Ordovician volcanicity

By CHRISTOPHER J. STILLMAN

Reconstructions of World palaeogeography through the Lower Palaeozoic period suggest extensive movement of long-lived continental or micro-continental masses which produced relatively shortlived ocean basins. These basins opened by rifting, spread with the formation of new ocean crust and then closed by subduction of that crust with the attendant development of island arcs, marginal basins and active continental margins. It was in these situations that the great majority of Ordovician volcanic rocks were erupted. Volcanics are found sporadically throughout Lower Palaeozoic strata and evidence of world-wide sustained climaxes of volcanic activity are preserved commonly in late Cambrian to early Ordovician and in middle to late Ordovician sequences.

There is undoubtedly a connection between geotectonic situation and the type and intensity of volcanism. Products of initial crustal rifting are widely seen in the Cambrian and post-orogenic continental volcanism was common in the Devonian, but Ordovician activity was dominantly subduction-related, pre- or syn-orogenic, occurring in submarine, island, coastal or cordilleran environments, often situated on crust whose instability was responsible for an abundance of distinctive features in the volcano-sedimentary record. The characteristics of this volcanism and the nature of its products is described, with reference to present day analogues.

The chemistry of volcanic rocks is largely controlled by their tectono-magmatic environment and geochemical descriminant analysis has been widely used as a means of distinguishing between the environments. By such means Ordovician volcanic rocks within, for instance, the Caledonide orogen have been recognised as the products of eruption above subduction zones bordering Iapetus; on continental plate margins that came together in collisions that largely destroyed the oceanic lithosphere, preserving it only in small remnants in obducted slices. The substantial replacement of volcanism by plutonic activity in late Silurian to Devonian times is believed to be due to the suturing of the plates which commonly terminated subduction.

Whilst adverting to the world-wide distribution of Ordovician volcanism, emphasis in this paper is placed on the Iapetus region. In particular the volcanic rocks of the British and Irish Caledonides are described in some detail as an illustration of features which might be expected anywhere in similar tectono-magmatic situations.

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Introduction

Many of the problems which face those who seek to reconstruct the palaeogeography of the World in Ordovician times derive from the difficulty of positioning accurately the remarkably mobile continental masses of that time. Palaeomagnetics and terrain analysis suggest the movement of relatively long-lived continental or microcontinental masses producing relatively short-lived ocean basins which opened and closed with extensive subduction and attendant development of island arcs and marginal basins. The "docking" of continental masses with a variety of relative motions ultimately created compressive or transpressive orogenic events, deforming and dislocating the sequences of rocks which were formed in the Lower Palaeozoic at the margins of these continents; rocks which include the great majority of Ordovician volcanics. There is undoubtedly a connection between the geotectonic activity

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and the intensity, extent and type of volcanicity; volcanic rocks are found sporadically throughout the Lower Palaeozoic, but widespread and sustained periods of volcanic activity are common only in late Cambrian to early Ordovician times and again in the middle to upper Ordovician, in both of which periods worldwide climaxes of activity have been recorded.

Almost everywhere these volcanics erupted in island arcs, marginal basins or volcanically active continental margins. Their magmas belonged to either or both of two magma "series"; 1) the "Orogenic Magma Series", a basalt-andesite-dacite association with chemistry ranging from sub-alkaline island-arc tholeiite through calc-alkaline suites to potash-rich shoshonites; or: 2) a characteristically bimodal association of tholeiitic basalt and calc-alkaline to alkaline rhyolite, often with a "within plate" chemistry. By analogy with modern examples, these Ordovician volcanoes are believed to have erupted above subduction zones, and the dramatic reduction of volcanicity and its replacement by essentially plutonic activity in late Silurian to Devonian times is believed to be due to suturing resulting from continental plate collisions which, in most cases, terminated the active subduction and initiated the variety of cratonising events which make up the end-Caledonian orogeny.

Characteristics of subduction-related volcanism

Present-day analogues indicate two principal environments; firstly the volcanic island arcs, often separated from the continental land masses by marginal back-arc basins, such as are seen in the western Pacific and South East Asia, and secondly the active continental margins such as the American Northwest, or the Andean region. In the first of these, the volcanism is of two distinct types: that of central volcanoes which build up arcs of oceanic islands, and that of seafloor rifts within extensional basins. The products of this latter type of activity closely resemble the new ocean floor produced by mid-ocean rifting except that, in many cases, the crust is sialic and the rifting is not complete. Thus the result is a suite of tholeiitic basalt dykes intruding a thinned continental basement, on the surface of which submarine basaltic lava flows and hyaloclastites are deposited together with pelagic and hemipelagic sediment. The island-arc volcanoes, on the other hand, are generated by calc-alkaline magma which is largely intermediate in composition, containing higher concentrations of volatiles and producing predominantly explosive eruptions which generate pyroclastic ejecta. This, in a marine environment devoid of terrigenous detritus, provides the volcanic sediment which is the principal infill to the adjacent back-arc basins. An example is the Granada Basin west of the Lesser Antilles arc of the Carribean, where volcanic sediment input has added 7 km of sediment in the 47Ma since the inception of volcanism (Siggurdson *et al.* 1980). The bed-forms, nature of grading and sorting depend both on the character of the source and the transport mechanism. Three of the major forms of transport described by Fisher (1971), are all important in volcanic sediments; these are slides, sediment gravity flows and suspension fall-out. Individual volcanoes provide point sources which may build up unstable piles of volcaniclastic material. These may shed sediment gravity flows which initiate as debris or grain flows and extend down-slope and across the basin floor as turbidites. The latter may demonstrate diagnostic features such as the doubly graded sequence recognised by Fiske & Matsuda (1964) in the submarine ash flows of the Tokiwa Formation in Japan. In some cases major deposits can be correlated directly with individual ignimbrite eruptions which commonly provide the largest volume of sediment; a fine example is the Minoan eruption of Thera, in the Aegean Sea (Bond & Sparks 1976). Ignimbrites with their zones of welding and reworked mudflows were formerly regarded as diagnostic of subaerial eruption but subaqueous examples have now been recognised. It is believed that these flows moved within a carapace of steam which insulated them and permitted a more complete and uniform welding throughout the full thickness of the sheet (Howells *et al.* 1979; Francis & Howells 1973). Accretionary lapilli remain one of the few unique indicators of subaerial eruption, but even these can commonly be reworked in aquagene deposits.

As the volcanoes build up from the sea bed, contemporaneous intrusion into the wet sediment is not unusual; magma bodies reach a

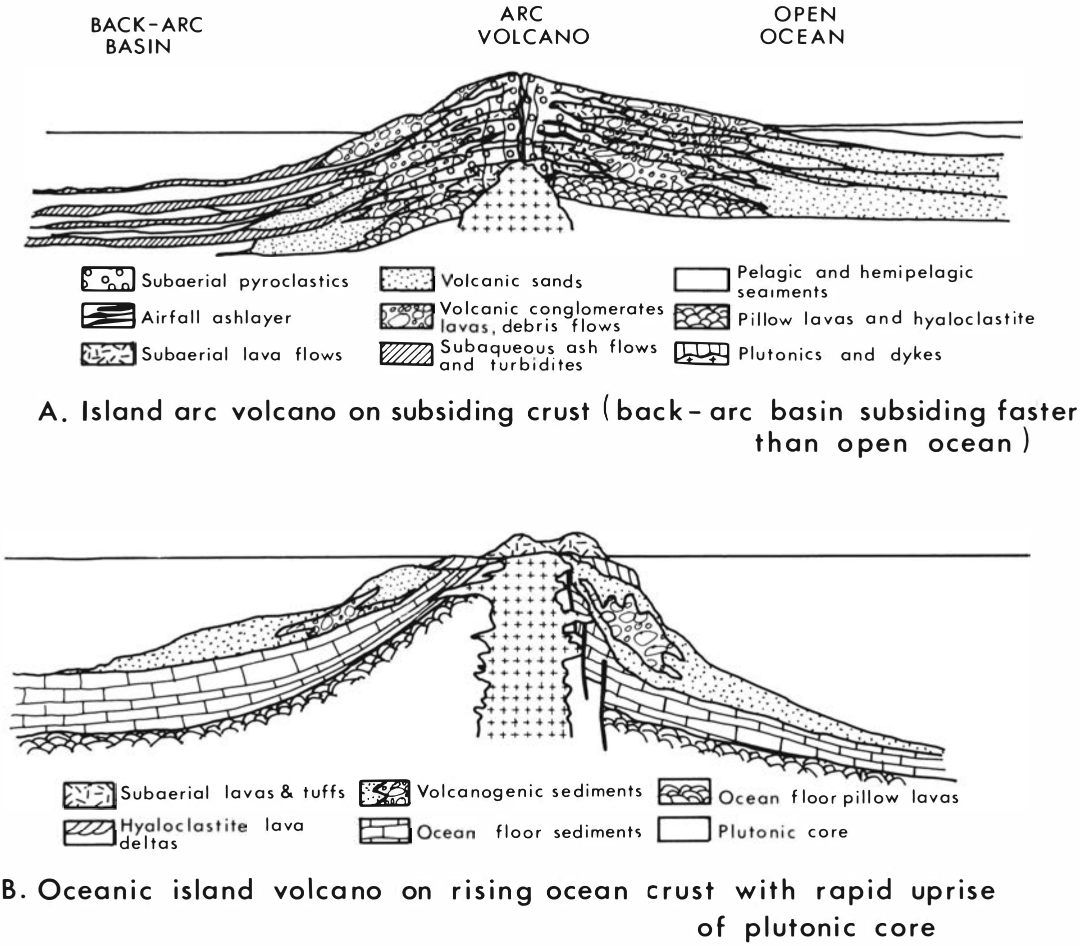

Fig. 1. Schematic cross section of island volcanoes, to portray the distribution of volcanic sediments. A *represents an island arc volcano, based on the diagrammatic model given by Siggurdson* et al. *(1980). The cross section also illustrates the asymmetry produced by the greater oversteepening of the slopes descending into the back arc basin.* B *represents an oceanic island volcano, based on a diagrammatic model given by Stillman* et al. *(1982). The cross section illustrates the effect of the rise at the ocean floor which is particularly rapid immediately adjacent to the plutonic core of the volcano.*

hydrostatic compensation level within the pile and spread laterally into the incoherent sediment producing a range of effects both in the igneous material which pillows or disintegrates, and on the sediment which becomes fluidised thus destroying the normal bed forms (Kokelaar 1982). At the foot of the volcanic slopes the build up of small fans is achieved, often with contributions from more than one volcano, and a multi-stage evolution of the sedimentary pile is common. Further from the vents, on the floor of the basin, the products of several volcanoes may interfinger and the volcaniclastic flows become intercalated with hemipelagic sediment fed from essentially airfall volcanic dust, which provides the main source of sediment at distances beyond the distal limits of the turbidites. Even more complex interrelationships of volcanic and non-volcanic sediment have been recorded in the western Pacific back-arc basins. Klein (1982) reports the recognition of nine depositional systems in the cores recovered by the Deep Sea Drilling Project, of which debris flow, subma-

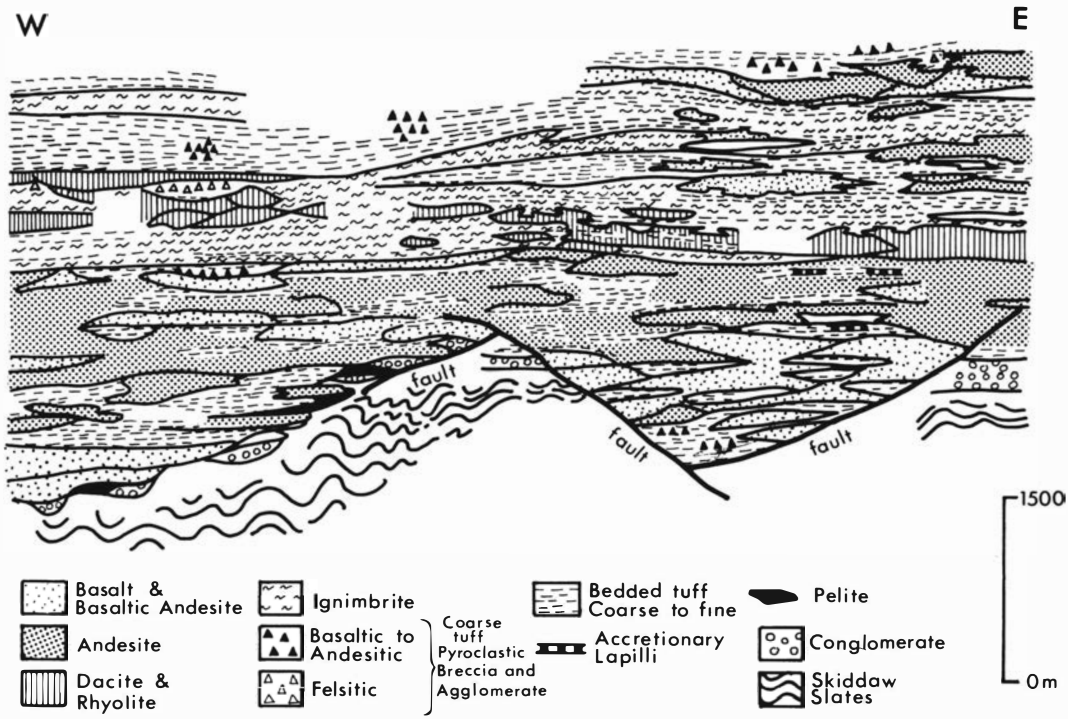

Fig. 2. Schematic representation of a segment of the lower part of the Borrowdale volcanic succession; after Millward et al. *(1978, fig. 37), to illustrate rapid facies changes and intraformational unconformities produced by the derivation of products from a number of separate and overlapping volcanic edifices.*

rine fans, resedimented carbonates and turbid-layer clay deposits occur during times of arc volcanism, of basin spreading and tectonism. Others such as biogenic pelagic systems accumulate all the time, but are dominant only in quiet periods. In these, pelagic clays dominate when the basin floor sinks below the carbonate-compensation-depth; otherwise pelagic carbonates are common. These extensive deposits are distinguished from the restricted island-fringing biogenic reef deposits which build up round the volcanic islands and contain essentially shallow water faunas and floras. Such reefs are often broken up into limestone breccias or conglomerates by seismic activity or by volcanic debris flows into which they may become incorporated. To some extent the bed-forms and the degree of continuity, or lack of it in the sedimentary record depends on the speed with which the submarine volcano builds up, and this in turn seems to relate to whether the volcano has a plutonic core which acts as an upward-moving piston producing extensive intraformational faulting, doming and uplift of the ocean floor (Stillman *et al.* 1982). A significantly different picture may emerge when there is subsidence, which, in arc situations may occur in the back-arc basin but not on the open ocean side of the arc (see Fig. 1).

The depositional environment of a volcanically active continental margin is different in that it is, at least in part, subaerial, and consists of shield volcanoes with abundant parasitic vents. These build up extensive plateaux with intermontane lakes providing scattered lacustrine and deltaic environments, and near the coast, as in Chile in historic times, occasional subsidence provides limited marine incursions. A characteristic of such an environment is extremely rapid lateral facies change with frequent intraformational unconformities and the reworking of volcanic sediments in re-

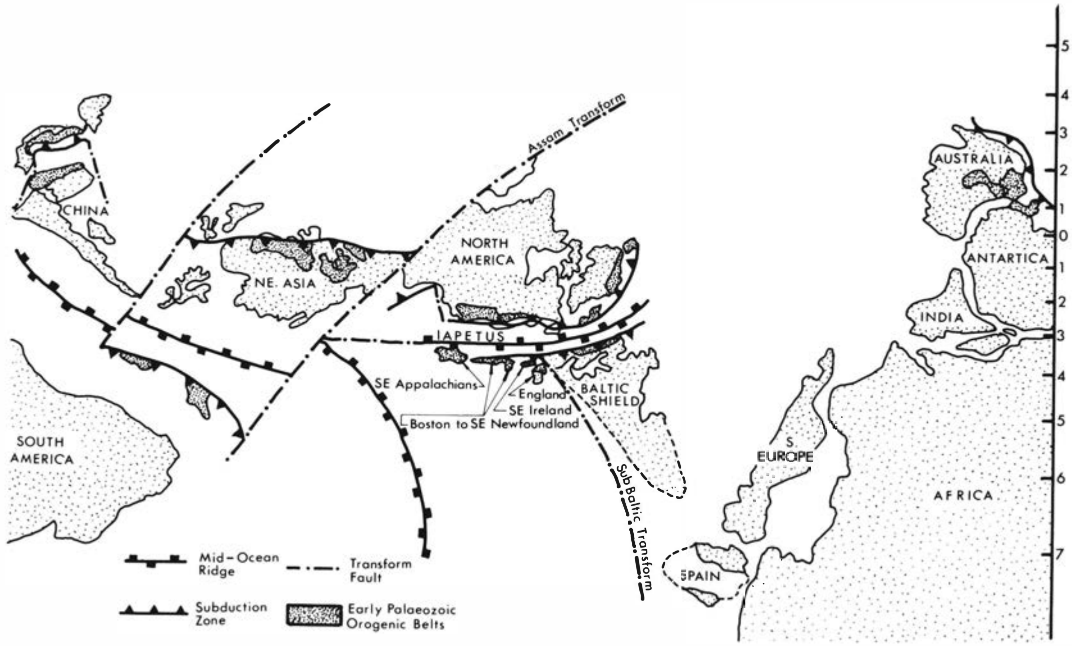

Fig. 3. Early Ordovician world map (on Mercator projection) to show distribution of continental masses, early Palaeozoic orogenic belts, subduction zones transforms and mid-ocean ridges (after Keppie 1977). (The map is centred upon the Iapetus region and part of the Pacific region is omitted.) Ordovician volcanism is largely confined to the orogenic belts, and is subduction-related.

peated cycles of construction and destruction, often overlapping from one centre to another. Such features are well displayed in the upper part of the Ordovician Borrowdale Volcanic Group of the English Lake District which demonstrates close similarities with present day volcanogenic sediments in northwestern USA (Moseley 1982), where, in a complex sequence of events, substantial eruptions of pyroclastics are reworked. However in general the radius of distribution of all but the air-fall ashes is much less than for the equivalent submarine flows and thus the contributions from different volcanic sources provide more rapid intercalation and facies change.

The global setting of Ordovician volcanism

In order to understand the timing and distribution of the Ordovician volcanicity it is necessary to examine briefly the crustal evolution of the world immediately prior to our period of interest. Towards the end of the Precambrian it appears that the continents were amalgamated into a Proterozoic super-continent (Piper 1976). From 1000 Ma to c. 850 Ma this was in a general state of tension with typical intraplate tensional igneous centres: layered intrusions, alkaline complexes, lavas and dykes. Around 850 Ma the super-continent began to crack up (Windley 1977), and by 600 Ma the Baltic and Laurentian plates had separated from the main mass and started to move apart, as had the Antarctic, Australian and Asian plates. The process of extension and rupturing was accompanied by the appropriate volcanic activity with dyke swarms and lavas of tholeiitic basalt; of such are the Tayvallich volcanics of the Scottish Upper Dalradian which Anderton (1982) attributes to the opening of the Iapetus Ocean.

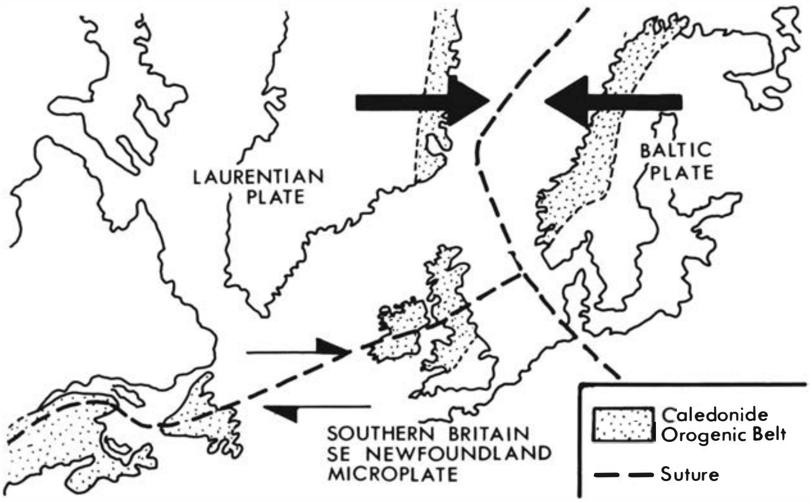

Fig. 4. A Caledonian plate reconstruction of the Iapetus region after closure of the ocean. The plate boundaries are taken from Anderton (1982), but the arrows indicating sense of movement have been added by the author.

New ocean crust to floor the Iapetus and other opening ocean basins was presumably being provided by basaltic mid-ocean rift volcanism, but almost all of this has vanished; traces only are found in scattered ophiolite complexes preserved in obducted slices stacked on the continental plate margins, sometimes in association with accretionary wedges of sediment. This is because by the early Ordovician, the sense of plate motion had changed and the oceans were beginning to close with the consumption of most of the newly formed ocean crust in subduction systems which started in Tremadoc times. Well documented examples are the Ballantrae Complex of the Scottish Southern Uplands (Bluck 1978, Bluck *et al.* 1980) and the ophiolite fragments of western Norway (Furnes *et al.* 1980; Sturt *et al.* 1980).

The processes of closure operating throughout the Ordovician and early Silurian eventually brought together the continental plates to produce a new super-continent, Pangaea. Though the process was complex and the nature and timing of approach of each plate and the tectonic situations on the leading edges was variable, a consistent pattern nevertheless emerges of volcanic activity related to the subduction systems.

Clearly it is not within the scope of this paper to describe all known areas of Ordovician volcanism, thus attention will be focussed on Iapetus, and in particular the British and Irish section of the Caledonides, which contains some of the best known localities (see Stillman & Francis 1979).

Iapetus and Caledonide volcanism

Two aspects of the tectonism of the British Isles sector of the Caledonide orogen are of major significance when discussing the apparent zonation of volcanism as it is preserved today. Firstly, when the continental masses came together to close Iapetus, they did not always approach in a direction normal to the plate boundaries; a great deal of lateral translation must have taken place with one margin sliding past another. Collision and subsequent deformation was not everywhere synchronous nor always compressive; the irregular outlines of the passing continents would have provided opportunity for the generation of pull-apart marginal basins and at a later stage the potential for high level pluton emplacement where thickened crust was wrench-faulted (see Hutton 1982). Secondly, the history of closure and collision of the Laurentian and Baltic plates (see Fig. 4) did not at first involve the crust which underlies southern Britain. This apparently belongs to a micro-plate which was detached from some other part of the African continent and did not enter the "Caledonide" orogenic belt until quite late in the process of closure (Anderton 1982), and then "docked" largely by strike-slip or transpression.

Closure of the Baltic and Laurentian plates however was compressional, and resulted in enormous crustal thickening and the peeling off of nappes which, driven by gravity, slid away from the suture across the Greenland and Scandinavian crust, preserving on the latter dismembered sequences of volcanic and plutonic rocks within the tectonically-bounded stratigraphic packages. A recent compilation by Stephens *et al.* (in press) shows that in the various nappes of the Upper and Middle Allochthon there are preserved relics of pre-Iapetus rifting, Iapetus opening with oceanic crust now seen as ophiolite fragments, and Iapetus closing with subduction-related arc volcanics and even late extensional magmatism developed on newly sutured crust. When reconstructing the ocean margins in which the igneous activity presumably took place, it is necessary to account for the curious asymmetry which resulted in the virtual absence of volcanic rocks in the East Greenland Caledonides until Devonian times, when acid lavas and tuffs were erupted through crust already remelted to produce orogenic granite magmas.

The Caledonide igneous activity in Britain and Ireland marks the approach and "docking" of the southern British microcontinent with the southern flank of Laurentia, south-west of its compressive collision with Baltica, and west of the debatable "Törnquist" line. North of the Iapetus suture, igneous activity relates to the margins of the ancient Laurentian crust, whilst to the south of it, magmatism developed on the edge of a less homogeneous and much younger crustal unit which may well have formed by volcanic arc accretion and cratonisation only a little earlier, in the late Proterozoic (Thorpe 1979, Piasecki *et al.* 1981).

Ordovician volcanicity south of the Iapetus suture in Britain and Ireland

It appears that all Ordovician magmas south of the suture may have been generated on or above a relatively simple southward-dipping subduction system which may have changed its position during Ordovician times. Geochemical and petrographic zonation indicates volcanism on a continental crust which thickened to the southeast (Stillman & Williams 1979). The Eycott volcanics of Arenig-Llanvirn age, rest on the Skiddaw Group on the northern flank of the Skiddaw anticline in the northern Lake District. These submarine basalt and basaltic andesite lava flows are intercalated with occasional more acid pyroclastics, suggesting periodic violent acid eruptions punctuating the quiet effusion of basaltic lavas which built up oceanic shield volcanoes (Millward *et al.* 1978). Chemically the basic rocks are tholeiites characteristic of early stage arc deveopment. They are similar in many ways to the basalts and basaltic andesites of the Ordovician inliers seen north of Dublin in eastern Ireland, which were erupted somewhat later to build up submarine sea mounts and oceanic islands (Stillman & Williams 1979). Earliest eruptives are Llanvirn but the vast majority are Caradoc to Ashgill, and are associated with local shallow water limestones and more widespread black pelagic muds. A Llanvirn plinian pyroclastic eruption at Bellewstown represents the only acid activity here.

Immediately south of the Eycott volcanics are the much better-known and extensive Borrowdale Volcanic Group (Llandeilo to Caradoc) eruptives. These are dominantly andesitic, calc-alkaline, and of an evolved island-arc type, associated with some more acid dacites and rhyolites. The abundant volcanic sediment indicates an initial environment of deposition around a chain of volcanic islands in shallow

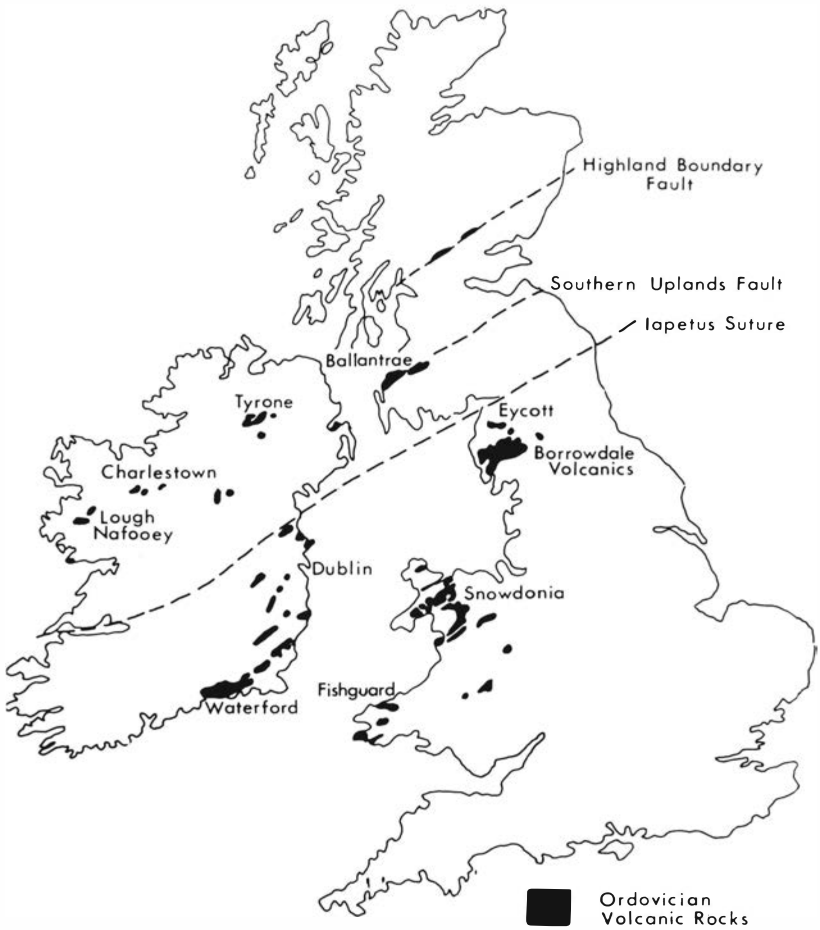

Fig. 5. Locality map of the Ordovician volcanic rocks in Britain and Ireland.

seas underlain by continental crust. The islands were dominantly strato-volcanoes composed of interbedded lavas and pyroclastics, together with acid shields of ignimbrite and acid lava. These, despite being continuously subjected to destructional erosion and redistribution in the waters around the islands, some of which, to judge from microfossils (Millward *et al.* 1978) were marine, built up to subaerial plateaux.

In south-east Ireland at this time volcanic activity dominated the infilling of a north-east trending linear basin which had been accumulating the terrigenous clastic sediments of the marine Bray and Ribband Groups. Amongst these are "coticule" beds now thought to indicate ocean-floor metalliferous sediment related to some form of volcanogenic-hydrothermal activity (Kennan pers. comm.). In Llanvirn to Llandeilo times, in what is now the Waterford coastal region, a number of submarine basaltic volcanoes began to erupt island arc transitional tholeiites, then calc-alkaline basalts and basaltic andesites. These built up shield volcanoes with much associated shallow intrusive activity emplacing high-level sills into unconsolidated volcanic muds and hyaloclastites. A pause in the upper Llandeilo allowed the widespread deposition of a calcareous sediment, then renewed igneous activity ejected large volumes of acid pyroclastics as ash-flows, both submarine and subaerial, with occasional andesite and basalt sheets. Quantities of rhyolite were injected as sills, dykes, and domes which sometimes broke surface to provide the setting for "Kuroko" type volcano-exhalitive copper-iron deposits, as at Avoca (Sheppard 1980). Here there is a bimodal association of basic rocks derived from subduction-related calc-alkaline magmas and acid rocks possibly derived from the partial melting of continental crust.

Whilst it seems likely that the south-east Ireland and Lake District volcanoes were parts of arcs situated on the margin of the southern Britain microcontinental plate, a recent very thorough re-examination of the evidence by Kokelaar *et al.* (in press) leaves little doubt that the Lower Palaeozoic Welsh Basin was actually founded on this continental crust and developed by extensional mechanisms, behind the arcs. At the very beginning of the Ordovician, in late Tremadoc times, a major graben controlled by north-east trending faulting and filled with Cambrian marine sediments was subjected to tectonism and associated subduction-related calc-alkaline volcanism, as seen at Rhobell Fawr. The subduction system would appear to have changed position in Lower Ordovician times, as the focus of arc volcanism moved to the southeast Ireland-Lake District centres and was succeeded in Wales by mainly tholeiitic magmatism emplaced in an environment of back-arc extension. This, with the exception of the Llanvirn Fishguard Volcanics (Bevins 1982) seldom fractionated to produce significant volumes of intermediate or acid rocks. The distinct bimodal character of Welsh volcamism is, in fact, provided by the addition of voluminous eruptions of rhyolite which again is interpreted as resulting from crustal fusion. Centres of volcanism migrated both in time and space from the Arenig to Llanvirn activity of southern Wales to the pre-Caradoc volcanism of southern Snowdonia and then the Caradoc episode of central and northern Snowdonia. In the Welsh borderlands and the Lleyn, activity of both episodes is represented. In all areas contemporaneous faults often controlled sites of eruption. Intrusive activity is represented by high-level basic sills and small granitic bosses, some of which are clearly coeval with the volcanics, but others may be later.

Ordovician volcanity north of the Iapetus Suture, in Britain and Ireland

No such simple zonation is apparent here. The Laurentian plate had a longer more complex history, which involved, during the Lower Palaeozoic, both the approach and interaction with the Baltic plate and the southern Britain microplate. The results were first a Cambro-Ordovician (Grampian) compressive event producing pronounced regional metamorphism and deformation, and a second, end-Silurian (Caledonian) event, in which oblique transpression resulted in strike-slip shuffling of segments of crust with relatively mild internal deformation, but with very extensive batholithic granitic plutonism. The sediments deposited in the Dalradian basins on this plate were affected by both, but early Ordovician to mid Silurian rocks deposited on its southern margin show only the Caledonian events.

There is evidence that the Dalradian supracrustal basins which were being stretched and ruptured in mid-Cambrian were, by Arenig times, fringed by ocean basins to the south. Remnants are seen at Ballantrae, where Bluck *et al.* (1980) have described an island-arc and marginal basin assemblage which evolved in a pre-Arenig marginal basin and was obducted northwards onto a pre-Caledonian continental margin between 470 and 490 Ma ago. The Highland Border Complex which is now known to be, at least in part, of Lower Arenig age (Curry *et al.* 1982) also contains southerly derived debris from a back-arc basin. In Northern Ireland the Tyrone Igneous Complex comprises a suite of high-level basic and intermediate intrusions closely related to volcanic rocks of similar composition in a setting which could well be a marginal basin and island arc. The complex is in tectonic contact with Dalradian metasediments in a manner analogous to that of the Highland Border Complex.

There is evidence not only of the existence of oceanic crust but also of the beginnings of subduction, with its related arc magmatism, at the same time as the Grampian orogenic event was taking place on the continental plate. In Connemara the interaction of the two may perhaps be seen; the Connemara migmatites contain an intrusive magmatic component which Yardley *et al.* (1982) interpret as the roots of an early Ordovician volcanic arc emplaced in Dalradian supracrustals during the Grampian event.

Whilst these deep-seated roots to not have direct volcanic associates, compositionally very similar coeval Tremadoc submarine lavas are found at Lough Nafooey, some 15 km to the north. These are island-arc tholeiites which in th Arenig, give way to more calc-alkaline evolved arc types (Ryan *et al.* 1980). It is not likely that these little-deformed arc volcanics with their pelagic black mud intercalations were erupted in close proximity to the Connemara orogenic zone; they must be situated on a block of crust which was tectonically juxtaposed with Connemara only from Llanvirn times onwards, when clasts of Dalradian lithology were transported from the south into the Maumtrasna Group conglomerates. The volcanics apparently initiated as an arc on the southern border of the South Mayo Trough, which evolved throughout Ordovician and Silurian times, during which the volcanicity was, like the Welsh Basin, bimodal acid and basic. Here again it seems that the acid magma may be the product of crustal melting, induced as the crust was thickened.

Similar Arenig volcanics and marine sediments are seen at Charlestown, 45 km to the northeast, where a mineral deposit, apparently of porphyry copper type, is associated with high-level quartz feldspar porphyry intrusions. Such deposits are characteristic of continental margin volcanic areas and again suggest some crustal involvement in the magmatism.

All these early Ordovician volcanic arcs and marginal basins fringe the Dalradian continent and it appears that an active continental margin with subduction-related arc magmatism and extensional marginal basins was established on this segment of the Laurentian plate boundary as early as the beginning of the Ordovician.

Immediately to the south, there is now to be found an accretionary prism of stacked, often inverted, slices of sediments, volcaniclastics and lavas which make up the Southern Uplands. This sequence, lying immediately to the south of the Ballantrae ophiolite, has been interpreted as comprising ocean-floor assemblages obducted northward onto the continental margin (Leggett *et al.* 1979). In the northern belt are basaltic lavas overlain by metalliferous sediments, cherts, graptolitic mudstones and greywackes, largely of Arenig age. Geochemical studies (Lambert *et al.* 1981), indicate a variation from alkaline to tholeiitic in chemical character from north to south through a series of tectonic slices, leading these authors to suggest that the Ordovician sequences were deposited on oceanic crust, alkaline in the north and tholeiitic in the south. They also suggest that this oceanic crust continued to be the basement throughout Ordovician and into Silurian times.

Along the northern edge of the Longford-Down extension of the accretionary prism into Ireland, Llandeilo to Caradoc pillow lavas, found on the northern shores of Belfast Lough at Helens Bay (Sharpe 1970, Craig 1982) and at Stokestown (Morris 1981), appear to have erupted in spreading marginal basins, and in South Connemara Ordovician basaltic pillow lavas are of apparently similar origin (Ryan *et al.*, in press). Although no actual fragments of oceanic crust have been recorded, all the Ordovician lavas are of extensional ocean floor origin.

However, also within the sediments, are volcaniclastic components which become dominant in the younger Ordovician sequences, and which appear to have been derived from the north. The succeeding Silurian beds also contain traces of volcanic material (Phillips & Skevington 1968, O'Connor 1975, Cameron & Anderson 1980), which is largely pyroclastic and may best be explained as the product of subduction-related arc volcanism, the source region of which is not clear but may well be to the north. This rather tentative evidence of a volcanic arc north of the accretionary prism which continued its activity into the Silurian is significant when the situation in Scotland is examined. Here though the Ballantrae conglomerates contain northerly derived clasts of volcanic arc rocks (Bluck 1978), the supply of these had apparently ceased by the end of the Llanvirn. The Southern Uplands Fault must have been active by this time as the Ordovician arc which supplied the clasts can scarcely have been in the region now occupied by the Midland Valley. The dislocations and juxtapositions such as are suggested for the Southern Uplands and for Connemara, which took place during the period of Iapetus closure, illustrate the complexity of the Laurentian plate margin that evolved during that closure. They may go far to explain the absence of a clearly defined geochemical zonation in the volcanic rocks, such as is seen in the subduction-related Ordovician volcanics of England, Wales and south-east Ireland, south of the Iapetus suture.

This detailed account of one small sector of just one plate collision zone should serve to indicate that Ordovician volcanity demonstrates a period of active plate motion. It also suggests that whilst geochemical descriminants provide perhaps the most powerful tool for the recognition of tectono-magmatic setting, palaeogeographic reconstructions may be better analysed with the help of the eruptive and depositional character of the volcanics which can effectively demonstrate the physical environment.

A final and cautionary comment must be that the widespread distribution of Ordovician volcanism virtually precludes its use in long range correlation. Similar tectono-magmatic settings on different plate boundaries can, and do, produce identical volcanic sequences in provinces which are geographically quite distinct and perhaps formed at different times.

Acknowledgements

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