Terrrane accretion in western Scotland

From Earthwise

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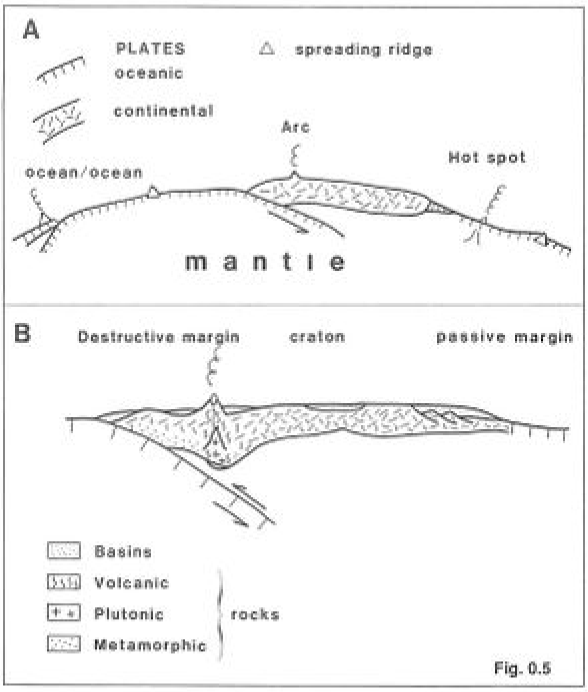

Figure 0.5. The disposition of plates and the tectonic environments associated with them.

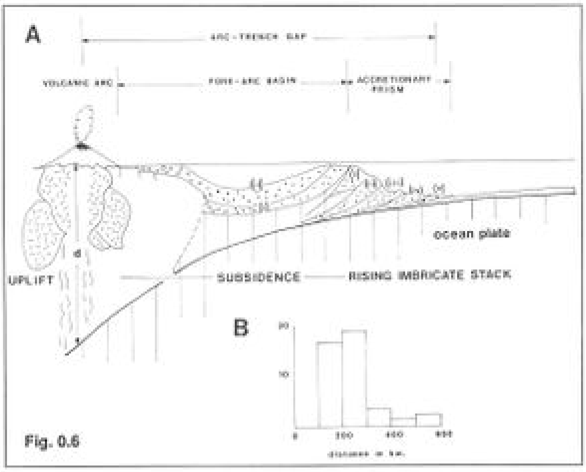

Figure 0.6. A, The detailed structural elements of a destructive margin, along with the spatial and vertical scales.

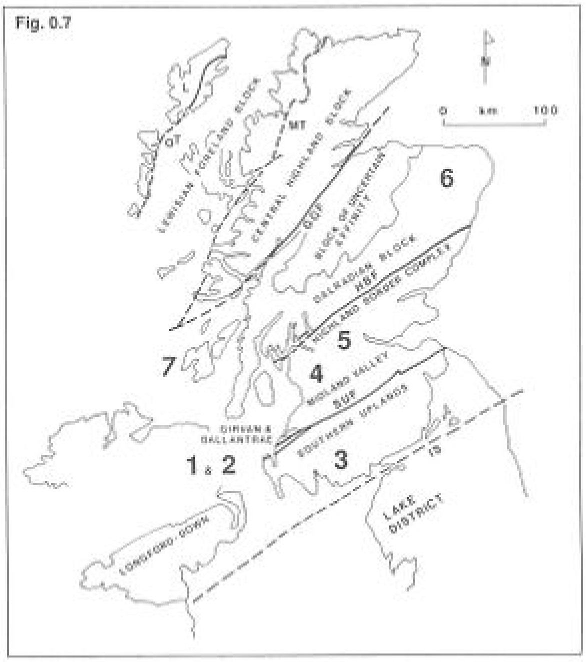

Figure 0.7. A map of the Palaeozoic tectono-stratigraphic blocks within Scotland.

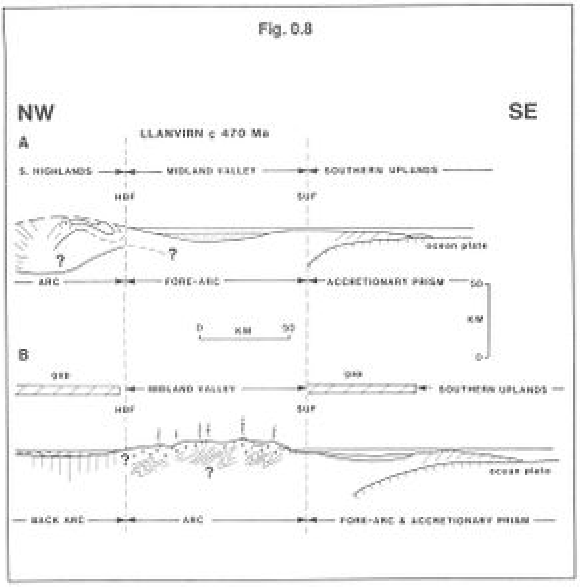

Figure 0.8. Cross sections through Scotland.

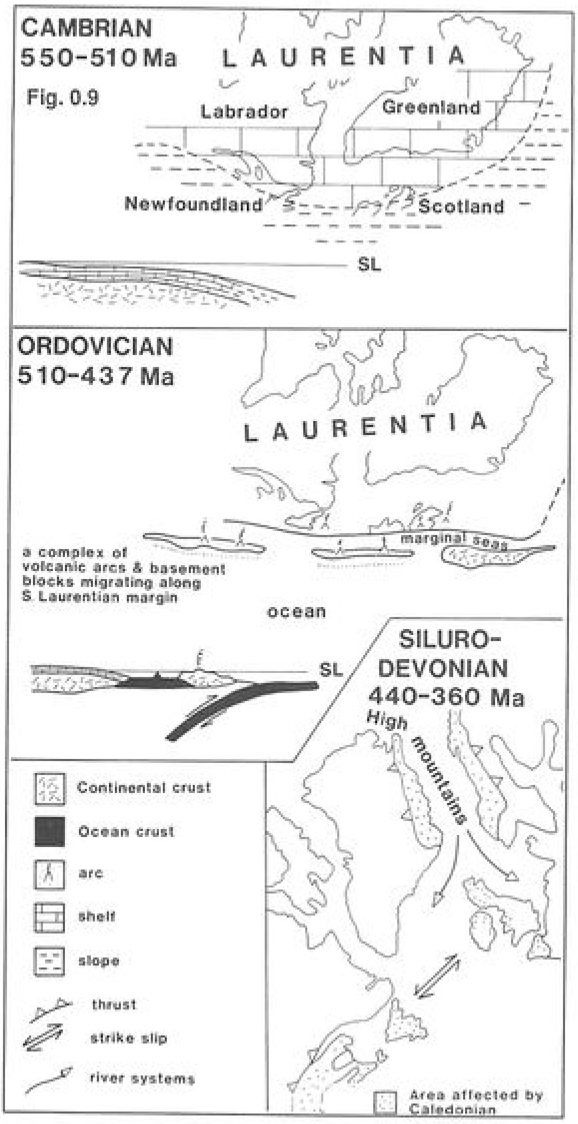

Figure 0.9. A general view of the dispositions of the landmasses of the North Atlantic during the Palaeozoic.

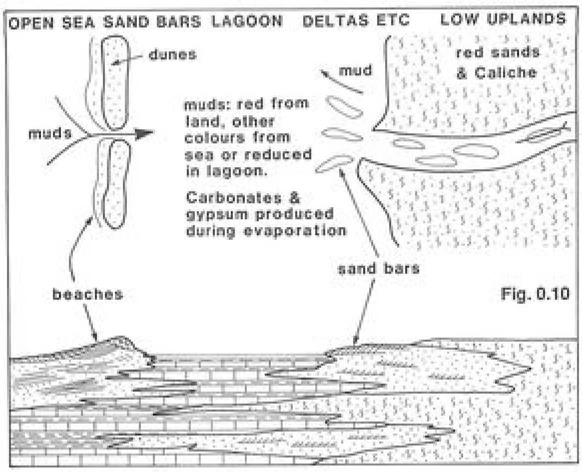

Figure 0.10. Diagram illustrating the origin of the Ballagan beds, and showing how the limestone-shale, sandstone and caliche can all be integrated into one environment of deposition.

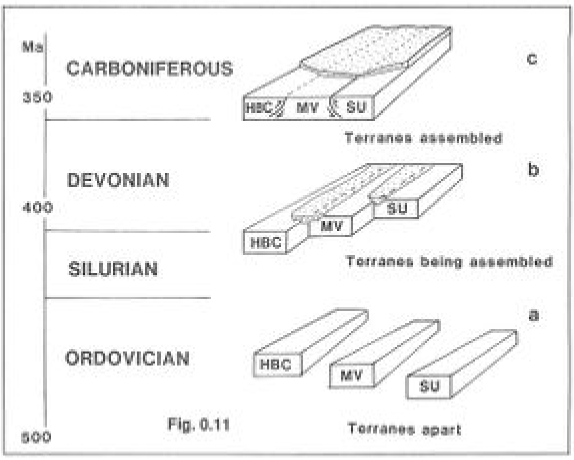

Figure 0.11. Showing the evolution of the main tectonic elements, Highland Border Complex, (NBC); Midland Valley (MV) and the Southern Uplands (SU) through time.

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By B.J.Bluck

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Contents

Introduction

Since the last edition of this guide our perception of geology in general and Scottish geology in particular has changed dramatically. New theories on the origin of continents and oceans have been postulated which are stimulating changes in the way we look at rocks and try to reconstruct their geological history. It is important therefore that the geology we study locally be no longer divorced from these all-embracing theories. Therefore, the orientation of parts of the new edition of this guide has been changed: particular observations and the explanations of them are now related to the wider geological regimes under which the rocks formed.

It is now generally accepted that oceanic plate is produced mainly at spreading ridges and that, after moving some distance from the ridge, it either descends back into the mantle or it is attached to a continental block without descending beneath it (Figure 0.5). Where the oceanic plate descends (is subducted) into the mantle oceanic trenches are produced and as the plate moves deeper into the mantle the higher temperatures cause part of it and the surrounding crust to be melted. The ascending molten rocks form volcanoes, giant granitoid batholiths and a host of intrusive igneous rocks associated together as a volcanic and plutonic arc. However, if the ocean plate descends beneath preexisting oceanic plate, (Figure 0.5)A, then island arcs are produced which are dominated by basic igneous rocks, and do not normally have the great plutonic masses characteristic of the continental margins.

The region below such an arc, being hot and under compression (because of the convergence of the two plates), is often the site of regional metamorphism and accompanying polyphase deformation. The continental crust here is thickened and its surface is divided into a series of basins in which sediments accumulate, sediments dominated by volcanic and plutonic arc sources–the foundation upon which the arc was built.

We have become increasingly aware as we examine the surface of the earth, that it may be divided into various regimes, each typified by a group of rocks generated ultimately by the dominant influence of a single, albeit complex, process. The types of metamorphic, igneous and sedimentary rocks, the ways in which they are folded and faulted, and the nature of their vertical and lateral associations are all typical of the major oceanic or continental regimes in which they are found.

These various regions, or plate regimes, where distinctive rock associations are found are illustrated in (Figure 0.5)B and (Figure 0.6) together with a brief statement of their essential nature.

If we accept the concept of plate tectonics, the establishment of a plate regime involves looking at all rock types over a wide area. When examining the rock assemblages of any one region, for example western Scotland, it is appropriate that we should ask the question -where on the oceanic/ or continental plate was the assemblage formed? Where was subduction taking place at this time? What was the plate tectonic regime? We are, by accepting the theory of plate tectonics also forced to think in a more global way. Probably for the first time, many excursions in this Guide are not seen in isolation, but as part of an integrated history which involves a great deal of Scotland and beyond. It is from such an integrated history for a given time span, the way in which the rocks are associated and the areal and vertical disposition of this rock association assessed, that we are able to identify the tectonic regime in which the rocks of a given region were generated.

A corollary of the comments listed above is that when the geology of an area is being summarised, rather than taking an entire, composite stratigraphical column for it, and explaining it as a sequence of geological events, it is now more appropriate to divide the area into regions which have similar rocks and have undergone a similar history. It then becomes important to examine the sequence of geological events within any one of these regions, to identify the types of process which could be responsible for creating the rocks and their history, and to relate the regions to each other to see if they can be assembled logically in terms of processes into the components of a plate tectonic regime as illustrated in (Figure 0.5). This is now attempted for the west of Scotland.

Western Scotland in the Lower Palaeozoic

The geological divisions of western Scotland are set out in (Figure 0.7). Each division is characterised by an area of rock with similar geological aspects; and each is divided from the others by major and well-known faults. The divisions are not new: they have been the traditional way of dividing Scotland geologically. It is their interpretation as individual blocks which is new. Each block will be briefly described and the relationships between them then discussed.

1. The Ballantrae Complex (Excursions 25, 26 and 27).

The Ballantrae Complex comprises black shales, cherts, pillow lavas, gabbros, minor granitoids, serpentinite and some metamorphic rocks. It appears a structurally dismembered ophiolite–a fragment of oceanic crust which is mainly of Arenig age(Barrett et al 1982; Bluck1985; Stone et al 1988). Oceanic crust of the type seen at Ballantrae can form in a number of different situations–at oceanic ridges, the most common way of creating ocean crust; at hot spots formed where the ocean crust moves over a fixed zone of magma rise; or at marginal basins where there is a complex relationship between arcs and ocean crust.

The origin of the Ballantrae Complex is conjectural. The hypothesis favoured here is that it is arc related; but in any event its presence in southwestern Scotland is significant, for it implies that during Arenig times there was some interaction between oceanic and some other crust (oceanic or continental), which resulted in the oceanic crust rising up rather than descending into the mantle. From the age determinations made at Ballantrae and its relationship to the cover sequence it is now apparent that the ophiolite was created and destroyed within c. 20 million years, implying that it was created near the margin onto which it was finally thrust (obducted). Had it been created at a ridge some distance from the continent to which it finally accreted, there would be a substantial difference between the age of generation of the ophiolite and the time of its emplacement onto the continent—a difference proportional to the width of ocean traversed by the ocean crust after its generation.

Ophiolites are typical of destructive margins. They are commonly part of the process of arc development, and after obduction may form the floors to fore-arc basins, as can be seen around much of the Pacific area today.

2. The Girvan cover-rocks (Excursions 28, 29, 30 and 31).

The Ordovician and Silurian rocks of the Girvan district are classical: they have been the studying ground for researcher and student for almost 100 years. To many, they are a geologist's Elysium where highly significant geological problems are abundant and never fully resolved. The Ordovician, and to a lesser extent the Silurian rocks are conglomerates, sandstones, shales and limestones which have been deposited in fault-bounded basins, and unconformably overlie the Ballantrae Complex (Williams 1962; Ingham 1978). The conglomerates are commonly mass flows or fan deltas which were deposited at the fault-margins of the basins and interfinger with deeper water sandstones laid down by turbidity currents. The tops of the fault blocks are coated with shallow water, often reefal, limestone.

Although the Ordovician rocks are divided from the Silurian by an unconformity, the lower part of the Silurian sequence was probably deposited in a regime similar to the Ordovician: coarse conglomerates being deposited near active faults but replaced by finer sediments away from the margins of the basin. Later Silurian rocks within the Midland Valley (including the sequence at Girvan) were deposited in shallow water conditions and finally become terrestrial, with the deposition of fluvial conglomerates. These terrestrial conditions which first appear in the Late Silurian become dominant in the Devonian, with a consequence that there is no clear lithological distinction between the two systems in the Midland Valley.

Within this stratigraphical framework several important observations can be made.

a. The conglomerates and sandstones are dominated by volcanic and ophiolitic rock fragments, which clearly indicate a provenance comprising ophiolitic rock and volcanic and plutonic rocks. The ophiolitic rocks will have come from the Ballantrae Complex, but the origin of the acid volcanic and plutonic rocks is far from clear. Age determinations made on the granitic clasts show that many of them are c.470 Ma (Llanvirn) in age (Longman et al 1979). As these clasts have a chemistry similar to some of the associated volcanic and hypabyssal rock fragments, they are thought to have come from a contemporary Ordovician igneous complex. We know that both ophiolites, volcanic and plutonic rocks typify destructive margins, so the discovery of the existence of an Ordovican igneous complex of this kind is clearly significant. But where was it?

b. The conglomerates are boulder-bearing and have palaeoflow indicators showing a flow towards the SE. In the reconstructions of the stratigraphy produced by Williams (1962) and Ingham (1978) the fault bounded basins deepened towards the SE. On these two lines of evidence a source block to the NW is indicated. But how far away was this source? The conglomerates contain boulders which are sometimes well over 2 m in diameter. Sailors and others are glad to know that boulders do not travel large distances by normal (i.e.non glacial) agents of transport, so that a source block a little way to the north, within the Midland Valley, is indicated.

c. Shallow water (neritic) faunas are strikingly Laurentian in aspect up to levels of late Caradoc age. Above this, such faunas become increasingly cosmopolitan.

3. The Southern Uplands (Excursion 32).

The Southern Uplands comprises a thick sequence of greywacke deposited by turbidity currents overlying black shales and cherts which rest on remnants of an ocean crust foundation. This essentially greywacke pile, most of which is vertical or dipping at very steep angles almost invariably youngs to the NW. The Southern Upland sequence begins in the Llanvirn and ends in the Wenlock, but the age of the basal greywackes where they rest on the black shales and cherts gets younger to the SE. The oldest rocks are therefore found in the north (the northern belt) and the central and southern belts contain progressively younger rocks.

The greywacke and the conglomerates which interfinger with them contain abundant volcanic rock fragments. As with the sediments at Girvan, boulders within the Ordovician and Silurian conglomerates have been dated and some show Ordovician (Llanvirn; 470 Ma) ages, indicating a source partly in a contemporaneous volcanic-plutonic complex. The palaeoflow in the Southern Uplands is, however, far from clear. There is considerable evidence in the greywackes for flows from the NE and SW; the coarse conglomerates, however show evidence of having been derived from the NW, and there is a favoured view that the greywackes were deposited by turbidity currents travelling along the axis of a large, elongate trough. There were points of sediment input to this trough which were in the NW; and these include the conglomerates which are thought to occupy deep channel systems.

The origin of the Southern Uplands is a matter of controversy and there are some important additional points which have to be considered:

a. The vertical rock sequence in the Southern Uplands indicates that the base is towards the SE, so that the sequence should get younger to the NW. The description above (and see (Figure 0.6)), shows the reverse to be true: the oldest rocks are found in the NW.
b. The whole sequence is cut by a series of strike faults, which also bring up to the level of erosion slices of the basement. This basement material is thought to be oceanic as it comprises black shale, chert and pillow lava (see Excursion 32 to Dob's Linn for black shales and cherts).
c. The conglomerates and turbiditic sandstones contain clasts of pre-existing shales which have already suffered some cleavage. No faunas have been collected from these shales but if they belong to older rocks of the Southern Upland pile, then it suggests that a recycling process is taking place in which older formations are being eroded to supply sediment to younger ones.
d. The age of the first turbidites to enter the basin i.e. the first turbidites to interfinger with the black shales as at Moffat, get younger as one goes south. This suggest that the greywacke pile grows towards the S or SE over a belt in which the black shale was accumulating.

On the basis of these observations McKerrow et al (1977) interpreted the Southern Uplands as an accretionary prism see (Figure 0.5), (Figure 0.6), (Figure 0.7). Since that time however, a number of points have been raised which challenge this model:

a. In middle Ordovician times there was also a source of sediment to the south or SE of the Northern Belt of the Southern Uplands, and this source supplied fresh volcanic sediment which has the characteristics of a volcanic arc (e.g. Stone et a/1987). This sediment, although fresh, nevertheless is older than the sediment in which it is included being c. 550 Ma (Early Cambrian). An accretionary prism would not normally have a source outboard of it.
b. The sediments are possibly rather coarse to have formed in a trench. Most of the conglomeratic sediment is derived from an arc to the NW. and much of the greywacke in sharing this arc-type 'petrography presumably came from the same source. The sediment would have to have been yielded from the arc, dispersed over a fore-arc region and then into the trench— a distance which is usually well over 100 km. By that time it should have been fairly fine grained, perhaps finer than the grain size now seen in the Southern Uplands greywackes.

Two alternative views are, therefore, that the Southern Uplands formed either in a back-arc basin or a fore-arc basin (see McKerrow 1987 for many diverse views).

Whatever may be the interpretation of the Southern Uplands in general, it is clear that the Midland Valley, Ballantrae-Girvan and the Southern Uplands all resemble the tectonic elements of a destructive plate margin ((Figure 0.8)) and if the Southern Uplands were to be an accretionary prism the whole areal sequence of tectonic blocks from there to the Midland Valley would be in the right order for being a destructive margin (cf. (Figure 0.6) and (Figure 0.8)).

Destructive plate margins are often very extensive: some are tens of thousands of kilometres long. The destructive margin of which Scotland was a part was also long. Evidence used to determine that a destructive margin characterised this part of Scotland is also used to show that this margin extended from north of Florida through the Atlantic states, Newfoundland, NW Ireland–Scotland and out into east Greenland. The large landmass bordering this destructive margin was called Laurentia (Figure 0.9). Laurentia was bordered to the south by a wide ocean over which it was sliding, often obliquely, and it is as a result of this interaction, that the southeastern margin of Laurentia is seen to have been destructive.

4. The Midland Valley (Excursions 5, 6, 7, 8, 14, 16, 21, 22 and 24)

Upper Palaeozoic and minor outcrops of Mesozoic rocks dominate in the Midland Valley. However, although there are few Lower Palaeozoic outcrops here, evidence from flanking areas such as the Southern Uplands, zones such as the Highland Border Complex, xenoliths in Carboniferous igneous rocks within the Midland Valley and evidence from existing Palaeozoic outcrops gives some clues about the nature of its rocks and the role it may have played in Caledonian times.

Many Lower Palaeozoic boulder-bearing conglomerates and sandstones within the Southern Uplands, and also at Girvan, have been derived from the NW and contain abundant metamorphic and igneous clasts. Lower Palaeozoic rocks of the Highland Border Complex also contain igneous and metamorphic clasts, although the direction of transportation of these sediments is not known. Blocks of metamorphic and igneous rocks (other than obvious Carboniferous) are found as xenoliths in Carboniferous volcanic and associated rocks. All these observations imply there to have been a metamorphic-igneous complex within the region which is now the Midland Valley.

Age determinations for the granitic detritus (see last section) suggest the Midland Valley to be the site of an igneous complex in Ordovician-Silurian times, and this may have continued on into the Devonian as the Ochil-Sidlaw volcanic pile. Metamorphic clasts and detrital sedimentary micas in the sediments of the Southern Uplands have Cambrian-Silurian ages (Kelley and Bluck 1989), and some clasts found in the Highland Border Complex have ages c. 1800Ma. During the Caledonian cycle the Midland Valley was probably a magmatic arc founded on an old metamorphic basement.

The Silurian rocks of the southern Midland Valley also contain metamorphic and igneous detritus which may have been derived from the Midland Valley arc. This sequence shows a basin which began with marine turbidites and by gradual infilling was converted to a basin which became terrestrial.

5. The Highland Border Complex (Excursions 9 and 10)

The Highland Border Complex, as its name implies, comprises a structural assemblage of rocks of differing ages and differing aspect. The rocks comprise pillow lavas, serpentinites, black shales and cherts, conglomerates and limestones, and various sandstones. The age and affinity of these rocks have always been problematical. They were once thought, on structural grounds, to belong to the Dalradian block against which they now lie. A Laurentian trilobite fauna in a limestone near Callander gives a Lower Cambrian age; a trilobite fauna in limestones at Dounan's Quarry, near Aberfoyle revealed a Lower Ordovician (Arenig) age (Curry et al 1982; Ingham et al 1985). As main Dalradian folding took place before 590 Ma (Rogers et al 1989), i.e. within the Late Precambrian, it is no longer possible to see the Highland Border Complex as part of this metamorphic terrane, but rather as a tectono-sedimentary unit of its own.

Further research has shown that there is a complicated stratigraphical and structural sequence within the Highland Border Complex. Bluck et al (1984) demonstrated the presence of an old ophiolitic assemblage which Dempster and Bluck (1991) showed was obducted at c 540 Ma (Lower Cambrian); on top of this were deposited shallow water carbonates and conglomerates (Arenig); these are structurally followed by shales, cherts and spilites (probably mainly Llanvirn), which in turn are finally unconformably overlain by sandstones and limestones. The sequence is thought to span most of the Ordovician.

The origin of this Complex is still not fully understood. Bluck et al (1984) believed it to resemble a collapsed back-arc basin sequence, but there is at the moment insufficient evidence for this or any other interpretation and the question must be regarded as open.

6. The Dalradian block (Excursions 10, 11 and 13)

The Dalradian belt comprises a Late Proterozoic sequence of quartz-arenites and carbonates which formed on a continental shelf, a pile of lavas and associated volcanogenic sediments which may represent a phase of structural extension of the shelf, tillites from an ice sheet the location of which relative to the Dalradian basin is uncertain, and finally some turbidites which are found along the southern margin of the block (Anderton 1985).

This rock sequence was subsequently folded and metamorphosed in two stages, before and after the intrusion of the Ben Vuirich granite. Rogers et al (1989) showed this granite to have cooled at 590 Ma. (Late Proterozoic) and now divide the folding into an early phase (D_1 and D_2) and probably a local metamorphism which is precedes the intrusion of the granite; and a later phase, (D_3 and D_4) with substantial metamorphism which is post the intrusion. Although the first stage in the Dalradian structure and metamorphism produced the the big D_1 overfold, the second was responsible for the main metamorphism and uplift of the block. These later events took place from c. 515 Ma-430 Ma for the main part of the belt and continued down to 390 Ma in the northernmost Dalradian.

The origin of the Dalradian block is at present uncertain and will be discussed at a later stage when the concept of terranes has been considered.

Growth of continents by terrane accretion

Although there is convincing evidence for there being a destructive margin in Scotland during the Lower Palaeozoic, examination of present-day margins of this type show that there is another major process at work. Many of the tectonic elements such as accretionary prisms and fore-arc basins, are bounded by major faults and it is fairly clear that in some instances these elements are no longer in the position of their growth. Subsequently or even during their generation they have moved either towards the craton or laterally along the cratonic edge. Large blocks which have suffered this type of displacement are referred to as terranes. From these observations a new theory of the growth of continental masses has arisen.

The new theory is a corollary of plate tectonics and was developed to explain some anomalies in the geology of parts of western U.S.A. Here were blocks of ground, usually major tectonic elements (terranes), bounded by faults, which had very clearly undergone quite a different history from the blocks now adjacent to them and also a different history from the North American craton. Some have sedimentary rocks with faunas which are totally different from the faunas of the same age found on cratonic North America. Indeed, some of the faunas resemble more the faunas found in Asia. This evidence, together with the more soundly based palaeomagnetic evidence, has been integrated to chart the paths taken by these terranes relative to North America. It has become clear that "blocks" of oceanic or continental crust became attached to North America at low latitudes, then migrated northwards along the continental edge towards, and often reaching, Alaska.

This type of accretion was achieved by the movement of North America westwards over a Pacific plate which is moving roughly eastwards. Blocks of high-riding crust, continental or oceanic, instead of disappearing down a subduction zone became attached to the western edge of the North American craton. However if a continent rides obliquely over an oceanic plate then the blocks of accreted crust may be dragged along the continental edge. This has been (and still is) the case along western North America.

Since these early discoveries it has become clear that any destructive margin where the overriding continent converges obliquely onto the underriding oceanic plate is liable to be a zone where terranes may move laterally along the continental edge. The terranes may include seamounts or other topographic highs on the oceanic plate, or microcontinents originating in totally different continental masses. Terranes of this kind are exotic; they did not originate in the continent to which they are now attached. However there are other terranes which are generated at the continental margin, as for example the microcontinent of Japan, which are then moved along the margin to accrete to the same continent which spawned them, but in a position different from their origin. Japan became detached from Asia during the opening of the sea of Japan; it may subsequently be pushed back to Asia, and thus back to the continent of its origin. The early part of Japan's history is similar to that of Asia. Subsequently their differing histories will reflect terrane isolation, and eventually, on accretion their histories will unite.

Destructive plate margins generate many outboard volcanic arcs and fore-arc regions, as can be seen along the western Pacific. Such tectonic elements (arcs, etc) are particularly liable to be moved laterally if subduction changes from head-on (orthogonal) to oblique. So it is not uncommon to find that destructive margins comprise assemblages of tectonic elements which are not in the exact position where they were formed. How does one recognise that a destructive margin has been re-assembled in this way?

Evidence for terrane accretion in Scotland

There is now considerable evidence to suggest that much of Scotland has been assembled from displaced terranes, and we here emphasise those which are covered in this field guide. The origin of the Moine, Dalradian and Islay-Colonsay terranes will be discussed briefly later.

1. The Ballantrae Complex

Being a fragment of oceanic crust on land, this is evidently a terrane of either island arc, oceanic hot-spot or oceanic ridge which has been accreted onto the northern margin of Laurentia.

2. The Southern Uplands

There are several lines of evidence suggesting that the Southern Upland Fault is a terrane boundary:

a. It has already been postulated that the cover rocks at Girvan (Excursions 28,29,30 and 31) belong to the proximal (near to the arc) part of a fore-arc sequence, and that the Southern Uplands (Excursion 32) is possibly an accretionary prism or prisms. The distance between the trench (where the accretionary prism forms) and the arc is usually >90 km. But the Southern Uplands Fault brings rocks of the accretionary prism into contact with rocks of similar age belonging to the proximal fore-arc sequence. There has been a loss of ground here (Figure 0.8), compare (Figure 0.6).

In Silurian-Devonian times the Iapetus Ocean to the south had closed and there were major continent-continent collisions such as in Scandinavia (Baltica–Greenland) and eastern North America. (America–Gondwana). Here fold-thrust mountain belts rose to yield vast quantities of sediment to very large river systems, much like the Himalayas do today. In the U.K.–Newfoundland region there was less fold-thrusting and a greater degree of strike-slip faulting.

b. This evidence is corroborated by the rocks of the Silurian inliers running along the northern margin of the Fault. Some of the rocks in these inliers show a palaeoflow from the SE, in which direction now lies the Southern Uplands greywackes which should, therefore, supply the Silurian conglomerates with clasts. However, of the three conglomerates present in the Silurian inliers, only the upper one contains greywackes and even these do not have the characteristics of a Southern Uplands-type greywacke. The lower-most two have quartzite and igneous rock clasts, which are unlikely to have come from the Southern Uplands. The direct inference therefore is that the Southern Uplands were not in their present position when these conglomerates were laid down and that the source of the conglomerates has either shifted or has been replaced by the in-thrust Southern Uplands.

c. The foundation for an accretionary prism is clearly oceanic crust, but the crust beneath the Southern Uplands may now be continental (Hall et al 1988). If this is the case then the accretionary prism has to have been thrust onto continental crust.

3. The Highland Border Complex

The Highland Border Complex is composite, comprising at least two discrete rock units. The first is an ophiolite, the obduction of which occurred during the Cambrian; the second, an assemblage of sedimentary and igneous rocks, mainly of Ordovician age. The ophiolite is a terrane in its own right; it is a fragment of oceanic crust which has been obducted onto a continental landmass. The overlying sequence did not form adjacent to the Dalradian block, and is also part of a separate terrane.

During Ordovician times the Dalradian landmass was undergoing uplift with a substantial volume of sediment being removed almost to the level we now see. The volume removed was in the range of 10–30 cubic kilometres for every square kilometre of Dalradian surface. This sediment load would have been removed partly by erosion and, possibly, partly by tectonic sliding—but in either case any nearby basins would have been filled by the coarse debris from the rising landmass.

The now adjacent Highland Border basin was in existence at this time. It was accumulating black shales and cherts in fairly deep water conditions; had it been lying adjacent to the Dalradian block it would have received a good deal of the debris eroded from it. On this evidence it is fairly clear that the two blocks were far removed from each other for most of Ordovician time. On evidence seen in western Ireland, where sediment of Llandovery age rests on rocks which are lateral equivalents of both these units, they had clearly been brought together sometime before or during the earliest Silurian (Figure 0.9).

4. Basement blocks

North of the Highland Boundary Fault there is a variety of basement blocks, and to give an account of each of these is outside the scope of this discussion. Only the basements to the south of the Great Glen Fault are dealt with as these have interacted with the Caledonides or, as with the Dalradian, form part of the Excursions in the Guide.

Early workers trying to solve the provenance and assembling-history of terranes, made the assumption that the basement blocks (Dalradian, Islay–Colonsay, Moine and Lewisian) had been part of the southern Laurentian continental margin, some time before the opening of the Iapetus Ocean. Recently the possiblity has arisen that all blocks except the Lewisian have been moved into Laurentia after the development of the ocean.

The Dalradian block for example, bounded on the north by the Great Glen Fault and on the south by the Highland Boundary Fault has a history which is quite unlike the history of any other part of the Laurentian margin between c.600–650 Ma (Late Proterozoic). Whilst the Laurentian margin was typified by extensional tectonics and the development of a passive margin, the Dalradian block was undergoing compression, typically found on a destructive margin. In contrast, the African-European margin to Iapetus was destructive at this time, and was undergoing a geological history very similar to that of the Dalradian block. For this and other reasons Bluck and Dempster (1991) suggested that the Dalradian may have been part of the larger African craton, then moved into Laurentia in Cambrian times.

The parts of Scotland which have been discussed so far are now seen, at least as far as the Ordovician is concerned, as a group of terranes each with its own history and divided from each other by well known fractures along which there has been considerable movement. Each terrane has a history which is not compatible with its being adjacent to another during Ordovician time. The Cambrian-Ordovician history of Scotland in the context of the North Atlantic is illustrated in (Figure 0.9).

The questions then arise, when was present-day Scotland assembled together, and what kinds of rocks formed while this process of assembling was taking place ?

Western Scotland in the Upper Palaeozoic, Mesozoic and Tertiary

Upper Palaeozoic rocks include the Devonian (Old Red Sandstone), Carboniferous and Permian (New Red Sandstone): rocks belonging to the former two periods are particularly well seen in the Glasgow district. Both these groups of rocks occur mainly within the Midland Valley of Scotland, but, significantly they also occur in the Lower Palaeozoic and pre-Palaeozoic terranes flanking it.

1. Lower Devonian

The base of the Devonian is not easily identified in midland Scotland: both Late Silurian and Early Devonian rocks lack fossils, are terrestrial and are often red in colour, so determining the boundary between them is difficult. These Silurian-Devonian (Lower Old Red Sandstone) rocks are found on the NW and SE margins of the Midland Valley, but it is the outcrops on the NE margin which are the most extensive, and where the sequence is thickest and the best exposed. Throughout the Midland Valley region rocks of this age and association are seen to comprise mainly red coloured conglomerates, sandstones and shales together with lavas. Most of the lavas form the Ochil–Sidlaw uplands; most of the conglomerates are found near the basement rocks which flank the Midland Valley and most of the finer rocks occur away from the flanks to dominate those outcrops removed from the NW and SE margins. This disposition of lithologies led many, including myself, to suggest that the flanking regions of the Southern Uplands and the Southern Highlands were the source of the Lower Old Red Sandstone sediment. This concept is now seen to be invalid, and there are now some considerable departures from former views about the source and sedimentation of the Lower Old Red Sandstone. The most critical of these changes are as follows:

a. On the northern margin of the Midland Valley the Lower Old Red Sandstone is not always faulted against the Dalradian basement or Highland Border Complex to the north. At many localities the basal Old Red Sandstone conglomerates rest unconformably on the Highland Border Complex. This fact has resulted in a number of important implications:

i. The Lower Old Red Sandstone is now seen to be not as thick as formerly thought.

ii. To the south of the Highland Boundary Fault, the basement to the Old Red Sandstone is the Highland Border Complex: to the north it is the Dalradian block.

iii. The great thickness difference between the Old Red Sandstone at Stonehaven and Lomondside is now explained stratigraphically rather than, structurally, where beds were thought to be faulted out in a SW direction.

b. The earlier views that the Old Red Sandstone sequence on the north margin of the Midland Valley was one of continuous lithostratigraphic units which extended from Stonehaven to Arran is not now supported by the evidence available. Detailed mapping along parts of the Highland Border is at present showing that the Old Red Sandstone conglomerates, at least for the NW Midland Valley, are a series of lenses, which may have been deposited in a series of basins, rather than a single one. The rock sequence for the southern Midland Valley appears to be more straightforward, with a conglomerate characterized by greywacke clasts being overlain by sandstones and lavas and a conglomerate with lava clasts. These units appear to run as laterally continuous sheets from the Pentland Hills to the Clyde.

c. When the lenses of conglomerate are examined in the NW Midland Valley they overlap each other as they are traced towards the SW (Excursion 9, Balmaha). This type of overlapping is not diagnostic of but is certainly characteristic of fault basins. For that reason the Lower Old Red Sandstone sediments there are thought to have been deposited in a series of fault-bounded basins in which the faults were active at the time of deposition.

d. The conglomeratic sediments along the northern margin are dispersed in a range of directions, some from the south, the NE and north. It is clear that sedimentation along this northern margin was indifferent to the presence of the Dalradian block and the Highland Boundary Fault.

e. The sediments which occur away from the bounding faults i.e. towards the central parts of the Midland Valley are mainly sandstones rich in metamorphic and igneous detritus of non-Dalradian type and near the north margin of the Midland Valley very thick siltstones. The discovery of a large river bar >12 m thick near Perth, prompted the notion that a very large river system, a little less extensive than the present-day Mississippi flowed into eastern Scotland and along the Strathmore area towards the Clyde. Large alluvial bars are also recorded in the sandstones which crop out in the southern Midland Valley. This river is thought to have drained the Norwegian-Greenland area. Laurentia, of which Greenland is a part, collided with Baltica during the Late-Silurian-Early Devonian and the result of this collision was a long series of mountains running to the present NE. These mountains would have yielded a great deal of sediment which Bluck (1990), Bluck et al (1989) thought was dispersed through central Scotland.

2. Upper Devonian

As with the base of the Lower Devonian there is a problem in identifying the base and top of the Upper Devonian. Fossil fish and spores used to date the Lower Devonian, are even less common in the Upper, and the top of the Upper is often gradational into the Carboniferous. For this reason red rocks which unconformably overlie the Lower Devonian (Excursion 8) and grade up into the Carboniferous are referred to as the Upper Old Red Sandstone. Rocks of Middle Devonian age, which form such thick and important sequences north of the Highland Boundary Fault, are not known from the Midland Valley.

During the Middle or late Lower Devonian times the main known events in the Midland Valley were the development of the Strathmore Syncline in the north, and a number of more local folds and faults in the south. The Strathmore Syncline is a very extensive structure which runs parallel to the Highland Boundary Fault. Its NW limb is steeply dipping, occasionally overturned, and is terminated by the Highland Boundary Fault which, in places, is steeply dipping towards the NW. The Syncline probably formed as a consequence of a reverse movement along the Highland Boundary Fault and the convergence of the Dalradian block onto the Midland Valley.

A similar interpretation is made for the folds in the southern Midland Valley which have steep limbs on the SE flanks, although here they are not as extensive as those along the northern margin. In this instance the Southern Uplands block was probably thrust NW, so folding the sedimentary sequences NW of it. Clearly sometime during the Middle Old Red Sandstone interval there was a compression which resulted in both blocks flanking the Midland Valley converging on it.

The Upper Old Red Sandstone occurs as separated outcrops which are generally found more within the central part of the Midland Valley, but the most complete exposures and also the thickest and most informative sequences are found in the region around the Firth of Clyde (Excursion 16). In the Clyde region the thickness of the Upper Old Red Sandstone is difficult to estimate because of faulting and poor exposure, but it may be as much as 3–4 km in the region of Inverkip–Rosneath–Helensburgh. At its most complete, the Upper Old Red sequence begins with conglomerates which grade upwards into sandstones and finally quartz-rich sandstones, with caliche forming the top of the sequence. This whole succession then thins and becomes finer to the NE, south and SW, and it is the thinning to the SE which can be reasonably well documented in sections running from the Firth of Clyde to the Southern Uplands (see introduction to Excursion 16). As well as thinning to the south, the whole sequence is replaced by sandstones with very thick caliche beds. Caliche and the quartz arenites associated with them are produced by crustal stability, and in the Upper Old Red Sandstone there are grounds for seeing the early conglomerate beds as the product of much structural activity : as one goes upward in the sequence the evidence for structural control diminishes so that towards the top of the succession mature sandstones are produced on tectonically stable surfaces. The Carboniferous rocks then replace the red sandstones and caliches.

The Upper Old Red Sandstone rocks were thought to have formed in an extensional regime which may have been initiated by shearing along older Caledonian faults, the Highland Boundary and related faults in particular (Excursion 16). In the Firth of Clyde region the effect of contemporaneous faulting on the deposition of the Upper Old Red Sandstone is well illustrated with the generation of at least three fault-bounded basins (Bluck 1980).

3. Carboniferous

The stability which characterised the Upper Old Red Sandstone was short-lived, to be broken in the Carboniferous with the reactivation of older faults, the widespread occurrence of volcanic rocks, and the re-development of thick local basin sequences.

The transition between the Old Red Sandstone and the Carboniferous is seen in Campsie Glen (Excursion 5), in the western Kilpatrick Hills east of Dumbarton, along the Clyde coast (Excursion 14) , and on Great Cumbrae (Excursion 15). With the exception of the Cumbrae islands and parts of the Clyde coast, caliche-bearing Upper Old Red Sandstone is replaced upwards by white sandstones and also by alternations of carbonate and shale beds (the Ballagan Beds). These beds are not present on the Cumbraes and the nearby mainland; basaltic lavas and tuffs which normally rest on Ballagan beds are seen to rest directly on the white or red sandstones on Little Cumbrae and the adjacent mainland.

The Ballagan Beds are well exposed in the Dumbarton Muir–Campsie areas. At Murroch and Auchenreoch Glens, Overtoun and Ballagan Glens they are quite magnificently exposed. Critical to their understanding is that they comprise not only dolomites but also sandstones, caliche beds and evaporite minerals such as gypsum. The sandstones are often cross-stratified, but some contain long, low-angled cross strata which have on their surfaces rounded fragments of shark teeth. These sandstones were deposited in the upper foreshore of beaches and once this is recognised the interpretation of the origin of the Ballagan Beds becomes clear. A model of the types of sedimentation developed is given in (Figure 0.10).

The Ballagan Beds were deposited in lagoonal areas trapped behind sand bars (Figure 0.10). These sand bars are now some of the sandstone sheets and wedges which occur within the sequence; the margins of the sand bars which faced the open sea developed upper foreshore low-angled cross strata with sedimentary lineations; the edges of the sand sheets which faced the lagoon are fine-grained, rippled, sometimes cross stratified and interfinger with the shales of the shale-carbonate facies. The caliche beds occur on the landward side of the lagoons. They are typical of the low-lying land fringe and are particularly common in the CLunbrae region, which appears to have been a low-lying upland area during deposition of these beds. When the water level in the lagoon rose, the carbonate-shale sequences of the lagoon spread over the peripheral caliches, but when the level fell the caliches prograded out over the lagoonal facies and the river deposits built into them, forming the cross stratified sandstone sheets.

This lagoonal episode was terminated in the west by the outpouring of a great number of basalt lava flows, now seen in the Campsie (Excursion 5), Kilpatrick and Renfrew Hills. Lava sequences are quite magnifiently exposed in many localities. They comprise tuffs and a red soil (bole) in alternation with vesicular and massive (although poorly jointed) basalt. This alternation of flow followed by weathering of its upper surface is common throughout the region and accounts for the 'trap topography' typical of these types of rocks. The lavas are variable in composition and texture and these two criteria have been used to divide the lava succession; they were probably extruded from fissures from which extensive flows spread widely.

Accompanying the lava extrusions are the volcanic plugs which have filled the conduits of volcanoes which originally covered a much wider area than the plugs themselves. These form small rounded hills all over the region and one is examined in detail at Dumbarton Rock (Excursion 7).

After a maximum of 900 m of lavas had been extruded, the lava field was covered in places by fine grained, dark grey, coal-bearing sediments, and some of which are rich in fireclays, shales, and thin coals. The fireclays are the seat-earths upon which Carboniferous plants grew, so they formed in low ground not far above sea or river level. Such sediments are typical of the lower reaches of river systems and their associated coastal and deltaic deposits. In the regions of Craigmaddie and Douglas Muir sheets of sands and gravels interrupted this phase of fluvial-deltaic sedimentation. These deposits, laid down by braided and meandering rivers are well developed in the west, and are succeeded by sandstones, shales, coals and limestones of the later Carboniferous. The deltas and alluvial coastal deposits which form much of the coal-bearing Carboniferous probably extended far into the Southern Highlands and Southern Uplands. The source for these sediments is probably to be sought in areas further to the north such as Scandinavia and Greenland where, on the basis of other evidence, the mountains, which reached their climactic uplift rates in the Devonian, are known to have been uplifting at a much diminished rate in the Carboniferous (Bluck 1990 and (Figure 0.9). These sandstone sheets covered terrane boundaries which were later reactivated to show only minor displacements (Figure 0.11).

Whilst rivers from the north spread sheets of sand and mud over most of Scotland and northern England, there were numerous marine transgressions reaching far into this coastal plain. These trangressions originated from the sea which covered the southern part of Britain and made irregular incursions into the deltas and alluvial plains: in the Midland Valley, for instance marine transgressions probably came from the SW and NE margins, avoiding the higher ground of the Southern Uplands. One such transgression deposited a widespread limestone bed in central Scotland, the Hurlet Limestone which is seen on Excursions 6 & 20; this limestone in particular, but others like it, provide the Carboniferous with excellent marker beds to aid in the correlation of sections over the Midland Valley.

4. New Red Sandstone

Rocks of New Red Sandstone age are not abundant in the western Midland Valley, yet those exposures which are present are most instructive. The main areas of outcrops are in Arran in the west and Mauchline in the south, and these are both remnants of a sandstone sheet which, at one time, spread widely over central Scotland and beyond. In both these localities, and particularly in Arran, there is abundant evidence for deposition from aeolian activity. Not only are there large scale cross strata produced by dunes, but also the dune interbeds are preserved, making some of these sections classical ground for the study of aeolian sediments.

There is now mounting evidence that much of the basement rock of Scotland was being uplifted at this time. Alluvial sequences, some deposited in active fault controlled basins are found on the western and eastern seaboards, having their sources in the intervening ground of the basement uplift. This deposition of New Red Sandstone sediment on the western and eastern margins of Scotland may be related to the extensional basins which now form the North Sea, and in the Minch (and ground to the west of it).

5. Other Mesozoic and Tertiary rocks

Rocks of the Jurassic Period are not represented in central Scotland but, as with the Permian and Triassic, they are found on the western and eastern margins of northern Scotland where, once again they are the marginal deposits to a much larger basins sited to the east (North Sea) and west (Irish Sea and the continental edge beyond).

The Cretaceous Period is, however, represented by a block of chalk found within a Tertiary intrusion on Arran—suggesting that rocks of that period may have been deposited over central Scotland but have since been eroded away.

Dykes of Tertiary age are particularly abundant along the Ayrshire coast where they have a characteristic NW–SE or WNW–ESE trend. These are related to the big Tertiary centres of the western edge of Scotland.

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