SERIES

Classic Rock Tours 4. Long Walks, Lost Documents and the Birthplace of Igneous Petrology: Exploring Glen Tilt, Perthshire, Scotland

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SUMMARY

The spectacular angular unconformity at Siccar Point is the most famous site associated with James Hutton (1726–1797), but it was not his only place of insight. In 1785, three years before he discovered Siccar Point, Hutton examined outcrops in the still-remote valley of Glen Tilt, in the Scottish Highlands. He documented contact relationships between Precambrian metasedimentary rocks and Paleozoic granite bodies, although he had no knowledge of their true ages. Near to the hunting lodge where he and his colleague John Clerk of Eldin stayed, veins of granite clearly cut through relict bedding in the stratified rocks and disrupt their layering, breaking apart individual strata and leaving fragments (xenoliths) surrounded by granite. Hutton correctly deduced that the granite must originally have been in a *'state of fusion'* and was forcefully injected into much older *'schistus'*. Such conclusions contravened prevailing ideas that granite bodies formed from aqueous solutions, and also refuted a wider philosophical view that granite and other crystalline rocks were the oldest and first-created parts of the Earth. Hutton's key outcrops in Glen Tilt are easy to visit, although they do require a long (but easy) roundtrip hike of some 25 km. These are certainly not the most spectacular intrusion breccias that I have ever seen, but they are very instructive, and were very influential, because they sparked a long, and at times acrimonious, debate about the origins of igneous rocks and especially granite. This controversy had many strange twists and turns. These include the disappearance of Hutton's original manuscript after his death, and its serendipitous rediscovery a century later, and the similar loss and rediscovery of exquisite drawings by John Clerk, almost two centuries after they were first penned. Among the lost drawings is an early example of detailed outcrop-scale mapping, which would become a key field-work technique.

Hutton's vision of granite as the product of hot, liquid material that moved upward in the Earth's crust (plutonism) eventually prevailed over the idea that crystalline rocks formed from a primordial ocean that once enveloped the Earth (neptunism), but this victory did not come easily or quickly. In another strange twist of history, new evidence from the Cape of Good Hope in South Africa eventually acted to further the plutonist cause. Glen Tilt has changed very little since the time of Hutton, but the observations that were made here, and the long debate that followed, brought fundamental changes in our understanding of the Earth. Although Siccar Point should remain the first entry on the bucket list of any prospective geopilgrim to Scotland, the long and beautiful valley of the River Tilt should also be a priority.

RÉSUMÉ

La spectaculaire discordance angulaire de Siccar Point est le site le plus célèbre associé à James Hutton (1726–1797), mais ce n'était pas le seul lieu qui l'ait inspiré. En 1785, trois ans avant de découvrir Siccar Point, Hutton a examiné des affleurements dans la vallée encore enclavée de Glen Tilt, dans les Highlands écossais. Il a documenté les contacts entre les roches métasédimentaires précambriennes et les corps granitiques du Paléozoïque, bien qu'il ne connût pas leur véritable âge. Près du pavillon de chasse où lui et son collègue John

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Clerk of Eldin ont séjourné, des veines de granit ont clairement percé le litage relique dans les roches stratifiées et perturbé leur superposition, brisant les strates individuelles et laissant des fragments (xénolithes) entourés de granit. Hutton a correctement déduit que le granit devait à l'origine être dans un « état de fusion » et qu'il avait été injecté de force dans des « schistes » beaucoup plus anciens. De telles conclusions contrevenaient aux idées dominantes selon lesquelles des corps granitiques se formaient à partir de solutions aqueuses et réfutaient également une vision philosophique plus large selon laquelle le granit et d'autres roches cristallines étaient les parties de la Terre les plus anciennes et les premières créées. Les principaux affleurements de Hutton à Glen Tilt sont faciles à visiter, bien qu'ils nécessitent une longue randonnée (mais facile) d'environ 25 km aller et retour. Ce ne sont certainement pas les brèches d'intrusion les plus spectaculaires que je n'ai jamais vues, mais elles sont très instructives et ont eu un rôle très influent, car elles ont déclenché un long débat, parfois acrimonieux, sur les origines des roches ignées et en particulier du granit. Cette controverse a eu de nombreux rebondissements étranges. Ceux-ci incluent la disparition du manuscrit original de Hutton après sa mort, et sa redécouverte fortuite un siècle plus tard, et la perte et la redécouverte similaires de dessins remarquables de John Clerk, près de deux siècles après qu'ils aient été esquissés. Parmi les dessins perdus, se trouve un premier exemple de cartographie détaillée à l'échelle des affleurements, qui deviendra une technique clé de travail sur le terrain.

La vision de Hutton du granit en tant que produit d'un matériau chaud et liquide qui s'est déplacé vers le haut dans la croûte terrestre (plutonisme) a finalement prévalu sur l'idée que des roches cristallines se sont formées à partir d'un océan primordial qui enveloppait autrefois la Terre (neptunisme), mais cette victoire n'est pas venue facilement ou rapidement. Dans une autre tournure étrange de l'histoire, de nouvelles preuves provenant du Cap de Bonne-Espérance en Afrique du Sud ont fini par faire avancer la cause plutoniste. Glen Tilt a très peu changé depuis l'époque de Hutton, mais les observations qui ont été faites ici, et le long débat qui a suivi, ont apporté des changements fondamentaux dans notre compréhension de la Terre. Bien que Siccar Point devrait rester en haut de la liste des lieux à visiter de tout visiteur potentiel lors d'un pèlerinage géologique en Écosse, la longue et belle vallée de la rivière Tilt devrait également être une priorité.

PROLOGUE

Scotland has no shortage of sites to interest geologically minded visitors, and Edinburgh is where modern geology was born through the work of James Hutton (1726–1797). The most famous Hutton locality is the unconformity at Siccar Point, described in many comprehensive accounts, and summarized in an earlier article from this series (Kerr 2018). Hutton also established some key principles in igneous petrology, which are equally relevant to our modern view of the dynamic Earth. In 1785, he examined river exposures in Glen Tilt, in the Perthshire Highlands, and proposed that granite formed in a "fused condition" and had forced its way through other (older) rock types. These linked concepts of intrusion and cross-cutting relationships are now central to field geology and petrology but contradicted the dogma of those times. Hutton's detailed descriptions of these key exposures did not appear in full until long after his death, but his initial suggestions sparked a long and at times acrimonious debate that endured for more than 50 years. Hutton was accompanied in the field by the famous artist John Clerk of Eldin, who captured Glen Tilt in drawings, watercolours and engravings, which include one of the earliest detailed geological maps. Hutton's text and Clerk's exquisite artwork were likely intended for the never-to-be completed third volume of Theory of the Earth, but both were lost for centuries. These lost documents form interesting stories in their own right, more fully recounted by Adams (1938), Bailey (1967) and Craig et al. (1978).

Glen Tilt may lack the fame of Siccar Point, and Hutton's key outcrops today bear not even a simple historical marker, but it is a place of insight, and is well worth visiting. It is easy to find, although you cannot drive there, and it requires a roundtrip hike of about 25 km. However, the hike is easy, and also leads into the Cairngorms National Park, so there is much to enjoy beyond local geology. The fastest mode of transport is with a mountain bike (these are allowed on the trail) and when I return, it will definitely be on two wheels rather than two legs. I have no doubt that the long downhill return run will be more fun than trudging back with sore feet.

This article was conceived following my own visit in 2019, but the bulk of the information comes from other sources (notably Craig et al. 1978; Stephenson 1999; Smith et al. 2011; Barron et al. 2011; Stephenson et al. 2013a, b), historical and biographical accounts (Geikie 1897; Bailey 1967; Dott 1967; Faul and Faul 1983; Pitcher 1993; Young 2003; Master 2009) and the words of Hutton and other early geologists (e.g. Hutton 1788, 1794; Playfair 1802; Seymour 1815; MacCulloch 1816). The article first summarizes key aspects of local geology and gives practical information to assist visitors, and then discusses Hutton's work and the ensuing debate in the wider context of 18th and 19th century natural science. Such knowledge is certainly not essential to hike in this lovely Highland glen, but I firmly believe that it can enrich such an experience.

GEOLOGICAL AND HISTORICAL BACKGROUND

Regional and Local Geology

Scotland is largely underlain by late Precambrian to Paleozoic rocks of the Caledonian Orogenic Belt (Fig. 1), and it was originally contiguous with parts of the Appalachian Orogenic Belt of eastern Canada. Central Scotland is dominated by the Midland Valley, underlain by Devonian and Carboniferous rocks, including coal measures. The northern boundary of the Midland Valley is the Highland Boundary Fault, north of which Precambrian to Paleozoic metamorphic and igneous rocks dominate the rugged landscape (Fig. 1). Large igneous intrusions are mostly of Silurian to Devonian age and are collectively termed 'Caledonian Granites'. These igneous massifs occupy most of the high country in the Cairngorms National Park, including Ben Macdui (1309 m), which is the second

Figure 1. (A) Simplified bedrock geology of Great Britain as published online by the British Geological Survey, showing the locations of Edinburgh, Perth and Glen Tilt. (B). Locations and major roads in the area around Perth, Pitlochry, and Glen Tilt, showing the route to the area of interest.

highest peak in Scotland. The Glen Tilt area lies along the southern edge of the Glen Tilt Pluton (or 'complex'), which is mostly granite, with lesser diorite (Smith et al. 2011; Fig. 2). This igneous complex includes some of the youngest Paleozoic granitic rocks in the Scottish Highlands, dated at 390 ± 5 Ma (Oliver et al. 2008). The adjacent older country rocks mostly form part of the Dalradian Supergroup, comprising metasedimentary rocks that were deposited between late Precambrian and earliest Paleozoic times, and then deformed and metamorphosed during the Grampian Event of the Caledonian Orogeny, ~ 470 Ma ago (see review by Stephenson et al. 2013a). This event correlates broadly with the Taconic Orogeny as defined in the Appalachians, and metasedimentary rocks that likely correlate with the Dalradian occur in Newfoundland, Canada (van Staal et al. 2014). Studies of the Scottish Dalradian were influential in geology, defining mineralogical changes associated with regional metamorphism (Barrow 1893) and later ideas about thrust faults ('slides') and fold interference patterns (e.g. Ramsay 1967). In Glen Tilt, the contact between Paleozoic igneous rocks and the Dalradian Supergroup is in part defined by the Loch Tay Fault, which also controls the course of the upper river valley (Fig. 2). The fault displaced the area to its southeast downward relative to its northwest side, and also caused a sinistral displacement of several kilometres. Most, but not all, of the Paleozoic plutonic rocks lie on the northwestern (upthrown) side of the Loch Tay Fault (Smith et al. 2011; Fig. 2).

The complex stratigraphy of the Dalradian Supergroup records sedimentation from late Proterozoic to earliest Paleozoic times (Harris et al. 1994; Soper et al. 1999; Tanner and Sutherland 2007; Stephenson et al. 2013a, b). The rocks around Glen Tilt are the lower part of the sequence, including parts of the Grampian, Appin and Argyll groups (Smith et al. 2011; Fig. 2). These are mostly quartz-rich metasedimentary rocks (termed 'psammite'), accompanied by aluminous units (termed 'pelite') representing original impure sandstone and mudstone, respectively. Terms such as psammite or pelite were used widely over the years and are retained here for consistency, even though usage is less common today. Discontinuous units of marble and amphibolite represent original limestone and mafic flows or dykes, respectively. There have been many debates about details and changes to the stratigraphic nomenclature of the Dalradian over time; in the absence of fossil control, differences of opinion about the exact assignment of lithologically similar units are unavoidable. The regional map shown in Figure 2 is therefore not completely consistent with more detailed interpretations of areas within it, as illustrated by Smith et al. (2011). The Dalradian experienced several episodes of ductile deformation, during which early recumbent folds ('nappes') were refolded repeatedly. For those with a taste for more detail, and insight into long-lasting debates, the review papers of Stephenson et al. (2013a, b) are highly recommended.

The post-Ordovician history of the region was largely one of uplift and erosion, with detritus from the crystalline rocks transported and deposited within the adjacent Midland Valley. Brittle deformation along the trace of the Loch Tay Fault like-

Figure 2. Simplified regional geology of the area around Blair Atholl and Glen Tilt, southern Scottish Highlands. Information compiled from the "Geology of Britain" website application provided by the British Geological Survey, and earlier published maps at 1:250,000 and 1:50,000 scales (British Geological Survey 1986, 2008). Note that due to scale differences, this map does not show detailed unit distributions discussed in the text. The site locations are approximate.

ly records this time period, although the structure may have an earlier history that partly overlaps the emplacement of Devonian igneous rocks (Smith et al. 2011). The Cairngorm Mountains are also well known for their glacial geomorphology and stratigraphy, discussed in detail by Smith et al. (2011) and Barron et al. (2011).

Neptunists and Plutonists: A Primer

In the 18th century, none of the above was known or even suspected, and the history of the Earth was viewed by most through the lens of the Bible, but early natural scientists speculated on the origins of various rock types and what they might tell us about Earthly processes. Modern analogues of sedimentary rocks could be seen in rivers and lakes or along seashores, so many thought that *all rock types* formed from some 'primeval ocean'. Abraham Werner (1749–1817), a mineralogist from Saxony (Germany) was the most famous of these *neptunists*, whose views prevailed for decades. Neptunists suggested that crystalline rocks were the very first to form from God's primeval ocean, much like salts precipitate from modern seawater. The stratified sedimentary rocks were then suggested to have formed by erosion and/or redissolution of such 'primitive' crystalline rocks, followed by redeposition. Such processes were generally assumed to have been catastrophic and were attributed to Noah's great flood. Thus, the neptunist view demanded that crystalline rocks be *older* than sedimentary rocks, even if the age difference between them was held to be thousands of years at most. After all, biblical scholars then decreed that the Earth itself had only existed for around six thousand years. Recent and modern volcanism presented problems for the neptunists, but these were seen as local phenomena, and volcanic heat was attributed to the local burning of underground coal seams (if it lacked a divine origin). Geologists had yet to make a connection between typically glassy modern lavas and ancient basalt or rhyolite units, which were considered to have 'aqueous' origins, because they commonly appeared to be stratified.

In 1785, James Hutton first proposed that geological processes were driven by heat from deep within the Earth, and he later pointed to the insolubility of quartz and feldspar, and their common intergrowth in granite, as evidence that granite had *"risen in a fused condition from subterranean regions"* (Hutton 1788, 1794). This idea carried no requirement that granite should always be *older* than sedimentary rocks, and he reasoned that it could be tested by observation. The initial expedition to Glen Tilt in 1785 was based on this premise, and Hutton became the first of the *plutonists*, who argued instead that igneous rocks formed directly from hot, molten liquids akin to modern lavas, rather than settling out of some mysterious primordial ocean. Such views were controversial, and provoked strong responses from the 18th century scientific establishment, which was heavily influenced by Werner and his fellow neptunists. For a wider discussion of the neptunist–plutonist controversy, which of course involved many more people than Werner and Hutton, readers are referred to the excellent book by Hallam (1983).

Geological Relationships near Forest Lodge, Glen Tilt

The exposures that Hutton first examined in 1785 from Glen Tilt would be familiar to most undergraduate students and many have probably visited similar sites. They are examples of 'intrusion breccia', in which older solid rock types (in this case, those of the Dalradian Supergroup) were broken apart and disrupted by liquid magmas of variable composition and state, probably in several discrete episodes. These exposures are chaotic and composite, dominated by metasedimentary rocks, but including many areas of granite, most commonly forming veins, sheets and diffuse irregular pods. Contacts between igneous and metasedimentary rocks demonstrate cross-cutting relationships, where primary layering (bedding) is truncated and disrupted by granite, proving that deposition and lithification of the original sediments long predated the arrival of the granite, which was emplaced as a viscous liquid. Recrystallization and new mineral growth in the older metasedimentary rocks demonstrates contact metamorphism, indicating that magmas were emplaced at high temperatures, and affected the older rocks in various ways. The actual concept of metamorphism did not exist in 1785, but Hutton recognized these physical changes, which he attributed to heating and 'softening'. This was another important insight from this locality.

Intrusion breccia outcrops are unusual but not exactly uncommon, and inferences about relative age based on such cross-cutting relationships would not generate any discussion today. I have seen plenty of exposures like these in my career, and many are more spectacular than those in Glen Tilt. But my comparison is irrelevant, as this idyllic spot on a Scottish river is where our *understanding and interpretation of such relationships first came*, and where the long conflict between plutonism and neptunism first began. In many respects, this is the birthplace of modern igneous petrology, so it has clear importance in the history of science and is rightly designated as a heritage site (e.g. Stephenson 1999). Although Siccar Point is rightly associated with our understanding of geological time, the intrusive relationships in Glen Tilt are an equally striking demonstration of its immensity.

EXPLORING THE GEOLOGY OF GLEN TILT

Directions, Local Geography and Local Access

Glen Tilt is a long, deeply incised valley in the southern Cairngorm Mountains (Figs. 2, 3) that is partly controlled by the trace of the Loch Tay Fault. The entrance to the glen is at Blair Atholl, located about 50 km from the city of Perth, northwest of Edinburgh (Fig. 1). The nearby town of Pitlochry, known as the "Gateway to the Highlands" contains abundant services for visitors. Blair Atholl is adjacent to the main trunk road between Perth and Inverness (A9), but along a parallel secondary road (B8079). There is a small railway station on the main line from Perth to Inverness, and the village is also served by long-distance buses, but such services are not frequent. The easiest way to visit the area is through use of a private vehicle. Coming from the southeast from Pitlochry into Blair Atholl on the B8079, turn right at the signpost for "The Old Bridge of

Figure 3. Location map for the lower section of Glen Tilt, from Blair Atholl to Forest Lodge and beyond. Information compiled and simplified from Ordnance Survey 1:50,000 map sheet 43 (Braemar and Blair Atholl).

Tilt" and carefully negotiate the narrow single-track road, which crosses the river on an even narrower bridge, and leads to a parking area on the left. From the railway station, turn right (east) on the road through the village to find this side road. Parking was free in 2019, but space is limited, and it may be busy in the summer months.

From the parking area, walk back towards the old bridge, and pass through a gated entrance on the left labelled "Atholl Estates". This unsurfaced road on the west side of the river leads to the important exposures and all branch hiking routes (Fig. 3). Like many parts of the southern Highlands, this is part of a private estate, but the road and trails are open for public use, although not by motorized vehicles. At times, access is restricted due to deer-stalking activities and shooting; information on activities and access is available from *atholl-estates.co.uk*. In the summer months, a small information centre operates in conjunction with the Cairngorms National Park in Blair Atholl. The route described here follows the narrow gravel road to the Forest Lodge area, but uses a secondary hiking trail for part of the return to avoid repetition and facilitate some scenic views (Fig. 3); however, the road can be used for a slightly quicker return. Approximate distances are provided in the following descriptions, and the sites are located using latitude and longitude values from GPS. The Glen Tilt area lies entirely within Ordnance Survey Landranger sheet 43 (Braemar and Blair Atholl; 1:50,000 scale). A copy of this map is strongly recommended for hiking beyond the route described below.

Although the lands around Glen Tilt are largely privately owned, the area is subject to restrictions intended to protect the natural environment of the region (Cairngorms National Park Authority 2007). Visitors are required to respect these at all times, and the estate suggests consulting the Scottish Outdoor Access Code for guidance. The exposures are all located in or adjacent to the River Tilt, and ease of safe examination depends on the water levels. In times of high water levels it may be impossible to examine some or all exposures safely. In all conditions, you should avoid wet surfaces and the danger of falling into the river. The location at Forest Lodge, where Hutton made many of his observations, includes two waterfalls separated by deep cliff-bounded pools with strong currents, and a mistake here could be deadly even for strong swimmers. Locations at Gilbert's Bridge and Forest Lodge are designated as Sites of Special Scientific Interest (SSSI) and hammering exposures or collecting samples are prohibited. Take great care at all times!

Blair Atholl to Gilbert's Bridge

It is about 4 km from the trailhead to Gilbert's Bridge, and this walk will take close to one hour. There is little to see as the trail is mostly high above the river valley on a steep wooded hillside. After about 3 km, the trail descends to cross the River Tilt on a stone bridge and continues northeastward closer to the river. A small and nondescript exposure of folded metasedimentary rocks (location: 56.7947 N; 3.8330 W) is the only site of geological interest on this section.

Gilbert's Bridge

This is another graceful old stone bridge (location: 56.8004 N; 3.8340 W) but the main route up the glen remains on the southeast bank of the river beyond it. Gilbert's Bridge is designated as a Site of Special Scientific Importance (SSSI), because exposures in the river downstream from the bridge form part of a zone of strong deformation known as the *Boundary Slide*, long considered to be an important tectonic boundary in the eastern Highlands (see Fig. 2). The site was summarized by Barron et al. (2011) and was described in more detail by R.A. Smith in Stephenson et al. (2013b). The area downstream of the bridge is not easy to access safely if water levels are high (as they were in 2019), but flaggy, highly strained metasedimentary rocks (pelite), showing spectacular muscovite on many foliation surfaces, can readily be seen under the bridge and upstream, where they dip steeply to the east (Fig. 4).

For many years, the Boundary Slide was considered to be the boundary between the Dalradian Supergroup and an older, more enigmatic, package of Precambrian rocks termed the "Moine Series" or simply *"the Moine"*. However, all of the metasedimentary rocks in Glen Tilt are now placed in the Dalradian (Stephenson et al. 2013b), so the structure has lost some of its former prestige, but is still traceable over long distances. It is now considered to be a tectonic boundary between rocks of the Appin Group and the older Grampian Group (lowermost division of the Dalradian), which occurs mostly to the northwest of the Loch Tay Fault (Fig. 2). The boundary is defined by an increase in the intensity of penetrative deformation rather than by lithological contrasts, although the rocks exposed upstream from the bridge are generally more diverse in character than those below. For a more complete discussion of the Gilbert's Bridge locality, and the long and convoluted debate about the details of Dalradian stratigraphy and structure and the significance of the Boundary Slide, readers are referred to Stephenson et al. (2013b).

Marble Lodge and Vicinity

From Gilbert's Bridge the access road continues northeast for about 2.5 km, along the southeast bank of the River Tilt, leading to the cottages at Marble Lodge, in more open country with fine views of the Cairngorm Mountains (Fig. 5). Upstream of Marble Lodge is the site of a small quarry or quarries that once exploited marble and calc-silicate units within the Dalradian Supergroup. The rocks exposed between Gilbert's Bridge and this locality are now defined as a discrete stratigraphic unit within the Appin Group, termed the Glen Banvie Formation (formerly 'series'), and are more varied in character than those seen downstream from Gilbert's Bridge. Notably, they include marble, calcsilicate units and amphibolite, in addition to the metasedimentary rocks (psammite and pelite) that typify much of the sequence.

The marble units are best exposed in the southeast bank of the river, downstream and upstream of the bridge just beyond the lodge buildings (example location: 56.8246 N; 3.8040 W). Here, they are interlayered with strongly deformed dark grey-green amphibolite, which may represent metamorphosed and

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Figure 4. Outcrops at Gilbert's Bridge, en route to Forest Lodge. (A) gently dipping, flaggy quartz-rich metasedimentary rocks now assigned to the Dalradian Supergroup, although originally considered to be part of an older package of Precambrian metasedimentary rocks known as "the Moine". (B) Mica-rich foliation surfaces in metasedimentary rocks upstream from the bridge. Gilbert's Bridge is considered to be an important locality, but the key section downstream from the bridge is difficult to examine safely in times of high water levels.

transposed dykes (Fig. 5). Some amphibolite–marble contacts here appear to me to retain some local discordance, although this would likely be debated by any group of visiting geologists. The marble units contain distinctive dark green patches, elongated within the foliation (Fig. 5), that consist largely of antigorite (a serpentine mineral). The antigorite is believed to be a retrograde metamorphic mineral formed from higher grade diopside or forsterite in the marble (Stephenson et al. 2013b). Isoclinal folds are also visible in many parts of the marble outcrop (Fig. 5). The Glen Banvie Formation has a complex structural history and, due to its relative compositional diversity, the pelitic rocks provide important information about metamorphic conditions, notably through the local presence of kyanite (Stephenson et al. 2013b).

Clachghlas and Vicinity

Just beyond Marble Lodge, the road crosses another bridge to the northwest side of the River Tilt, and then continues for about 2 km to Clachghlas (location: 56.8335 N; 3.7550 W). This upper section of Glen Tilt is strikingly linear and is oriented almost exactly northeast–southwest, as it is controlled by the Loch Tay Fault, which is exposed here in the river. A wooden bridge with a gate provides access to the opposite (southeast) side of the river. The exposures in the river upstream from the bridge consist largely of fractured and brecciated pink to brick-red granite (Fig. 6), with screens of silicified metalimestone and massive quartzite of the Dalradian Supergroup. The fault plane is marked by a waterfall directly underneath the bridge and downstream in the southeast bank are intermittent exposures of metasedimentary rocks (pelite) and metalimestone. The term 'metalimestone' is used for carbonate-rich units in this area because most lack the coherency and texture of true marble (D. Stephenson, pers. comm. 2020). From Clachghlas to the exposures described by Hutton around Forest Lodge, the local geology is dominated by granite and diorite, rather than by metasedimentary rocks, at least on the northwest side of the river.

Forest Lodge and Vicinity

From Clachghlas, it is about 3 km to Forest Lodge, where James Hutton stayed during his field work. The lodge is a large building that enjoys a spectacular setting in this narrow section of Glen Tilt, and it looks very much the same today as in a drawing completed by John Clerk in 1785 (included in Craig et al. 1978). Beyond the lodge, the gravel road becomes a narrower track, passing through a gate. There is then another gate after several hundred metres, beyond which the upper waterfalls and river exposures are easily visible. The location for the main site (designated as a site or special scientific interest or SSSI) is 56.8512 N; 3.7422 W. There are smaller river exposures visible all along the route from Clachghlas Bridge; those on the northwest side of the river are mostly granitic, but strongly affected by proximity to the Loch Tay Fault; folded metasedimentary rocks of the Dalradian Supergroup can be seen locally on the opposite bank. The key area for examination at Forest Lodge lies between the upper waterfalls, which include a prominent rocky island in the middle of the river, and the ruins of a bridge. Interesting exposures also occur downstream from the bridge ruins but are harder to access if water levels are high. The most detailed description is by Stephenson (1999) who also provided a detailed map of the contact region (simplified as Figure 7). The key exposures are part of the contact zone between the Glen Tilt Pluton, which forms the mountains to the northwest, and the quartzite, psammite and metalimestone of the Dalradian Supergroup. In most locations, this regional contact is marked by the Loch Tay Fault Zone, and the River Tilt lies almost exactly along the line of the fault, but this small area lies northwest of the brecciated fault zone, so the original relationships are better preserved. Important features of these exposures are highlighted in Figure 8.

Figure 5. The Marble Lodge area, about halfway to Forest Lodge. (A) View upstream of the river valley, south of Marble Lodge, with the Cairngorm Mountains in the background. (B). White to pale beige marble exposed in the riverbank, in contact with dark grey massive amphibolite, possibly representing originally intrusive mafic dykes. (C) Tight folds defined by relict lamination (?) in the white marble. (D) Detail of marble containing dark green patches of serpentine minerals (antigorite) interpreted to have been derived by retrogression of metamorphic forsterite and/or diopside (R.A. Smith in Stephenson et al. 2013b).

The upper waterfall and its prominent rocky island consist largely of metasedimentary rocks, which strike across the river and dip steeply to the southwest. These include a grey metalimestone unit, and an overlying unit of more pelitic composition. The carbonate-rich units show distinctive recessive weathering and locally preserve tight to isoclinal folds, like those seen at Marble Lodge. Brown garnet is locally prominent, notably at the contacts between carbonate-rich and quartz-rich metasedimentary rocks, and probably indicates contact metamorphism and metasomatism (Stephenson 1999). This part of the outcrop also contains numerous thin granite veins, but many are subparallel to the strong fabric in the metasedimentary rocks, so they are not obvious at first sight. However, closer examination reveals that granite veins cut across the compositional layering (relict bedding) of the country rocks. In the area of the ruined bridge, and further downstream near the lower waterfall, granitic material forms many more extensive pod-like zones, separated by grey metasedimentary rocks that are pervasively dissected by thinner veins. These relatively homogeneous zones of pink granite also contain numerous inclusions and xenoliths of metasedimentary rocks (pelite and psammite, and also of marble). In some areas later thin granitic veins cut through xenoliths or earlier granite veins, attesting to the multistage nature of intrusive brecciation. More detailed descriptions (Stephenson 1999) also referred to dioritic rocks that are locally in contact with metasedimentary rocks, but these are not as obvious as pink granite, and the diorite–granite contact relationships were reported as equivocal in terms of age relationships (Beddoe-Stephens 1999; Smith et al. 2011). Dioritic rocks were reported to not contain the diverse xenolith populations typical of the granitic hosts, suggesting that they might be younger, and perhaps postdate initial brecciation caused by granite intrusion (Stephenson 1999). In summary, these exposures contain

Figure 6. The Clachghlas area, en route to Forest Lodge area. (A) View northeastwards along Glen Tilt, which is here defined by the trace of the Loch Tay Fault; the area to the left is dominated by intrusive rocks, and the area to the right is mostly Dalradian Supergroup. (B) Relatively well-preserved granite exposed in the riverbed, containing prominent white quartz crystals; most of these exposures exhibit tectonic brecciation due to late fault movements.

many excellent examples of intrusive relationships, at a wide variety of scales from centimetres to tens of metres (Fig. 8).

The northwest bank of the river is easy to access as it is adjacent to the trail. It may not be possible to safely cross the river in any location here if water levels are high, as they were in 2019. However, features similar to those noted above can be readily seen on the opposite bank, looking across the water, and several larger zones of pink granite are evident. Descriptions by Stephenson (1999) and Smith et al. (2011) indicate that deformational effects related to the Loch Tay Fault are displayed well on the southeast side of the river. The granite is affected by fault-related deformation and brecciation, but earlier movements on the fault were likely synchronous with the emplacement of some granite (Oliver et al. 2008; Smith et al. 2011). To examine these areas directly might require returning to Clachghlas and then walking back upstream on the southeast bank, which adds significantly to an already long hike. The Dail-an-Eas bridge (meaning "Field of the Waterfall"), located below the falls, unfortunately collapsed in the 1970s. Its presence undoubtedly made field work far more convenient for Hutton and his colleagues, as did the comforts of nearby Forest Lodge!

Return Hiking Options and Other Diversions

To return from Forest Lodge, hikers must unavoidably retrace much of the hike described above, as the valley is narrow and steep-sided. About 1 km southwest from Marble Lodge, a side hiking trail leads up the hillside and continues southward at higher elevations for around 4 km to eventually join a road that leads back downhill to the Old Bridge of Tilt and the parking area. This diversion provides some superb views towards the Cairngorm mountains in the northwest and is a welcome break from the gravelled surface of the access route. In the village of Blair Atholl, the Atholl Arms Hotel is the most obvious choice for the refreshment that such a long walk clearly demands. The entire hike requires at least 9 hours, allowing time for examining the exposures and a suitably timed lunch break. The best-known visitor attraction at Blair Atholl is the magnificent Blair Castle (Fig. 3), the seat of the Duke of Atholl, which is open to visitors for much of the year. It may seem familiar, perhaps because it has been used as a location for many historical dramas and films. The castle and grounds can easily occupy much of a day, so a visit cannot easily be combined with a hike into the glen. It might better be reserved for a second more leisurely day, following good food and an overnight stay.

GLEN TILT, GENESIS AND GRANITE: THE LONG DISCOURSE

The peaceful nature of Glen Tilt, little changed since the time of Hutton, belies the long and fierce debate that his observations here initiated. The exposures in the river allowed him but one interpretation, i.e. granite is *younger* than the adjoining rocks and had forcefully invaded them in a liquid state. At least here, granite could not represent the 'primitive' material of the Earth. Hutton's view opposed prevailing scientific dogma, and indirectly opposed theology, so such implications were strongly resisted. It would take another half century and two more generations of geologists to make plutonism a core principle of geology, but at least in part this may have been Hutton's responsibility. A few scraps of supporting evidence were published in his lifetime, but the complete account only appeared after the serendipitous rediscovery of the lost manuscript for the third volume of *Theory of the Earth* at the end of the 19th century. In the early 1800s, adherents of the neptunist doctrine mounted strong defences against this plutonist heresy. To make things worse, the centre for the neptunist world view had by then shifted from Werner's Germany to Scotland, and some of its most vociferous advocates were influential Edinburgh intellectuals, such as John Walker and Robert Jameson (see below).

Most field geologists place more faith in observation than on theory, and the largely philosophical neptunist concept

Figure 7. Local geology in the valley of the River Tilt around Forest Lodge, where Hutton completed his early work. This map is simplified from Stephenson (1999), who described the relationships and rock types in this area as part of the Geological Conservation Review. Aspects of site geology were also discussed by Smith et al. (2011).

slowly lost many of its champions. By the middle of the 19th century the concept of hot liquid magmas ('subterranean lavas', as they were initially called) that penetrate upward through the Earth's crust had largely prevailed. A wider debate about how magmas formed, and indeed whether *all* granite had such origins, would later begin, but another full century would pass before global plate tectonics provided our modern context for magmatic processes. This is another long story, told well by Davis Young's excellent book *Mind over Magma* (Young 2003). In this article, I summarize only some of the earliest steps on the long road that began in Glen Tilt and eventually led us to more-or-less unified theories of magmatism.

The Glen Tilt Expedition of 1785 and Other Early Investigations of Granite

The *Theory of the Earth* is renowned for many things, but not for its clarity of writing. Hutton's good friend and first biographer, John Playfair (1748–1819) is rightly credited with bringing his ideas to others, through his *Illustrations of the Huttonian Theory of the Earth* (Playfair 1802; hereafter, simply *The Illustrations*). Hutton first went to Glen Tilt in 1785, the same year that his ideas were first presented to the Royal Society of Edinburgh in abbreviated form (Hutton 1785), but there is little mention of granite in the earliest writings. Nevertheless, his references to internal heat driving a dynamic Earth, and the implication that some rocks might originate in a 'fused' condition did not escape the notice of his nemesis, the Irish scientist Richard Kirwan (1733–1812), who attacked him on several points (see Kirwan 1793). In response, Hutton read a short paper on granite to the Society in 1790, but four years elapsed before its publication (Hutton 1794). By the standards of Huttonian prose, it is unusually lucid, and it illustrates his evolving thoughts, albeit with scanty observational details.

Hutton (1794) initially confessed that

Figure 8. (Panel 1). Exposures in the area near Forest Lodge, where James Hutton made his key observations about the nature and origin of granite. (A) A general view of the key exposure at the upper waterfall, just above the ruins of the Dail-an-Eas bridge. The grey rocks at left and on the prominent rocky island are metasedimentary rocks of the Dalradian Supergroup, intersected by veins of white and pink granite; the area to the right is a chaotic mixture of pink granite and older country rocks (grey) forming an intrusion breccia. (B) Detailed view of bedded quartz-rich (psammitic) metasedimentary rocks with both concordant and discordant white granite veins. (C) Detailed view of granite vein cutting compositional layering (relict bedding) in the metasedimentary rocks. (D) Intrusion breccia near the ruined bridge, consisting of older country rocks (grey) and younger granite (pink) forming veins and irregular masses.

> *"...at that time, however, I was not perfectly decided in my opinion concerning granite; whether it was to be considered as a body which had been originally stratified by the collection of its different materials, and afterwards consolidated by the fusion of those materials, or whether it were not rather a body transfused from the subterraneous regions, and made to break and invade the strata, in the manner of our whinstone or trapp, and of the porphyries, into which the whinstone often graduates."*

Hutton then described his visit to Glen Tilt in 1785, and later visits to Galloway in southwestern Scotland in 1786, and to the island of Arran in 1787, where he observed several other contacts between granite plutons and adjacent rocks. His interest was in examining contacts to determine if *"...the granite that is found in masses has been made to flow in the bowels of the Earth."*, and he stated that this question could only be resolved by *"...the examination of that species of granite upon the spot, or where it is to be found in immediate connection with those bodies that are evidently stratified; bodies, consequently, whose natural history we have some means of tracing."*

He was seeking key contact relationships, as do all makers of geological maps, in order to clarify age relationships between stratified rocks and granite units. This use of cross-cutting relationships in determining the timing of events was a very important deductive step, every bit as fundamental as Nicolas Steno's principle of superposition. Hutton already knew that granite was abundant north of Blair Castle (the seat of the Duke of Atholl, who owned the hunting lodges in Glen Tilt) but that *schistus* (a general term then in use for low- to medium-grade metamorphic rocks) dominated most areas to the south. He concluded that by ascending the River Tilt or some of its branches he must meet eventually encounter the

Figure 8. (Panel 2). Exposures in the area near Forest Lodge, where James Hutton made his key observations about the nature and origin of granite. (E) complex intrusion breccia showing numerous thin veins of pink granite cutting metasedimentary rocks and numerous xenoliths within more continuous areas of granite. (F) Detailed view of granite veins and xenoliths in a clean section of this exposure. (G) Pink granite veins emplaced within white calc-silicate unit in a broadly concordant fashion, although discordant in detail. (H) Discordant pink granite vein cutting through banded metasedimentary rock and bedding-parallel quartz segregations, but itself cut by a later fine-grained aplite vein just above the pen.

junction between schistus and granite. So, Hutton and his artist colleague John Clerk of Eldin arranged to visit the Duke of Atholl (who was well known to Clerk), and they stayed at Forest Lodge as his guests. This proved to be fortuitous, as the key location was only ten minutes on foot from residential comfort, and a very convenient bridge allowed them to explore both sides of the river without even getting their feet wet. Reportedly, it was from this bridge that Hutton first noticed the distinctive exposures of intrusion breccia, and its viewpoint must have aided Clerk greatly in his depiction of their features. In Hutton's own words:

> *"Little did we imagine that we should be so fortunate as to meet with the object of our search almost upon the very spot where the Duke's hunting-seat is situate, and where we were entertained with the utmost hospitality and elegance.....I had here every satisfaction that it was possible to define, having found the most perfect evidence, that the granite had been made to break the alpine strata, and invade that country in a fluid state."*

Hutton (1794) continued with some descriptions of similar relationships observed in coastal outcrops in Galloway, and then alluded to his field observations on the island of Arran, although he provided no actual details of the latter. The conclusion of the paper included a clear summary statement:

> *"GRANITE, which has been hitherto considered by naturalists as being the original or primitive part of the Earth, is now found to be posterior [i.e. later] to the Alpine schistus; which schistus, being stratified, is not itself original; though it may be considered, perhaps, as primary, in relation to other strata, which are evidently of a later date."*

In addition to its statement on the origins of granite, this sentence also encapsulates Hutton's thinking on the repeated cyclic nature of geological processes, and the implications for the vast age of the Earth. The final sentence of the short 1794 paper asks that his contribution be *"....considered merely as a notice given of certain new facts and observations, which I mean fully to describe and explain hereafter"*. Unfortunately, this did not happen, as he died in Edinburgh just three years later.

At the time of his death, the full account of Hutton's work at Glen Tilt, Galloway, and Arran existed only in a manuscript for the planned third volume of *Theory of the Earth*. It would not actually appear in print until 1899, largely through the efforts of Sir Archibald Geikie (1835–1924), director general of the Geological Survey of Great Britain. Hutton's lost manuscript apparently first passed into the hands of John Playfair, who for some reason did not push it through to publication, and it eventually came to rest in a cupboard at the Geological Society premises in London, where it was accidentally discovered by the Canadian geologist Frank D. Adams (1859–1942). Adams brought it to the attention of Geikie, who had been looking for it in other locations for many years. Amazingly, Hutton's lost manuscript was sitting next to the Society's treasured original copies of Volumes 1 and 2 of *Theory of the Earth*. Bailey (1967) provides an interesting account of the manuscript's long odyssey and its eventual publication at the end of the 19th century (as Hutton 1899) and tellingly comments that *"It is a great pity that Chapters IV, V and IX, dealing with Glen Tilt, Galloway and Arran, were not published in Hutton's lifetime, or as soon as possible after his death. They show Hutton at his best, and could scarcely have failed to accelerate the advance of geology."*

Bailey (1967) also provides a good summary of the main observations and points that Hutton made through his work in these areas, and he provides some memorable quotes. One phrase in particular has been quoted in many other accounts (e.g. Stephenson 1999) but it still bears repetition:

> *"...the granite is now found breaking and displacing the strata in every conceivable manner, including the fragments of the broken strata, and interjected in every possible direction among the strata which appear. This is to be seen, not in one place only of the valley, but in many places, where the rocks appear, or where the river has laid bare the strata."*

It appears that Hutton also travelled widely, and with some effort, into the rugged and remote hill country around Glen Tilt, trying to understand the wider relationship between the massive granite and the *schistus*:

> *"Having, therefore, with some difficulty, mounted the precipitous bed of a rivulet that comes from this long ridge of mountain, and which is fit for no other than the footsteps of a goat, we were rewarded with a view of the strata of the hill, being a perpendicular section across this ridge of mountain, the nucleous (sic) of which, or the internal strata, were the object of our search.....Immediately after which we found the granite under the alpine schistus"*

It is difficult to establish the exact location of this panorama, but I would very much like to find it on some subsequent visit.

John Playfair did not participate in the 1785 expedition, but he would later visit the area with Sir James Hall (1761–1832), the founder of experimental petrology, who would also play a key role in later debates (see below). Nevertheless, Playfair (1802) provided an account of Hutton's Glen Tilt antics in *The Illustrations*, based apparently on information from John Clerk of Eldin, which showcases both Playfair's skilful and amusing writing, and aspects of Hutton's character that many modern geologists can probably identify with:

> *"....when they reached Forest Lodge, about seven miles up the valley, Dr. Hutton already found himself in the midst of the objects which he wished to examine. In the bed of the river many veins of red granite (no less, indeed than six large veins in the course of a mile) were seen traversing the black micaceous schists, and producing by the contrast of colour, an effect that might be striking even to an unskilful observer. The sight of objects which verified at once many important conclusions in his system, filled him with delight; and as his feelings, on such occasions, were always strongly expressed, the guides who accompanied him, were convinced that it must be nothing less than the discovery of a vein of silver or gold, that would call forth such strong marks of joy and exultation."*

Not surprisingly, this snippet of text has also found its way into other accounts of Hutton's contributions. Although there was apparently no testimony from Clerk on such matters, I think it very likely that there was a lively celebration in the warm and presumably well-fed comfort of Forest Lodge following that particular day of field work.

Lost Drawings, Lost Maps and Lost Samples

Hutton's manuscript was not the only item that vanished for centuries after his death. A folio of drawings, paintings and engravings by John Clerk of Eldin languished for years in the family archives, only coming to light in 1968 after the death of one of his distant descendants. These were later published with notes about the field expeditions and those involved in them (Craig et al. 1978). Many of these beautiful illustrations are related to Glen Tilt. Craig et al. (1978) is not easy to locate but some of these images can be viewed at *www.clerkofeldin.com*, where high-resolution colour reproductions can be purchased; notes from a lecture about Clerk's wider work and its significance (Bertram 2012) are also available there.

The most striking image appears to be a geological map of part of the key river exposure, painted as if Clerk was floating tens of metres above the water (Fig. 9). This image can also be found in the USGS online archives, although the artist is there misidentified as Hutton. Significantly, it is described as a map, and this is what it is. There is undoubtedly artistic license (as in any geological map) but the depiction of geological relationships is remarkably accurate, even down to individual granite veins (Craig et al. 1978). Beyond its great intrinsic beauty, this is an historically important document, as it represents one of

Figure 9. Watercolour image by John Clerk of Eldin, completed in 1785 or shortly thereafter, and rediscovered as one of the "lost drawings" intended for inclusion in the never-completed third volume of James Hutton's Theory of the Earth. The image is a stylized but accurate geological map of the key exposures in the River Tilt that influenced Hutton's thinking on the origins of granite. The flow direction of the river is towards the top of the image, in a southwesterly direction. The rectangular areas at the top of the image are the foundations of the bridge that used to exist here. Image recovered from the United States Geological Survey (USGS) online archives, also available at www.clerkofeldin.com. The original image measured 48 cm by 27 cm.

the earliest known geological maps, and perhaps records the first use of detailed mapping as a method of understanding three-dimensional problems.

Other striking images from Glen Tilt feature boulders that contain intrusive contacts between granite veins and metasedimentary rocks (Fig. 10). Several accounts suggest that Hutton was partial to collecting very large samples that demonstrated important relationships, and some were transported to Edinburgh, despite weighing hundreds of kilograms. It seems that the father of modern geology was like some present-day colleagues of mine who, given time, will easily fill all available storage space with their expedition trophies. The removal of such massive specimens from a remote Scottish glen long before proper roads or motorized vehicles is an interesting accomplishment in itself. James Hutton's rock collection is long lost, although it might lurk here and there in the foundations of modern Edinburgh. He died intestate, and his rock collection was acquired by the University of Edinburgh, but it was apparently never seen again; this might perhaps have some connection to individuals who were then directing the Department of Natural Sciences at that institution. Two similarly large boulders were removed more recently from Glen Tilt, to have prominent places in the *James Hutton Memorial Garden*, situated on the exact site of his house in Edinburgh. Some other boulders in the garden are of conglomerate, intended to illustrate his concept of cyclicity in geological processes (Butcher 2002; Fig. 11). An encounter with the Memorial Garden on a walk in Edinburgh led journalist Ben Dolphin to write a short article about Glen Tilt that provides an excellent summary for non-geologists (Dolphin 2015). As Hutton's actual burial site is unknown, this is now the only place in Edinburgh for geological pilgrims to pay their respects, but Siccar Point or Glen Tilt are probably more inspiring choices.

Neptune's Response: Why and How Field Evidence was Questioned

Hutton's initial writings contained enough inferences to provoke prominent scientists of the day. His nemesis Richard Kirwan (1733–1812) was opposed to the idea that rocks could form from a liquid state, but was equally disturbed by Hutton's heretical concept of an unimaginably old Earth. There was then little knowledge of internal heat in the planet, so the lack of a mechanism to liquefy rocks was a key objection. He asked *"...where then will he find those enormous masses of sulphur, coal or bitumen necessary to produce that immense heat necessary for the fusion of those vast mountains of stone now existing?"* In responses to Hutton's ideas on granite, Kirwan (1793, 1794) did not address the field evidence, but focused instead on how crystallization from aqueous solutions better explained the textures of granite. Of course, nothing was then known about the complexity of crystallization in silicate magma. Ironically, the familiar term plutonic was actually coined by Kirwan in his critiques to express his derision for a theory that, in his mind, was *"fanciful and groundless"*.

Transcription of hand-written caption:

"Two blocks of stone lying in the bed of the River Tilt a little way below where the junction of granite with the Alpine schistus takes place"

A Granite
B Schistus
CC Red porphyry
DD Junction

Figure 10. An engraving of two large granite boulders collected by James Hutton from the riverbed at the Forest Lodge locality, completed by John Clerk of Eldin in the late 18th century, and including a hand-written caption. There is no scale included, but samples collected by Hutton were reputedly very large, weighing hundreds of kilograms. The boulder at left demonstrates the multi-cyclic nature of intrusive processes, as the 'red porphyry' (CC) cuts both metasedimentary layering and the discordant contact of a wider granite vein (DD). The boulder at right shows the perpendicular discordant contact between a granite vein and the layering in the older 'schistus'. The faint hand-written caption (transcribed below the image) may be the writing of Clerk, or perhaps even that of Hutton himself. The original artwork measured 30 cm by 24 cm, and remains in the collections at Blair Castle, in Blair Atholl. Image from Craig et al. (1978), also available at *www.clerkofeldin.com*.

Both Pitcher (1993) and Young (2003) suggested that Kirwan's initial attacks on Hutton might have prompted him to express ideas about 'plutonic granite' more clearly in 1794, and then to respond to Kirwan's objections with a full chapter in the 1795 edition of *Theory of the Earth*. Kirwan's arguments were in truth driven as much by his religious convictions than by any scientific observations. Hutton (1795) offered this summary statement:

> *"I had given, as I thought, a kind of demonstration, from the internal evidence of the stone, that granite had been in the fluid state of fusion, and had concreted by crystallization and congelation from the melted state. This no doubt must be a stumbling block to those who maintain that granite mountains are the primitive parts of our Earth. It must also be a great, if not invincible obstacle in the way of the aqueous theory, which thus endeavours to explain those granite veins that are found traversing strata; and therefore necessarily of a posterior formation."*

As noted by Bailey (1967) the progress of igneous petrology might have been more rapid if the information from Glen Tilt, Galloway and Arran had actually appeared in the 1795 version of *The Theory*. It is believed that these descriptive accounts were written prior to 1788, but by 1797 Hutton was dead and buried, and his pivotal work would remain buried for another full century. In the early 1800s a new generation of plutonists, including both contemporaries and younger disciples of Hutton, then had to mount a progressive assault on the defences of the neptunists. The torch first passed to Hutton's friend and advocate John Playfair, and then to other early geologists, many of whom (like Playfair) had originally studied under prominent neptunists such as John Walker (1731–1803) and Robert Jameson (1774–1854) at the University of Edinburgh. Scotland was very much at the centre of this debate, and until the 1820s, it was actually the only place where 'plu-

Figure 11. Photos from the Hutton Memorial Garden in the City of Edinburgh. (A) A boulder retrieved from Glen Tilt that contains granite veins cutting metasedimentary rocks, sitting alongside a boulder of conglomerate. They respectively are intended to illustrate the principle of intrusive granite and the cyclicity of geological processes, both key elements of Hutton's thinking. (B) The plaque at the Memorial Garden, including the most famous quote from Hutton's work, "we find no vestige of a beginning, no prospect of an end". The photos were taken by journalist Ben Dolphin, and are used with his permission. For more information about the Hutton Memorial Garden, including its location, see Butcher (2002) and Dolphin (2015).

tonic granites' were claimed to exist. But reinforcement would eventually come from a faraway location that would ultimately prove influential in concluding at least this part of the granite debate.

John Playfair worked quickly by the standards of the time to complete his landmark *Illustrations of the Huttonian Theory of the Earth* (Playfair 1802), but the evidence from Glen Tilt and other areas remained obscure, because Playfair had not then visited these localities. Playfair argued on textural and chemical grounds that granite simply could not form from aqueous solutions. Some neptunists then suggested that granite 'veins' were not equivalent to more important 'massive granites' and formed from aqueous solutions that percolated downward from the surface, dissolving and redepositing the 'primitive' granite elsewhere. In modern parlance, this corresponds to 'remobilization', which is sometimes still invoked to dispose of inconvenient field relationships. Playfair (1802) also contended that xenoliths provided clear evidence of both age relationships and the forceful injection of granite, stating that *"it is impossible to deny that the containing stone is more modern than the contained"*. In response, neptunists claimed that these relationships were simply illusions produced where three-dimensional geometry intersected a planar surface, and that xenoliths did not really exist. These were all attempts to cast doubts on the reliability of field evidence.

The most prominent later neptunist critic was Robert Jameson (1774–1854) who presided in Natural Sciences at the University of Edinburgh for many decades, and was a former student of John Walker (1731–1803), who had held that same post during the period when Hutton's rock collection vanished. Walker was a contemporary of Hutton but also one of his fiercest early critics, and both Walker and Jameson were also ministers in the Church of Scotland. John Playfair was another former Church minister, and also another former student of Walker, so it is perhaps not surprising that Jameson took direct aim at his plutonist ideas in an essay shortly after *The Illustrations* appeared (Jameson 1802). In it, he contended that many granite bodies were clearly stratified, but that the degree of stratification was perhaps least evident in the oldest, most primitive, examples. He also concluded that granite veins were nothing more than 'strata of granite', and that there was no evidence to connect such features to larger masses of more homogeneous granite. Metamorphic rocks as we define them were not yet recognized, and many rocks that we now call gneiss were then termed 'stratified granite', which Jameson argued to have sedimentary origins. Strangely, he argued that the *absence* of granite veins from most outcrops of sedimentary rocks argued against such veins being products of liquid injection wherever they were actually observed. Another prominent critic was the Scottish geologist John Murray (1786–1851), best remembered as a *scriptural geologist* determined to explain the geological record as consistent with Genesis. On these grounds alone, Hutton's theories were unlikely to impress Murray. He argued that the presence of feldspar crystals within quartz crystals was inconsistent with crystallization of both from a liquid because feldspar was *'a substance of easy fusibility'* compared to quartz (Murray 1802). At the time, of course, there was no knowledge of binary or ternary eutectic systems.

During this debate, it seems that the key outcrops in Glen Tilt received few visitors, and even John Playfair had yet to see this key evidence. In 1807, he arrived with another prominent amateur natural scientist of the era, Lord Webb Seymour (1777–1819), but the actual presentation of their opinions was delayed for several years (Seymour 1815). Another Scottish geologist, John MacCulloch (1773–1835) had presented a very lengthy and rambling discourse about Glen Tilt in 1813, and this possibly roused Seymour and Playfair to the task. In the end, MacCulloch's written effort actually appeared *after* Seymour and Playfair's paper (MacCulloch 1816). MacCulloch somehow managed to avoid expressing any clear opinions on the origin of granite, and he rivals Hutton himself for length of presentation and opacity of meaning, but he did include a cross-section depicting relationships that is completely consistent with the views of Hutton and Playfair (Fig. 12). It is very hard to trace and attribute the observations in these articles to the actual individuals involved, and MacCulloch himself published a later discussion that more explicitly supported the plutonist views (MacCulloch 1822). Seymour (1815) provided better descriptions of relationships, and he and Playfair also made a key observation. They suggested that igneous rock (described this time as a 'sienite') was:

> *"....in a state of igneous fusion, was impelled from below, by a violent force, against the strata; that it bent them, dispersed them, and filled up the intervals, which it now occupies; that the fragments of the strata were in some degree softened by the heated sienite, so as to admit of a mutual action; that, while the whole intermixed mass was still soft, some further dislocation took place in it, and that all this occurred under a great confining pressure of incumbent matter."*

This is both a clear statement of the forceful nature of magmatic injection and also one of the first descriptions of what we would now call contact metamorphism, although the term itself had yet to be coined.

From Caledonia to the Cape: The Weight of Evidence Finally Prevails

Although debate over the origins of granite in the early 1800s remained focused on Scotland, granite itself is widely distributed, and must surely have been observed by many other early geologists. I find it rather strange that so many years passed before someone actually argued for the plutonic origins of granite from another location. The discourse also remained focused on observational data or philosophical principles, rather than experimentation. The founder of experimental petrology was Sir James Hall (1761–1832) who had discovered the Siccar Point unconformity with Hutton and Playfair in 1788, and then went on to re-examine outcrops in Galloway that Hutton had also briefly described, fully supporting his views (Hall 1794). Before Hutton's death, Hall began experimenting with natural rocks at high temperatures, by placing modified gun barrels in early blast furnaces, and he eventually

Figure 12. A schematic cross-section of the valley of the River Tilt near Forest Lodge (looking southwest), included by MacCulloch (1816) in his very lengthy description of Glen Tilt and the surrounding area. Although he did not seemingly express any clear opinion on the origins of the granite and its relationship to the metasedimentary rocks, this representation clearly accords with the views of Hutton and John Playfair. It does not show the Loch Tay Fault, which commonly forms the boundary of granite and metasedimentary rocks, as this structure was not then recognized. This line drawing was redrafted from a representation given by Pitcher (1993) rather than the original.

published a landmark study outlining his results (Hall 1800). He was the first to suggest that mixtures of minerals might have substantially lower melting temperatures than the individual minerals, and he also observed that rates of cooling determined grain size and crystal development in both commercial glasses and natural systems. This provided a mechanism by which the coarse-grained crystalline textures of granite and other igneous rocks could develop. Over the years, James Hall would make many other important and influential contributions to experimental petrology, as reviewed by Wyllie (1999). Note that Hall's name should not be linked with that of the prominent American paleontologist James Hall Jr. (1811–1898), who was unrelated. Sir James Hall the Scottish aristocrat did indeed have a son, but he was named Basil. Basil Hall (1788–1844) eventually pursued a naval career but he maintained a strong interest in geology and natural sciences from times spent with his father and John Playfair.

Basil Hall travelled the world with the navy, and one of his ports of call was the Cape of Good Hope, at the southern tip of Africa, where he climbed Table Mountain and made observations of the geology. He wrote to his father and John Playfair about his findings, and in 1812 he became the first person to advocate an igneous, plutonic origin for granitic rocks beyond Scotland. The story of early work on the "Cape Granites" is told in an excellent article by Master (2009), drawn from Basil Hall's autobiography and many other diverse sources, and my account is drawn from this paper. The oldest rocks in this region are deformed and folded clastic metasedimentary rocks of Neoproterozoic age that are intruded by Neoproterozoic to Cambrian (550 to 510 Ma) granite plutons. Both the Neoproterozoic metasedimentary rocks and the granite bodies are then unconformably overlain by early Paleozoic quartzite, sandstone and conglomerate (Master 2009, and references therein). Thus, the Cape of Good Hope contains two classic elements of Hutton's thinking – intrusive granite and unconformities – and reveals them in three dimensions. Basil Hall described how veins of granite transected older inclined and folded sedimentary rocks, but never penetrated above the unconformable base of the younger sedimentary sequence. He compared relationships to those described from the Scottish Highlands by Hutton, Playfair and his own father, and the results were presented to the Royal Society of Edinburgh (Playfair and Hall 1815). Unfortunately, these new contributions from far away did not convince the formidable and still-fulminating Robert Jameson, who in his response (Jameson 1819) was nothing short of dismissive:

> *"The junctions of the granite and gneiss, and of the sandstone and slate, do not present any species of veins, or varieties of intermixtures, or of imbedded portions (fragments of the Huttonians), or convolutions, that do not occur at the junctions of universally admitted Neptunian rocks, such as limestone, claystone, gypsum and sandstone."*

Others who visited the Cape of Good Hope also concurred with the idea that granite must have been emplaced forcefully in a liquid state. These included naturalist Clarke Abel (1780–1826) and the botanist and geologist Dugald Carmichael (1772–1827). Interestingly, both Abel and Carmichael were former students of Robert Jameson at the University in Edinburgh, but had obviously abandoned the neptunist doctrine. Master (2009) also described several other early studies related to the geology of the Cape of Good Hope, from both plutonist and neptunist perspectives, completed during the 1820s and 1830s. Finally, in 1837, the Cape was visited by Robert Jameson's most famous student, who was then on the last leg of a voyage on an equally famous schooner named the *Beagle*. Charles Darwin (1802–1882) needs no introduction as the joint originator of the then theory of evolution, but he had originally studied geology, and actually blamed his early disenchantment with it on Jameson's teaching. Luckily, Darwin would later be strongly influenced by Charles Lyell (1797–1875), the famous author of *Principles of Geology* and originator of the principle of uniformitarianism. Darwin eventually described his own observations from the Cape long before writing the *On the Origin of Species*. Master (2009) provided a quote from Darwin's descriptions (published in 1844), in which he made the key observation that granite seemed to have preferentially intruded along the 'cleavage planes' of the 'clay-slate' as it disrupted these strata, thus accounting for the consistent orientations of cleavage and bedding among remnants of the older rocks. The Glen Tilt exposures, along with many other examples of intrusion breccia, also illustrate this important process. The study of the Cape granite played an important role in finally dispelling the remaining neptunist resistance, and by the mid-19th century the idea of granite as the product of liquid magma was widely accepted by geologists, as was the igneous origin of rocks such as basalt and rhy-

olite. Robert Jameson never publicly accepted the victory of plutonism over neptunism at the hands of his former students, but anecdotal accounts (e.g. Adams 1938) claim that he eventually verbally acknowledged the intrusive and igneous origin of granite at a meeting of the Geological Society of Edinburgh. Just prior to finalization of this article, Stone (2020) published an interesting analysis of Jameson's reluctant conversion based on some archived lecture notes compiled by former students. These suggest that he did eventually concede some ground to plutonism in the 1830s.

EPILOGUE

Glen Tilt is not as famous or as spectacular as Siccar Point, and I have seen more explicit and extensive examples of intrusion breccia elsewhere. Nevertheless, the site clearly shows that liquid granitic magma invaded, disrupted and altered pre-existing stratified rocks of sedimentary origin. Just as Siccar Point demonstrated cyclicity and unimaginable periods of time, Glen Tilt refuted an accepted chronology that linked Earth History to the Bible. Glen Tilt is thus an important place for geologists because it caused a fundamental change in thinking, which established key principles that endure, but not without lengthy argument. Glen Tilt was the starting point for the long and arduous debate that proved the intrusive igneous origins of granite, and replaced the misguided philosophy of neptunism by deductions based upon logical reasoning that could be confirmed by further observation and (or) experiments. It is the birthplace of modern igneous petrology. I believe that the long walk up the valley to Forest Lodge is well worth the effort, and I hope that those who complete it will agree.

Geologists relish a good controversy, so it is no surprise that discussions about the *exact origins* of granite continued long after the mid-19th century, and some contend that questions remain. There were long exchanges on the relationships between the parental magmas to mafic and felsic rocks, and then more sophisticated experimental studies, culminating in the landmark research of Tuttle and Bowen (1958). The books by Pitcher (1993) and Young (2003) provide a full account of this long story. There was also an interesting 20th century division between those who adhered to Hutton's original concept of liquid magma, and those who believed that granite was actually produced by solid-state metasomatic transformation of other rock types. This great debate was most famously framed by H. H. Read (1889–1970) in his book entitled *The Granite Controversy* (Read 1957). In the introduction to his book, Read uses a quote from *Theory of the Earth* that I have not seen elsewhere, but which seems very appropriate to close this article, because it applies to science in general, as well as to granite.

> *"While man has to learn, mankind must have different opinions. It is the prerogative of man to form opinions; these are often, commonly I may say, erroneous; but they are commonly corrected and it is thus that truth in general is made to appear."*

Read (1957) probably liked this quote because he considered his theory of metasomatic 'granitization' to be the final scientific truth, although the work of Tuttle and Bowen (1958) would soon prove otherwise. But this detail is unimportant. Advances are made by forming ideas but then accepting that others should try to demolish them, even if they are not invited to do so. Hutton's ideas survived many such efforts and it is appropriate that the global conference on the geology and petrology of granite, held every four years, is known as the *Hutton Symposium*.

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