Terrane Provenance and Amalgamation: Examples from the Caledonides

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Phil. Trans. R. Soc. Lond. A 1990 **331**, 599-609
doi: 10.1098/rsta.1990.0092

Phil. Trans. R. Soc. Lond. A **331**, 599–609 (1990)
Printed in Great Britain

Terrane provenance and amalgamation: examples from the Caledonides

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The Scottish Caledonides have grown by the accretion of terranes generated somewhere along the Laurentian margin. By the time these terranes had been emplaced along the Scottish sector, they were structurally truncated then reassembled to form an incomplete collage of indirectly related tectonic elements of a destructive margin. The basement to some of these tectonic elements and the basement blocks belonging to the previously accreted Precambrian are of uncertain provenance and a source in the Pan-African craton is possible.

As terranes migrate along the orogen they generate in the fault zones and on their periphery a reservoir of mature sediment. This mature sediment is produced because of the recycling produced during the generation and destruction of sedimentary basins developing during terrane translation. At each period of recycling the mature sediments are mixed with less mature sediments yielded from local uplifts generated by the new basin formation.

If a large part of the orogen suffers orthogonal closure, giant river systems may form and disperse sediment across terranes. This is likely to have happened during the Devonian–Carboniferous of parts of N. Europe.

1. Introduction

The identification, provenance and amalgamation history of terranes in the Palaeozoic may require the use of techniques which are not normally applied or are inappropriate for use in the younger parts of the stratigraphic record where there are clearly defined faunal provinces and where there may be a comparatively straight-forward palaeomagnetic record. The Palaeozoic has no off-shore record of an ocean spreading history which may otherwise aid in determining the provenance of terrane blocks. Reliance has to be made on other criteria and some of these, as used in the Caledonides, are presented in this paper. In Caledonian terrane analysis there are three aspects which are important: (i) terrane identification (ii) terrane provenance, often in the absence of a meaningful faunal record, and (iii) terrane amalgamation history.

2. Criteria for terrane identification

At least seven terranes make up the Scottish Caledonides (figure 1) and the following criteria have been used to identify them and their boundary zones.

(*a*) *Incompatible histories*. Where the uplift of a basement block has not resulted in the supply of sediment to a basin now lying adjacent to it when both uplift of the basement and subsidence of the basin are known to have taken place at the same time, then large-scale movement between basement and basin can be inferred.

An example of this can be seen in the juxtaposition of the Highland Border Complex with the Dalradian block (figure 1*a*). The Highland Border Complex comprises a fragmented

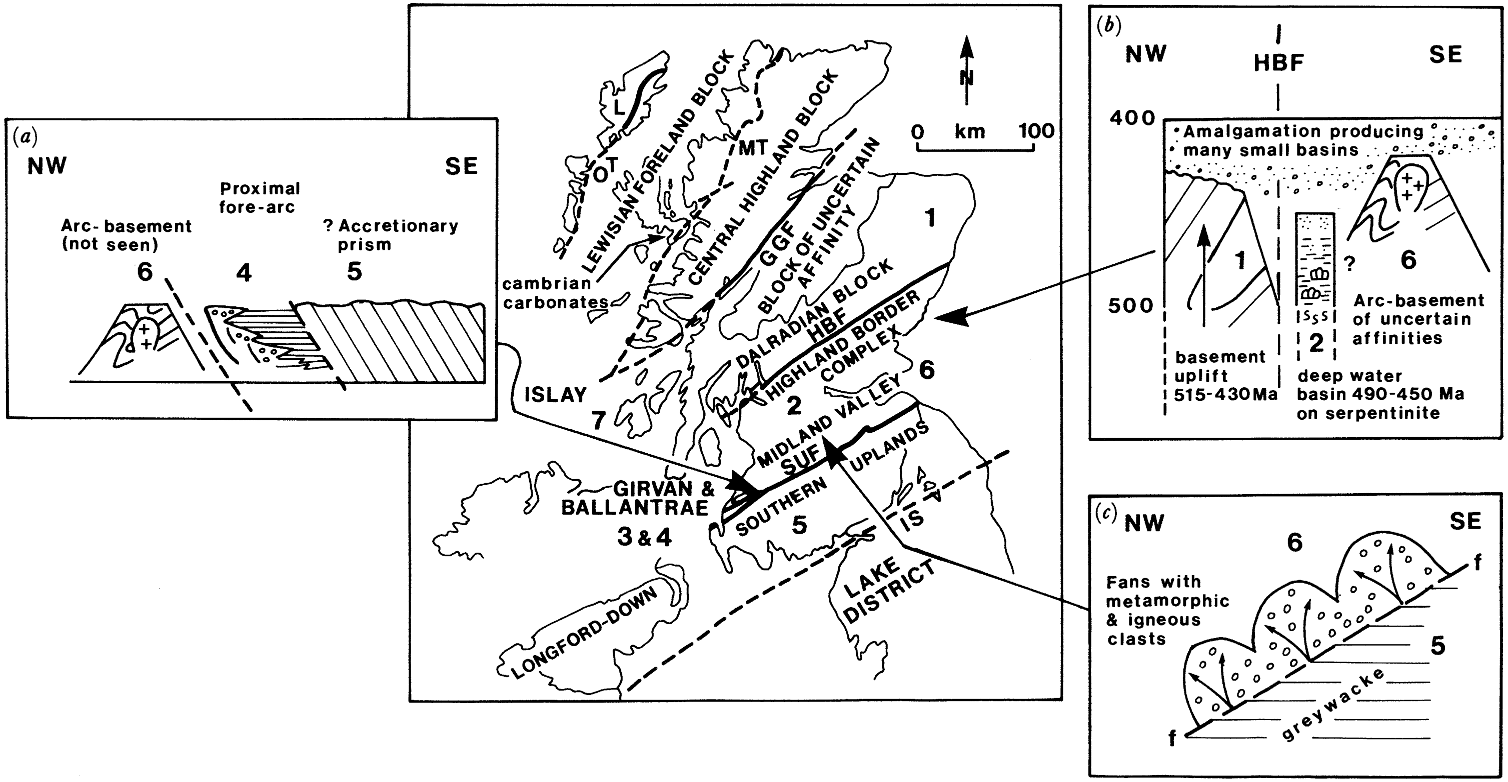

FIGURE 1. Terrane map of the Scottish Caledonides showing some of the criteria by which they have been recognized. 1, Dalradian Block (metamorphic basement); 2, Highland Border Complex (Ophiolitic and other rocks); 3, Ballantrae Complex (Ophiolite); 4, Girvan (forearc); 5, Southern Uplands (accretionary prism?); 6, Midland Valley of Scotland arc-basement); 7, Islay–Colonsay (metamorphic basement). L, Lewis; MT, Moine thrust; GGF, Great Glen Fault; HBF, Highland Boundary Fault; SUF, Southern Uplands Fault; IS, Iapetus Suture. (*a*) Section showing the incompatible history of events across the Highland Boundary Fault zone. (*b*) Section showing loss of tectonic elements across the Southern Uplands Fault. (*c*) The mismatch of clast type and local potential source across the Southern Upland Fault.

ophiolite, black shales, limestones and lithic-arenites with a provenance in volcanic and ophiolitic sources. It extends as a thin sliver all along the Highland Boundary Fault in mainland Scotland; is thought to be present in the Tyrone inlier in central Northern Ireland and may have as its lateral continuation the Clew Bay sequence in W. Ireland (Harper *et al.* 1989). Deposition of these sediments ranges fairly continuously from Lower to Upper Ordovician but a sliver of Middle Cambrian rocks occur in the region of Callander (Curry *et al.* 1982). The Dalradian block now adjacent to the north underwent uplift and erosion during the late Cambrian–late Ordovician as recorded in a variety of age determinations (Dempster 1985). The Highland Border Complex is neither in a facies nor does it have the type of sediment expected if it were lying adjacent to such a block during the period of its uplift.

(*b*) *Missing sediment piles.* Large-scaled metamorphic terranes should have associated sediment piles which were generated during their uplift. On the other hand some metamorphic complexes, particularly core-complexes, would have a record of uplift dominated by structurally bounded sheets of cover. Studies of recent mountain belts have shown that these two forms of unroofing are often seen together, and the sediment yielded from such uplifted areas is sometimes a complex mixture derived from various sources and differing levels within the orogen. Sediment may not be dispersed directly to a permanent basin but may be stored in many small, temporary basins which exists within the orogenic zone and so may be polycyclic by the time it reaches a preservable basin. Sediment is seldom a direct and simple record of the source uplift.

A corollary of (*a*) (above) is that the sediment generated by the late Cambrian–late Ordovician uplift is missing. The Dalradian sequence is seen as a nappe pile diverging from a central root zone of vertical rocks which occupies the ground parallel with and just south of the Great Glen Fault. The nappes, and possibly an early thermal-uplift event, were generated in late-Precambrian times (Rogers *et al.* 1989). To the SE and NW there should have been foreland basins produced during this nappe emplacement episode, but there is no known record of these basin. Neither has the Cambro-Ordovician uplift related to the second phase of Dalradian development left any known sedimentary record to the SE or the NW. No sediment from this uplift is recorded in a coeval limestone sequence of Cambro-Ordovician age to the NW, although these rocks would have been distanced from the areas of Dalradian uplift by the amount of displacement on the Moine Thrust.

(*c*) *Missing tectonic units.* Terrane accretions on destructive margins are often typified by assemblages of arc-complexes and marginal basins created somewhere along the margin then to be reassembled elsewhere. In that sense they are not exotic to the continent to which they accrete. Each of the elements of a destructive margin are often divided from others by faults or zones of structurally weak rock. This characteristic may allow the preferential fragmentation of the complete destructive margin assemblage along these zones of weakness so that parts of it become detached and move as separate blocks. The reassembling may or may not take place in the order of its generation or some of the tectonic elements may be missing.

Since the Cambrian, most of the tectonic elements which have accreted along the Southern margin of Laurentia have faunas of North American aspect, so they were probably generated somewhere along that margin and then transported elsewhere. Examination of the existing record shows that there are many gaps between tectonic elements, and some are now only recorded as slivers along fault zones. The boundary between the Southern Uplands and the Midland Valley provides an example of ground missing between tectonic elements (figure 1*b*).

If it is accepted that the Southern Uplands is an accretionary prism and the Girvan region, to the immediate N of the Southern Uplands Fault, a proximal fore-arc basin, then there is gap between these two tectonic elements normally filled by a fore-arc region which is usually more that 100 km in width (Bluck 1983).

(*d*) *Incomplete tectonic blocks.* These may be identified where there is a need for the presence of additional crust to explain of the genesis of the existing crust. In this case the folded and metamorphic, Dalradian block is now juxtaposed against the relatively unmetamorphosed Highland Border Complex. Dalradian greenschist facies rocks with vertical structure lie in this contact, but the cover needed to produce the degree of metamorphism in these greenschist rocks is in the order of 10–15 km. This cover is now missing and must have been stipped off before or possibly during the emplacement of the Highland Border Complex.

(*e*) *Mismatches between compositions of the sediments and the composition of the blocks in the direction of dispersal.* In the final stages of terrane amalgamation there are a number of problems associated with this kind of relationship (as will be discussed later) but in some instances the mismatches are fairly clear. Along the Southern Uplands Fault sediments dispersed from the SE do not contain clasts of the blocks which presently lies in that direction (figure 1*c*). The sediments, deposited in alluvial fans contain abundant igneous and metamorphic clasts up to boulder size, but in the direction from which they were transported lies the Southern Uplands, a sequence of greywackes and shales. In this instance a source block has been laterally displaced or overthrust by the greywacke sequence (Bluck 1985).

(*f*) *Identification of cryptic terranes.* A terrane may be detached from the sediment that it sheds. In the case of the Dalradian block, there is an Ordovician sediment source with no certain, identifiable sediment pile related to it. The converse also applies, and this is probably true of much of the sediment which has accumulated in basins around the Midland Valley of Scotland.

The provenance of sediment in the Southern Uplands and the nature of the Southern Uplands Block are both a matter of controversy. The block itself is bounded by the Southern Uplands fault to the north and the Solway-line to the south, and is cut by a prominent fracture, the Orlock Bridge Fault. This fault is thought by Anderson & Oliver (1986) to be a terrane boundary bringing together two blocks of similar lithology but with different geological histories. The tectonic nature of the Southern Uplands, whether it is an accretionary prism, fore-arc basin, back-arc basin or a compound of basins with different affinities have all been discussed at length (McKerrow 1987). In addition, the dispersal within the Southern Uplands is also debated; there are undoubtably flows directed towards the SE, and NW, but the bulk of the sediment is dispersed axially along the trough.

The sediments are mainly lithic-wackes and arenites, together with lutites, mudstones, and some conglomerates. The wackes contain abundant igneous clasts, metamorphic minerals and fragments, and often an abundance of compacted and sometimes sheared shales and mudstones. Although there is a wide range in the dispersal directions for the wackes, the conglomerates, some of which are boulder bearing, are usually dispersed from the NW. Among the clasts contained in these conglomerates are granitoids, volcanic, metamorphic and some sedimentary detritus. The granitoids clasts have cooling ages very near to the estimates of the time of their sedimentation; metamorphic clasts and muscovite micas in the wackes and arenites both have cooling ages which are also near to the depositional age of the sediments containing them (Kelley & Bluck 1989). The isotopic data taken together with the general composition of the sediment suggesting a provenance in an arc terrane with metamorphic basement, probably to the NW.

At present there is no such arc terrane with plutons and associated metamorphic basement to be seen in the ground to the immediate NW; it may be buried under a cover of Upper Palaeozoic sediment now comprising much of the Midland Valley and its extension SW into Ireland. However, there may be grounds for interpreting the metamorphic basement, the acidic intrusive, and extrusive rocks of the Tyrone Complex (Hartley 1933) as *in situ* Midland Valley basement.

3. Provenance of terranes

The signature given by faunas to crustal blocks is probably among the most diagnostic in terms of tracing the provenance of terranes. Faunal provincialism is the great gift to the Phanerozoic terrane tectonist. For the deciphering of terrane provenance before the emergence of faunas and provincialism other, and altogether less satisfactory techniques have to be used.

Precambrian cratonic blocks in the N. Atlantic region at least grew in two main cycles, at roughly 3.0 Ga and 2.0 Ga (Patchett & Arndt 1986); from that last growth event up to the base of the Cambrian, crustal units underwent further deformational and growth periods which gave them a degree of characterization which allowed them in a very general sense to be recognized as distinctive. The release of a basement block into the zone of terrane migration, or the irregular fragmentation of a continent during the initiation of a spreading cycle allows many blocks with a variety of signatures to be available for incorporation into the terrane collage. These blocks may subsequently be coated with a sedimentary record diagnostic of a particular faunal province or may become intruded, covered with extrusives or remetamorphosed in a totally new tectonic régime.

Much of the North American Archaean and early Proterozoic craton was sealed off from the zone of Caledonian terrane migration by the pervasive Grenville (1.2–0.9 Ga) event (figure 2). Blocks entering the Caledonides without Grenville overprinting either did not originate from this part of the craton or escaped via tectonic lines which transected the craton. On the other hand, the Pan-African block was suitable for the release of tectonic blocks without pervasive Grenville overprinting since the Grenville event is poorly represented there and appears not to have pervasively modified the crust at its Atlantic margin.

There is another great advantage that results from periods of rapid crustal growth during the Precambrian. Where the crust has grown rapidly, there is usually a substantial or dominant contribution directly from the mantle, which can be recognized from model Nd age studies (see Patchett & Arndt 1986). The thermal events which may accompany such periods of rapid crustal growth or subsequent intra-crustal episodes are recorded in the radiometric ages of the various mineral phases, each of which blocks at a characteristic temperature. By combining information from both crustal growth processes and from thermal resetting it is possible to constrain the provenance of a suspect crustal block of Precambrian age.

In the Caledonides, clasts of metamorphic rock which occur in the Highland Border Complex, have Rb–Sr cooling ages of *ca.* 1800 Ma, indicating involvement in a 1.8–2.0 Ga thermal event which is usually associated with the crustal growth event of that age. However, model Nd ages of 2.5–2.9 Ga, indicate a provenance in that part of the orogen where sediment of the protolith was derived partly from the Archaean. The block which supplied the sediment had clearly missed any Grenville overprint, at about 1.0 Ga and had not been involved in Pan-

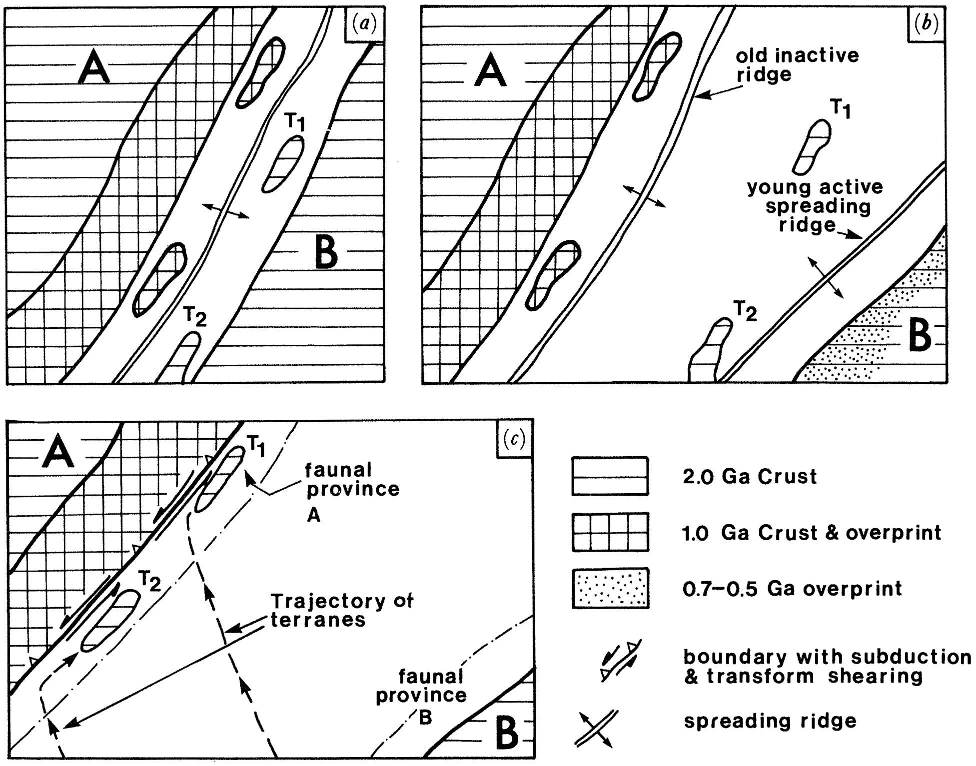

FIGURE 2. Possible paths taken by Precambrian basement terranes during the early phases of ocean opening. Two continents, A (N. America) and B (Pan-Africa) share a history at 2.0 Ga but develop differently from that time on. The terranes generated during initial separation have different histories depending upon where and when they leave the mother continent, and these differences can be read from isotopic data. Whatever their provenance their later history will be dominated by the events on the margin to which they accrete and to recognize the true nature of the terrane one should read through these later events. T_1 and T_2 are terranes and the associated sediment they produce. They came from B but reached A after the establishment of faunal provinces. The boulders and the block from which they came in the Highland Border Complex (Dempster & Bluck 1989) and the Islay–Colonsay terrane may have had this route.

African or Caledonian thermal events. However, by Arenig time (the estimated age of the deposit in which the boulders occur), the block, or sediment yielded from it was in a Laurentian faunal province (Dempster & Bluck 1989).

The possible routes for blocks with this signature are modelled in figure 2, where two continental masses, A (N. America) and B (Africa) are divided by an opening ocean (Iapetus). Both A and B have had a period of accelerated crustal growth at *ca.* 2.0 Ga, but A has, in addition undergone a thermal and crustal accretion event at *ca.* 1.0 Ga (Grenville). The ocean opened parallel and to the right (east) of this later event. During the initial splitting, there are many small continental blocks which are detached from their parent continental masses: those from A carry the record of two widespread crustal events, but those from B (T_1 and T_2) the signature of only one. After the separation of the crustal blocks from B a third thermal event occurred there (Pan-African 1 and 2), but as the continent A and the blocks of B are now some distance away from it they did not take part in this stage of the history of B (figure 2*b*).

A second spreading ridge developed to the right of the first, and oblique subduction is initiated at the margin of continent A. By this time two important things have happened (i) faunas have developed on the Earth's surface, and (ii) continents A and B are sufficiently far away from each other to permit the development of faunal provinces which become characteristic of the seas bordering each continental mass. Terranes T_1 and T_2 are now being transported on oceanic crust towards continent A where they acquire the signature of the faunal province there as well as the tectono-thermal history that this margin is undergoing and will undergo. In this way Precambrian crustal blocks, in themselves exotic to the continent to which they accrete, may after accretion bear the characteristics which may lead one to assume that they have always belonged to the continental mass in which we now find them.

Although this explanation is offered for some of the boulders in the Highland Border Complex, it may well apply to the Precambrian metamorphic terranes of the Caledonides. It may therefore be argued that the basement blocks which are pre-Caledonian in age, and which may already have accreted to the craton by Cambrian times (i.e. before faunal provinces have been established) could belong to cratons which are now far removed from them. The Islay–Colonsay terrane (figure 1; Bentley *et al.* 1988; Marcantiono *et al.* 1988), for example, appears also to have escaped a Grenville overprint, and as with the terrane which supplied the boulders to the Highland Border, it may have had a similar and complex route to its final docking in Scotland. Rogers *et al.* (1989) have pointed out that because of a change in the time scale of sedimentary and structural events in the Dalradian block its affinities with the Laurentian craton are no longer clear. Indeed the early deformation event in this block being now pre-590 Ma, fall within the time span of the early Pan-African tectono-thermal events, so it is difficult to rule out an origin for this block in Gondwana. In this case a separation would have taken place after the Pan-African events, and the later part of Dalradian history may have taken been acquired within the Laurentian domain.

It follows too that the tectonic and thermal evolution of a terrane need not have taken place in the region where it is at present located. In this context, for example, the Dalradian block may have been undergoing structural and metamorphic developments while moving into its present position.

4. Terrane amalgamation

The amalgamation history of terranes is partly written in the sedimentary record of terrane borderlands and the plexus of faults surrounding terrane blocks. In both these areas basins are created and destroyed in a very short space of time as the locus of fault activity changes from one sector of the fault zone or branch of a fault to another. In the Betic Cordilleras, for example there have been three periods of basin formation within the past 8–10 Ma, with unconformities separating each period of basin development (Boccaletti *et al.* 1987). Along the Cadiz–Alicante line, a zone of strike–slip activity, basins less than 5 Ma old have been folded and eroded (Boccaletti *et al.* 1987). This rapid basin development and erosion implies a very considerable recycling of sediment. The labile clasts are broken down but the durable lithologies such as quartzite and vein quartz resist degradation to become progressively more rounded. Rather than disappearing from the sedimentary system altogether, these quartzites and vein-quartz clasts tend to form a reservoir of mature sediment even down to sand size which is retained within the fault zones and on the terrane margins which border them. When new basins are opened up, these clasts are then available for redeposition, but now along with the immature sediment which may have been generated by a new uplift accompanying the phase of basin development. In this way highly rounded, mature sediment is mixed with angular labile sediment and both are seen to contribute to sedimentary basins either as complex mixtures or segregated assemblages delivered from one side or the other (figure 3).

The nature of the fill to these sedimentary basins is also fairly diagnostic. They are often filled laterally with coarse sediment derived from alluvial fans bordering the basins. As the basin floor migrates relative to the source overlapping fans are created, and the sense of relative displacement between basin and source is given by the direction of fan overlap (Crowell 1982).

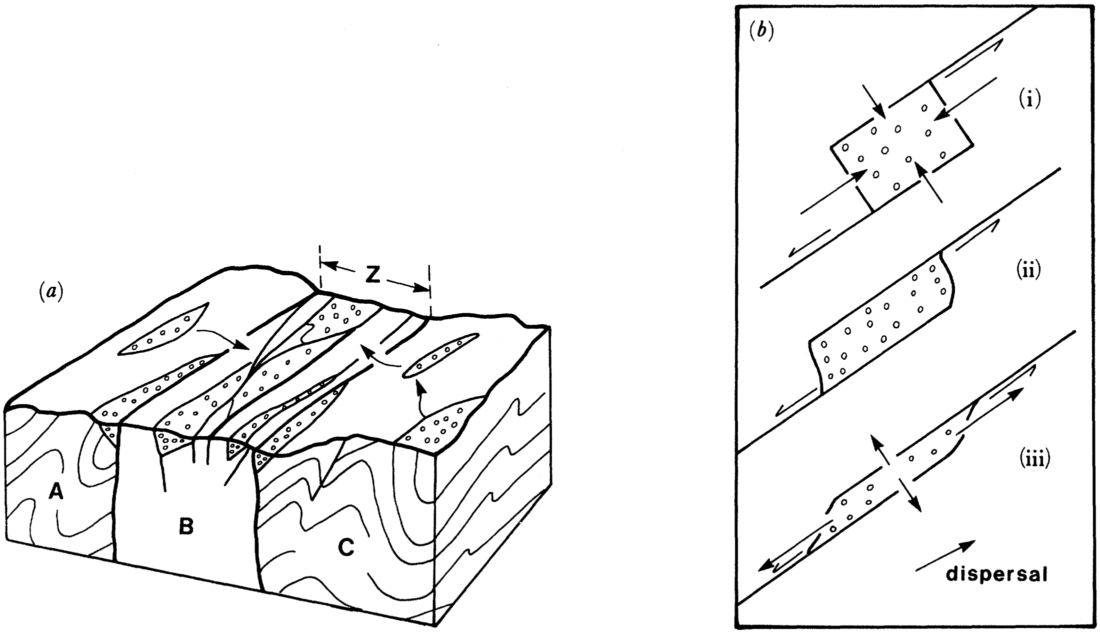

Figure 3. (*a*) The development of basins on the margins of terranes (A and C) and their development in the fault zone (Z); arrows show dispersal, B refers to a suitable lithology, e.g. serpentinite within which the fault zone has developed. (*b*) Simplified history of a basin formed within the fault zone: (i) development of a pull-apart basin; (ii) stretching and deformation; (iii) inversion of basin to yield detritus to new basin.

Basins with mixtures of mature and immature sediments characterize the stratigraphical sequences which occur along two main terrane boundaries in the Caledonides: the Southern Uplands and Midland Valley Faults. Mature coarse sediments in the form of conglomerates with well-rounded quartzite clasts, appear as early as mid-Ordovician in the Southern Uplands (Floyd 1982) and are also present on the north side of the Midland Valley as well as in the Mayo Trough, but they are particularly characteristic of basins developed during the Old Red Sandstone. Here along the Highland Boundary Fault, basins with overlapping fans are characterized by quartzite clasts, which are often broken and re-rounded, or rimmed by red discolouration both characteristics indicating their involvement in pre-existing cycles of deposition and erosion. In addition some of the sandstones are sublithic arenites which are very rich in rounded and subrounded quartz. Conglomerates rich in quartzite clasts and sandstones rich in quartz grains are sometimes interstratified with lithic arenites which have almost no quartz, and conglomerates which are dominated by subrounded fragments of volcanic or other highly labile rock. The sediments with a mature clast assemblage are often seen to have a different dispersal direction from those dominated by immature sediment. Thick, coarse conglomerates with highly mature clast assemblages imply a source in recycled sediments.

When these sediments are interstratified with units with highly immature clast assemblages it suggests that the tectonic and other conditions under which the sediment accumulated were unstable enough to preserve abundant labile debris. The presence of supermature clast assemblages then becomes an anomaly which can easily be explained in terms of a reservoir of mature grains being available for sedimentation in rapidly subsiding basins. In this Silurian–Devonian régime these reservoirs of highly immature sediment along the Southern Uplands and Highland Boundary Fault zones were probably produced by prolonged periods of sediment recycling during the opening and closing of sedimentary basins.

Terrane amalgamation is also recorded other events. Where the orogen is partly or totally the result of orthogonal collision, then high mountains with high sediment yield and high orographic rainfall may produce giant river systems which disperse sediment over other terrane blocks. A classic example is the Himalayan collision with its huge sediment yield and the dispersal of its sediment over a wide area by rivers like the Indus, Ganges, Yellow and Lena. The signature of the collision in this instance is evidently diverse, and dispersed over terranes belonging to more than one orogenic cycle.

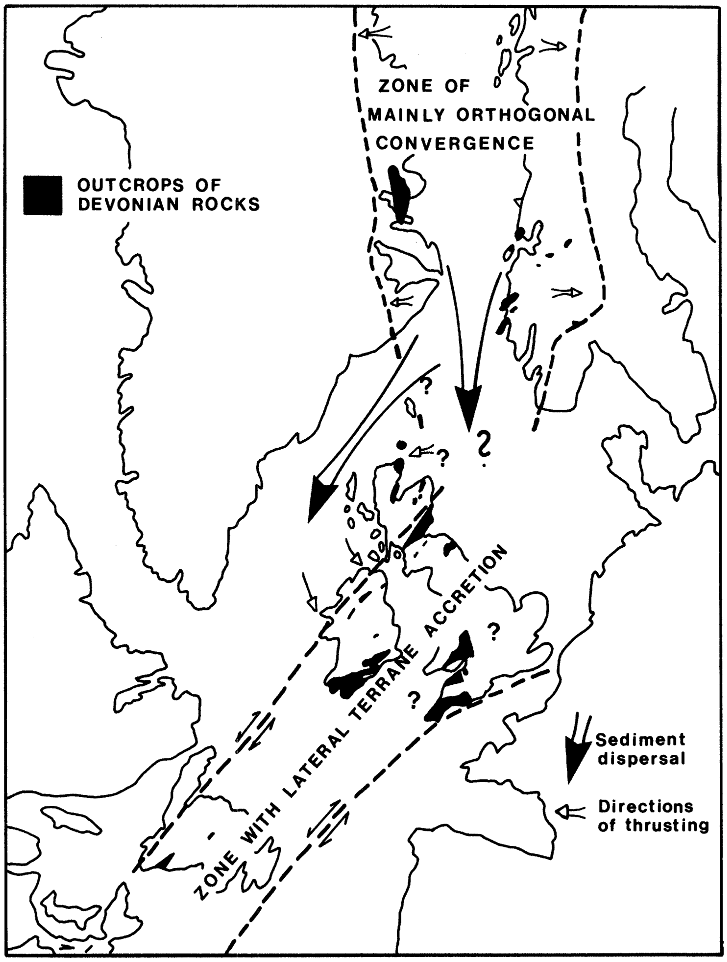

Figure 4. Showing the locations of strike–slip and orthogonal collisions during Devonian times. The orthogonal convergence has created high mountains and the sediment dispersed from these mountains dominate the record elsewhere. Small fault basins in the Midland Valley of Scotland are filled by streams which are far larger than one would anticipate from the scale of the basin.

In the Caledonian orogen, the strike–slip régime which controlled the development of the British sector during the Old Red Sandstone is replaced to the NW by an orogenic episode characterized by orthogonal collision in the Scandian (Gee 1978) (figure 4). The length of this orogen exceeds 1500 km, and involves Greenland as well as Scandinavia. It is characterized by rapid uplift (Cuthbert *et al.* 1983) and would certainly have been the site of high sediment yield and orographic rainfall. The evidence, in the form of sediment bars greater than 15 m thick, for large river systems in the Old Red Sandstone of the Midland Valley, and the Carboniferous of Northern England (McCabe 1977), together with the widespread occurrence of mica and meta-clast bearing sandstones of Devonian–Carboniferous age suggests a source in this orogen. It also follows that small fault basins may develop in regions such as the Midland Valley of Scotland to be filled by river systems which are far larger than one would anticipate from the size of the basin. In this way the sedimentary fill to these small basins may be dominated by fine sediment from a large distal source rather than the usual coarse sediment from a local source.

5. Conclusions

Terranes in Caledonian Scotland are truncated fragments of a destructive margin which existed along the edge of Laurentia. Scotland has lost ground during the Caledonian cycle; it is relatively narrow for a destructive margin which has formed in situ. Older crustal blocks, but with Caledonian overprinting in terms of thermal (metamorphic) or igneous events, may not have had their provenance in Laurentia; the Pan-African landmass also provides a more suitable source on the basis of the meagre data available. These may be the truly exotic terranes of the Caledonian. During the latter stages of terrane accretion reservoirs of mature sediment were available for deposition into sedimentary basins, and so mixtures of highly mature and immature sediments were deposited.

Orthogonal collision in Scandinavia may have generated sediments which swept over much of Northern Europe much as sediment from present-day orogens disperse sediment widely from them to accumulate at some distance from their site of genesis.

I thank Dr Nigel Harris for his constructive comments.

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