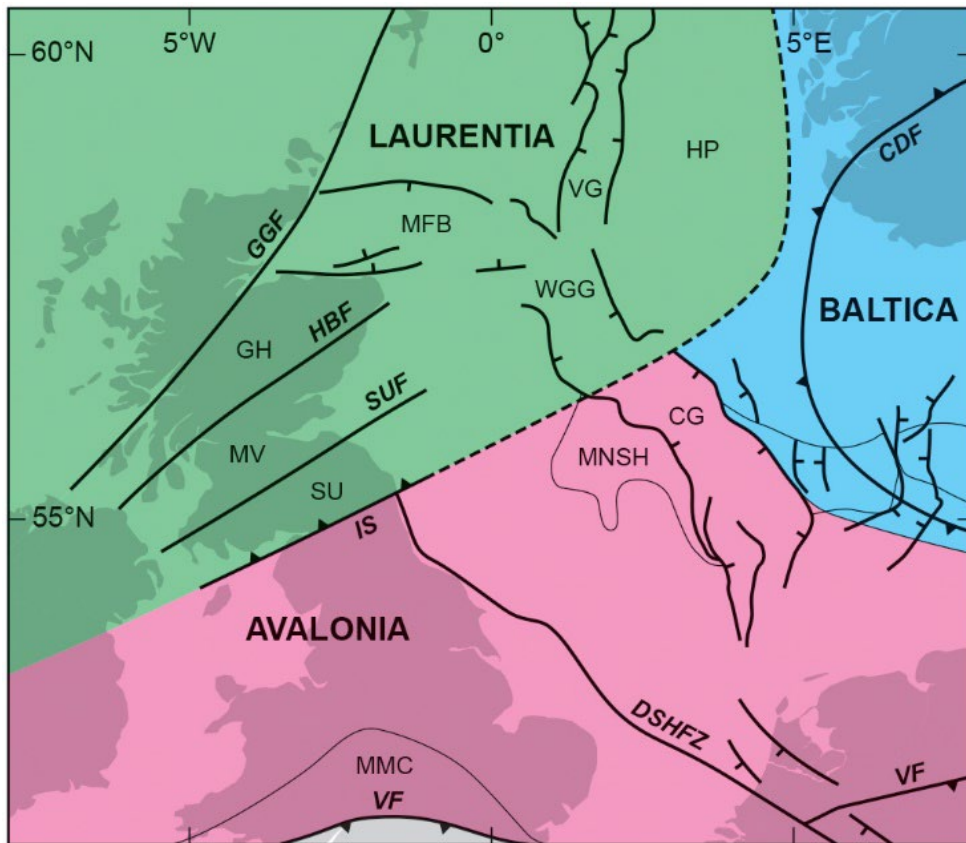
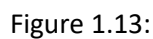


Fig. 1.11:



CDF	Caledonian Deformation Front	MMC	Midlands Microcontinent
CG	Central Graben	MNSH	Mid North Sea High
DSHFZ	Dowsing-South Hewett Fault Zone	MV	Midland Valley
GGF	Great Glen Fault	SU	Southern Uplands
GH	Grampian Highlands	SUF	Southern Upland Fault
HBF	Highland Boundary Fault	VG	Viking Graben
HP	Horda Platform	VF	Variscian Front
IS	Iapetus Suture	WGG	Witch Ground Graben
MFB	Moray Firth Basin		

Fig:1.12:



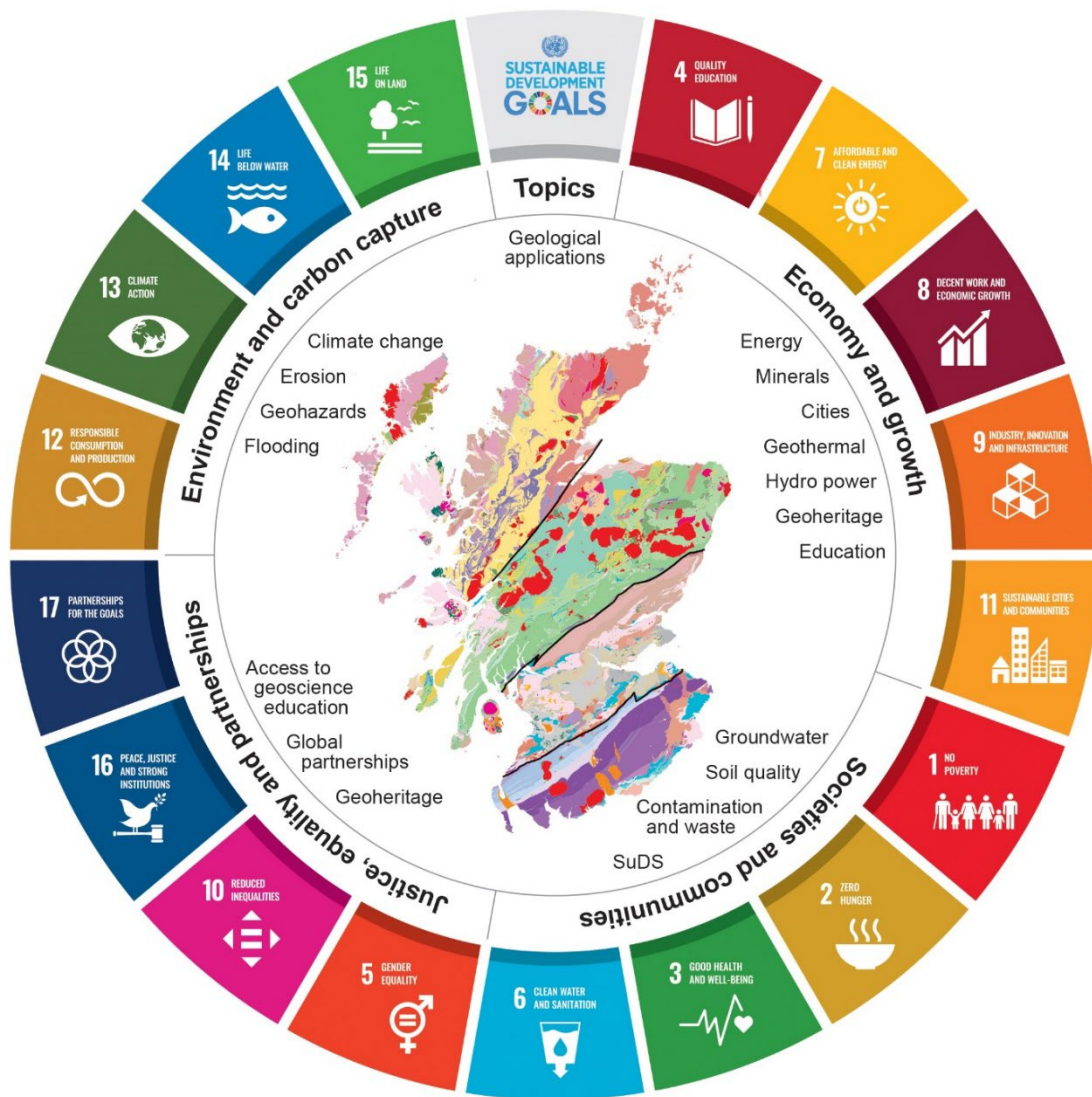


Fig. 1.14:

Global Topic	Activity	Technique	Scotland's Geology	UK & Scottish Government Policy and Guidance Instruments
CLIMATE CHANGE ADAPTATION	Urban resilience	Water quality	Water supply and urban catchments	• SEPA Water Environment (Controlled Activities) (Scotland) Regulations 2011
		Sustainable Urban Drainage System	Run-off, geological underground storage and flooding	• Natural Flood Management Handbook 2015 • SEPA National Water Scarcity Plan 2015
		Contaminated land	Soil chemistry	• Contaminated Land (Scotland) Regulations 2005 • SEPA Regulation on Waste Management Act
	Landscape change	Landfill	Geological containment	• SEPA Regulation on Waste Management Act
		Landslides	Rock and soil type, slope analysis	
		Soil erosion	Slope analysis, material transport	• Scottish Soil Framework 2009
SECURITY OF SUPPLY	Extraction	Coastal erosion	Rock strength and fracturing (hard and soft rocks and Quaternary deposits)	• Coastal Protection Act 1949
	Extraction	Minerals, aggregates and mining	Proterozoic to Permo-Triassic sediments and intrusive rocks in Highlands and Borders Quaternary deposits onshore and offshore	• National Planning Framework 3 2014 • Scottish Planning Policy, Promoting Responsible Use of Resources 2014 • SEPA Regulation on Waste Management Act • Aggregate Levy Tax (Scotland Act) • Marine (Scotland) Act 2010
		Groundwater boreholes and rivers	Devonian and Permo-Triassic aquifers and fractured basement rocks	• EU Groundwater Directive 2006 • SEPA Water Environment and Water Services 2003 • EU/SEPA Regulations for Licensing Groundwater Abstractions including Dewatering 2017
	Extraction - high carbon	Coal mining, deep and open cast Not permitted	Carboniferous rocks of Midland Valley	• SEPA Regulation on Waste Management Act • Coal Authority exploration licences
		Oil & Gas drilling offshore	Triassic to Neogene sedimentary reservoirs and source rocks in North Sea, Rockall and Faroe-Shetland	• Scottish Oil & Gas policy 2018 • North Sea Transition Authority Regulation
		Unconventionals (CBM, Shale gas) onshore drilling Not permitted	Carboniferous rocks of Midland Valley	• Scottish Unconventional Oil & Gas policy 2018 • SEPA Regulatory Guidance 2015
	Extraction - low carbon and clean power	Shallow geothermal (GSHP) trenching and drilling	Clay-rich soils and shallow aquifers	• Local planning
		Shallow geothermal (including mine waters) drilling	Mining of Carboniferous deposits (coal, ironstone, limestone) in Midland Valley and offshore	• SEPA Requirements for activities related to geothermal energy 2019 • Coal Authority permitting
		Deep geothermal drilling	Sedimentary rocks (Hot Saline Aquifers) Intrusives - granites (Hot Dry rock) in Highlands	• Regulatory Guidance for Geothermal Heat in Scotland 2016
		Hydro power pumped storage	Major fault-related topographic features, basement rocks and granites in Highlands	• Hydroelectricity (Scotland) Development Act 1943 • Water Environment (Controlled Activities) (Scotland) Regulations 2011
		Offshore wind	Sea bed and foundation conditions (bedrock and Quaternary deposits) offshore	• Scotland's National Marine Plan 2015
Injection - carbon mitigation	UCCS	Offshore Oil & Gas fields in Triassic to Neogene sedimentary reservoirs	• The Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 • Marine Scotland and North Sea Transition Authority	
	Compressed gas storage	Offshore Oil & Gas fields in Triassic to Neogene sedimentary reservoirs	• Guidance on the Regulatory Regime for Gas Storage Facilities in Great Britain 2015	

Fig. 1.15

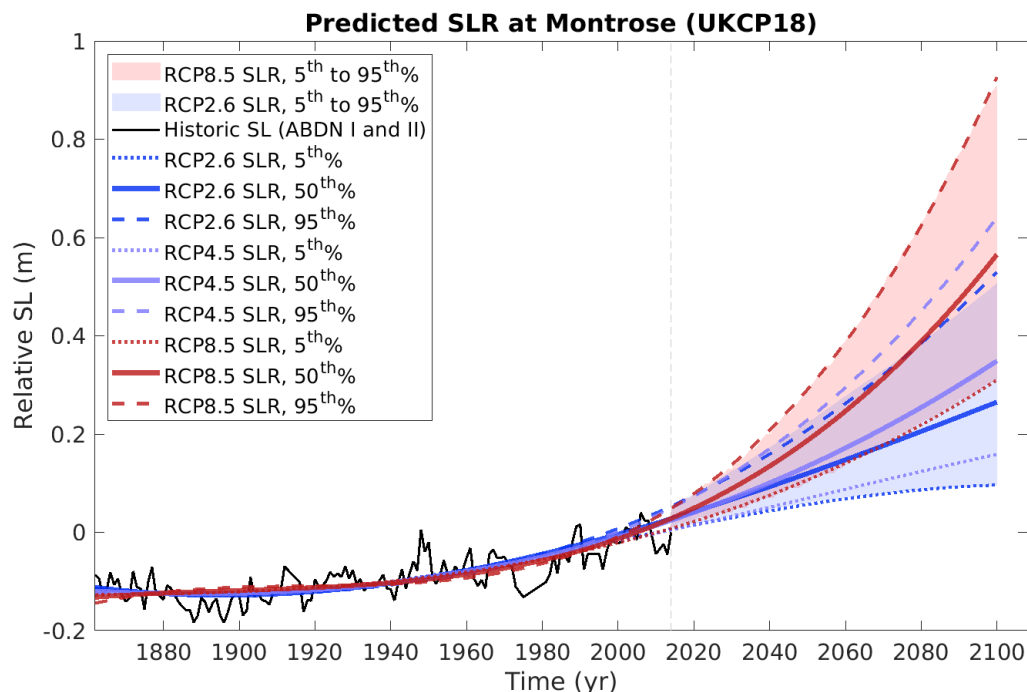


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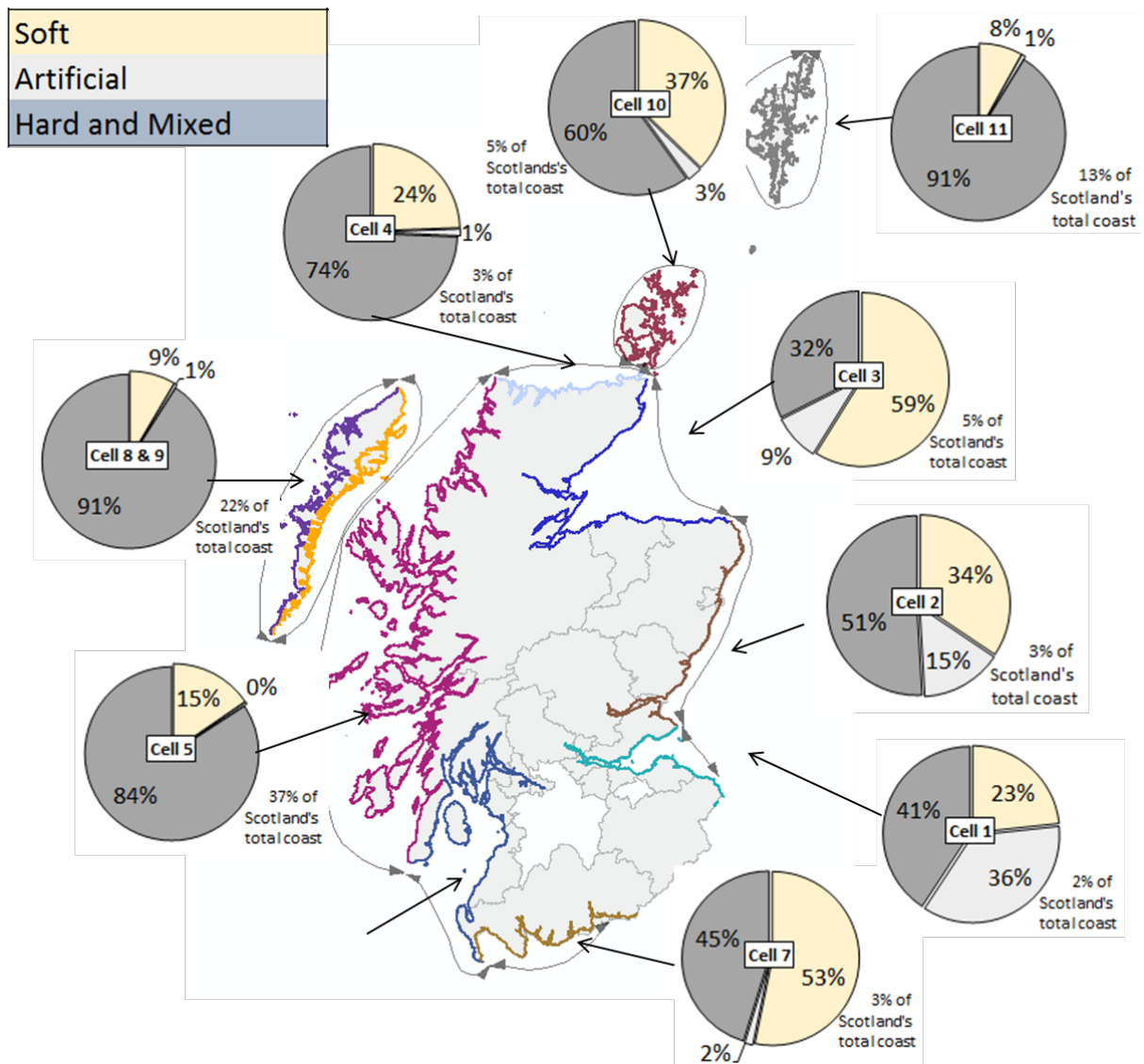


Fig. 1. 17:



Fig. 1.18: