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Geikie's field researches and their geological controversies

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Figures – now in colour (except historical reproductions from papers) and photographs added of some field locations to better illustrate the paper.

Rob Butler
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Geikie's field researches and their geological controversies

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Abstract

Archibald Geikie's (1835-1924) field research led to better understanding of geological relationships and, ultimately, earth processes. We consider three pieces of research in Scotland, from his early work on Skye through the execution and impact of his 1860 expedition to the NW Highlands with Murchison, returning to Skye to consider arguments with Judd on igneous relationships. We describe the field locations and place modern interpretations in their historical context. We discuss how methods and approaches for building interpretations in the field were modified and improved through debates. Reliance on a few "critical outcrops" served to anchor interpretation at the expense of understanding more complex exposures. Similar bias appears to have arisen from using simple exploratory transects which were only mitigated by proper mapping approaches. Significant misunderstandings between protagonists appear to have arisen through the reliance of text description rather than diagrammatic illustrations. The vitriolic nature of debate seems to have anchored misinterpretations, obscured interpretational uncertainty and promoted false-reasoning by inhibiting inclusive scientific engagement.

In the 19th century, the rocks of the Highlands and Islands of Scotland inspired early understanding of many geological concepts – and the key to these insights was fieldwork. Even before the start of his professional career, Archibald Geikie (1835-1924) was driven to be a leading figure in these efforts. It was an ambition that underpinned his life's work as a practicing geologist. Geikie had a passion for rocks and for travel that saw him undertake fieldwork all over the planet. But we can explore his activities by using examples from NW Scotland that dealt with the structure of the NW Highlands and the igneous geology of Skye (Fig. 1). Not only did these two sets of investigation shape his legacy, they also promoted and provoked intense debate through the later part of the 19th century. Some of the issues rumble on today. Central to these debates were the relationships between data, basic field observations, and interpretation in terms of structural (geometric) relationships. A number of questions arise: How are individual "critical" outcrops used to test or promote particular hypotheses? Once developed, how far do hypotheses serve to anchor future interpretations? And how do these anchors become more firmly rooted by the nature of the debates surrounding them, especially through the words of their advocates?

In his account of Geikie's researches, Oldroyd (1980) warns of seeking motives and explanations for historical actions from a modern standpoint. It is however useful to explore rationales behind various approaches and choices adopted by Geikie and his contemporaries. Oldroyd (1997) presents a case for Geikie's professional ambition driving his endeavors – a narrative followed by Dewey (this volume). Geikie was scarcely alone in this, then and now. But focusing on the outcomes of Geikie's research can obscure some of the decisions – especially in the types of scientific problem that he chose to investigate. We show here that Geikie operated within a fiercely adversarial scientific community – one in which advocacy played a role perhaps as important as the conduct of the science itself. In the preamble to one of his papers in the arguments with Judd, Geikie (1894, p. 215) writes: "Disliking controversy so thoroughly as I do, I even refrained from replying to what I regarded as misconceptions or mis-statements of my views…" As we shall see, this belies a rather more combative approach instilled throughout 19th century geoscience.

The sequence of discussions and debates are important here as successive presentations and publications ratcheted up the rancor between participants. Until well into the 20th century it was common practice for research results to be audibly read at meetings of the Geological Society in London – either by the principal author of the work or, if they were unable to attend in person, by another individual – commonly the Society's president. There commonly followed a discussion, in effect a question and answer session, where the assembled fellows of the Society could cross-examine, confirm or generally applaud the presented paper. The paper itself, together with an account of these discussions, perhaps with further reflections by the authors, was then printed in a subsequent issue of the Quarterly Journal – usually within a few months of the presentation in the Society's chambers. These documents provide much of the material for this paper, supplemented by Geikie's own commentary from his autobiography (Geikie 1924), Oldroyd's definitive histographies (1980, 1990, 1997; Oldroyd and Hamilton 1996) and by our own knowledge of the field locations themselves. Readers wishing to visit the field localities are recommended to consult the excursion guide to Skye by Bell and Harris (1986) and, for the southern Moine Thrust Belt, the Geological Conservation Review volume on the Lewisian, Torridonian and Moine Rocks (Mendum et al. 2009).

Strath

The fieldwork that led to Geikie's first major scientific publication (Geikie 1858) was carried out on Skye. This might appear to be a curious choice – given its remove from his home in Edinburgh coupled with the difficulties of travel in the mid 19th century. However, following the pioneering work by John Macculloch (1819), the ground between the village of Broadford and Loch Slapin (Fig. 2) had achieved special importance in settling the debate between Neptunists and Plutonists in the early decades of the century, as Geikie later noted (Geikie 1888). For Neptunists igneous rocks, including granite, crystallized from an ocean whereas Plutonists considered igneous rocks to have originated in the deep earth and from there were either erupted or intruded. Igneous intrusions into rocks of clearly sedimentary origin were inconvenient for the Neptunists

whilst the occurrence of fossiliferous strata in association with igneous rocks could be problematic for the Plutonists. The Isle of Skye contains both of these occurrences.

In the parish of Strath, fossiliferous Lower Jurassic limestone outcrops on the coast – both at Broadford and Loch Slapin (Fig. 2) but "no sooner do they strike into the interior [inland] than, in many localities, all seems to be involved in hopeless confusion" (Geikie 1858, p2). Rocks, apparently devoid of fossils, were locally strongly metamorphosed into marble, interleaved with other sedimentary rocks and invaded by various igneous rocks.

The "hopeless confusion" demanded understanding. This was a general scientific problem: the approaches for understanding connections between igneous and sedimentary rocks formed the first item of advice in the "Instructions for the Local Directors of the Geological Survey of Great Britain and Ireland" issued by survey chief Henry de la Beche (1845). Although Macculloch's (1819) work had established the intrusive origin of many igneous rocks and that this was associated with metamorphism, and apparently deformation of the surrounding sedimentary rocks, the nature of these effects and the processes that might be deduced from them were very poorly resolved. In his autobiography, Geikie notes that he discussed his plans with Hugh Miller, who visited him in the field in 1853, and they exchanged ideas on the geology there until Miller's death in 1856. The geology of Skye was topical and whatever came out of his early researches, Geikie was sure to interest a highly influential audience.

Geikie began his work on Skye in September 1853, staying with the minister in Strath (in modern Broadford, Fig. 2), Rev. John Mackinnon, returning for the following three summers. The ground over which Geikie worked is not especially well-exposed, except along the coast (Fig. 3). Although the limestones and granite do form significant outcrops, the boundaries are generally obscure and tracing geological boundaries demands some diligence. Geikie recounts that he was assisted by an otter-terrier who was able to track down rock outcrops in the thick summer vegetation. All these efforts clearly did not go un-noticed: Geikie again recounts being referred to by the crofters of Strath as " gille na clach" – the lad of the stones.

Undoubtedly a challenge facing Macculloch in his original work on Skye earlier in the 19th century, as elsewhere, was a lack of accurate base maps. By the 1850s Geikie had the advantage of Admiralty charts (Fig. 4) that depicted bathymetry and an accurately surveyed coastline. The hills visible from sea were also well-located – for sighting purposes by shipping. However, other inland features and hills hidden from the sea were shown only schematically if at all. He traced out his own base-maps from copies of the charts belonging to a naval captain, resident in the Kyle of Lochalsh (Geikie 1858). Geikie supplemented these with his own compass bearings but acknowledged that the final map was "far from being accurate" (Geike 1858, p. 23). He continued his own research on Skye even as began employment with the Geological Survey. It is unsurprising therefore that he persevered for four field seasons, before declaring his mapping of the parish of Strath to be complete. The results were read by Professor Andrew Ramsay in London to a meeting of the Geological Society in April 1857 and published in the society's Quarterly Journal the following year (Geikie 1858).

Geikie (1858) provided an exceptionally thorough description of field locations, illustrated by a map, cross-sections and sketches of field relationships reproduced as a large fold-out (Fig. 5). His detailed text descriptions were tied explicitly to specific locations for the Liassic strata from Broadford area, and the shores of lochs Slapin and Eishort on the SW side of Strath. He then turned his attention to the "hopeless confusion" of the interior, where "the bedded limestones of Broadford Bay are altered into a crystalline mass" (Geikie 1858, p. 18) basing his account on a series of cross-sections. These illustrate broad NE-SW-trending folds but he noted that these belie complexity. The stratigraphic continuity was not as expected: "its regularity has been assailed by syenite and faults" (Geikie 1858, p. 8).

Various forms of acid igneous rocks on Strath were conflated under the term "syenite". Oldroyd and Hamilton (1996) suggest that early workers, including Macculoch and Geikie, avoided the term "granite" because, in some quarters, it still held "Neptunian" connotations of having crystallized out of a primordial sea. Comprehensive petrological descriptions and their related classifications had to wait until the fundamental work, commissioned by Geikie in his later years, by Arthur Harker (1904). Nevertheless, Geikie described field

relationships that allowed him to distinguish two distinct suites of syenite. One was concordant to bedding within fossiliferous Jurassic strata and had "insinuated itself between these planes" while the main "bosses" of syenite had "tilted up, pierced and greatly metamorphosed the strata" (Geikie 1858 p. 14-15). He also describes the regional NW-SE-trending swarm of basic dykes. By examining them away from the other intrusions (on the island of Pabbay; Fig. 2), Geikie (1858 p. 16) recognized that the basic dykes were not the key agents of "hopeless confusion" because the adjacent Liassic strata show no metamorphism beyond "the mere hardening of the shales in the immediate contact". So by elimination Geikie established that it was main granites ("bosses of syenite") that were responsible for the metamorphism of the limestone.

The "hopeless confusion" was more than a simply metamorphic problem. Geikie (1858, p.2), as Macculloch before him, recorded that "long tracts of red sandstone are brought into the heart of the Lias". These additional structural complications were unexplained by both men. Given the incompleteness of his own work it is surprising that Geikie (1858) chose to introduce his account with strongly worded criticisms of Macculloch's (1819) work. Despite being "sensible that my remarks tend to throw a shade of discredit over other portions of his work on the Western Islands" he opines that "evidence of faults is ignored, long tracts of syenite are inserted where none exists" and consequently Macculloch "can only have examined a limited portion of the district and that too but superficially". Given what happened later in his research career, it is not clear whether Geikie came to regret this hubris of youth.

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<u>A correction</u>

In the 1850s Geikie had inherited, perhaps unwittingly, from Macculloch (1819) the notion that the unfossiliferous limestones that outcrop principally inland in his study area of Strath, were the metamorphosed equivalents of the fossiliferous Liassic strata at Broadford. By the 1880s he knew better. On the basis of lithological character he made the correlation with the Palaeozoic limestones of the Durness Group, and "certainly does not deserve the name 'marble'" (Geikie 1888, p. 67). The Palaeozoic age was confirmed by fossil finds by Henry Cadell, who accompanied Geikie on a revisit in 1886. The "hopeless

confusion" of the 1850s was not a consequence of igneous activity but by the pre-Liassic strata being "constantly brought in again by thrusts, faults and folds " (Geikie 1888, p. 67). In this he was applying insights from the breaking research from the NW Highlands that was uncovering the Moine Thrust Belt, discussed below. The Durness limestones had been interleaved with Torridonian sandstones to form part of what we now know as the Moine Thrust Belt, then eroded and overlain by Liassic strata before being intruded and metamorphosed by Tertiary igneous rocks. Complicated yes, but not hopelessly confusing.

A key outcrop is found on the eastern shore of Loch Slapin, an area widely used today for field training, at the outfall of the Allt nan Leac (called Allt Leth Slighe by Geikie 1888, Fig. 6). The section here clearly displays unconformable relationships between the fossiliferous and well-bedded Liassic strata from the more compact, steeply bedded white Durness limestones. In his earlier study Geikie (1858) recorded that "here the marble has vertical dip and a few yards southwards it inclines to the SW". He also noted that the limestones "gradually lose their metamorphic aspect till they pass into a coarse shelly limestone". The mis-interpretation lies in the word "gradually". 30 years on, Geikie reflected that "it was this coast-section which chiefly deceived me in my early rambles over the ground and blinded me to the meaning of the evidence" (Geikie 1888, p. 65) and, with regard to Macculloch's work at the beginning of the century, "I imagine that it had the same unfortunate influence upon him". Thus, as he begins his 1888 revision, Geikie excuses his own superficial examination of field relationships as "unless one's suspicions were aroused to look for a break between these limestones, no such break would probably be noticed even by a tolerably alert observer" (i.e. himself).

The challenge faced when building interpretations from fieldwork lies in finding the "right outcrops". Even in well-exposed ground, which Strath surely is not, most outcrops can be explained by several different geological relationships. But despite easy access and clear exposures, Geikie failed to appreciate the unconformable relationship between Liassic and Palaeozoic strata. He simply inherited Macculloch's assumption that the two units were one and the same. Only after his extensive further research in other igneous provinces around the world and specifically the understanding of tectonic and stratigraphic

relationships in the NW Highlands was Geikie's curiosity sparked sufficiently to challenge his own earlier work on Skye. He presented his revisions to a meeting of the Geological Society on 5th December 1887, receiving a very positive response. In the discussion the Society's President is reported as expressing his satisfaction with Geikie's new interpretations, having previously "fallen into the same error as others with regard to the passage of Lias limestone into white marble in Skye" (Geikie 1888, p. 73). The President was John Wesley Judd, of whom more later.

Wester Ross

The role of metamorphism and its interpretation provides a linking theme into the next part of Geikie's field research to be considered here. It concerns the status of what are now known as the Moine rocks of the northern Scottish Highlands. This is the Highland Controversy – not only one of the pivotal debates of 19th century earth science but one which has impacted on Geikie's reputation ever since. Readers should consult Oldroyd's (1990) peerless account of this and it is not our intention to repeat his narrative here. However, it is pertinent to examine, in rather more detail, Geikie's role in the formulation of the Controversy and especially to examine the context surrounding the publication of the pivotal paper (Murchison and Geikie, 1861). It is this work that cemented the erroneous interpretation of Highland geology as an upwardly conformable stratigraphic succession. The fieldwork behind this paper in Wester Ross, conducted in 1860, included Geikie's reconnaissance traverse of the ground between Loch Maree and Ullapool (Fig. 1) that has gained some notoriety in recent years (Oldroyd 1990; Butler 2000; Dewey this volume). The critical ground is now known to be part of the Moine Thrust Belt.

Context

As Oldroyd (1990) recounts, the Highlands Controversy grew out of a disagreement between one-time scientific partners, Sir Roderick Murchison and Professor James Nicol. The structure of northern Scotland originally centred on establishing the relationship between two sandstone successions – the Old Red

Sandstone (largely Devonian) on the NE coast– and the Torridon Group (now known to be Neoproterozoic in age) in the West. Building on their collaborative fieldwork, Nicol and Murchison each established that these two units were of distinctly different ages (as analysed by Oldroyd 1990). Their interpretations are reproduced here, using the Ullapool – Loch Broom transect (Fig. 8). In the absence of palaeontological evidence, the Torridonian was assigned to the Cambrian and the overlying, distinctive quartzites and carbonates assigned to "Lower Silurian". These younger strata are now known to be Cambrian in age. Elsewhere in the NW Highlands the limestones get as young as the Ordovician (Durine Formation of the Durness Group). In the Ullapool transect, these sedimentary rocks are in turn overlain by what Murchison (1859) termed "Micaceous Sandstone and Younger Gneiss" – but following usage established by Peach et al. (1907) - are now known as the Moine Group. The modern terminology is used here for simplicity. All these strata dip eastwards regionally and from this, following the simple adoption of the Steno's "Law of Superposition", Murchison deduced that the rocks formed a conformable succession that became systematically younger to the east. However, both Nicol and Murchison agreed that the Moine succession was metamorphosed – overlying non-metamorphic strata. Although of course this is inconsistent with simple superposition, Murchison chose to place greater value in the orientation of apparent stratification in the Moine rocks, which had the appearance of bedding, simply dipping eastwards (e.g. Fig. 8).

In 1857, James Nicol published an account of the geology of the NW Highlands that contradicted Murchison's model. He accompanied this with a new geological map for northern Scotland (Fig. 9a), clearly recording the juxtaposition of meta-sedimentary (Moine) rocks resting upon unmetamorphosed (Cambrian) strata. He dwelt on the relative merits of two explanations: that the overlying strata were somehow metamorphosed in place without any effects passing to the underlying non-metamorphic rocks; or that the metamorphic strata had been carried in laterally over the sedimentary rocks below. Interestingly – Nicol drew back in his 1857 paper from strongly arguing for lateral translation because "the great extent over which the relationship has been observed, of fifty or a hundred miles, is unfavourable to the view that it is a

result of slip or convolution of the beds (p. 35) and there is " almost no trace of the powerful agent by which they were effected appears on the surface". The powerful agent Nicol had in mind was igneous activity. Even Nicol, who had correctly identified the regionally continuous and low-angle juxtaposition of rocks of very different origins, had great difficulty in conceiving a process that would facilitate this arrangement.

Murchison's response to Nicol's publication and map was to present his own version to the Geological Society, spread over two occasions in 1858, appearing in print the following year (Murchison 1859). In this he strongly asserts the simple upward succession into the metamorphic (Moine) rocks from underlying non-metamorphic strata – classifying it firmly as Silurian in age: "Vast breadths, in short, of the so-called *"primary"* crystalline rocks, which were considered to be antecedent to all strata containing the remains of animal and vegetable life, must in that case be considered as simply metamorphosed Lower Silurian rocks" (p. 420). This was illustrated on Murchison's "first sketch of a new geological map of the north of Scotland" (Fig. 9b). Yet he recognized that large tracts of "this little map must be considered as suggestive only" (p. 419). There was unfinished business with the added lack of a clear cause for the *in situ* metamorphism.

Both Nicol and Murchison presented their competing interpretations of Highland geology at the 1859 meeting of the British Association for the Advancement of Science – held coincidentally in the city of Nicol's home university - Aberdeen. Oldroyd (1990) reports that it was Murchison's interpretation that held sway, not that either party was minded to seek common ground. The next time Nicol reported on the subject, presenting to the Geological Society on 5th December 1860, he was compelled to present a vast array of information to challenge "the weight of authority opposed to the views I propose" (Nicol 1861, p. 86). In this he presumably harks back to discussions following the Aberdeen conference.

In his extensive presentation, Nicol (1861) provided cross-sections all along the NW Highlands. They consistently showed the Moine overlying unmetamorphosed rocks. But he went much further, describing arrays of strange foliated rocks along the contact (" clay-schist"). It would take 25 years more, and

the petrological work pioneered by Charles Lapworth (1885) and subsequently by Teall (1918), before these enigmatic rocks would be revealed as mylonites. In this enhancement of his 1857 account Nicol came down firmly in favor of the tectonic emplacement of the Moine over the unmetamorphosed Cambrian rocks. Although this removed a specific cause for the metamorphism within the Moine, as they could be carried up from depth, Nicol (1861) continued to seek igneous explanations for the faulting itself. His cross-sections show various intrusions along the contact between metamorphic and non-metamorphic rocks. Again it took many years before many of these materials were correctly interpreted as thrust-bound slices of Lewisian. In the Highland Controversy the status of these rocks became something of a distraction (see Oldroyd 1990). But for Nicol it was clear, there was no simple stratigraphic passage from west to east across the northern Highlands.

The fieldwork of 1860

Murchison was not idle either following the Aberdeen meeting. There was unfinished business in the NW Highlands. Apparently out of the blue, Murchison wrote to Geikie in mid July 1860 inviting him on an expedition to the west coast – just three weeks before they were due to leave. As Geikie (1924) himself notes: "to a geologist his legs are of as much consequence as his head". In engaging Geikie as a fellow investigator in his 1860 field campaign, Murchison had chosen a young, fit and enthusiastic field geologist. But through his work on Skye, Geikie had actively sought, and apparently resolved, explanations for structural complexity and metamorphism through igneous activity. For Murchison this must have been a winning combination.

Compared with earlier times, travel through Great Britain in the 19th century had become rapid and secure thanks to the development of a rail network. However, the railways Highlands of Scotland were amongst the last to be built. Although Inverness was connected to Aberdeen by 1862 (a six hour journey) and on to Lochcarron by 1870, getting out to the Kyle of Lochalsh had to wait until 1897. Until then steam-shipping connected Lochcarron to Portree. So the key to effective fieldwork in the NW Highlands in the middle 19th Century was by "steamer ship". Services were operated by David Hutcheson & Co, a

forerunner to the modern-day Caledonian MacBrayne ferry company. Glasgow was connected to Oban via the Crinnan Canal and hence on to fishing villages on the west coast and Hebridean Islands. Inverness was connected via the Caledonian Canal. So although not speedy, the west coast was fairly well-connected. However, it was not cheap. The cost of a return journey to Inverness from Greenock on a Hutcheson steamer, one of their "Royal Routes", cost 70 shillings, significantly more than the equivalent modern day airfare between the UK and New Zealand, bearing in mind the salaries of Survey staff at the time. Oldroyd (1990) reports that Murchison covered Geikie's expenses.

Once in the NW Highlands, it was Murchison's personal connections that were critical. During their tour, the two enjoyed the hospitality and house parties of several wealthy landowners at their Highland lodges. Otherwise the few coaching inns provided more basic accommodation. A rough network of coach-roads provided some inland access but otherwise fieldwork required long walks.

Geikie kept extensive notes during the field excursion, summarized in his autobiography (Geikie 1924) and reported by Oldroyd (1990). Given the published outcome of the fieldwork (Murchison and Geikie 1861a) was the reassertion of Murchison's (1859) interpretation of Highland geology, attention in recent years (Oldroyd 1990, Butler 2000, Dewey this volume) has focused on Geikie's somewhat slapdash activities – particularly in relation to his reconnaissance between Loch Maree and Ullapool. Given Murchison's seniority, it is not clear how much of the scientific agenda was Geikie's - at an age of 24 one suspects very little. However, the fieldwork from 1860 raises more complex issues, as we now discuss.

The purpose of the fieldwork in 1860 was to "complete a baseline from which the rest of the Highlands should be worked out in detail " (Murchison and Geikie 1861a, p. 172). Given this lofty ambition, clearly built upon the assumption that Murchison's (1859) understanding was inviolate, the fieldwork was surprisingly rapid. On 29th August the pair reached Balmacara then travelled onto to "Jeantown" (modern-day Lochcarron, Fig. 7). They then continued over to Kishorn. This will have taken them into the Moine Thrust Belt, crossing the Kishorn Thrust sheet (with Lewisian gneiss and inverted Torridonian sandstone) before dropping down into the undeformed Torridonian of the

Applecross hills. According to Oldroyd's (1990) researches, the pair were not unduly disturbed by any structural complexity at Kishorn and they continued on to Kinlochewe (Fig. 7), arriving there on the evening of 30th August.

Breaking out on his own, Geikie then spent 2-3 days exploring the hills to the SE of Glen Torridon (Fig. 7). It was an area that Nicol had also visited and a cross-section features in his 1861 paper. Oldroyd (1990) had difficulty relating the published sections of Nicol and Murchison and Geikie (1861) to modern-day locations, as they use now-forgotten place names and give no specific orientations for their cross-sections. Some insight can be gained from consulting John Arrowsmith's topographic atlas from 1832, to which one assumes Murchison and Geikie had access. However, we are directly familiar with the terrain, having constructed our own maps and sections over the years (Butler et al. 2007; Watkins et al. 2016) and can now explicitly identify the key profiles.

The ground SE of Glen Torridon contains large-scale repetitions of Torridonian sandstone and Cambrian quartzites, stacked up on imbricate thrusts. The finest exposures are on the ridge of Beinn Liath Mhor (Fig. 10). The ridge lies within the "Dun Tolleah hills" of Murchison and Geikie (1861). The section clearly displays the imbrication and this was recognized both by Nicol and Geikie. The key structural elements are evident on Geikie's cross-section (Fig. 10b). So on the evening of 2nd September at Kinlochewe, Geikie, as Nicol (1861) before him, had seen enough to realize that the relationship between Cambrian and Moine could have a structural component, rather than be purely stratigraphic.

One assumes that Geikie discussed his cross-sections with Murchison that evening – the two went in the field together the following day to examine rather more accessible outcrops to the NNE of Kinlochewe. What is remarkable is that Murchison had experience of this type of structural complexity, indeed he had published on it a decade earlier (Murchison 1849). During his tour of European mountain ranges in 1847-8, Murchison was shown around canton Glarus in Switzerland by Arnold Escher von der Linth, seeing examples of tectonically repeated Mesozoic stratigraphy and even the now-famous Martinsloch site (Segnespass) where metamorphic "crystalline schist" lay directly above Tertiary "flysch" (Fig. 11). Today this structure is known as the Glarus Thrust. But

Murchison was aware of other outcrop analogues. His discussion of the structure at Martinsloch cites the work of the Rogers brothers in the Appalachians, where, during the 1840s, they had begun to map out significant thrust repetitions: "Thus, the comparatively low chain of North America may throw light on some of the most complicated problems of our science, which could scarcely ever have been satisfactorily worked out amid the confusion of the Central Alps, such large portions of them being inaccessible to man and covered with eternal snow " (Murchison 1849, p. 249). It is curious indeed that Murchison did not at least keep a structural component in mind when developing geological interpretations of the NW Highlands.

On the morning of 4th September, Geikie left Kinlochewe and headed alone into what even today is a road-less tract of rough country. Before him lay 35 km of generally well-exposed ground that he had to traverse before nightfall. His first task was to head up Glen Bianasdail, leaving the shores of Loch Maree and walk along strike beneath crags of Cambrian quartzites (Fig. 12a). Viewed in retrospect, this was the first problem for Geikie's route. Tucked in at the foot of the cliffs he presumably was unaware of the rocks above the quartzites – that include Lewisian gneisses and Torridonian sandstone (Fig. 12b; the modern-day Kinlochewe Thrust Sheet; see Butler et al. 2007; Butler and Matthews in Mendum et al. 2009, p 302-307).

The ground opens out at the head of the Glen Bianasdail, around the outfall of Lochan Fada. There is patchy outcrop on the pathless slopes that lead to Bealach na Crioise but excellent views onto the southern slopes of a ridge connecting the hills of Sgurr Dubh and Mullach Coire Mhic Fhearchair (Fig. 7). As with the slopes of Beinn Liath Mhor that Geikie had seen just a few days earlier, the hillside that would have confronted him is also a natural cross-section through what is now known as the Moine Thrust Belt. Unlike the ground south of Kinlochewe, the Cambrian quartzites that lay ahead of Geikie maintain a gentle eastward dip, lying unconformably above Torridonian sandstone. So for the first time he would have seen these relationships in their unfaulted state. But what of the massive, unstratified rocks that lay on top?

On the north side of the pass of Beallach na Croise, Geikie's route took him into the long valley containing Loch an Nid (Fig. 7). The dip-slope of Cambrian

quartzites forms the west side of the valley (Fig. 12c), capped by what Geikie called “gneissose rocks” (Fig. 13). His field notes, and the published account (Murchison and Geikie 1861a) find nothing remarkable in these relationships – gneisses on top of bedded sedimentary rocks. Indeed they simply confirmed Murchison’s (1859) stratigraphic order. Geikie continued on his way. The track follows close to the geological contact between the Moine rocks and underlying Cambrian strata (Fig. 12d). The final drag up to the shoulder overlooking Ullapool and north to Assynt (Fig. 12e) gives access to the slopes down to the SW shore of Loch Broom, opposite Ullapool (Fig. 12f). Overall the geology must have appeared remarkably straightforward to Geikie.

He wrote up his field notes from the traverse the following day, while based in Ullapool and exploring the shores of Loch Broom. He recognized a number of the key elements of the geology, in particular the presence of gneisses, subsequently determined to be part of the Lewisian, resting directly on the Cambrian strata and gently inclined to the SE. This seems to have presented him with no interpretational difficulties or doubts – indeed the relationships are reported by Murchison and Geikie (1861a, Fig. 8c). And so upon arrival in Ullapool Geikie, in the course of a few days fieldwork, had removed the doubts in Murchison’s geological sketch map of 1859 (Fig. 9a) - the relationships between Moine and underlying strata was resolved once and for all. For Murchison and Geikie (1861a), both were clearly of Silurian age, assuming a Cambrian age for the Torridonian below. Geikie travelled alone towards Assynt, examining the classic outcrops at Knockan Crag (Fig. 14) but paid them no particular heed. The Moine rocks have a prominent layering that is essentially parallel to the bedding in the unmetamorphosed strata below and thus bore out more than ever, the Murchison (1959) doctrine of simple upward succession.

There remained the vexing question of the metamorphism of the Moine. Murchison rejoined Geikie in Ullapool and the pair spent a couple of days examining outcrops along the side of the coaching road to Dingwall. Heading up Loch Broom they were struck by the apparent simplicity of the Moine – with kilometres of gently inclined rocks (Fig. 8b). They described these as “gneissose schists” and were adamant that the E-dipping rock fabric (Fig. 8c) is bedding – even publishing a distinct paper on the subject (Murchison and Geikie 1861b).

Indeed the rocks appeared to be barely metamorphosed at all but rather were "fissile finely-laminated flagstones, where the layers of stratification are as parallel and unbroken as in any freestone-quarry among the Carboniferous rocks of the south" (Murchison and Geikie 1861a, p. 186). But of any igneous cause for the metamorphism they could find not a trace. The pair went on to debunk Nicol's (1861) assertion that the lower contact of the "gneissose schists" is marked by intrusive "feldspar porphyry" stating that the unit is in fact sedimentary with clear pebbles (Fig. 8d; Murchison and Geikie 1861a, p. 185). A modern view would interpret these relationships on the shores of Loch Broom as a thrust bound slice of Torridonian (the sedimentary component) and pegmatitic Lewisian (the porphyry of Nicol) – a far-travelled "horse" along the Moine Thrust (Elliott and Johnson 1980). The prominent fabric in the Moine above (Figs 8c, 14c), unequivocally interpreted by Murchison and Geikie (1860a) as bedding, is now established to be the product of intense deformation. It is mylonitic foliation.

Geikie and Murchison left Ullapool and arrived in Skye on the 11th September. The key fieldwork had taken Geikie rather less than two weeks. In that time he had travelled some 90 km along what is now known as the Moine Thrust Belt, much of it on foot. He had visited a number of key sections and walked out the contact, albeit in haste, between the "gneissose schists" of the Moine and the non-metamorphic rocks below. Murchison then integrated these findings with his own work from that summer and his previous excursions to the region in readiness for a presentation to the Geological Society the following winter.

A bitter division

As we have seen, while Murchison and Geikie were working up the results of their fieldwork, Nicol was doing the same with his work. He presented his findings to the Geological Society on 5th December 1860. The upshot was that "The diversity in the strata brought into contact with the eastern gneiss proves that the line of junction is along a fault, and not one of conformable upward succession" (Nicol 1861, p. 108). As Oldroyd (1990) points out, this is not in itself especially convincing for the relationship as described could have been an

unconformity as much as a fault. But Nicol backs this up with what, with hindsight, are descriptions of fault rocks in the Cambrian quartzites along the contact. He wrote: where "the disturbance has been most violent, the quartzite is often much hardened and semifused, still it is a decidedly fragmentary, granular rock. The gneiss or mica-slates, said to rest on it, are no less distinctly crystalline in structure" (p. 109). So there is an abrupt metamorphic break too – incompatible with the model of *in situ* metamorphism he had toyed with in his earlier paper (Nicol 1857) as an alternative to tectonism – and an absolute requirement of Murchison's (1859) model. Nicol goes on: "In the Alps, where such superposition of crystalline on unaltered strata is seen, the most distinguished and experienced geologists have found it *necessary* to admit that the strata had been inverted, not by frequent folds . . . but in one enormous overthrow, so that over the wide horizontal area, the uppermost strata, which might have been lying in troughs or depressions due to some grand early plication, were covered by the lateral extrusion over them of older and more crystalline masses" (Nicol 1860, p. 109). In this he is directly citing Murchison (1849)! The tone and content of Nicol's (1860) paper was clearly provocative and can scarcely have been expected to lead to a rapprochement with Murchison, who was in the audience. Despite the evidence presented though, Nicol was, in the short-term at least, destined to lose the argument.

Two months after Nicol's paper was read at the Geological Society, Murchison presented the account of the work from the previous summer, integrated into his own far more extensive studies through the rest of the Highlands that had occupied him previously. The paper (Murchison and Geikie 1861a) includes sketch sections that chiefly illustrate the apparently conformable contact of "gneissose schists" (Moine) upon non-metamorphosed strata (Cambrian) that Geikie had studied – albeit described in the paper from north to south (the opposite direction to that followed by Geikie). A critical omission was the lack of any detailed description of the contact itself – in contrast to Nicol's (1861) account. But this evidence would not have suited their model.

To conclude the paper Murchison added a five page single-authored rebuttal of Nicol's 1861 paper as an addendum. His views can be summarized in

his own words that “Professor Nicol had been misled by assigning much too great an importance to what I considered to be local and partial disturbances only” and that his interpretations “are either erroneous or founded on deceptive local appearances” Murchison and Geikie 1861a, p 228). The message is clear - fieldwork is about finding structurally simple outcrops that could be perceived as showing straightforward stratigraphic concordance. Murchison concluded in typically assertive fashion that “being now convinced that the principle of classification I suggested is established on a sound basis, I take my leave of the subject, trusting to Mr. Geikie and my other able colleagues of the Geological Survey, as well as to Professor Harkness and younger geologists than myself, to discover new truths, which may improve or modify my conclusions”. In making what amounted to a victory speech, Murchison had relied heavily on the field observations of Geikie. He went on, in his magnum opus Siluria (Murchison 1867, p 171) to cite the fieldwork from 1860 and concluded that “instead of presenting a mass of disorderly rocks from which no system could be evolved (i.e. the Moine rocks and Nicol’s interpretations), the Scottish Highlands are found, on examination, to consist of mountains and valleys in which the same geological laws are followed as among those where the strata are in no way metamorphosed”.

Before continuing it is worth contrasting the fieldwork of 1860 in Wester Ross with that undertaken by Geikie on Skye a few years earlier. It is interesting to consider Geikie’s assessment of the quality of his own work in the late summer of 1860. Was he not opening himself to the very same criticisms he had himself leveled at Macculloch’s descriptions of the geology of Strath? History does not record any such introspection. Perhaps he was simply swept along by the enthusiasm and belligerence of Murchison. It would take a couple of decades before those particular chickens came home to roost.

Tectonics confirmed

“When a geologist finds…gneiss overlying gently inclined sheets of fossiliferous quartzite, shale and limestone, he may be excused if he begins to wonder whether he himself is not really standing on his head.”

So wrote Geikie (1884) in coining the term "thrust" and writing up the concept in *Nature*. The Survey geologists that Geikie had commissioned to work at Loch Eriboll to disprove the work of Charles Lapworth were Ben Peach and John Horne. They showed him the critical outcrops that spelt the end of the Murchison and Geikie (1861) model of upward stratigraphic continuity from the unmetamorphosed Cambrian strata into the Moines. It is probable that the outcrop to which Geikie (1884) was referring lies on the northern flank of Ben Arnaboll, on the eastern shore of Loch Eriboll (Fig. 15). Lewisian gneiss has been thrust on top of Cambrian Pipe Rock quartzites.

A modern account of the Highlands Controversy, as it pertains to the descriptions of mylonites and to deformation in general, is provided by White (2010). Oldroyd (1990) recounts the role of geologists in the early 1880s who were not part of the establishment of the Geological Survey, especially Charles Lapworth and Charles Callaway, in creating an environment to challenge the Murchison orthodoxy. It is probable that Peach and Horne were introduced to the outcrop on Arnaboll by Charles Lapworth for this was his key site to demonstrate mylonites. It is also the site where Lapworth was able to demonstrate structural repetitions of quartzites, through walking them out along strike (Oldroyd 1990). Lapworth had previously introduced the Arnaboll site to Jethro Teall in 1883. Teall eventually wrote up the encounters in 1918. Lapworth created an explanation not only for the development of foliation in the Moine, he explained its character and showed the potential for misinterpretation (as made by Murchison) as bedding. This in turn removed the necessity of seeking an igneous explanation for metamorphism that so vexed Nicol 25 years earlier.

So when Geikie infamously credited the Geological Survey, in the guise of Peach and Horne, for resolving the Highlands Controversy, without recognising Lapworth (1883) and other notables, such as Callaway (1883) or even Nicol, all hell broke loose. Oldroyd (1990) and White (2010) document this thoroughly elsewhere. Around the Highland Controversy two issues recur. The first is the ability of an individual to hold a line of argument beyond the accumulating body of evidence against it, just because of force of personality and standing. The second is the absence of the concept of an earth mechanism that could tectonically juxtapose differing rock-types over such a widespread area and in

the attitudes in which these were seen in NW Scotland. Murchison, and by association, Geikie perhaps could be forgiven the latter in the absence of any plausible explanation for the crustal scale, lateral movements of the type that led to the Moine thrust Belt. However in the former they are complicit, with Geikie holding the line until Murchison was no longer in a position to influence his career.

To his credit, Geikie directed considerable human resources within the Geological Survey in supporting the efforts of Peach, Horne and colleagues to map out the Moine Thrust Belt (their "zone of complication") from Eriboll to Skye. This led to the famous memoir on the NW Highlands (Peach et al. 1907), as extensively reviewed Law et al. (2010). It is not clear if Geikie returned to the NW Highlands to revisit the sites of the 1860 expedition. The sketch looking up to Loch an Nid and beyond (Fig. 13a) is undated but, given the geological colouring, was presumably made in situ after his Survey colleagues had begun their mapping of the thrust belt. In the meantime Geikie's field attentions for the UK had returned to the Hebrides.

The Red-Hills – Cuillins controversy

Beyond his administrative duties within the Geological Survey, Geikie himself played no direct role in developing understanding of the structure of the Moine Thrust Belt. He left this to the direction of John Horne, who signed off on the field maps of the Survey geologists, oversaw the creation of the synthetic "clean copy" maps and publications, including the classic memoir (Peach et al. 1907). But as noted earlier, Geikie retained an interest in the geology of Skye, correcting his earlier interpretations from Strath (Geikie 1888). Everything was leading to his great synthesis "*The ancient volcanoes of Great Britain*" (Geikie 1897). And so it was Skye that embroiled him in another especially acrimonious debate, this time with John Judd.

<u>The feud between Judd and Geikie</u>

The original debate between Geikie and Judd was concerned with origin of basalt lava flows of the Inner Hebrides and Northern Ireland – as fed from

fissure eruptions or from a few central volcanoes (Walker 1996). The argument crystallized into the relative age of some of the major intrusions on Skye. Beyond the battle between the personalities involved, at first sight such issues may appear somewhat esoteric, even for the 19th century. However, the trends between basic and acidic composition magmatism in major volcanic centres (so-called Richthofen's Law; Richthofen, 1868) was a matter of extensive debate at the time, just as the relationships between igneous and sedimentary rocks were for the early 19th century. The Inner Hebrides of Scotland again became an obvious testing ground for models of igneous processes.

The initial disagreements between the two men had deep roots – as extensively laid out by Oldroyd and Hamilton (1997) – apparently stretching back to the 1870s, just as Judd prepared to present his first research from the Inner Hebrides. Judd had begun his researches on the stratigraphy of Mesozoic strata in England but, by the 1870s, turned his attention to Scotland. His first paper was an extensive near-memoir on the Jurassic of the NE coast, centred on the Brora area. He then turned his attentions to the Inner Hebrides and their extensive sections of Jurassic strata. This of course led Judd to the ground on which Geikie had published (Geikie 1858) and into the igneous rocks. After several years fieldwork he was set to present his results to the Geological Society, in January of 1874. At the time he seems to have considered that his study on the Tertiary volcanics was a diversion from his prime research interests on the Mesozoic sedimentary rocks (see footnote in Judd 1874, p. 220). In tackling the volcanics Judd was setting himself in direct competition with Geikie. And he knew it. Oldroyd and Hamilton (1997) report the correspondence between Judd and Geikie at the time. Judd wrote to Geikie informing him of his forthcoming presentation to the Geological Society. Geikie replied in surprise: "Of course I have no right to dictate to you or even perhaps to suggest to you how far you should trench on the volcanic geology of the Hebrides. I am quite sure from all the intercourse I have had with you that it is far from your wish to interfere with the work of any fellow labourers in the same field. I can only say however that such a paper as you proposed to write will cut away much of the ground which I am under promise to describe to the Geological Society" (quoted in Oldroyd and Hamilton 1997).

Geikie's promised paper to the Geological Society never did materialize. He did not visit the Hebrides again until 1882-3 to complete fieldwork that led to his revision of the geology of Strath, as discussed above (Geikie 1888). Meanwhile Judd developed a growing reputation as an expert in volcanology. In recognition of this work in 1876 he was appointed to a chair in geology at the Royal School of Mines (Oldroyd and Hamilton 1997)). His specific skills lay in petrology. In his early career as an analytical chemist in the steel city of Sheffield, Judd met Henry Clifton Sorby, and became an early adopter of the polarizing microscope (Oldroyd and Hamilton 1997). The feud with Geikie began in earnest in the 1880s as Judd published a string of papers that re-interpreted the igneous geology of the Inner Hebrides (Judd, 1885, 1886). These included explicit criticisms, many of which were overblown or unfounded, of Geikie's earlier work (Oldroyd and Hamilton 1997).

There followed years of publication and counter-publication (reviewed by Oldroyd and Hamilton 1997) but events came to a head at Judd's reading, before the Geological Society on 25th January 1893, of his investigations. At stake was the competence of the two protagonists as reliable observers and interpreters of field relationships. The issue came down to Skye and the age of the main gabbroic series of the Cuillin Hills relative to the granites of the Red Hills (Fig. 2).

Judd's (1893) paper is in effect a 20 page attack on the competence of Archibald Geikie. After reviewing a plethora of other examples of igneous geology, and upon reaching the geology of Skye, Judd began by suggesting that Geikie's 1888 paper, where he revised his much earlier work in Strath, was simply "adopting in their place the views I [Judd] had put forward in 1874" (p. 192). He went on to state that Geikie's new explanation for the sequence of igneous activity "was not only one for which there was no foundation, but could be maintained only by those who had not properly examined the evidence." He then addressed Geikie's interpretations of the relationship between the Cuillin Hills and Red Hills. He concluded: "It then soon became evident how the mistake on the part of Sir Archibald Geikie--for that it was a mistake no one who examines the evidence now adduced can for one moment doubt--has arisen". He had been observing key field relationships "from a distance, as they represent whole mountain-sides" (Judd 1893, p. 193). In contrast Judd had previously

(Judd 1891) given "full petrographical details concerning this remarkable series of rocks" (Judd 1893, p.194). In this he showed that the texture of the granite was granophyric (finely intergrown quartz and feldspar) with a fine-grained, banded ground-mass. Judd took this to imply that the granite had been recrystallized by being in contact with the gabbro. Thus for him, the gabbro post-dated the granite. The broader implication was stark: Geikie did slipshod science based on quick tours that only viewed rocks from a distance, while Judd did methodical, detailed work.

Geikie was present at the reading of Judd's (1895) paper and his objections were given a full hearing. Most critically he accused Judd of being selective in his use of field evidence, a challenge that led to Judd having to add a postscript to his main text for the written publication. And this led directly to Geikie heading to the field again that summer.

Drium Hain: 1893

The critical ground lies on the western slopes of upper Glen Sligachan, around the ridge Drium Hain (Fig. 2). To visit the key outcrops, Geikie responded by gathering a team – who seem to have been dragooned as witnesses in the forthcoming debate. These were three members of the Geological Survey, Ben Peach, John Horne and photographer Robert Lunn - together with the American petrologist, Joseph Paxson Iddings. Iddings' work had been cited by Judd (1893) and so his support would be especially important to Geikie. Access is straightforward, if long-winded. It would have been a strenuous day out, especially for Robert Lunn, given late 19th century photographic equipment.

The ridge itself contains abundant outcrops of coarse banded gabbro with granite and lies adjacent to a large mass of granite on the adjacent hill, Meall Dearg ("red hill", Fig. 16a). And so the debate revolves around the nature of the granite within the gabbro outcrop – a typical detail of which is shown in Fig. 16b. For Judd (1895), the granite patches were effectively xenoliths within the gabbro. And some of the granite masses are irregular and might, without close examination, be misinterpreted as such. However, most of the granite is in the form of narrow veins and these clearly cross-cut banding in the gabbro (Fig. 16b). For Judd (1893), in his postscript, these veins were late segregations from

the basic magma and therefore not related to the granite on Meall Dearg. But part of the problem arises because the Meall Dearg granite is not well-exposed as it approaches the contact with the granite (Fig. 16a), although the contact is well-expressed in the landscape as a low escarpment. It is understandable why Judd was unable to link his granite "inclusions" within the gabbro back to the main granite. But, the deduction that therefore the granite veins within the gabbro were not connected to the adjacent Meall Dearg granite body is highly suspect. Geikie (1894, p. 215) asks how could "Judd suppose that a few such blocks from one little ridge were to disprove the definite testimony of scores of sections cited from all parts of the region?"

But what of the granophyric textures used by Judd to invoke recrystallization of the granite? Geikie mapped these out, tracing the fine "flow-banding" along the margins both of the veins and of the main granite (Fig. 17). He also showed that the banding in the gabbro truncated against the granite. And so he could add textural evidence to go alongside the field relationships to contradict Judd's (1893) paper.

The end-game

On 21st February 1894, fellows of the Geological Society gathered to witness the final debate between Geikie and Judd on the volcanic geology of the Inner Hebrides. Geikie (1894) presented his findings from the fieldwork on Drium Hain. For him (p. 216), " the evidence from this Skye locality is so abundant and conclusive, and the point to be proved is so simple and elementary, that I cannot help feeling as if some apology were due to the Society for the necessity of bringing the subject before it". This is a bit rich – for it might have helped if he had himself used this type of evidence and documentation himself more routinely. But the case appeared overwhelming.

Judd did not apologize and in the discussion of Geikie's paper reasserted his own views – especially concerning the interpretation of granophyric texture as evidence for recrystallization caused by contact metamorphism. Geikie was adamant that it was typical of the marginal facies in the granites and should be interpreted as formed by cooling against adjacent rocks, not reheating. Indeed, in fairly brutal terms, Geikie (1894, p. 228) challenged Judd's competence as a

university educator. Banded granophyric textures are classically interpreted as flow under cooling conditions but, if he were to instruct his students that these textures were instead "produced by re-fusion and such excessively slow cooling as must take place within a deep-seated basic eruption; that blocks of granite, several yards in diameter, may in such a position be melted, and instead of assuming a distinctly crystalline structure acquire a fine felsitic texture, an exquisitely perfect spherulitic flow-structure, conforming to the surface of the enclosing material and presenting all the usual signs of true rhyolitic movement. His[1] bewilderment will be still further increased when he learns from Prof. Judd that this alleged order of change is entirely borne out by microscopical investigation". He goes on… "With the microscope, the influence of the same unfortunate misreading has led him to invert the actual succession of structures". So for Geike (1894, p. 231) the primacy of field relationships over petrography was clear as "no amount petrographical ingenuity could withstand the plain evidence in the field that the granophyre sends offshoots across the gabbros".

Fieldwork – importance of mapping then and now

Beyond the histography, the accounts of Geikie's fieldwork in Scotland give insight into the general conduct of field research and its place in the development of earth science. The primacy of mapping, to establish the viability of explanations for the relationships between rock units, was evident to Geikie from the very start of his career. His criticisms of Macculloch's work related directly to the quality of mapping. And it is interesting that the theme is maintained some forty years later in Geikie's demolition of Judd's model for the relationship between the granites and gabbros on Skye. The field relationships assumed priority over the microscopy – without a resolved geometric context for rock units the microstructure can be ambiguous.

However, rock texture was clearly important for resolving the Highlands Controversy and the "discovery" of the Moine Thrust Belt. Lapworth's (1885)

[1] Note that writing at the time assumed that all protagonists, including students, were male.

recognition of mylonites allowed other geological contacts, especially at the base of the Moines, to be interpreted as thrusts. Nicol (1861) got close to achieving this insight in recognizing that the quartzites below what is now known as the Moine Thrust are "semi-fused". But at that stage Geikie (with Murchison) did not consider this kind of detail to be important.

So what of the conduct of the mapping? It is hard to judge the method behind Geikie's mapping on Strath in the 1850s. On the 1860 excursion in Wester Ross he was clearly simply viewing the outcropping geology through the prism of Murchison's (1859) model of stratigraphic continuity. This is a classic example of cognitive bias – anchoring (Mussweiler and Strack 1999) – which was compounded by Murchison's belligerent defence of the resultant geological model. The advances in methodology came from Lapworth at Eriboll (as recounted by Teall 1989; see Oldroyd 1990). It was the exercise of tracing out geological units that undermined Murchison's model of stratigraphic continuity. Thus Lapworth was breaking anchor chains, not being constrained by them. Systematically tracing out the boundaries between rock units and depicting these through complex topography exerts a primary test of the validity of structural interpretations. This was a leap in scientific approach. It came about on the eastern shores of Loch Eriboll, was adopted by Ben Peach, John Horne and others of the Geological Survey and was promoted by Geikie. And it was this approach that Geikie adopted to falsify Judd's model for the sequence of granite and gabbro on Skye. The use of mapping to test models for the relationships between geological units remains as powerful today, especially in the subsurface where 3D seismic data have revolutionized the understanding of stratigraphy and in the relationships between faults in complex structures. Maps are interpretations, built to test and challenge understanding of rock relationships rather than simply spatial indexes to the locations of geological materials.

Anchoring bias in field mapping remains a problem, with the issue discussed rarely even today. This is reflected in the notion of the "critical outcrop". Consider understanding the relationship of metamorphic rocks above sedimentary that lay at the heart of the Highlands Controversy. For those following Lapworth it is the outcrop on Ben Arnaboll of the eponymous thrust (Fig. 15) that has been most illuminating. But for Murchison and Geikie (1861)

surely it would have been Knockan Crag (Fig. 14). Given the difficulties of travelling in the NW Highlands, few other geologists will have seen either until the 20th century. But the geological interpretation of a region or simply between two different geological formations must satisfy broad examination and not just be left to declared type outcrops. Relying on a small number of especially illuminating sites, while aiding the communication of a particular geological model, may obscure general understanding of a geological problem. And debates on competing models would be more helpfully resolved if protagonists directly addressed the field locations of their opponents, as Geikie did when reporting from Drium Hain, interpretations that were distinct from those of Judd.

Reporting the evidence

One of the critical issues that led to the protracted controversies is the reporting of field evidence. Both Geikie (1858) and Murchison and Geikie (1861) relied heavily on written description. The lengths of the two narratives are somewhat similar and packed with outcrop locations. This may convey that the author has an encyclopedic knowledge of all outcrops in a given area and therefore they are "qualified" to present an interpretation of field relationships. Both papers suffer from a paucity of basic illustrations. For 19th century geologists a fundamental problem lay in the ability to properly illustrate their publications. This was partially compensated by the ability to show rock samples, large maps and other illustrations at the readings of the papers at the meetings of the Geological Society. But, little of this material made it into the publications themselves. Only now can field data be properly represented through digital media, tied to virtual globes. This is exemplified by the application of field mapping to understand the surface geology of extraterrestrial bodies. The various space agencies make full resolution imagery, as used in publications, openly available so that others can reproduce the interpretations – or create new ones.

Concluding remarks

In the 40 years, from Geikie's work on Strath to the controversy with Judd, the nature of debate had changed. What had begun with the vehemence of advocacy had been replaced with field evidence that was carefully collected, recorded, interpreted and reported. Yet the heat and vitriol, often marked by un-necessary asides and slights against one's competitors, remained. Walker (1996), as others before, pondered that scientific advance commonly arises out of controversy. Certainly in the two cases here, on the volcanic geology of Skye and the structure of the NW Highlands, great studies arose from the refocused efforts of the Geological Survey – the memoirs of Harker (1904) and Peach et al. (1907) respectively.

But at what cost? Engaging in these types of debate was scarcely for the faint-hearted. It is widely acknowledged, though not absolutely demonstrated, that Charles Lapworth experienced some form of mental illness brought on by stress as the Highlands Controversy broke around him (e.g. Oldroyd 1990). He never did properly publish his work – leaving the first effective descriptions of mylonites to Teall (1918) some thirty years later. And what of others who might have engaged in understanding the structure – both in the NW Highlands and in the volcanic terrains of the Inner Hebrides? We are perhaps fortunate that in the modern world, in general, the machismo of Victorian scientific debate has abated and this encourages a more diverse community to engage. Given the ambiguities inherent in much geological interpretation, surely leaving behind the animus, while retaining vigorous argument and robust discussion based on observations, is a good thing.

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Figures

Fig. 1. Simplified geo-tectonic map of NW Scotland showing the sites of Geikie's fieldwork as described in this paper.

Fig. 2. Simplified geological map for south-central Skye, located on Fig. 1. Boxed area A is that covered by Geikie's research in the 1850s (Fig. 5), B is the critical ground for the controversy with Judd in the latter part of the 19th Century. MD – Meall Dearg; DH – Druim Hain; AL – Allt an Leac.

Fig. 3. Landscapes and outcrops of SW Strath, Skye. a) looking East across Loch Slapin to its eastern shore; b) looking N across Loch Slapin with the critical ground for separating Liassic limestones from those of the Durness Group in the foreground .

Fig 4. Part of the Admiralty chart for 1860 for SW Skye (Scotland, west coast, sheet 7). The bathymetric depths are fathoms (1.83m).

Fig. 5. Geikie's field results from 1858, showing his geological map for Strath (boxed area (a) on Fig. 2).

Fig. 6. Geikie's later outcrop interpretation of the relationships between granite (granophyre - c), Durness Group carbonates (a-b), Triassic breccias (d) and Liassic shelly limestones (e), based on the Allt an Leac section (Fig. 2). Scale and orientations are not given in the original but West is left, East is right and the section represents c. 100m on the ground.

Fig. 7. Geological sketch map of the southern Moine Thrust Belt – Kishorn to Ullapool. (located on Fig. 1).

Fig 8. Comparing interpretations and outcrops across the contact at the base of the Moine Group at Loch Broom (Ullapool, see also Fig. 12f). a) from Nicol (1857)

for the south side of the Loch; b) Murchison and Geikie (1861) section from the north side. In both cases NW is to the left. c) typical exposure of Moine mylonites along the Loch Broom transect – seen in road section near Corrieshalloch. d) texture of sedimentary grains within the slice of Torridonian rocks caught up in the thrust belt SE of Ullapool.

Fig. 9. The evolving geological maps of NW Scotland through the Highlands Controversy, illustrating approximately the same area as in Fig. 7. a) Murchison (1859); b) Murchison and Geikie (1861). c) Geikie's (1910) map of part of Wester Ross showing the same ground as a) and b) after the interpretation of the Moine Thrust and related structures.

Fig. 10. The Moine Thrust Belt in the Achnashellach culmination as illustrated on the ridge of Beinn Liath Mhor (located on Fig. 7). a) the view onto the section from the north. b) the section as interpreted by Murchison and Geikie (1861a)

Fig. 11. Murchison's (1848) cross-section through the now-famous Martins-loch location in the Swiss Alps. The contact at the base of the "Crystalline schist" (y) was interpreted by Murchison as tectonic – what is now called the Glarus Thrust.

Fig. 12. Photographs of the ground covered by Geikie on his walk on 4th September 1860 (Fig. 7 for locations). a) looking across from the slopes of Beinn Eighe onto the southern part of the walk, up Glean Bianasdail and on to Bealach na Croise (first watershed). b) the eastern side of Glean Bianasdail seen from the stalkers' path up to Lochan Fada with prominent field relationships. c) looking SW towards Mullach Coire Fhearchair at Loch an Nid (see Fig. 13). d) the second watershed on the east side of the mountain An Teallach. e) the final slopes – looking from Beinn nam Ban to the Coigach hills north of Ullapool. f) the SW shore of Loch Broom, at the end of Geikie's walk.

Fig. 13. The Loch an Nid area from Geikie's "long-walk" in September 1860. a) an undated pen and ink sketch by Geikie of the Loch an Nid valley seen from the North, with the ridge of Mullach Coire Mhic Fhearchair. b) Geikie's

interpretation of the geology from his field notebook. (c) the published interpreted from Murchison and Geikie (1861).

Fig. 14. The famous Knockan Crag locality, a) view, looking east, onto the outcrops. The Moine Thrust (base of the Moine Group) is arrowed. The height of the escarpment is 100m. b) cross-section through the outcrop and surrounding hills from Murchison and Geikie (1861a). c) mylonitic Moine Group metasediments at Knockan Crag showing the prominent planar foliation that was mistaken for bedding by Murchison and Geikie (see also Fig. 8c).

Fig. 15. The Arnaboll Thrust at its type locality, carrying Lewisian gneisses and pegmatites onto Cambrian quartzites.

Fig 16. The outcrops on Druim Hain, Skye, that settled the debate between Geikie and Judd. a) looking from the edge of the outcrops of gabbro on Druim Hain towards the granite of Meall Dearg, c 400m from the viewpoint. The contact between gabbro and granite is arrowed. b) relationships between granite sheets and veins and the host gabbro on Druim Hain.

Fig 17. Geikie's (1894) sketch map of the field relationships on Druim Hain. .

Figure 1

Click here to download Figure Fig 1_locationscolour.pdf

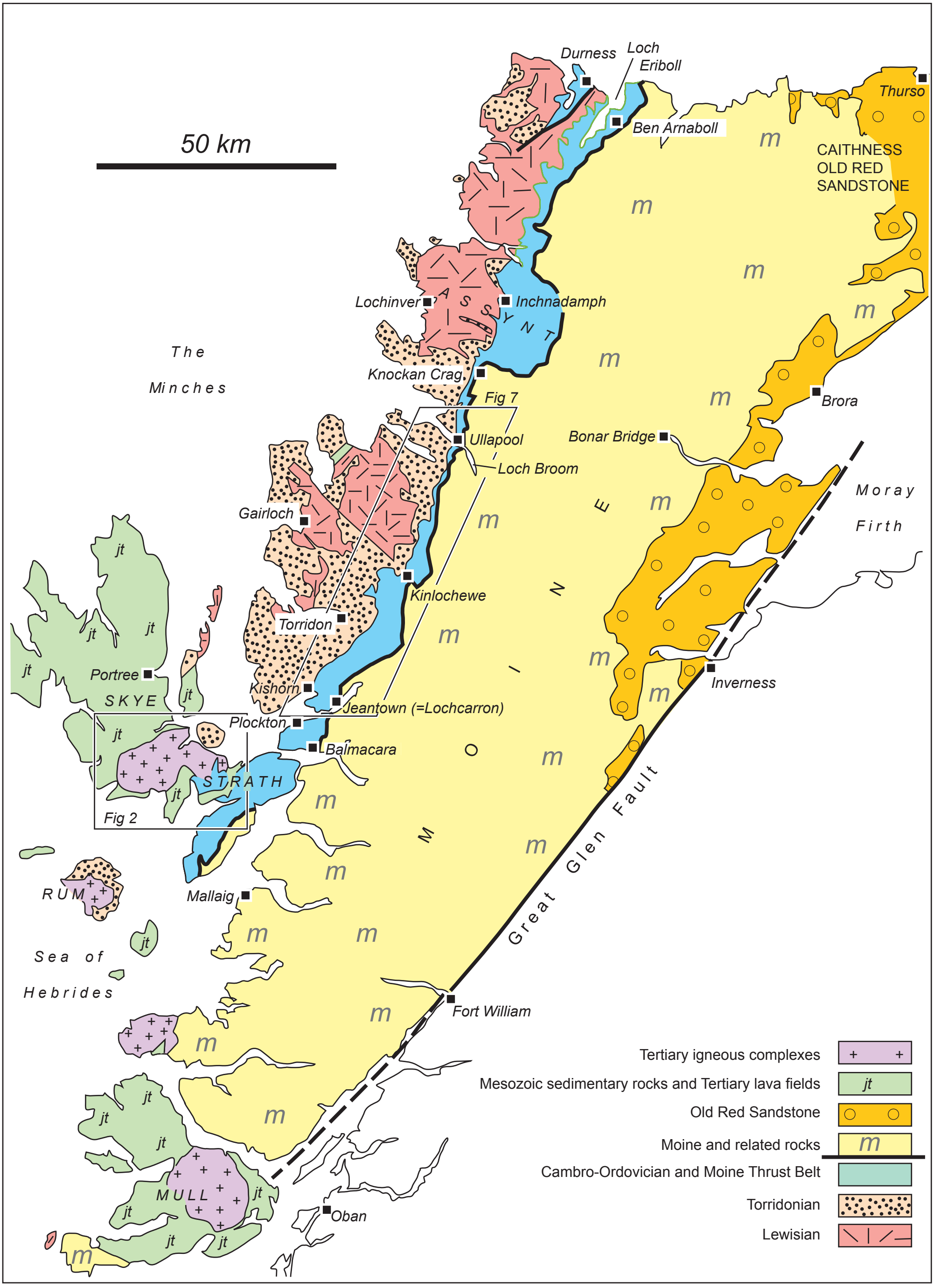

Figure 2

Click here to download Figure Fig 2 _Skyenewmapcolour.pdf

Tertiary Igneous Rocks

basalt lava

breccia

acid (granite etc) intrusions

basic and ultrabasic intrusions (gabbro etc)

sedimentary rocks (and metamorphosed)

J Jurassic

Durness limestone

Cambrian quarzites

Torridonian

WESTERN RED HILLS

CUILLINS

Glen Sligachan

Bla Bheinn

M D

DH

B

Scalpay

Pabbay

Broadford Bay

Broadford

Beinn na Caillich

Beinn an Dubhaich

Loch Slapin

AL

A

Loch Eishort

Soay

10 km

Figure 3

Click here to download Figure aFig 3 Slapinviews.jpg

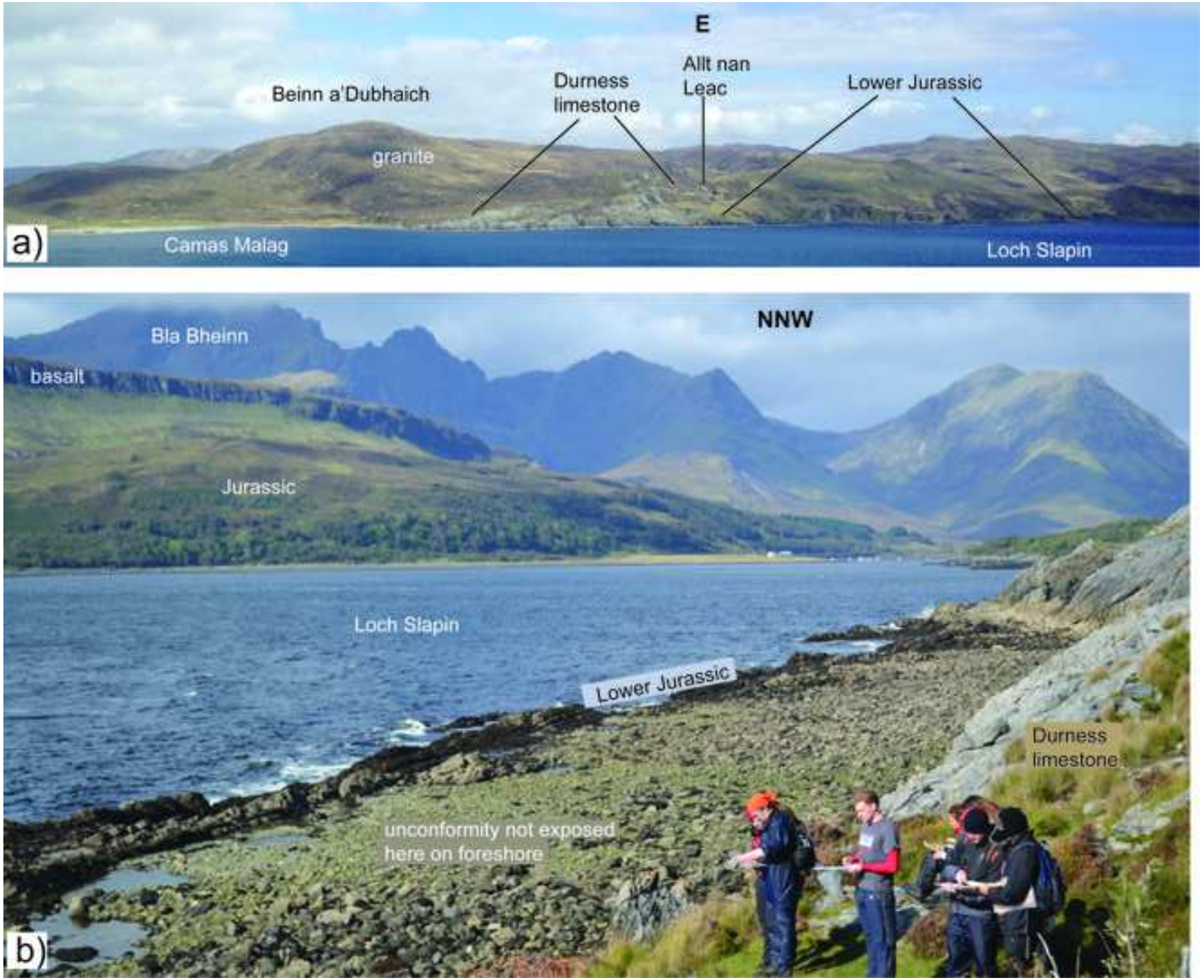

Figure 4

Click here to download Figure aFig 4_adchart.jpg

Figure 5

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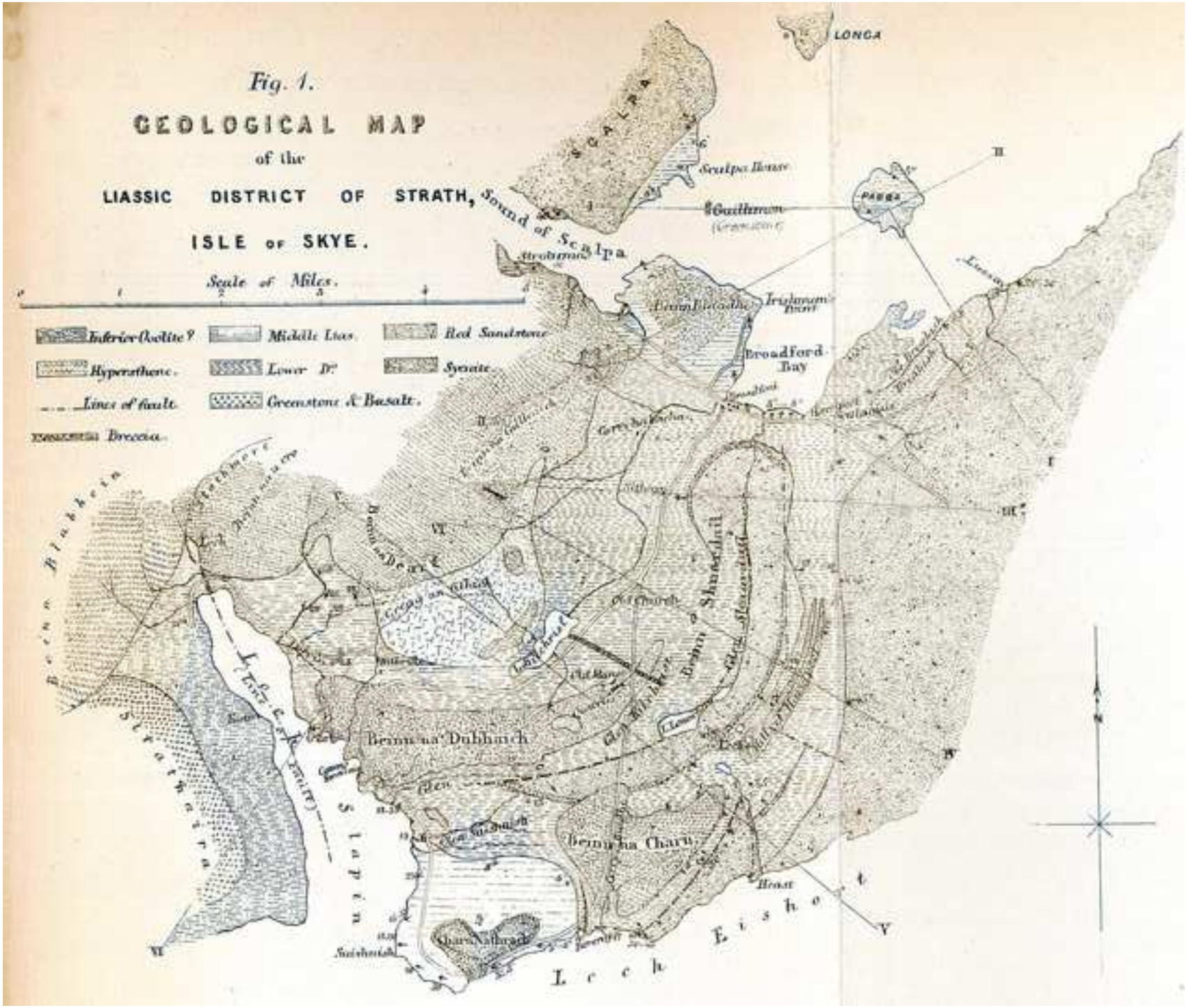

Figure 6

e. Blue, somewhat fetid limestones, full of broken shells (Lias). *d*. Limestone breccia (50–60 feet) consisting mainly of fragments of the underlying limestones, with abundant pieces of chert and quartzite. *c*. Granophyre ("Syenite") of Beinn an Dubhaich. *b*. White limestone. *a*. Dark-grey limestone full of worm-casts and pieces of chert.

Figure 7

Click here to download Figure aFig 7_Szonemap.jpg

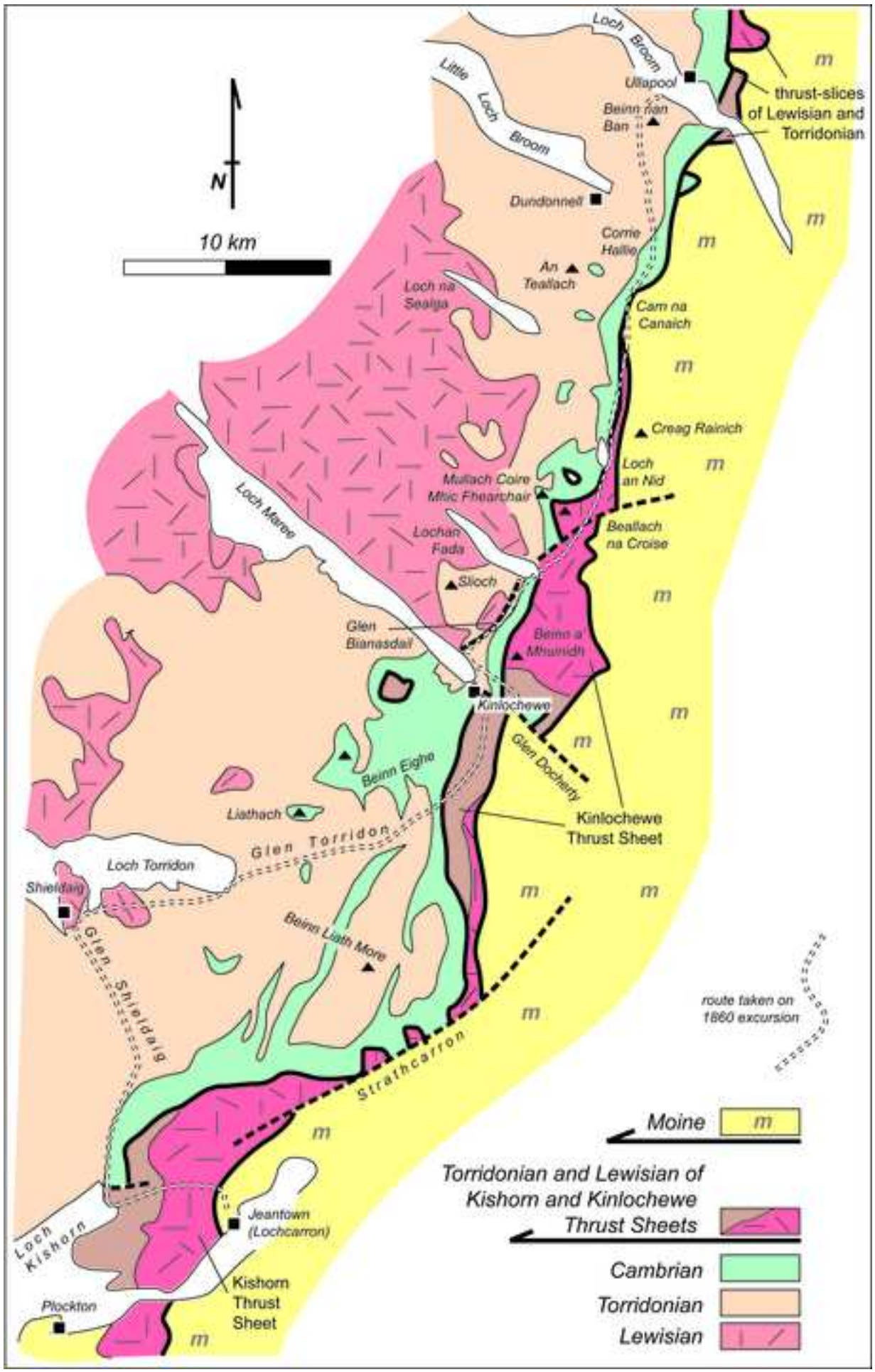

Figure 8

Click here to download Figure aFig 8_LochBroom.jpg

Fig. 2.—*Section along the South side of Loch Broom.*

f. Gneiss (upper).
e. Serpentine or felspar-porphyry.
d. Limestone.
c. Quartzite.
b. Red Sandstone.
a. Gneiss (lower).

a) - Nicol (1857)

a. Gneiss.
b. Cambrian sandstone and conglomerate.
c^1. Quartz-rock.
c^2. Limestone.
d. Gneissose schists.
* Serpentinous and felspathic rock containing pebbles of jasper.

b) - Murchison and Geikie (1861)

Figure 9A

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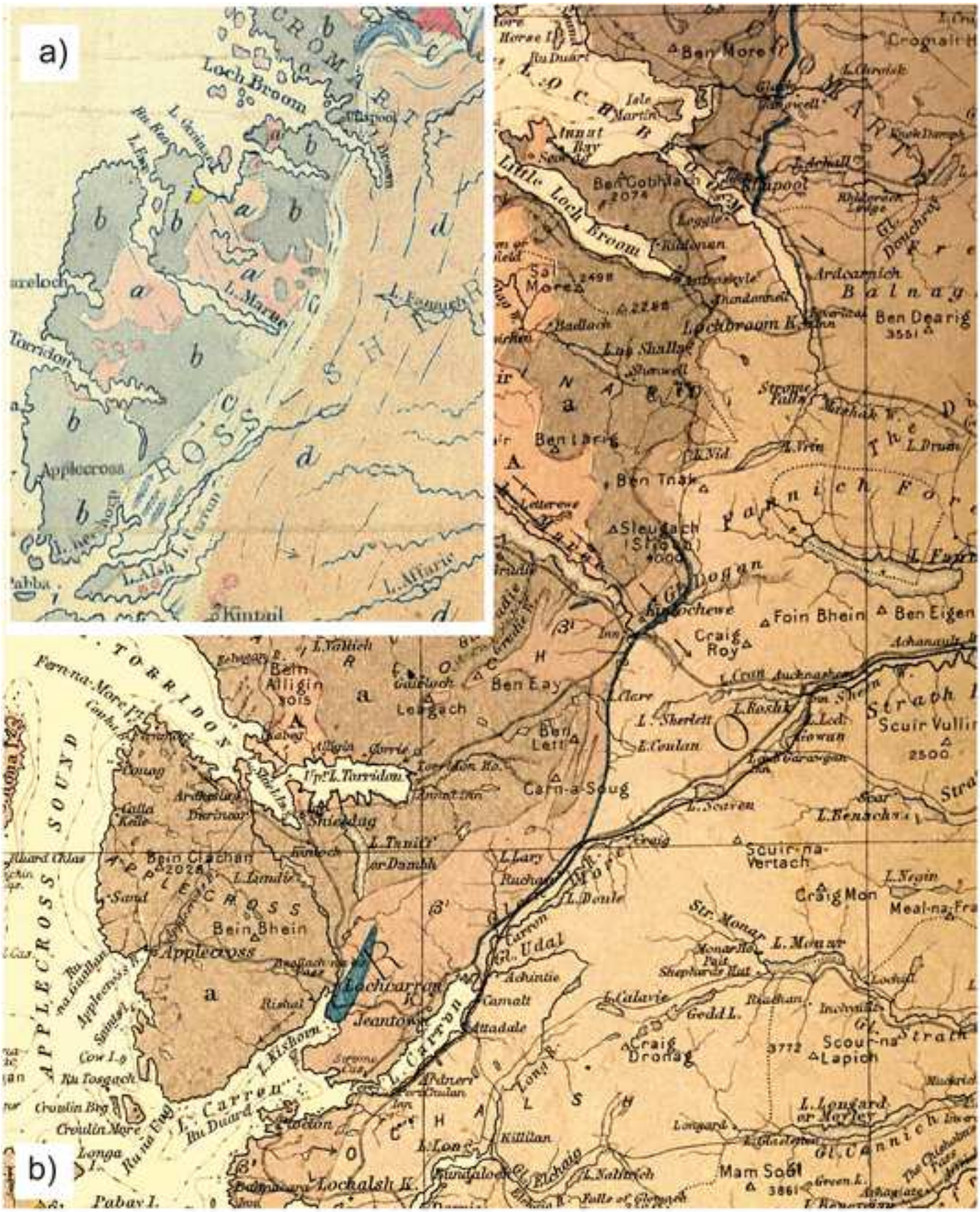

Figure 9B

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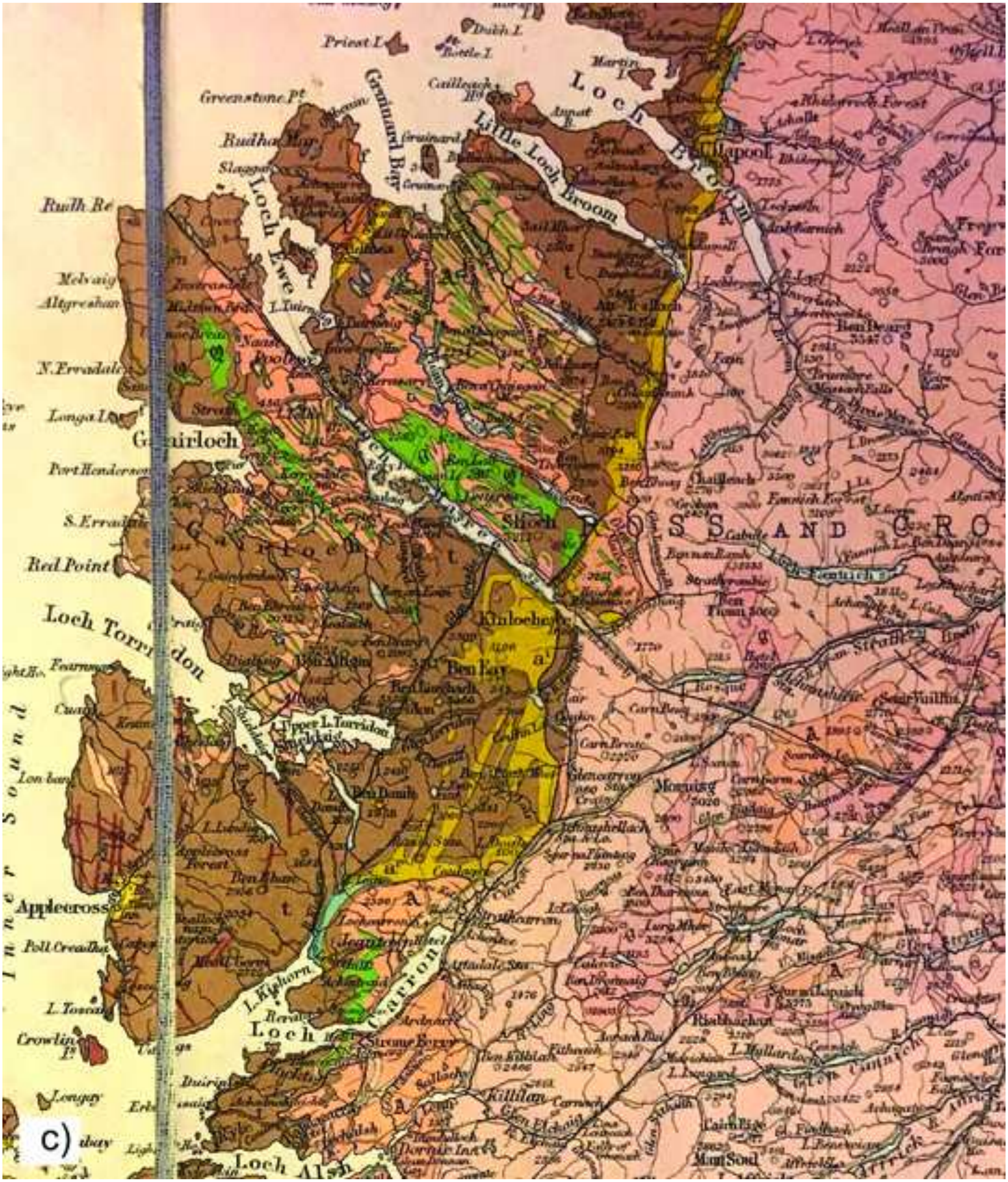

Figure 10

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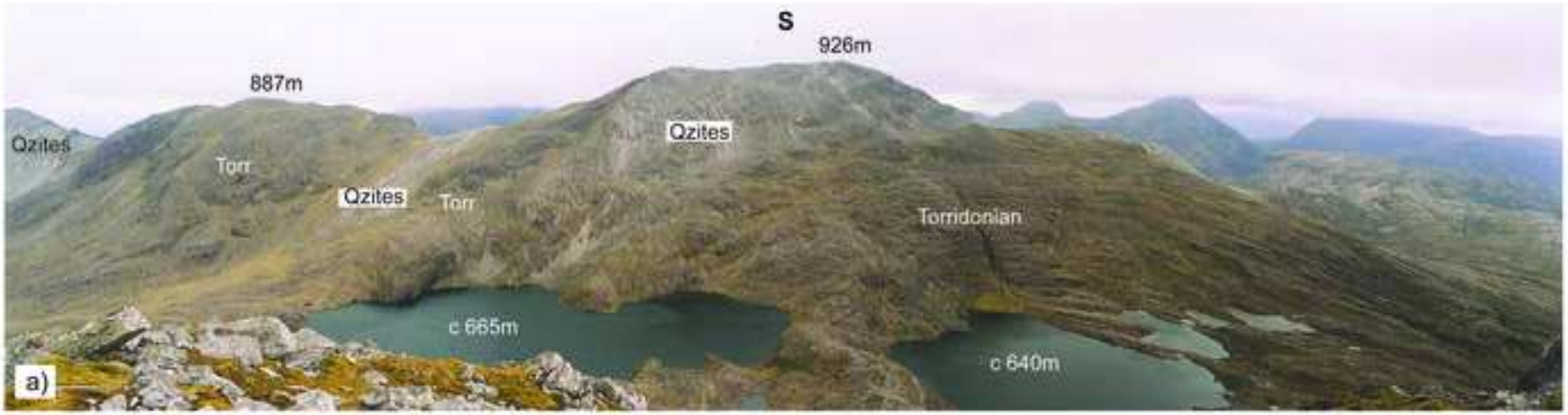
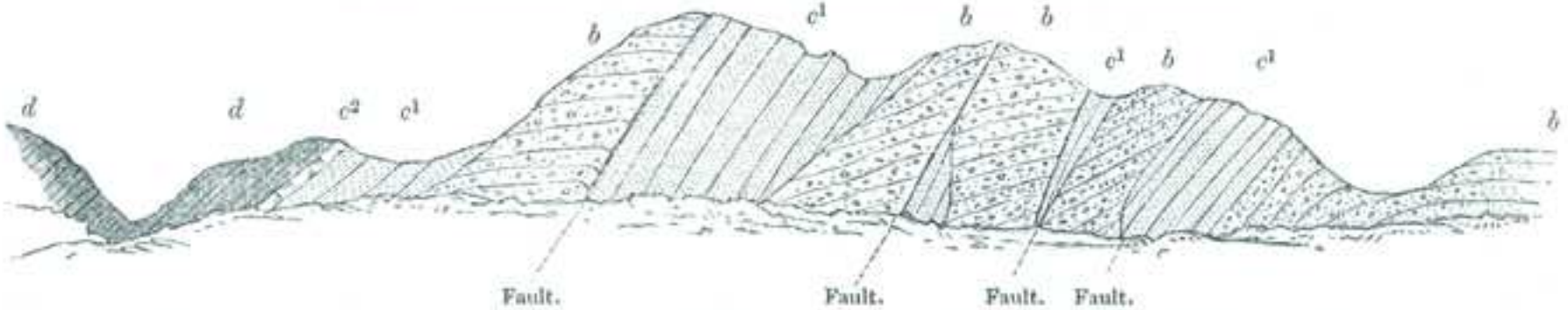


Fig. 13.—*Sectional View of the Dun Telleah Hills.* Length 2 miles.



b) *b.* Cambrian sandstone and conglomerate. c^1. Quartz-rock. c^2. Limestone. *d.* Gneissose schist.

Figure 11

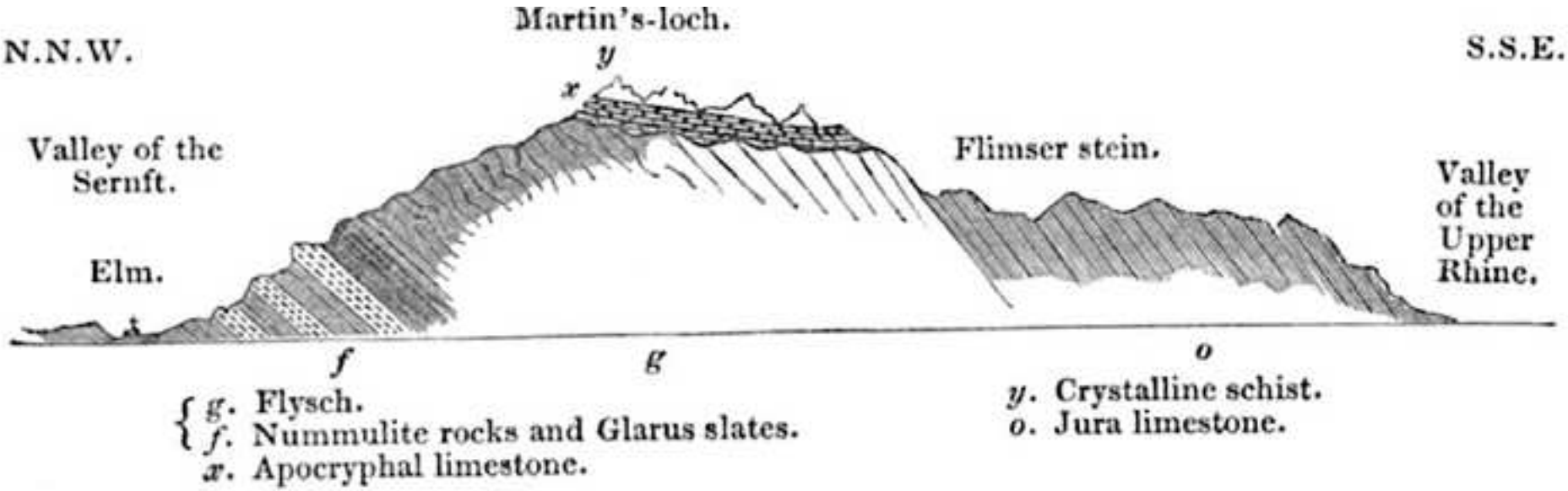


Figure 12A

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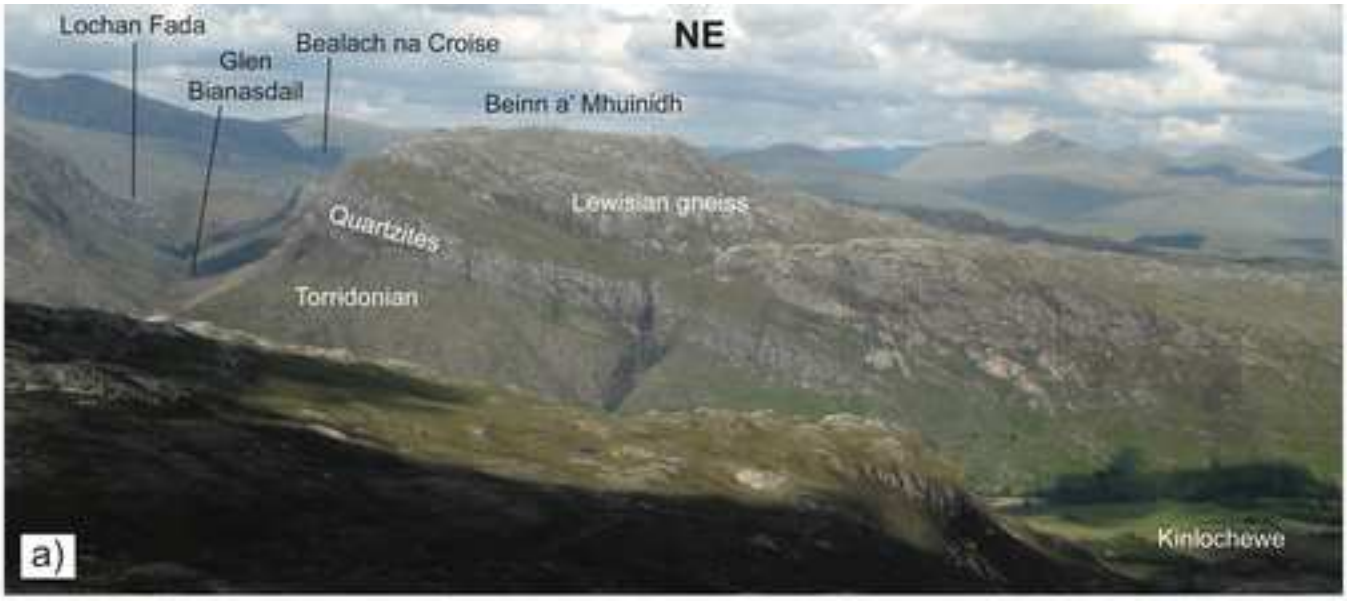

Figure 12B

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Figure 13

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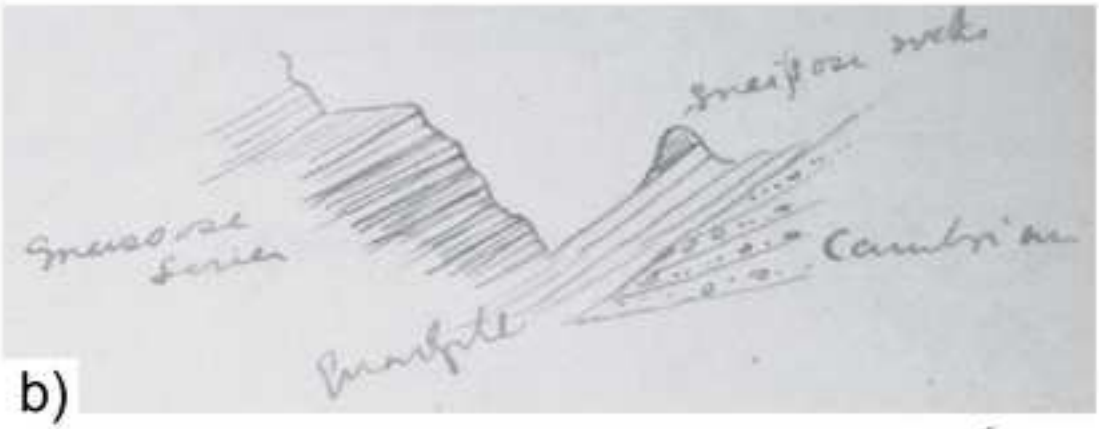
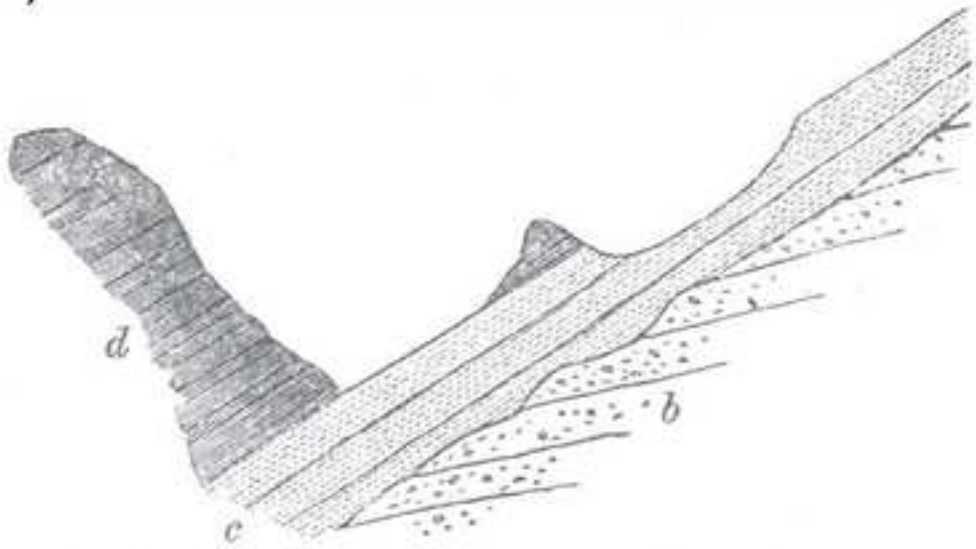
a)



b)



b. Cambrian sandstone and conglomerate.
c. Quartz-rock. *d*. Gneissose schists.

c)

Figure 14

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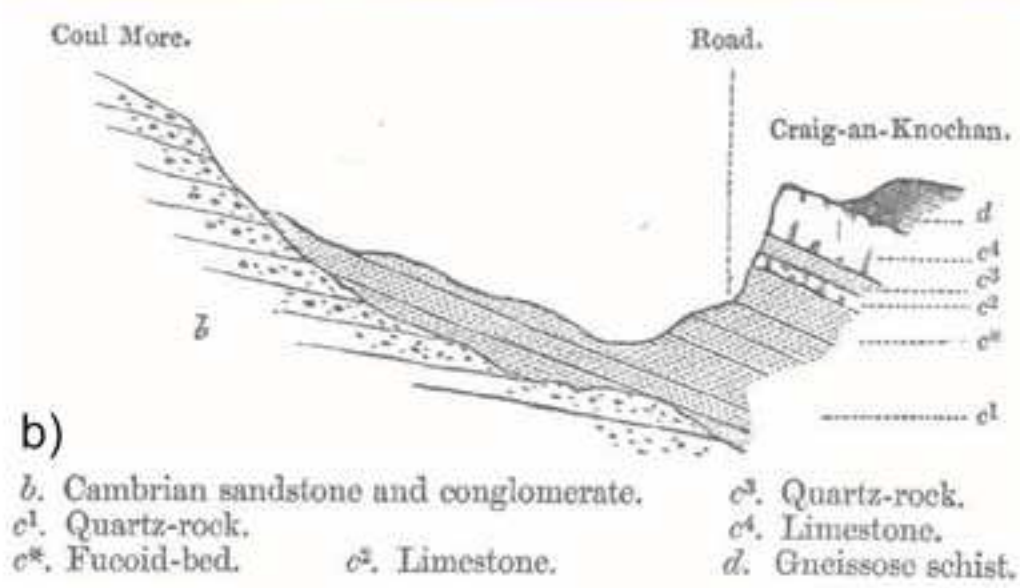

Figure 15

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Figure 16

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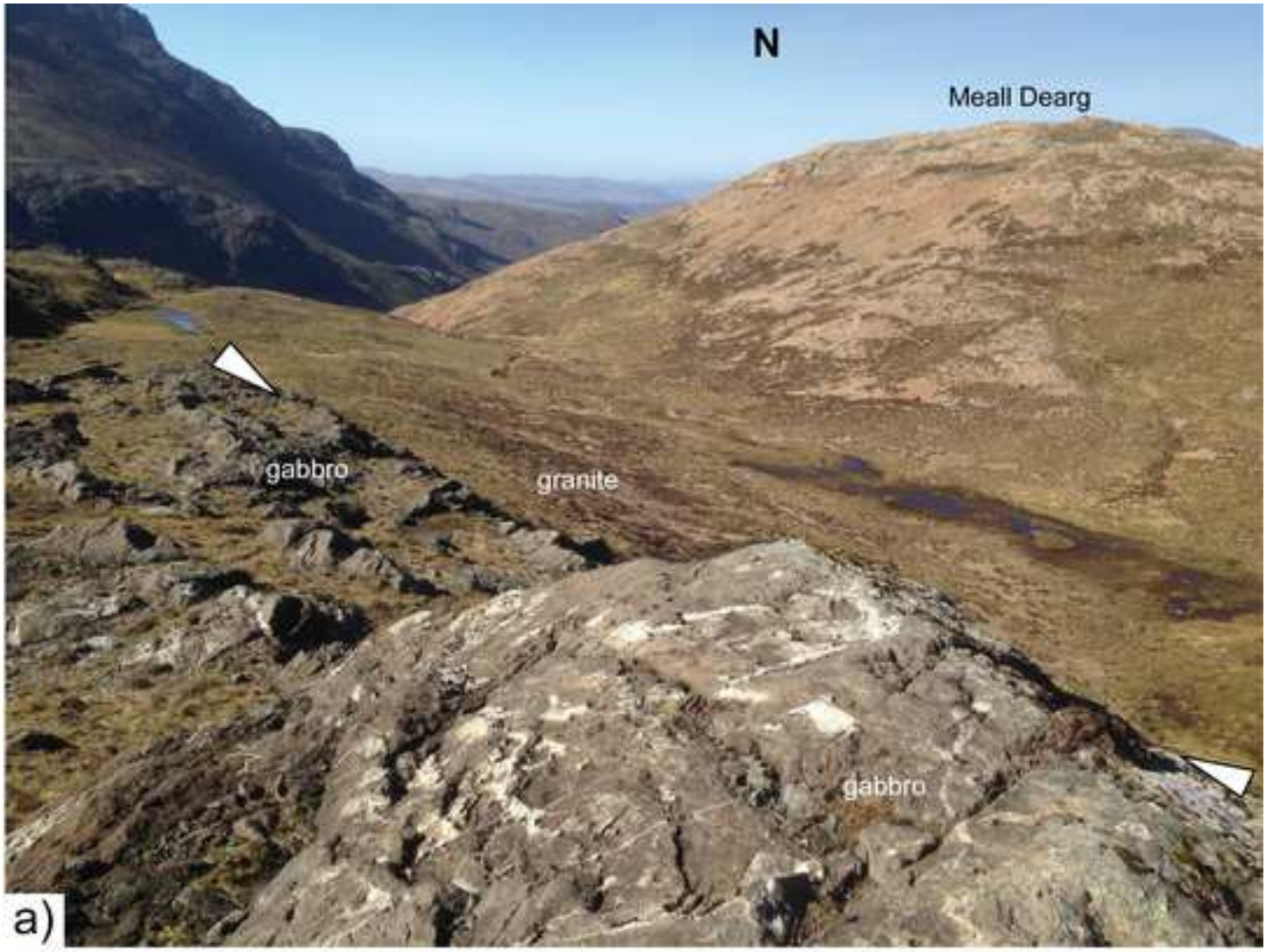


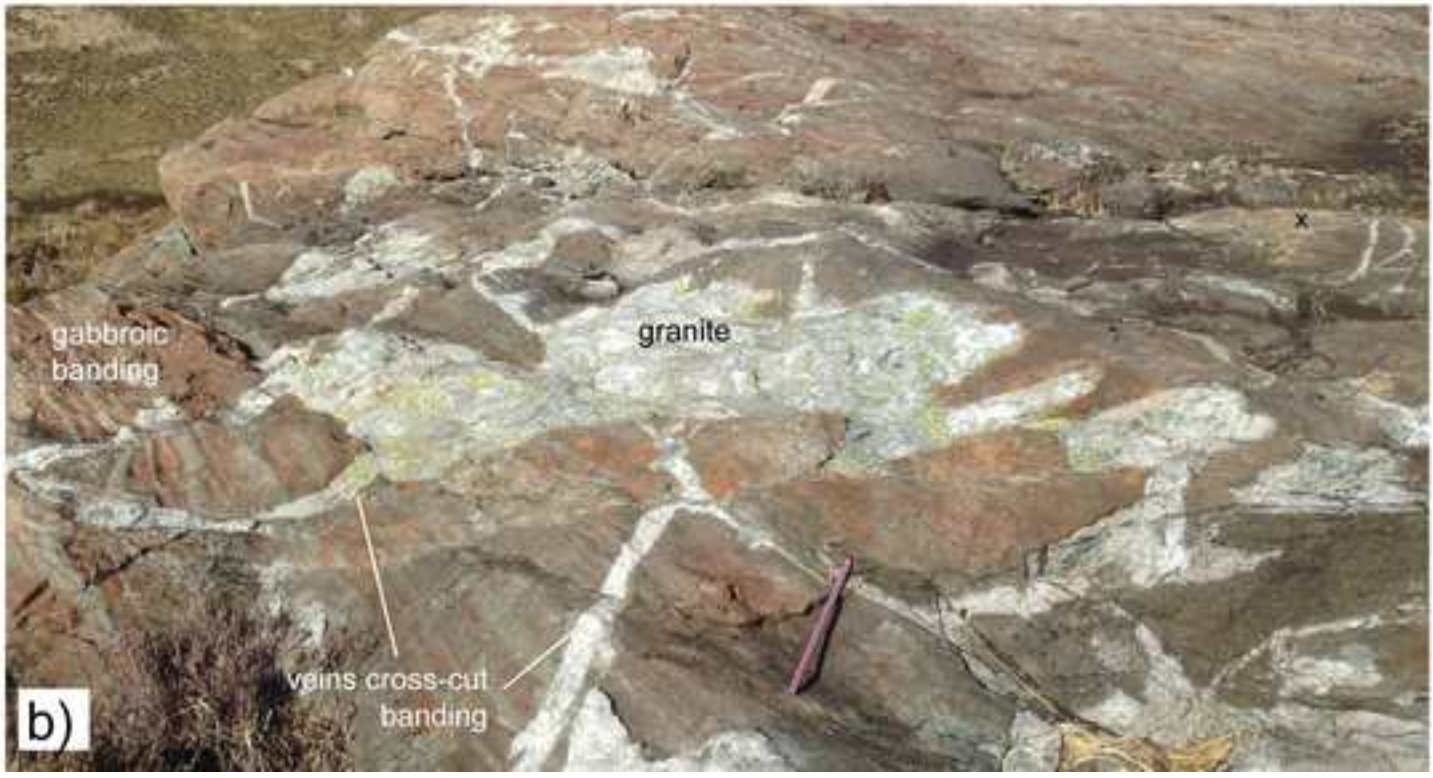
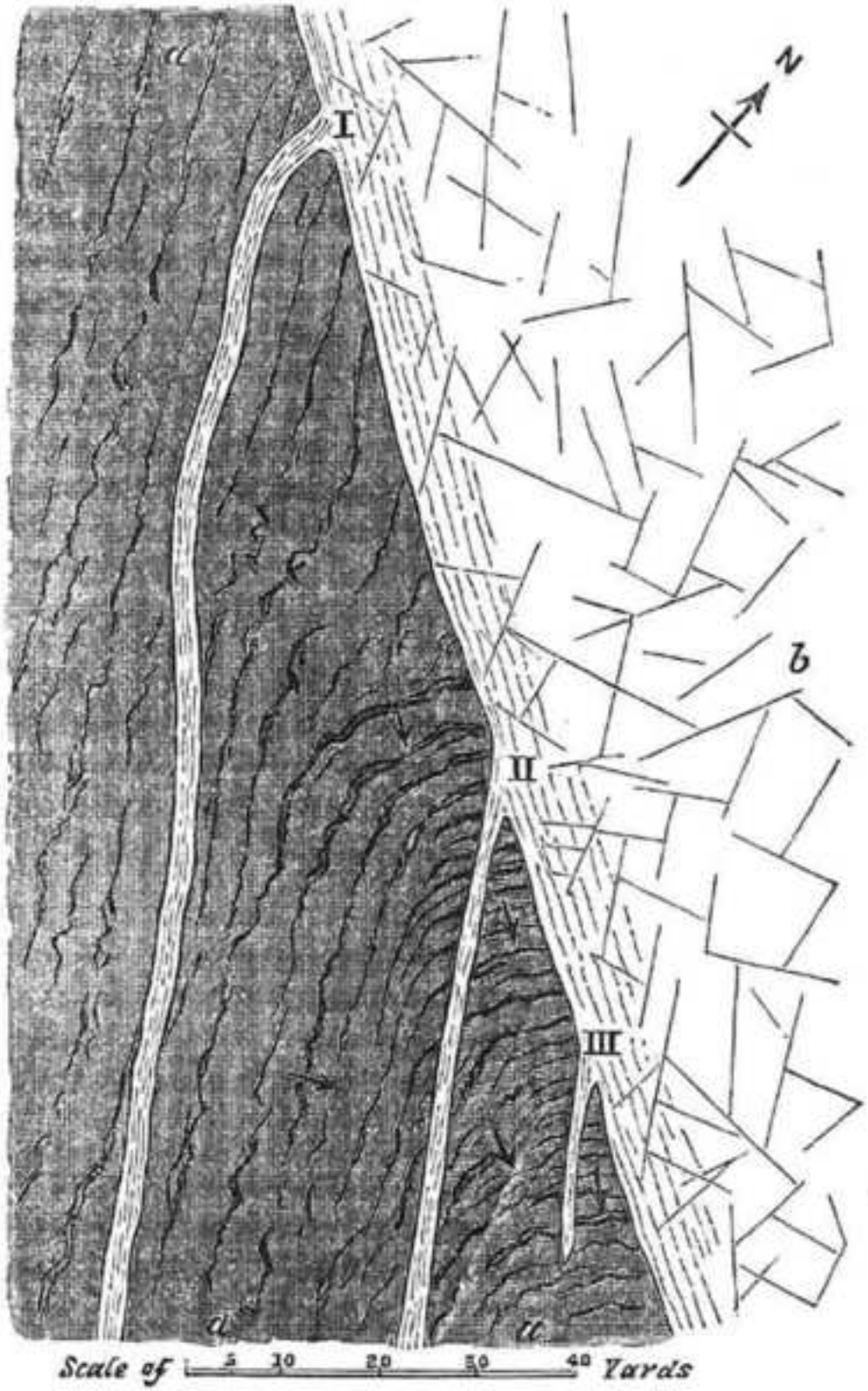


Figure 17 Click here to download Figure aFig 17_DHsketch.jpg



a. Gabbros; *b*, granophyre; I., II., III., three dykes proceeding from the granophyre. The arrows show the direction of dip of the bands of gabbro.