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Flood basalts versus central volcanoes and the British Tertiary Volcanic Province

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Abstract: A controversy in the final decades of the last century developed between Geikie and Judd over the nature of the volcanoes in the British Tertiary Province. Geikie regarded the lavas as in Antrim and Skye as plateau basalts (today called flood basalts) erupted from widely scattered fissures, while Judd regarded the intrusion complexes as in Central Mull and Skye as eroded stumps of major central volcanoes from which the lavas originated. Soon after, instigated by the controversy, British volcanology flowered for several decades in what may be called its 'Classic Period'. Detailed mapping projects were undertaken, and new concepts were developed that are basic to volcanology. This paper views the controversy and its aftermath, and also briefly reviews recent conceptual developments in the North Atlantic Volcanic Province of which the British Tertiary rocks are a part. The paper discusses the present understanding of flood basalts and central volcanoes, and presents new criteria based on structural features of lava flows (such as the dependence of lava thicknesses, and the occurrence of pipe vesicles, on ground-slope angle) to distinguish between them. Magnetic fabric study of magma-flow directions in intrusions and lava flows, and palaeomagnetic study of post-emplacement tilting of igneous rocks, have great unrealized potential.

Controversies can be healthy in the advancement of science. They direct attention to the issues involved, and provoke others to enter the arena and contribute new data and ideas. Controversies are, however, not always resolved within the lifetime of the principals. The pages of the *Journal of the Geological Society* record many controversies, some of them very spirited and having varied outcomes. Quite commonly the truth, or more correctly the eventual consensus view, proves to be a compromise. This was the outcome of the controversy discussed in this article.

This controversy developed just over a century ago between Archibald (later Sir Archibald) Geikie and John W. Judd over the exact nature of the piles of lava flows and associated intrusive igneous rocks (notable in Antrim, Skye and Mull) in the British Tertiary Volcanic Province. About a century earlier, the same area had been an arena of a much more embittered controversy which was fought between the Huttonians or Plutonists and the Wernerians or Neptunists regarding the igneous or sedimentary origin of basalt. It is a matter of history that the Huttonians prevailed.

There are two aims here: to present a personal view on the Geikie–Judd controversy and the flowering of British volcanology that was its immediate sequel; and to review the present state of understanding of the British Tertiary Volcanic Province, together with that of the North Atlantic Volcanic Province of which it is an important part.

The Geikie v. Judd controversy

Geikie (1871, 1984, 1897) wrote eloquently about the basaltic plateaus of Antrim and the Hebrides. He regarded these as magnificient remnants of a much more extensive plateau possibly coincident with the far-ranging Tertiary dyke swarms of the British Isles and extending as far as Iceland and the Faeroes. Plateau basalts are today more commonly called flood basalts, following Tyrrell (1937).

Geikie's reasons for regarding the basaltic lava piles as remnants of extensive plateaus or flood basalts were that 'successive sheets of basalt have proceeded from no one centre of eruption. They die out now towards one quarter, now towards another, yet everywhere retain the universal regularity and gentle inclination of the whole volcanic series' (Geikie 1897, p. 194). Furthermore, he observed, the dykes and volcanic necks that are likely to represent feeders of the lava flows are widely scattered. These reasons are equally valid today.

Judd on the other hand directed attention towards the intrusive complexes such as those in Central Mull and the Cuillin Hills of Skye, and postulated that these were 'the denuded cores and basal wrecks of great volcanoes' (Judd 1874, 1881, 1886, 1889). Judd was less persuasive than Geikie, and partly spoiled his case by apparently getting wrong the sequence in which the rock-types were emplaced. Geikie also made mistakes and for a short time considered that the Cuillin gabbros in Skye were metamorphic rocks of Archaean age.

Geikie had lived as a youth in Scotland and had wandered extensively through the Hebrides. He was understandably annoyed by this outsider entering the field and forestalling his own plans for publication. He was also somewhat resentful because Judd, being a university professor, seemingly had more leisure to pursue his studies than had Geikie as a Geological Survey geologist.

The Classic Period of British volcanology

Following closely upon and provoked by the Geikie–Judd confrontation, British volcanology flourished as never before. I think it is appropriate to call the first three or four decades of the present century the Classic Period of British volcanology. It was a period of intensive research rewarded by important discoveries. The efforts of a few dedicated, creative and hardy individuals opened up new vistas in volcanology.

The period commenced with publication of the memoir by Harker (1904) on the Tertiary igneous rocks of Skye, which was a model of careful observation and clear description, and it strongly influenced many, including me. Harker made many discoveries. One was that the gabbro intrusions of the Cuillins and Blaven have a banding (today it would be called layering) which dips towards a focus. Another was that a great complex of intrusive sheets (later called 'cone-sheets') occurs in the Cuillin Hills, inclined towards the same focus as the inward-dipping layering in the gabbros. He also recognized that magma-flow directions in dykes are not necessarily vertical, and can sometimes be inferred from structural features of the dykes. Harker followed this with his memoir on the Geology of the Small Isles of Inverness-shire (Harker 1908) in which he described the great ultrabasic intrusive core of the Island of Rum.

Two masterpieces of volcano mapping soon followed, namely Ben Nevis and Glencoe (Clough *et al.* 1909; Bailey & Maufe 1916) and Mull (Bailey *et al.* 1924). The concept of cauldrons as subsidence features bounded by ring faults and ring dykes was developed at Glencoe and applied in Mull, and has proved to be of fundamental importance in volcanology.

The described cauldrons are relatively deep-seated structures but their probable relationship to surface calderas was recognized. Cauldrons and calderas were seen as two manifestations of the same igneous events exposed at different levels.

Regarding Mull, never before had such a complex mapping project been achieved. The 'one-inch to the mile' (now published at 1:50,000) map of Mull revealed the details of the core of a major central volcano as had never been seen before and emphasized how incredibly numerous are small intrusions in this situation. The ring complexes in Mull were recognized to comprise broadly two kinds of intrusions having a ring-like plan view, namely vertical or steep outwardly dipping ring-dykes, and inwardly dipping cone-sheets, emplaced respectively by a relaxation of or an increase in pressure in the magma chamber (Anderson 1936; Richey 1932).

It is now known that probably all major basaltic and central volcanoes have great intrusive complexes (the 'coherent intrusion complexes' of Walker 1992) in their core. Like the innumerable basaltic flows that form the superstructure of a major volcano, these complexes of small intrusions are generated by innumerable and frequent magma excursions out of the magma chamber.

Studies of other intrusive centres in the British Tertiary Volcanic Province followed, as summarized by Richey (1932) and Emeleus (1982). Each centre showed distinctive features. Thus the structures of the Mourne Mountain Granites (Richey 1928) were such as could be accounted for by being emplaced as subterranean cauldron subsidences; the Goatfell granite in Arran (Tyrrell 1928; recently restudied by England 1992) is a superb example of a diapir, partly bounded by a ring fault inside which uplift occurred; and the intrusion-centre of Ardnamurchan (Richey & Thomas 1930) is remarkable for the large number of annular gabbroic intrusions. Meanwhile the finding of great thicknesses of lavas in East Greenland by Wager (1934) and by others in West Greenland, more or less doubled the size of the North Atlantic Tertiary Volvanic Province.

This account concentrates attention on structural studies but acknowledges that the Classic Period also contributed greatly to petrological thought, as ably summarized by Thompson (1982*a*, *b*) and Wilson (1993 and this volume). The Geikie–Judd controversy followed closely on the birth of microscopic petrography: Sorby's important paper on the microscopic structure of rocks was published in 1858 and Zirkel's 'Mikroscopische Gesteinsstudien' followed in 1863. Prior to about 1890, microscopic studies were mainly descriptive petrography, but from about 1890 onward attention was increasingly directed at chemical relationships. Harker (1909) and Judd were pioneers in this field.

The mapping in Mull provoked significaant advances in petrology. The concept of magma type was introduced by Bailey *et al.* (1924). The question of the genetic relationships of Hebridean rocks was pursued by Bowen (1928), and a petrogenic scheme was proposed by Kennedy (1930, 1933) and by Kennedy & Anderson (1938) that is a clear antecedent of today's concepts of basalt magma types. Meanwhile Wager & Deer (1939) recognized that a remarkable story was told by the Skaergaard intrusion, and when they presented this story—the story has been retold since (e.g. Stewart & DePaolo 1990)—they provoked a worldwide interest in gabbroic intrusions that is still very much alive (see for example, the recent study of the Kap Gustav Holm intrusion by Bernstein *et al.* 1992).

Subsequent research in the British Tertiary Province

The past three decades have seen steadily continued research in the British Tertiary Province, mostly as a period of consolidation and quantitative documentation. The big revolution in volcanology during this period came with the study of pyroclastic rocks and explosive volcanism, and took place mostly on young volcanoes elsewhere. A recent topic has been the relation of the Hebridean volcanic centres to the Mesozoic basins of the region; Butler & Hutton (1994) have made a structural analysis of this for the Skye centre.

The North Atlantic Province

Increasingly in recent years attention has tended to shift from the British Tertiary Province to the larger entity of the North Atlantic Province of which it is a small but important part. This change in emphasis has been associated with the development of ideas on hotspots and mantle plumes, and with geophysical exploration of the ocean floor.

Geikie recognized that Tertiary dykes are distributed over roughly half of the area of the British Isles, and speculated that basaltic flows may originally have covered a similar area. He considered that the existing lavas as in Skye and Antrim were remnants of a previously much greater area that extended to the Faeroe Islands and Iceland.

Tyrrell (1949) pursued this theme, pointing to the basalts in East and West Greenland and postulating that a vast basaltic plateau had extended from England to Baffin Land, a plateau that in East and West Greenland, Iceland and the Faeroes consists of enormously thick basalt piles. A prodigious volume of basalts, enough to stretch the most vivid imagination, was implied. Tyrrell realized however that Greenland and Scotland were contiguous before continental drift and hence that the area and volume of basalts, although great, was less than might appear.

Tyrrell did not know that the Tertiary basalts in Iceland are significantly younger than those of Antrim, Skye, and Greenland; non-steady-state conditions were implied, early Tertiary volcanism being on a much bigger scale than recent volcanism in Iceland.

About this time, studies made on zeolite zonation (Walker 1960*a, b*) showed that the lavas of Antrim and eastern Iceland thin up-dip and hence probably form remnants of more or less isolated lava lenses (Fig. 1g–3), and with less certainty that the lavas of Mull are remnants of an eroded upstanding central volcano broadly similar to the lava shields of Hawaii (Walker 1970, Fig. 1g–1).

The up-dip thinning in eastern Iceland is particularly striking and was detected because the zeolite zones, inferred to be parallel with the top of the lava pile, demonstrably cut across the lava stratigraphy (Walker 1960*b*). Bodvarsson & Walker (1964) attributed the up-dip thinning and strong tilting to isostatic sagging, as new lavas were superposed on preceding lavas that were being conveyed away from the rift zone by spreading caused by dyke injections. Palmason (1980) successfully modelled the mechanism for this process on the basis of steady state volcanism.

The development of the plate tectonics paradigm including the concept of hotspots and mantle plumes, and the dating of volcanic rocks in the North Atlantic area by radiogenic methods and magnetic stratigraphy, together with the geophysical exploration of the North Atlantic in recent years, have critically changed our views on the Province. More or less steady-state hotspot volcanism and spreading since about 16 Ma have created Iceland, and are in process of enlarging it. Over a more extended period of 60 Ma, they created the other volcanic accumulations of the North Atlantic Province.

Among recent new ideas, that of thinspots (Thompson & Gibson 1991) explains well the isolation of the Hebridean Province from other volcanic areas in the North Atlantic region and concentration of the volcanism in sedimentary basins; that of incubating plumes (Kent *et al.* 1992) explains well the uprise of large silicic diapirs early in the volcanic history of Mull and other centres. Also the utilization by magma of structures such as tectonic pull-aparts (Hutton 1988; Butler & Hutton 1994) well explains the localization of the Mull and Arran centres so close to major faults.

The finding of seaward-dipping reflectors under the North Atlantic, thought to be basalt accumulations, and the possible large-scale underplating of the crust by basaltic intrusions, are among the latest and most exciting developments (White & Mackenzie 1989; White 1992). The seaward-dipping reflectors are consistent with the seaward dip and down-dip thickening of lava piles in East and West Greenland, and also the down-dip thickening towards the spreading axis in Iceland. If interpretation of these deep structures is correct, a truly prodigious output of basaltic magma from the Province is implied, besides which the volume inferred by Tyrrell in 1937 and even more so by Geikie in 1897 fade almost into insignificance.

Central volcanoes: a modern view

The controversy between Geikie and Judd concerned the identification of plateau (flood) basalts and central volcanoes in a setting of deep erosion. Here it is appropriate to consider the present state of understanding of these volcanic structures and the nature of the distinction between them.

Walker (1993*a*) recognized five kinds of basaltic-volcano systems, namely lava-shield volcanoes, stratovolcanoes, central volcanoes, flood-basalt fields and monogenetic volcano fields. Volcanoes of the first three kinds erupt more than once and are termed polygenetic. Individual volcanoes in the last two types are monogenetic and erupt only once. Central volcanoes differ from the others in having voluminous silicic as well as basaltic volcanic rocks.

Active polygenetic volcanoes possess a high-level magma chamber, which is sustained by (a) a sufficient input rate of magma from the source and (b) a sufficient frequency of upcoming magma batches, to keep hot the magma pathway from the source to the chamber. The high-level chamber modulates magma excursions into the volcanic edifice and *inter alia* heats groundwaters and sustains high-temperature geothermal fields; fossil geothermal fields are recognized from the occurrence in them of such secondary minerals as epidote.

The concentration of magma input to the magma chamber of a polygenetic volcano has several consequences: (a) magma excursions from the chamber are channelled into narrow rift zones where coherent dyke complexes may form, or alternatively into coherent intrusive-sheet (cone-sheet) complexes, and (b) a cumulate prisms grows under the chamber.

Intrusion complexes and cumulate prisms are responsible for the large localized positive Bouguer gravity anomalies such as coincide with rift zones and summit calderas of volcanoes in Hawaii (Kinoshito 1965; Strange *et al.* 1965) and Reunion (Rancon *et al.* 1989), and the intrusive centres of Rum, Ardnamurchan and Skye (McQuillin & Tuson 1963; Bott & Tuson 1973).

Shield volcanoes in Hawaii and the Galapagos have sometimes been regarded as close analogues of Mull and Skye. They form upstanding edifices having common sub-aerial slopes exceeding 4°. The British Tertiary centres however occur on continental crust; they include great volumes of silicic intrusives, and of silicic volcanics now largely removed by erosion (Bell & Emeleus 1988). Shield volcanoes in Hawaii and the Galapagos have negligible amounts of silicic rock.

Good analogues in rift or hotspot environments occur for example in Afar and the Red Sea/Gulf of Aden area, notably the volcanoes of Aden (Cox *et al.* 1970) and Jebel Khariz (Gass & Mallick 1968). Other examples such as the Tweed volcano (Stevens *et al.* 1989) occur in the eastern part of Australia. These examples are sufficiently young that the form of their volcanic edifices may still be discerned, and the Tweed volcano is sufficiently eroded to reveal the intrusive core. All are probably smaller and more alkaline than were the Mull and the Skye Cuillin volcanoes.

Larger analogues occur in Tibesti and Manchuria. In Manchuria, a flood-basalt field (the Gaima Plateau) covering about 11 000 km^2 occurs astride the China/North Korea border. Near the middle of the field and rising some 1500 m above the basaltic plateau is the central volcano of Changbaishan, which is an eruption centre for silicic lavas, ignimbrites and fall deposits (Machida *et al.* 1990) with a caldera 7 km wide.

Flood-basalt fields: a modern view

Most reviews on flood basalts (e.g. Cox 1980; Yoder 1988) concentrate attention on the geochemistry. Here attention is directed at other aspects.

A flood-basalt field is an accumulation of overlapping or superposed tabular lava sheets that is erupted from scattered

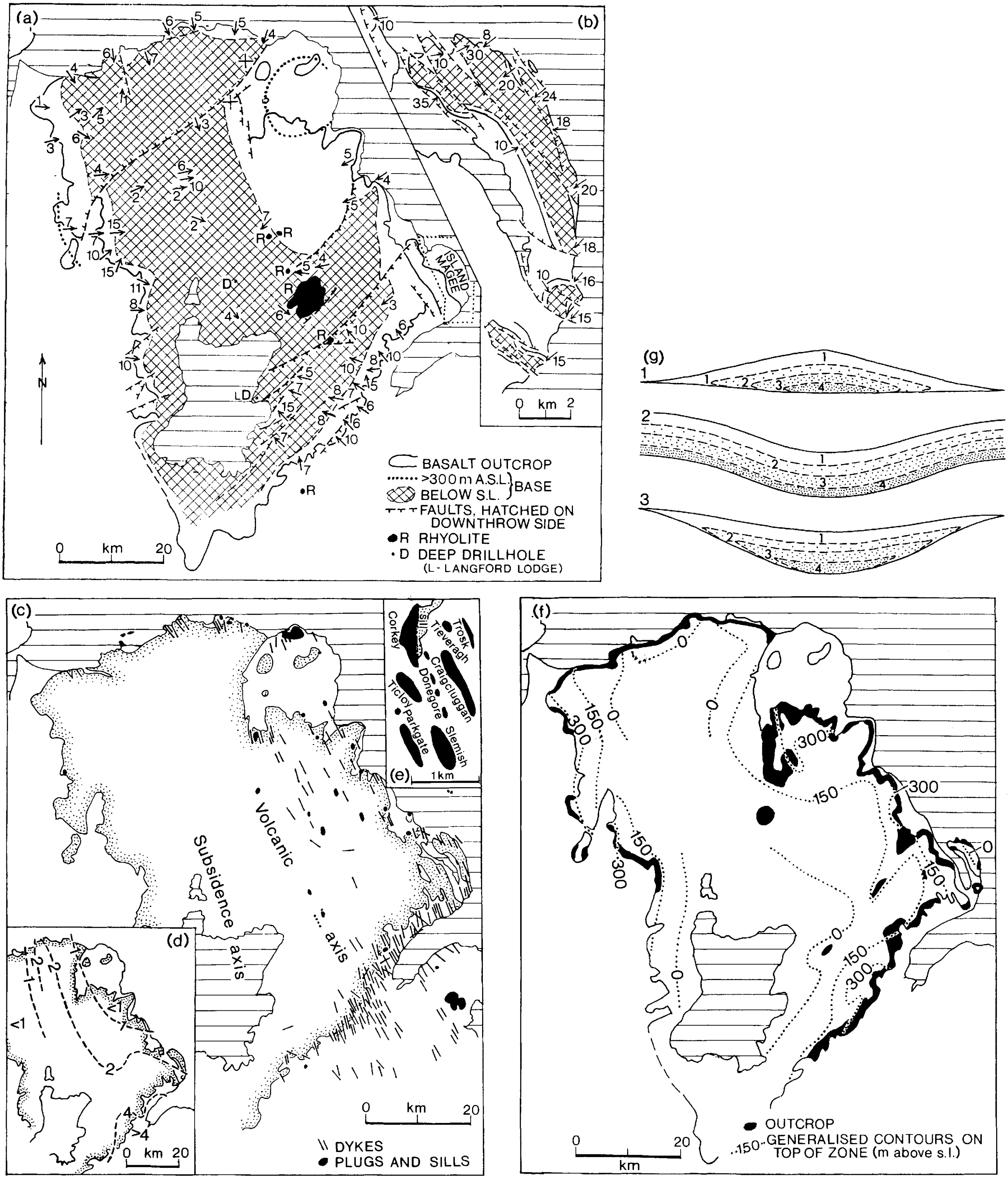

Fig. 1. Maps of the Antrim basalts. (**a**) Structural features. Arrows give dip, in part measured from attitude of prismatic cooling joints in the lavas. Sub-sea level parts are speculative, mostly extrapolated. (**b**) More detailed map of Islandmagee area where faulting is anomalously intense and throw direction is inconsistent, possibly because of dissolution of underlying Triassic salt. (**c**) Distribution of dykes and volcanic plugs (after Walker 1959). Plugs are elongate parallel with the dyke trend, and some consist of several discrete bodies on this trend; they probably evolved by local widening of dykes. (**d**) Generalized contours of the intensity of the dyke swarm, expressed as the percentage of dykes in the total rock. (**e**) Outlines of some volcanic plugs, drawn on the same scale. (**f**) Distribution and elevation of the top of the analcime/natrolite zone which embraces roughly the lowest 100 m of the basalts. Sea-level contour mostly extrapolated. The zone is down-bowed towards the subsidence axis although less strongly than the lavas. (**g**) Possible relationships of zeolite zones to basaltic piles shown in cross-section. Diagram 1 best fits the basalts of Mull. Diagram 3 best fits the Antrim basalts.

vents and lacks any centralized vent system. The individual flows tend to have greater volumes (commonly >0.5 km^3) than are normally erupted from polygenetic volcanoes, and the whole accumulation has the aspect of a low plateau or plain. Where lavas infill and flow down valleys, they present the aspect of flooding the topography. Eruptions tend to be either from fissures or from point-source vents. It should be borne in mind that fissure-vents evolve with time into single-point vents (where volcanic plugs may develop) as wall-erosion locally widens the fissure (Bruce & Huppert 1990).

In accounts of flood-basalt fields, attention is usually directed at the giant fields exceeding 100 000 km^2 in area and 100 000 km^3 in volume that are distributed sparsely through the geological record. Many small to moderate-sized flood-basalt fields also occur and are better analogues to the British Tertiary basalts. Good examples of moderate-sized fields are Rahat and Khaybar/Ithnayn/Kura in Saudi Arabia, both 20 000 km^2 (Camp & Roobol 1989; Camp *et al.* 1991) and the McBride and Nulla fields in Queensland, 5800 and 6600 km^2 respectively (Stephenson *et al.* 1980). The volcanism in each field has been spread over the past 5 to 10 Ma and each field has the potential to erupt again. Some of the lava flows particularly in the Queensland fields are very large (Stephenson & Griffin 1976).

Close associations of flood basalts and central volcanoes

Distinct types of volcanic systems, notably flood-basalt fields and central volcanoes, commonly occur in close association with one another, as in the example in Manchuria cited above. It is supposed that a central volcano may develop if and where magmatic activity in a flood-basalt field becomes sufficiently concentrated. Iceland illustrates the close association particularly well. A number of active rift zones from which occasional flood-basalt eruptions take place, occur in a zone crossing the country, and several have a central volcano on the rift zone (Saemundsson 1986). Active central volcanoes include Hekla, Askja, and Krafla. Several scores of extinct central volcanoes are known amongst the Tertiary lava piles of eastern, northern and western Iceland, each more or less enclosed by flood basalts (Fig. 2).

Studies of lava-flow structures

Lava flows constitute the bulk of the British Tertiary and North Atlantic Provinces. In a logical scheme of things they would attract the greatest attention and might reasonably be expected to help distinguish flood basalts from central volcanoes. Strangely however most of the structures described by Geikie (he commented that 'a more detailed description of them seems to be required') still have not been explained. A notable exception from this neglect is the columnar-jointing shown by a few lava flows.

The occasional spectacularly columnar jointed lavas as at the Giant's Causeway and Staffa attracted much attention from early geologists, some of whose explanations for the columnar rock would be classified today as fanciful. Tomkeieff (1940) recognized the multi-tiered character of columnar-jointed flows and initiated the modern terminology of colonnade and entablature for the tiers. The regularity of the prisms in the colonnade is now attributable to solidification of lava under static conditions, as when it infills a depression, and the closer joint spacing in, and common greater thickness of, the entablature are due to water cooling (Saemundsson 1970).

Recent morphometric research (yet unpublished) on lava flows in Hawaii has an important bearing on the environment of basalt effusion. The thickness of basaltic lava is quite sensitive to the ground-slope angle. On slopes exceeding about 4° the average flow unit is about 1 m thick whereas on slopes under 2° it is 5 m or more thick. The lavas of Antrim and north-western Skye have thicknesses generally indicative of slopes of <2° (Table 1).

Recent research shows that the internal structures of lava

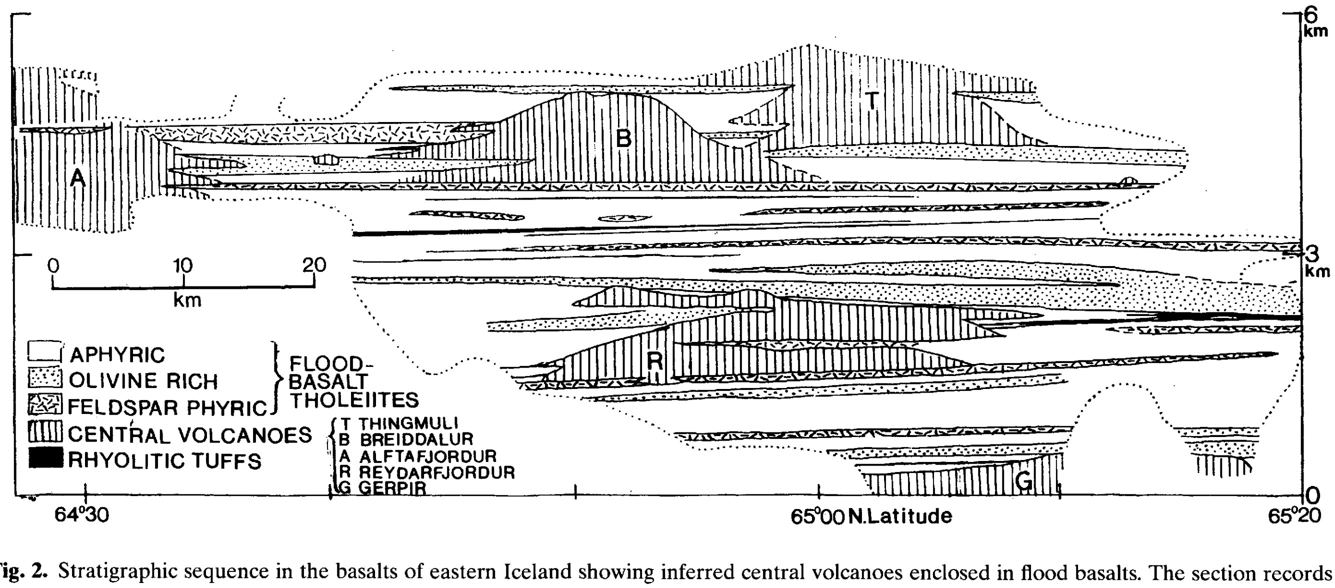

Fig. 2. Stratigraphic sequence in the basalts of eastern Iceland showing inferred central volcanoes enclosed in flood basalts. The section records about 10 Ma of volcanism. Note that the succession is composed of successive westward and upward overlapping of younger flows as the growing lava pile was transported eastward by spreading. Central volcanoes contain rhyolite and intermediate rocks, show evidence for having stood up as topographic highs, show rapid wedging of rock unit, have concentrations of intrusions, and show high-temperature hydrothermal alteration. Flood basalts show uniform dips and strikes and persistent stratigraphic units that can sometimes be followed laterally for 75 km.

Table 1. *Average thickness of lava flow units*

	No of units	Rock type	Total thickness (m)	Average thickness (m)
Shield volcanoes, Hawaii and Samoa, on average slopes of 7°				
Oahu, Hawaii	445	Pahoehoe	262	0.59
	127	Aa	276	2.17
Tutuila, Amer. Samoa	246	Mostly aa	707	2.87
Lavas of the North Atlantic Province, interpreted to be flood basalts				
Antrim	106		747	7.05*
Storr and Quirang, Skye	—		—	11.00†
Eastern Iceland	900		8800	9.80

* Walker (1959)
† Preston (1982)

flows are also sensitive to ground-slope angle. In Hawaii, pipe vesicles and related vesicle cylinders and segregation veins are virtually absent from lava erupted on ground-slopes of 4° or more (Walker 1987), and are most abundant in lava on slopes of <2°. These features are extensively developed in the lavas of Antrim and north-western Skye, and also in Iceland, indicating that emplacement took place on prevalent very shallow ground-slopes and favouring the view that those lavas are flood basalts.

Studies of magma-flow directions

Harker's discovery that magma-flow directions in dykes can be inferred from structural features of the dykes has not yet been followed up, apart from the study by Macdonald *et al.* (1988) which showed lateral magma flow in the Cleveland dyke of N England. Meanwhile a powerful technique, based on the anisotropy of magnetic susceptibility of rocks, has become available that permits flow directions to be readily determined from the magnetic fabric. In dykes in the rift zones of the Koolau volcano in Hawaii, magma flowed upwards and sideways at an angle varying from 20° to 70° to the horizontal (Knight & Walker 1988). On a bigger scale, dykes of the continent-ranging Mackenzie swarm in Canada (Ernst & Baragar 1992) flowed vertically within 500 km of the centre of magmatism, and horizontally farther out. It is not known what magma-flow direction will be revealed by this magnetic method in the British Tertiary rocks.

A study of flow directions in the Skye dyke swarm and cone-sheets of the Cuillin Hills has recently been initiated (Walker 1993*b*). The anisotropy of magnetic susceptibility technique also successfully yields the flow direction in lava flows (Canon & Walker in press) and might be very revealing when applied to a large basaltic field such as that of Antrim. Our study of the Cuillin Hills can significantly contribute to understanding major basaltic volcanoes. Volcanoes in Hawaii, built on oceanic crust, subside so much and so rapidly during their first two million years that erosion can never penetrate deeply into the volcanic core. Rafted as it is on continental crust however, the core of the Cuillins volcano is dramatically revealed for study.

Antrim: the largest flood-basalt remnant in Britain

The largest basalt remnant and the most clear example of a flood-basalt field in the British Tertiary Province is that of Antrim. As a boy, the writer discovered the challenge and joys of fieldwork in Antrim. The Antrim basalts cover over 4300 km^2 and originally covered probably at least twice that area. The maximum thickness is not known: 769–780 m was penetrated in two drill holes near the centre of the basin.

Studies of zeolite distribution contribute to knowledge of the lava structure. In the basaltic pile of eastern Iceland, the top of the analcime zeolite zone is at a depth of 600 m. In peripheral parts of Antrim, analcime characterizes a nearly-continuous zone along the base of the lavas that is about 100 m thick, and the original lava pile thickness was therefore 700 m thick. In the Langford Lodge drill-hole the zone containing analcime and its proxy, stilbite, is 460 m thick, and the lava thickness was therefore originally about 1060 m.

The basalts of Antrim lack any visible intense dyke concentrations. Instead dykes are scattered through an area that in south Antrim is 30 km wide, and the maximum dyke-intensity is only about 5%. No localized large positive Bouguer anomaly is known that might be interpreted to be a coherent complex or cumulate prism. No epidote-bearing altered rocks of fossil high-temperature geothermal fields are seen at the present exposure level, and rhyolites are present only in minor amount.

The Antrim lavas have dips commonly of 5° to 15°. If, as now seems probable, the lavas formed mostly on slopes <2° then the present dip must largely be due to tilting. In general the dip is centripetal and delineates a saucer-shaped structure elongated NW-SE. The axis of maximum subsidence lies some distance west of the volcanic axis along which intrusions are most concentrated and rhyolites occur.

This structure raises the question whether the dip was caused by a general isostatic sagging. The attitude of the zeolite zones shows that the lavas thicken down-dip towards the middle of the saucer, and lends credence to sagging caused by the load, but the apparent displacement of the subsidence axis from the volcanic axis (Fig. 1c) would then be anomalous.

There is an alternative, preferred explanation for the saucer shape, namely tilting due to a general late-volcanic or post-volcanic regime of crustal extension. Evidence in favour of this comes from the orthogonal systems of NW–SE and NE–SW faults that cut the basalts (Preston 1982; Parnell *et al.* 1989). These faults in general downthrow outward away from the centre of the basalt outcrop and the several faults in each system repeatedly step in the same direction. This and the considerable dip of the lavas suggest that the faults are of listric type. One consequence of this faulting is that the maximum known depth to the base of the lavas—780 m in the Langford Lodge borehole—is significantly less than the 2500 m that would be calculated by extrapolating the dip of the surface lavas and assuming no faulting.

There is an exceptionally high concentration of faults in a narrow zone of subsidence in Islandmagee, and the fault-throw is not consistent in direction (Fig. 1b). It is in this area that the underlying Trias contains thick beds of halite, and the suggestion is made that the anomalous faulting here is related to subsidence due to localized dissolution of salt by ground-water circulation induced by magmatic activity. The zeolites that occur in this same area are also anomalous and include an abundance of the rather rare sodic species, gmelinite.

Conclusion

Geikie and Judd, the two principals in the historic controversy regarding the exact nature of volcanism in the British Tertiary Province, were probably both right although a full evaluation of the issues has not yet been made. The extensive basalts were no doubt erupted from fissures, as Geikie maintained, and the dykes that mark these fissures extend far from the volcanic centres. The great concentrations of dykes found in volcanic centres as in the Cuillin Hills and central Mull mark the rift zones of central volcanoes. Some of the basalts were no doubt erupted from these rift zones and built large volcanic edifices. Where flood-basalt lavas end and central-volcano lavas begin is not yet resolved.

Geikie emerged from the fray better than Judd, and of the books they published (presumably spurred by the controversy), Geikie's 'Ancient Volcanoes' (1897) was a more enduring and scholarly work than Judd's rather inconsequential volume on Volcanoes (Judd 1881). More important, the controversy instigated mapping by exceptionally gifted geologists in Skye, Mull, Glencoe and other centres and this mapping (that, incidentally, did most to prove Judd's case) and the important discoveries in volcanology that resulted is perhaps the protagonists' greatest legacy to volcanology.

Antrim and northern Skye are certainly flood basalts, and the Harrats east of the Red Sea/Dead Sea rifts are close modern analogues. Uncertainties exist for example on where the foci of eruption and deposition were, and how primary depositional dips are distinguished from volcanically induced tilts, or tilts related to postvolcanic extension. Some uncertainties are readily resolved by physical volcanology. Thus, depositional groundslope angles can be estimated to the nearest 5° or better from lava structures, and magnetic fabric (magnetic anisotropy susceptibility) study yields lava-flow direction.

The Hebridean magmatic activity also generated central volcanoes as in Mull. Here a complex pattern of updoming by silicic diapirs, subsidence caused by volcanic and intrusive loading, and the deformation needed to accommodate great swarms of dykes and conesheets, may prove less tractable to analyse. The lava-flow structures, magnetic fabric study of flow directions, and palaeomagnetic study of tilting, may however go some way towards disentangling the relationships.

The regional Hebridean linear dyke swarms span both the flood basalts and the central volcanoes and extend far outside both. No general model of dyke behaviour is yet available. Did the magma ascend vertically near volcanic centres, and horizontally farther away as in the Mackenzie swarm of Canada (Ernst & Baragar 1992) or, conversely, did the magma travel almost horizontally in and near volcanic centres and almost vertically farther away, as maintained in Iceland by Gudmundsson (1992)? The availability of the magnetic fabric technique will help resolve this problem.

This is SOEST Contribution number 3819.

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From *QJGS*, **27**, 279.

2. *On the* Tertiary Volcanic Rocks *of the* British Islands. By Archibald Geikie, Esq., F.R.S., F.G.S., Director of the Geological Survey of Scotland, and Professor of Geology in the University of Edinburgh.—First Paper.

[Plate XIV.]

In the present communication I propose to offer to the Society the first of a series of papers descriptive of those latest of the British volcanic rocks which intersect and overlie our Palæozoic and Secondary formations, and which, from fossil evidence, are to be regarded as of miocene, or at least of older Tertiary, date. Materials for this purpose have been accumulating with me for some years past. In bringing forward this first instalment of them, I wish to preface the subject with some general introductory remarks regarding the place which the rocks seem to me to hold in British geology, and on the nomenclature which I shall use in describing them. These remarks will be followed by a detailed description of the first of a succession of districts where the characteristic features of the rocks are well displayed. Other typical districts will be described in future memoirs.

General Introduction.

1. *Area occupied by the Rocks.*

The rocks to which I propose to direct attention cover many hundreds of square miles in the British Islands. They spread over the north-east of Antrim, from Belfast to Loch Foyle, forming there a great plateau or series of plateaux, with an area of fully 1200 square miles and an average thickness of 550 feet. From Ireland the same rocks are prolonged northwards through the Inner Hebrides. They form nearly the whole of the islands of Mull, Rum, Eigg, Canna, and Muck. They cover fully three-fourths of Skye, and extend even as far as the Shiant Isles. But far beyond our own area they reappear with all their characteristic features in the Faroe Islands, and again in the older volcanic tracts of Iceland. In

From *QJGS*, **30**, 220–221.

23. *The* Secondary Rocks *of* Scotland. Second Paper*. *On the* Ancient Volcanoes *of the* Highlands *and the* Relations *of their* Products *to the* Mesozoic Strata. By John W. Judd, Esq., F.G.S. (Read January 21, 1874.)

[Plates XXII. & XXIII.]

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