The long and moving story of the Great Glen Fault

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Abstract: The Great Glen fault is perhaps the best known fault in Britain, and its nature and history have been discussed extensively. It defines a very obvious trough SW-NE across the full width of the Scottish mainland, occupied by a series of lochs and the Caledonian Canal. Concensus is that it is a strike-slip fault within a broad zone of structural complexity, originating towards the end of the Caledonian orogeny. Open to debate have been the amount, direction, timing and number of episodes of movement. The favoured conclusion is of two main periods of movement: sinistral slip of around 100-200 km during the Devonian (late-Caledonian), with dextral slip of up to 30 km during the Mesozoic or Cenozoic, but this generalisation conceals a wealth of varied opinion. The fault zone remains seismically active, and offsets in the modern drainage pattern suggest that movement is far from over. A literature review reveals how methods of research have changed, and ideas have evolved through new technological capabilities and better understanding of the Earth, over the last 180 years.

The Great Glen Fault is a major geological feature that traverses southwest to northeast across the Scottish mainland from Fort William to Inverness. The deep trough eroded along its path is occupied by several lochs, which Thomas Telford linked during 1803–1822 by a series of short waterways to form the Caledonian Canal at a cost of about £900,000 (£70 million in today's money). The floor of this kilometre-wide trough lies at about 40m O.D., with flanks rising to over 700m on either flank (Fig. 1).

The offshore continuations of the fault have given rise to much discussion, but it is reasonable to assume that they control the linear western coast of the Moray Firth and continues north-eastwards, close to the Caithness coast (Fig. 2). Some researchers (especially Flinn, 1961) have suggested a direct link with the Walls Boundary Fault through the Shetlands, others (Bott & Watts, 1970) preferring a passage east of these islands. McBride (1994) has described a "stepover structure" to associate the two faults while allowing them to retain independent movement histories. Harland (1969) proposed an extension as far as Spitsbergen's eastern boundary fault. Towards the south, the fault passes along Loch Linnhe and has been traced in Morvern and southeastern Mull. Bailey (1916) suggested it continues as the Loch Gruinart Fault on Islay, but this was disputed by Westbrook & Borradaile (1978); Pitcher et.al. (1964) suggested a continuation as the Leannan Fault in Ireland, and Wilson (1962) speculated on a link with the Cabot Fault in Canada.

Electrical resistivity data suggested to Meju (1988) that the structure is a very deep one, extending to a depth of at least 60 km, essentially to the base of the crust. This was echoed by Canning et.al. (1998) who concluded from contrasting neodymium isotopic signatures that the fault represents "a major vertical lithospheric boundary" separating "two suites of lamprophyric dyke segregation" generated at depths greater than 100 km. Stewart et al. (1997) noted contrasting, deep, Lewisian and Rhinnian basement rocks either side of the Great Glen Fault, but did not see evidence for reactivation of an older, Proterozoic, structure.

***Figure 1**. The southern part of the Great Glen, looking northwards to Loch Lochy, with Loch Ness barely visible in the distance (photo: British Geological Survey).*

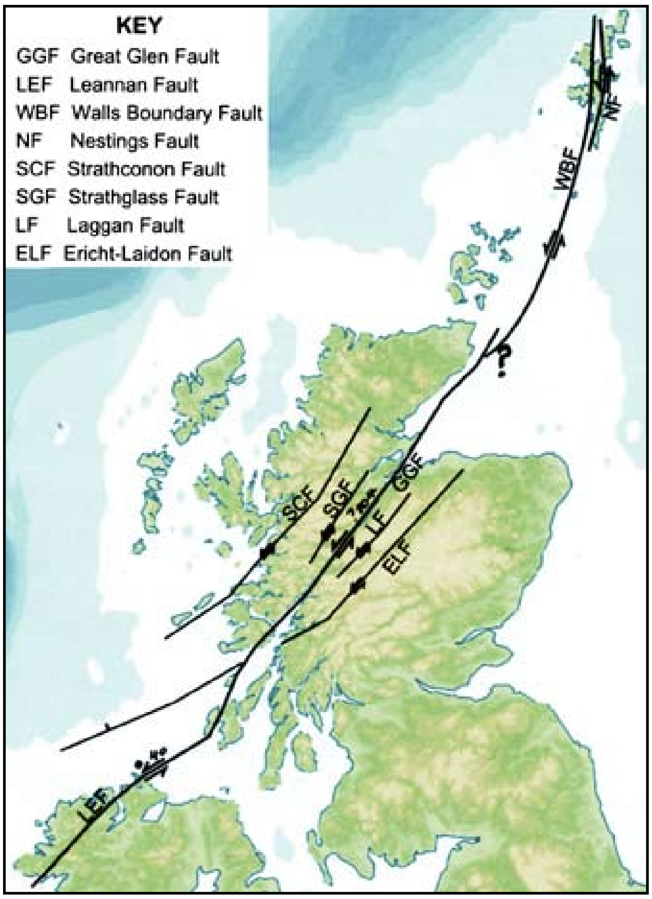

***Figure 2**. Major faults associated with the Great Glen.*

Historical Observations

Early commentaries on the Great Glen include Hugh Miller's 1841 description of "a foot track hollowed by the frequent tread of earthquakes". This suggests an understanding of the presence of a fault line, apparently a step up from MacCulloch's 1836 seminal geological map of Scotland, which does not specify this (or any other) major Scottish faults. Murchison and Geikie (1861) appear to have been the first specifically to describe this fault as "a fracture.... without a throw......formed by preferential erosion along a line of crushed and broken rock". Geikie (1865) modified this, suggesting a normal fault with downthrow to the southeast.

The Early Surveyors

Survey geologists were next to offer their observations and opinions in the course of their systematic field mapping. Horne and Hinxman (1914) suggested a downthrow of at least 6000 feet and Cunningham Craig (1914) noted the presence of horizontal slickensides as the first sound evidence of lateral displacement.

In later contributions, Shand (1951) and Parson (1979) seem to have been the only authors to cast doubt over what is now the prevailing acceptance of a strike-slip fault. Neither was able to discern direct evidence for transcurrent movement in the field. Bailey (1916) and his co-workers drew attention to a mis-match between metamorphic grades, being much higher on the northwestern side of the fault (which could be explained by either vertical or lateral movement). They further suggested that the Loch Gruinart Fault on Islay was a continuation of the Great Glen Fault, and that the Moine Thrust was offset along this extension. His diagram suggests a dextral displacement of some 40 km, but this is the result of an unsustainable 'kink' in the line of the Moine Thrust, which he later retracted. Barrow held the alternative view that the Great Glen Fault was a thrust-plane (in discussion of Tilley, 1925).

The Academic Era

Richey's 1939 analysis of Scottish dyke swarms of various ages led him to conclude that the Great Glen structure formed sometime between the early Devonian and late Carboniferous; his was the first attempt to ascribe an age to the fault. This coincided with a seminal work read by Kennedy in 1939, but only published after the war in 1946. The main elements of his argument for a sinistral displacement of 104 km were the separation of the Foyers and Strontian granites, which he regarded as a single intrusion, and the displacement of several features, notably the Highland metamorphic zones, the Moine Thrust and a "great belt of regional injection" within the Moines (Figs. 3, 4). The concurrence of small, isolated, late Carboniferous outcrops at Inninmore (Morvern) and in the Pass of Brander guided him towards the early Carboniferous as the latest possible date for such movement, which he erroneously believed to be an early manifestation of Hercynian events.

The unity of the two granites has found few proponents (Marston 1967, 1970) and rather more opponents. Munro (1965, 1973) saw structural differences between these two bodies; Ahmad (1967) found geophysical reasons to separate them (and, incidentally, project the fault line out into the Atlantic rather than across to Ireland); Pidgeon and Aftalion (1978) discriminated between the two granite bodies with zircon parameters, and Pankhurst (1979) did so on the basis of trace element studies. This particular criterion does now appear to have had its day.

Although somewhat subjective, rather than describing a chronological list of research, further discussions trace individual criteria that Kennedy's paper had introduced, as nearly all subsequent workers tended to follow single threads of the argument. This perhaps reflects the fact that geology had moved into an age when individuals specialised in particular aspects of the science. The day of the generalist was largely over.

A scatter of papers over several decades continued Richey's theme of investigating the Highland dyke swarms. Johnstone and Wright (1951) were the first to suggest two periods of movement, before and after the intrusion of the Permian dyke swarm across the region. Leedal (1951), working on the same Permian

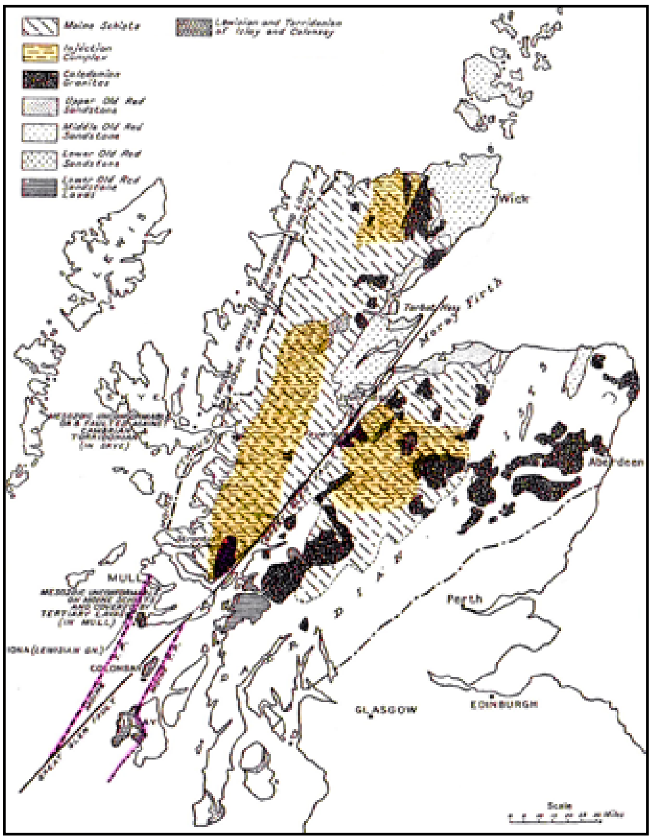

Figure 3 *[above]. Key elements of the geology of the Scottish Highlands, as seen by Kennedy in 1946.*

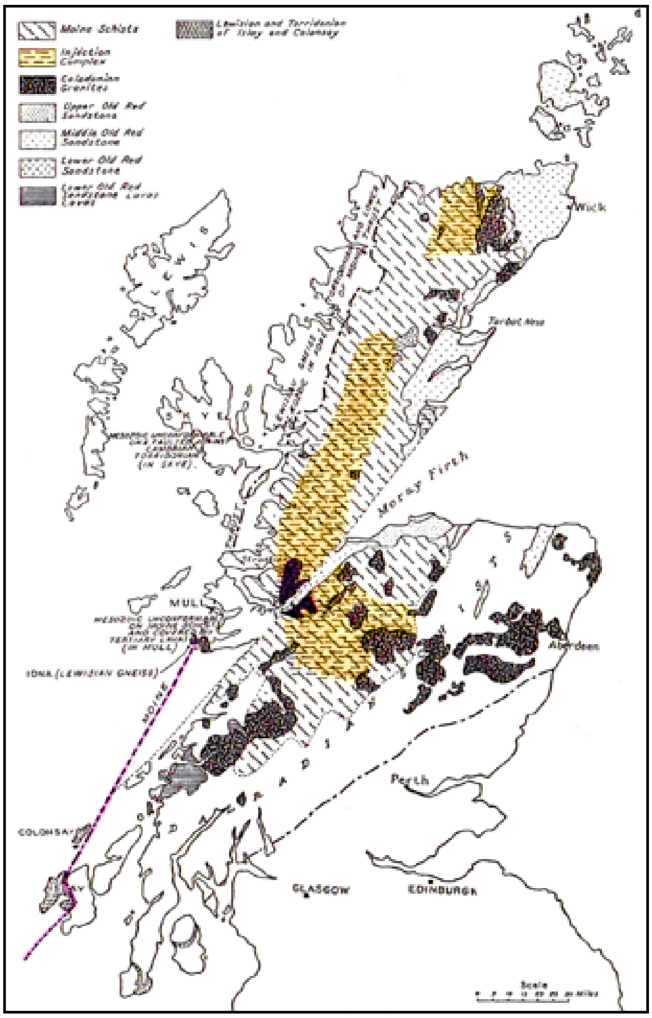

Figure 4 *[right]. The Scottish Highlands prior to sinistral displacement of 104 km along the Great Glen Fault, as interpreted by Kennedy, 1946.*

lamprophyre dykes in the Loch Arkaig area, concluded there had been a "small" sinistral movement on local minor faults and, by extension, along the related Great Glen Fault. Holgate (1969) also recognised two periods of movement: while noting a pre-mid Old Red Sandstone sinistral shift (earlier than Kennedy's timing), he also believed that a sharp change in intensity of the Skye Palaeogene dyke swarm between Morvern, Lismore and Lorne pointed to a later dextral shift of some 29 km (Fig. 5). In similar vein, Speight and Mitchell (1979) analysed the Permo-Carboniferous dyke swarm in Argyll and demonstrated that there was a sharp discontinuity in crustal dilation across the Great Glen Fault that was best explained by a dextral shift of around just 7–8 km sometime between the Permian and Tertiary dyke swarm events.

Another field of research, especially in the late 1960s and 1970s concerned studies of major intrusions. Halliday (1979) added to this with a study of the 'Newer Granites' of Northern Scotland and found that the ^{87}Sr/^{86}Sr isotope initial ratios were more in accordance with a dextral displacement of around 80–100 km. More obliquely, both Hutton & McErlean (1991) and Stewart et. al. (2001), worked on separate intrusions (the Ratagan granite, dated to 425 Ma, and the Clunes tonalite, dated to 428 Ma) to show how the focus of magmatic activity was influenced by sinistral shearing on the Strathconon and Great Glen faults respectively, producing a clear planar fabric in the two granitic bodies. This supports a relatively early, mid-Silurian, date for initiation of movement on the suite of faults trending NE-SW in this area, and accords with the fact that the earliest fault rocks are blastomylonites that one would associate with ductile viscous creep at considerable depth and elevated temperature. Miller and Flinn (1966) determined a maximum middle to late Carboniferous age for initiation and dextral movement on the Walls Boundary Fault based on the age of the Sandsting complex, but this has since been called into question as better, older, dates have been obtained.

Metamorphic or thermal histories of the region proved fertile ground, mainly between 1970 and 1974, since Bailey and Kennedy first noted a discontinuity in the grade and pattern of metamorphic zones in the region. Marston (1967, 1970) believed this could be explained by vertical movement resulting in contrasting erosion levels within the Caledonian orogen. Winchester's (1973, 1974) zonal mapping arrived at the conclusion that there was a sinistral post-metamorphic shift of 160 km along the Great Glen Fault, offering detailed reasons why his use of index minerals in Moinian calc-silicate gneisses produced more reliable results. This figure was accepted by Piasecki et al. (1981), who found that it also brought into better alignment other features of Neo-Proterozoic stratigraphy. An allied approach involves the contouring of intrusion ages and cooling dates. Dewey and Pankhurst (1970) applied this method and fitted their “chrontours” with Kennedy’s 104 km sinistral movement (although believing the movement to be late Silurian, much earlier than Kennedy had concluded) but this was challenged by Brown and Hughes (1973), whose Caledonian isochrons revealed a dextral movement of 120 km, mainly during the Lower Devonian with some later reactivation. They also argued that this was incompatible with sinistral movements of just 40 km on the Leannan Fault, which must therefore be, at best, a splay off the Great Glen structure.

An ambitious and wide ranging contribution to the debate appeared at this time (Garson & Plant, 1972) and added complexity to the argument by introducing two branches to the Great Glen structure, having separate displacement histories. Their conclusion distils down to 120 km of dextral displacement in the Lower Devonian along a southern branch extending from the Leannan Valley to the Moray Firth and beyond. Simultaneously, there was 88 km of dextral displacement along a northern branch, through eastern Mull and along the Great Glen (continuing just to the east of Shetland?) forming the northern edge of a graben. Further movement occurred in late Cretaceous times, in particular 32 km dextral displacement affecting sediments deposited and dykes intruded in the interim; this followed an intermediate course in the west before passing via the Firth of Lorne Fault into the primary graben of crushed rock and linking up with movement on the Walls Boundary and Nesting faults in Shetland. The detailed evidence for all this is not made entirely clear, but their reconstructions for the juxtaposition of various igneous and metamorphic features, included two areas of unusual early Devonian fenitic metasomatism. This was supported and developed by Garson et al. (1984) who suggested possible dextral movements of either 0, 25 or 50 km.

The first use of any geophysical technique was in relation to the Strontian and Foyers granites (Ahmad, 1967). Flinn (1969) used aeromagnetic and other data in suggesting a link with the Walls Boundary Fault, and a prolonged exchange of views with Bott and Watts on the line of the Great Glen Fault ensued thereafter. Flinn suggested 65 km of post-Devonian, dextral, displacement in Shetland, and surmised that this might be even greater in basement rocks. Bacon and Chesher (1975) deduced from seismic reflection work in the Moray Firth that Mesozoic movement on the Great Glen Fault was entirely normal. By contrast, McQuillin et al. (1982) came to the opposite conclusion, arguing that crustal extension in the Moray Basin necessitated about 8 km of dextral displacement on the Great Glen Fault during the Mesozoic. Underhill and Brodie (1993) supported this within a more complex and long-lived framework of both compressional and extensional reactivation during phases of basin inversion. Other contributions from geophysical work were by Meju (1988) and McBride (1994). The geophysicists seem to have been silent on the subject since the mid-1990s.

Perhaps the most arresting chapters in the overall story come from the field of palaeomagnetic research. This began in 1974 with the first of several contributions from Storetvedt, who hypothesised 200–300 km of sinistral displacement based on Old Red Sandstone (ranging from upper Silurian to upper Devonian) poles for northern Scotland and Norway, while conceding that some of the data includes an “exceedingly complex magnetic record”. In response to a generally unfavourable reception (Storetvedt, 1975) he drew comfort from Winchester’s similar overall conclusion (see above). He further suggested that a still larger displacement “of the order of 500 km” might be even nearer the mark, and that the real evidence may lie offshore and hence require a geophysical solution. A yet grander suggestion came from Van der Voo and Scotese (1981) working on middle and late Devonian palaeomagnetic data from cratonic North America

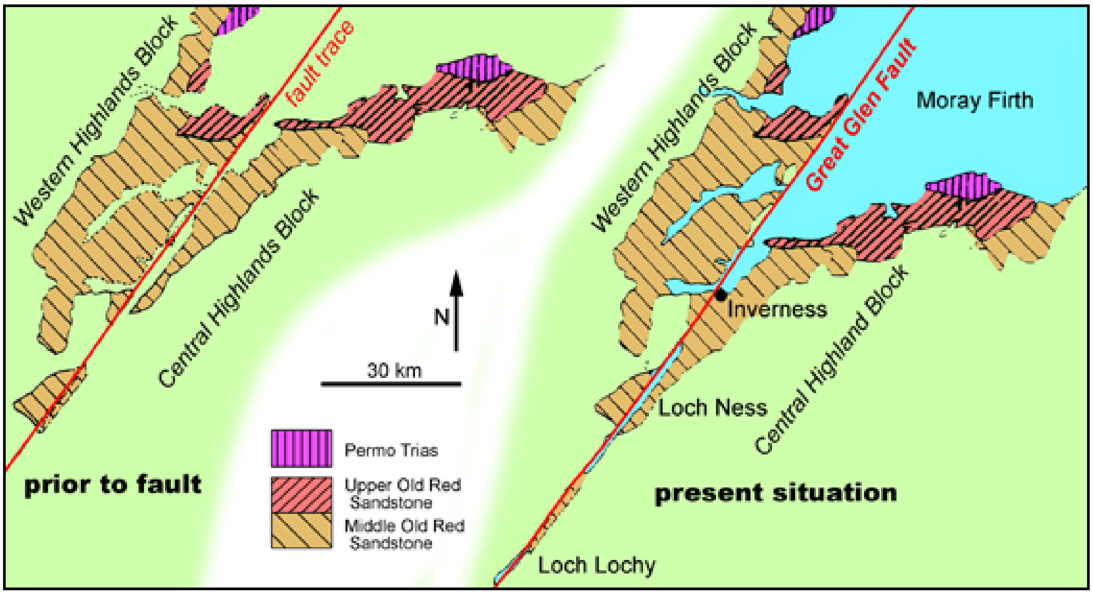

***Figure 5**. Outcrops of the Old Red Sandstone before and after 29 km of dextral movement on the Great Glen Fault (as interpreted by Holgate, 1969).*

and Europe. They registered 2000 km of sinistral displacement between these continents at that time and believed the Great Glen Fault was the likely focus for this movement. The reaction to this has been largely negative. Torsvik (1984) demonstrated that the magnetizations of several “Newer Granites” were incompatible with such large movements. Storetvedt (1987) rejoined the debate with a further rebuff, using a synthesis of palaeomagnetic data spanning both Ordovician and Devonian formations; he believed that he had “uncovered two major phases of transcurrent motion”, namely some 600 km of sinistral movement during the late Middle Devonian and 300 km of dextral movement during the Hercynian orogeny. In a final contribution (Storetvedt, 1990), he adds a third period of (? mainly) vertical movement during early Tertiary (Alpine) times. Other workers in this field (e.g. Turner et al., 1976) have noted the difficulties of using Devonian red sandstones to unravel tectonic histories due to their complex diagenetic and palaeomagnetic properties. This area of research has also had little to add since around 1990.

Some contributions do not fit comfortably into the main criteria, and are more conveniently seen as miscellaneous researches, just one of which reaches any conclusions about the amount of movement. Mykura (1975) noted the unusual occurrences of scapolite mineralisation on Fair Isle and in the Shetlands, and postulated a dextral displacement along the Walls Boundary Fault of about 80 km to reconcile them. However, he remained uncertain about a direct link with the Great Glen Fault.

Many commentators, especially through the 1960s to 1980s, tried to unravel this problem by identifying stratigraphic inconsistencies astride the line of the fault: this is, after all, the most obvious way to approach such a question, especially for small to moderate displacements. Unfortunately Highland geology is sufficiently complex to make this a seemingly intractable proposition, and only a few attempts have resulted in any quantitative results, mostly in regard to later, and smaller, phases of movement. In addition to his dyke-intensity argument, Holgate (1969) used the pattern of upper Old Red Sandstone and Permo-Triassic outcrops around the Moray Basin to support his case for a dextral movement of 29 km post-dating the Palaeogene dyke swarm on Skye (Fig. 5). This gained support from Sykes (1975) and Parnell (1982), focussing on details of the Jurassic and Old Red Sandstone respectively. Donovan et al. (1976) also agreed that such views were more suited to the disposition of the middle Old Red Sandstone of the Inverness district, and were strongly opposed to large scale post-Devonian movements. Johnstone and Mykura (1989) likewise specifically supported the reduced scale of this later phase of movement, while making no judgements on earlier displacements. Astin (1982) arrived at a displacement of around 95 km based on the similarities of the Old Red Sandstone successions on Fair Isle and the Walls Peninsula in Shetland. Donovan and Meyerhoff (1982) added that sufficient similarities exist within the Moinian rocks either side of the Great Glen to preclude vast displacements in the order of 2000 km. Smith and Watson (1983) expanded stratigraphic studies to include the Archean and Proterozoic basements as well as the Dalradian metasediments, revealing criteria that are incompatible with the large displacements suggested by the palaeomagnetic fraternity. Rock et al. (1984) examined anomalous Precambrian calcareous rocks along both sides of the Great Glen and implied, irrespective of their precise stratigraphic position, that they form an homogeneous association inimical to large subsequent dislocations. Similar successions occur astride the Walls Boundary Fault in the Shetlands, where the same conclusion applies. Based on the nature of surviving Devonian stratigraphy, Rogers et al. (1989) reached different conclusions on the amount and timing of dextral movement along the Great Glen and Walls Boundary faults. They agreed with around 25–29 km on the former (considering most of that movement to have taken place between the late Devonian and early Permian), but followed Mykura’s (1975) figure of around 80 km on the latter. They also discerned greater deformation in older rocks, in line with earlier sinistral movement that had ceased by the middle Devonian.

***Figure 6**. The long and very deep Loch Ness, in the Great Glen.*

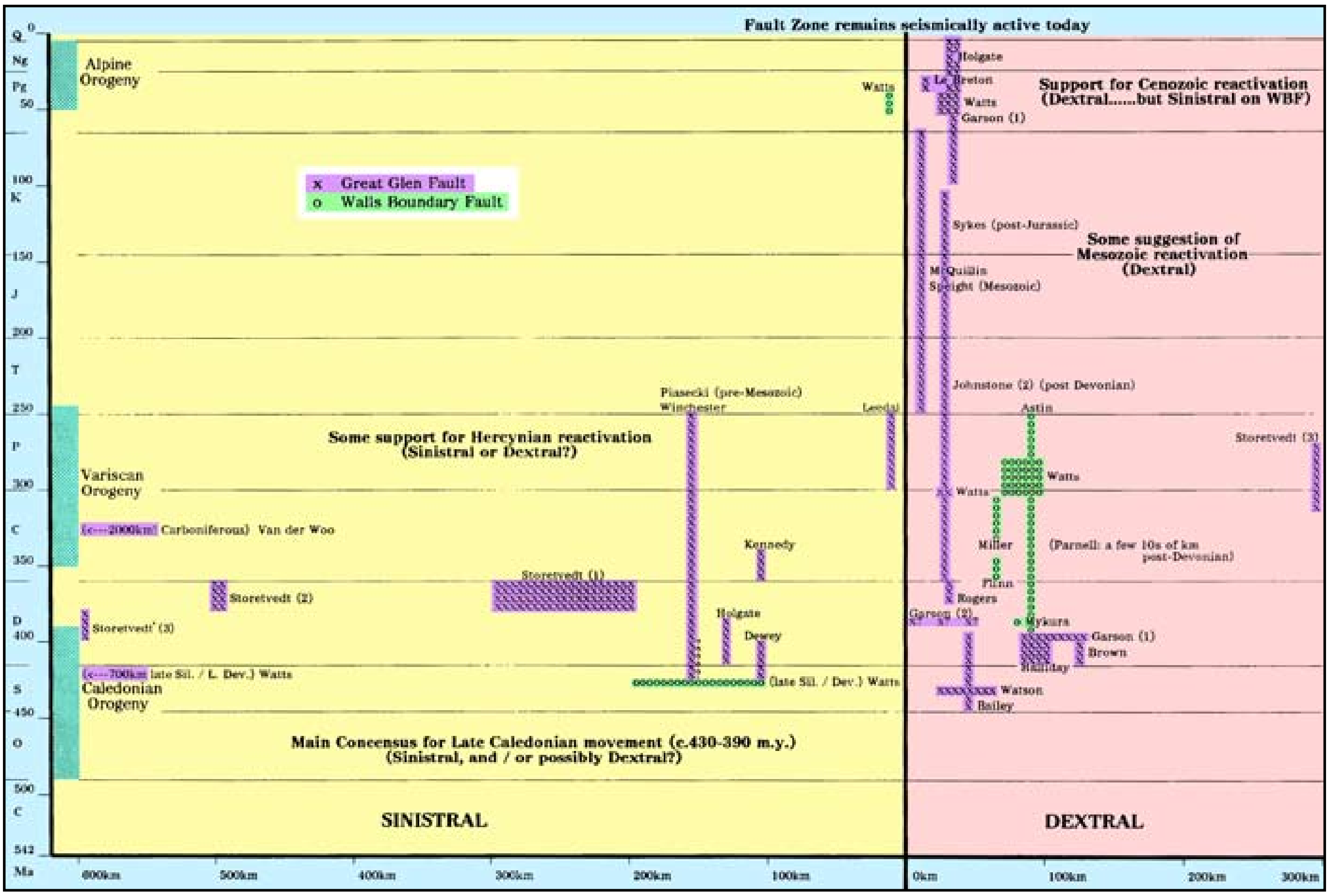

***Figure** 7. Movements of the Great Glen Fault as interpreted by multiple researchers.*

Finally, most contributions on the Great Glen Fault have been founded on structural or tectonic data. However, some later researches, especially since around 1990, have given more attention to the kinematics and broader plate-tectonic context of fault movements in the region, with less inclination to quantify them. One exception was Watson (1984) who believed that the fault system originated around 420 Ma (late Silurian) and, on examination of the overall basement fracture pattern, noted a discontinuity between areas on either side of the fault where east-west fractures are more conspicuous. Although not explicitly stated, her map implies a dextral shift of around 50 km, and certainly favoured the lower end of the range of values suggested by others. Most recently, Le Breton et al. (2013) have described minor folds and faults in Jurassic, marine, off-shore sediments with bedding-parallel calcite veins that most probably developed in response to displacement along the Great Glen Fault during Cenozoic exhumation. Much in line with previous estimates, they suggested a shift of between 10 and 18 km, and their preferred timing is 37–26 Ma to coincide with "an uplift episode of Scotland, intraplate stress from the Alpine orogeny, a pulse of the Iceland mantle-plume, and [conjugate] left-lateral slip along the Faroe fracture zone". Watts et al. (2007) provided a most comprehensive investigation into the kinematic history and nature of the fault rocks associated with the Walls Boundary Fault. They conclude that early Caledonian, sinistral-slip, ductile deformation products (mylonites) are widely obscured by later, dextral-slip brittle overprinting (cataclasites) "probably during late Carboniferous inversion of the Orcadian basin". Finally, there is evidence of post-Triassic dip-slip and Tertiary sinistral strike-slip reactivation producing more brittle fault products and fault gouges. Similar work by Stewart et al. (1999) on the Great Glen Fault broadly produced the same pattern in fault-rock products, but with significant differences in the displacement history. Thus the Caledonian sinistral movements were estimated to be 100–200 km on the Walls Boundary Fault but possibly as much as 700 km on the Great Glen Fault: this was a return to the realm of 'palaeomagnetic-scale' displacements! They claimed that late Palaeozoic dextral shifts were in the order of 65–95 km on the Walls Boundary Fault, but only 20–30 km on the Great Glen Fault, whereas Tertiary shifts were more in line with each other at around 15–30 km magnitude, but, in a final twist of complexity, sinistral in Shetland and dextral on the mainland!

Synthesis

Whilst the movement history of the Great Glen Fault has received much attention, only a general concensus has been established. The matter has been approached in a variety of ways with, at times, widely diverging conclusions. Different criteria have been topical at different times and no single approach seems capable of yielding the overall picture. In recent times there has been a move to focus more on the general kinematic history, after earlier researches had often sought to be more specific in quantitative terms.

An attempt to gather all the published quantitative results is presented in graphical form (Fig. 7). The main facts agreed upon are that the Great Glen Fault originated as a wrench-fault during the later phases of the Caledonian orogeny, probably during the Silurian or possibly early Devonian period. A strong concensus associates early sinistral displacement with closure of the Iapetus Ocean at this time. Early deformation has been shown to be consistent with a more ductile environment where the evidence survives, but this has been widely masked by later, increasingly brittle, fault products. There is less concensus on these later phases of movement, which may have recurred two or three times from the late Devonian onwards, particularly during late Mesozoic or early Cenozoic times, and are generally believed to have been dextral displacements.

The thorny issue of the identity of the Great Glen Fault beyond the mainland has not been established with any certainty, and the convenient notion that it continues directly through Shetland as the Walls Boundary Fault must be in some doubt as their respective movement histories appear to be quite different. Likewise, the link with the Leannan Fult in Ireland is difficult to reconcile in detail. The likeliest situation is that of a complex fault zone with many splay faults only loosely associated with each other, perhaps to the extent of a two-sided graben structure as suggested by Garson and Plant in 1972.

Later Events

Present day seismic activity suggests that movement on the Great Glen Fault is continuing. There have been at least a dozen recorded earthquakes since the largest historical event in Scotland, which reached a magnitude of M 5.1 near Inverness in 1816. It has been suggested that the Quaternary drainage system shows signs of disruption, so incremental movements are presumably on-going. That we do not associate this with any orogenic activity serves to highlight the disjunct between movement history on ‘deep-time’ scales and that which we perceive on the human time scale. Perhaps the fault’s movement record has really been more of a continuum throughout geological time, with some periods of enhanced tectonic activity showing up more clearly in the geological record.

Any description of the Great Glen would not be complete without a mention of ‘Nessie’. One final thought concerns the suggestion (Piccardi, 2001) that seismic tremors releasing bubbles from the bed of Loch Ness may lie behind the myth of the Loch Ness Monster. This is perhaps no less believable than some of the things written in more serious vein!

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