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Trace element and Pb isotopic constraints on the provenance of the Rosroe and Derryveeny formations, South Mayo, Ireland

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ABSTRACT: The Rosroe Formation comprises a series of Lower Ordovician (Llanvirn) conglomerates and sandstones, that lies on the southern limb of the South Mayo Trough, within the Iapetus Suture Zone of western Ireland. Trace element chemistry of granite boulders within the formation indicates a continental, rather than a volcanic arc character that can be correlated to latest Precambrian granites within the Dalradian Metamorphic Block, part of the deformed Laurentian margin. A minority of the clasts may correlate with syn-collisional granites, similar to, but older than, the Oughterard Granite of Connemara. Pb isotope compositions of K-feldspar grains within the sandstones, measured by both ion microprobe and conventional mass spectrometry, show a clear Laurentian affinity, albeit with greater source variability in the sand grains compared to a limited range in the proximal boulders. Palaeo-current indicators demonstrate dominant derivation from the NE, with a significant axial E–W flow. We propose that the Rosroe Formation records unroofing of a rapidly exhuming Dalradian metamorphic belt in North Mayo, following extensional collapse of the Grampian Orogen starting at $\sim$468 Ma, with minor input from a southerly arc source. The lack of metamorphic input from the S until deposition of the Derryeeny Conglomerate argues that the Connemara terrane was not positioned S of South Mayo Trough through strike-slip faulting until after the end of Rosroe sedimentation (460–443 Ma).

KEY WORDS: Caledonides, Connemara, Dalradian, geochemistry, isotopes

The early Llanvirn Rosroe Formation is a prominent, coarse-grained sequence of sandstones and conglomerates exposed on the southern limb of the South Mayo Trough of western Ireland (Fig. 1). The South Mayo Trough is unusual in being located in the suture zone, but without having suffered strong deformation or metamorphism. Although it has been variously interpreted in the past, a consensus now agrees that the trough represents the forarc to an intra-oceanic Lough Nafooey Arc (Dewey & Shackleton 1984). Deposited within the suture zone, the Rosroe Formation is ideally located to constrain the timing and erosional response to docking of the apparently oceanic Lough Nafooey island arc and its forearc basin (South Mayo Trough) against the passive margin of Laurentia. The Early Ordovician arc-continent collision event is considered to be the cause of subsequent Grampian Orogeny (Dewey & Shackleton 1984; Dewey & Ryan 1990; van Staal *et al.* 1998). The age of arc-continent collision is presently constrained to 475–465 Ma by the timing of magmatism and peak metamorphism in the Connemara Dalradian terrane, located immediately S of the Rosroe Formation outcrops (e.g. Cliff *et al.* 1996; Tanner *et al.* 1997; Friedrich *et al.* 1999a, b). Recently, Draut & Clift (2001) used the evolving chemistry of the colliding Lough Nafooey Arc to indicate 'soft collision' (i.e. subduction of the outer passive margin of Laurentia) prior to 480 Ma, followed by 'hard collision' (i.e. crustal thickening and high-grade metamorphism), and orogenic collapse after 468 Ma.

The evolution of the Laurentian margin after the Grampian Orogeny, but prior to final Iapetus suturing in the early Devonian (e.g. McKerrow *et al.* 1991), is less well understood. In particular, although there is general agreement that the metamorphic rocks of Connemara are Laurentian and were displaced S of the South Mayo Trough by high- angle strike-slip faulting (Hutton 1987), the timing of this event is not well understood. The orientation of granite and gneiss boulders within the Derryveeny Conglomerate, located within the South Mayo Trough (Fig. 1), suggests transport from the S, and boulder lithologies have been correlated to rocks in Connemara (Graham *et al.* 1991). The Late Llanvirn to Caradoc (460–443 Ma) age of the Derryveeny Conglomerate thus provides a lower limit to the age at which Connemara was located S of the South Mayo Trough.

In this study we examine the provenance of the Rosroe Formation, a conglomeratic unit located within the South Mayo Trough, in order to test the proposed age for arc-continent collision, and to assess whether this unit can further constrain the timing of Connemara's emplacement to the S of the Iapetus Suture. We choose to focus on this unit because of its stratigraphic location at the base of exposed stratigraphy of the post-collisional Murrisk Group on the southern limb of the South Mayo Trough, and because of the recent suggestion by Dewey & Mange (1999) that it is the oldest unit to contain high-grade metamorphic detritus from the unroofing Dalradian metamorphic terranes to the N.

1. Geological setting of the Rosroe Formation

The Rosroe Formation is exposed in Lough Nafooey and along the southern shores of Killary Harbour in western Ireland, where it forms part of the South Mayo Trough (Fig. 1).

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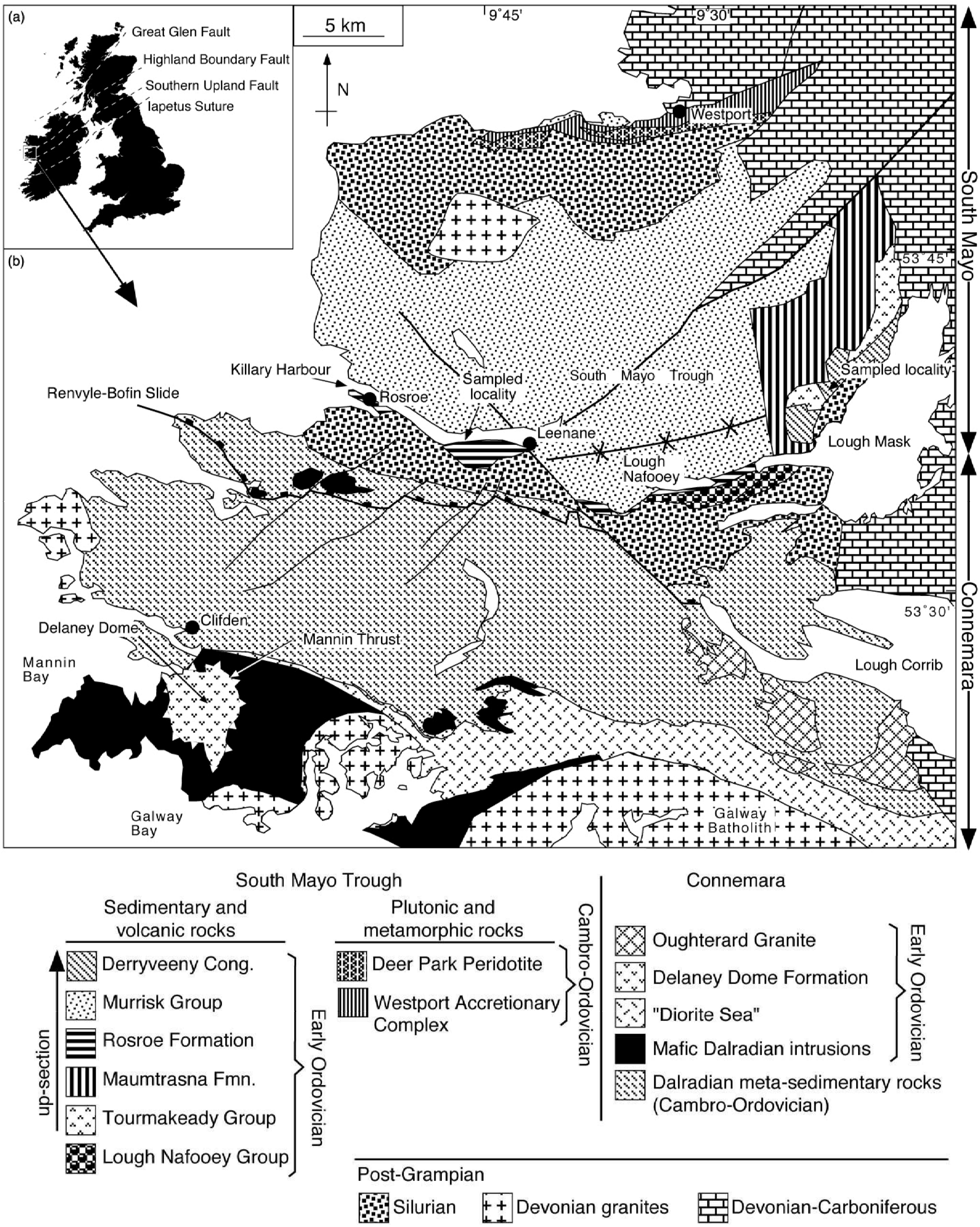

Figure 1 (a) Outline of British Isles showing the major Caledonian terrane boundaries and the location of the South Mayo area. (b) Simplified geological map of the South Mayo and Connemara area, showing outcrops of Rosroe Formation along the southern shore of Killary Harbour.

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Previous work has demonstrated that an intra-oceanic arc, preserved as the Lough Nafooey Volcanic Group, formed in the Iapetus remote enough from the Laurentian passive margin that the volcanic products do not show evidence for reworking of continental turbidite sediments through the roots of the arc (Ryan *et al.* 1980; Cliff & Ryan 1984). This arc subsequently collided with the Laurentian margin significantly prior to final suturing of Iapetus in the early Devonian (e.g. McKerrow *et al.* 1991). The Laurentian margin was passive prior to arc-continent collision, but subsequently developed a SE-facing continental arc due to a reversal in subduction polarity (e.g. Dewey & Ryan 1990).

The Murrisk Group (~477–464 Ma) comprises the majority of the forearc and syn-collisional sediments which form the South Mayo Trough. The six formations of the Murrisk Group, going up-section, are the Letterbrock, Derrymore, Sheeffry, Derrylea, Glenummera, and Mweelrea Formations (Fig. 2; Graham *et al.* 1989). Together they have a total thickness of over 6 km in the South Mayo Trough (Fig. 1). The Rosroe Formation appears to underlie the Glenummera in Killary Harbour, and is generally correlated biostratigraphically with the Derrylea Formation in the northern limb of the South Mayo Trough, as well as the Maumtrasna Formation, exposed in the Partry Mountains E of the main exposures (Figs 1 and 2). Sediments on the northern limb of the trough are presumed to represent deposition in the more distal area of the forearc basin to the Lough Nafooey Arc, as well as in a syn-collisional basin during Grampian metamorphism and exhumation. The Letterbrock through to the Glenummera formations consist largely of slates, shales and turbidite sandstones, with occasional interspersed tuffs. The Mweelrea Formation at the top of this sequence is dominated by quartz sandstones, but also contains five well-defined ignimbrites.

On the southern side of the South Mayo Trough the Rosroe Formation is dated as early Llanvirn (lower Artus graptolite zone, 464–467 Ma according to the time scale of Tucker & McKerrow (1995)). It is distinctive within the South Mayo Trough for comprising very coarse conglomerates and sandstones (Fig. 3), including abundant granite and volcanic clasts (Archer 1977). The Rosroe Formation had been interpreted to represent the deposits of large submarine fan deltas eroding a volcanic and plutonic arc source located S of the modern outcrop region (Fig. 1; Archer 1977, 1984). On the northern limb of the South Mayo Trough the Rosroe Formation can be correlated to the Derrylea Formation (Graham *et al.* 1989). Up-section the sedimentary fill of the South Mayo Trough shallows, culminating in the middle Llanvirn Mweelrea Formation which comprises a >3 km-thick package of W-flowing fluvial sandstones derived from a rapidly eroding Dalradian Highland source (Pudsey 1984).

Apart from the apparent arc source to the Rosroe Formation, Dewey & Shackleton (1984) recognised the influx of ophiolitic material in the upper parts of the formation which they related to the progressive unroofing of the forearc, now preserved as the Deer Park Peridotite Complex (Fig. 1) on the northern edge of the South Mayo Trough. Chemical data from the sediments on the northern limb (Wrafter & Graham 1989) show a progressive increase in Cr, Ni and Mg up into

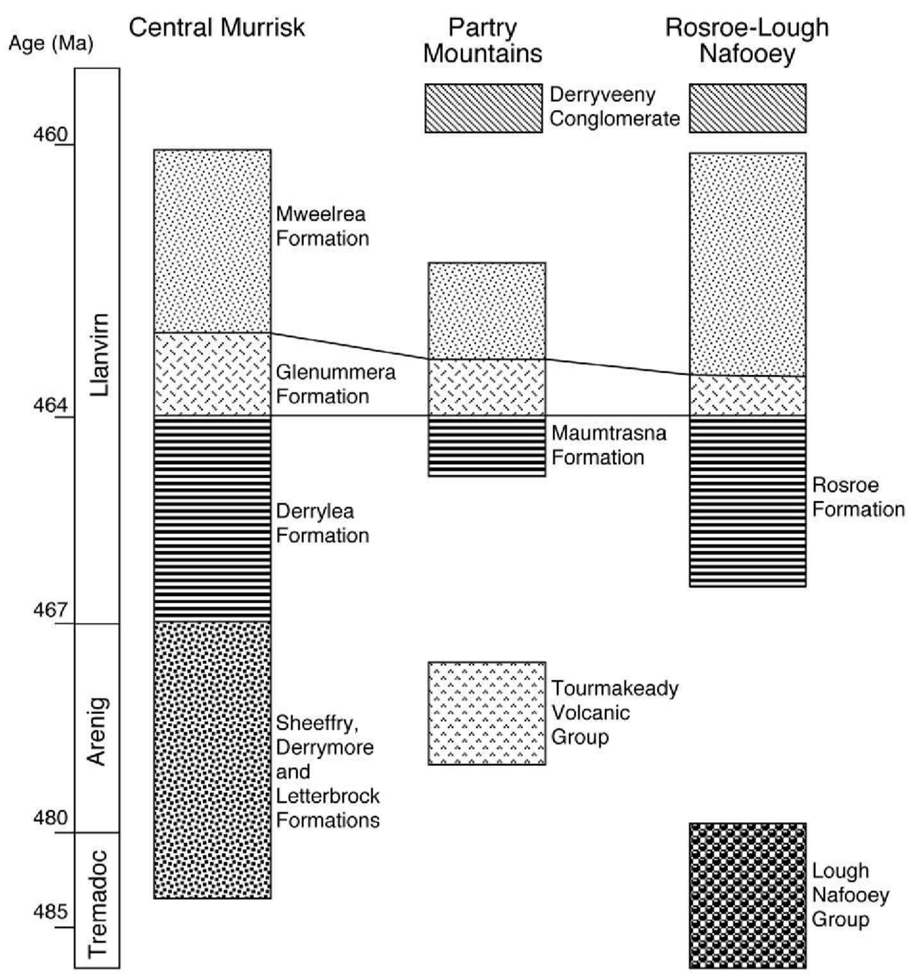

Figure 2 Schematic stratigraphy of the South Mayo Trough, showing the correlation of units across the South Mayo Trough (modified after Graham *et al.* 1989).

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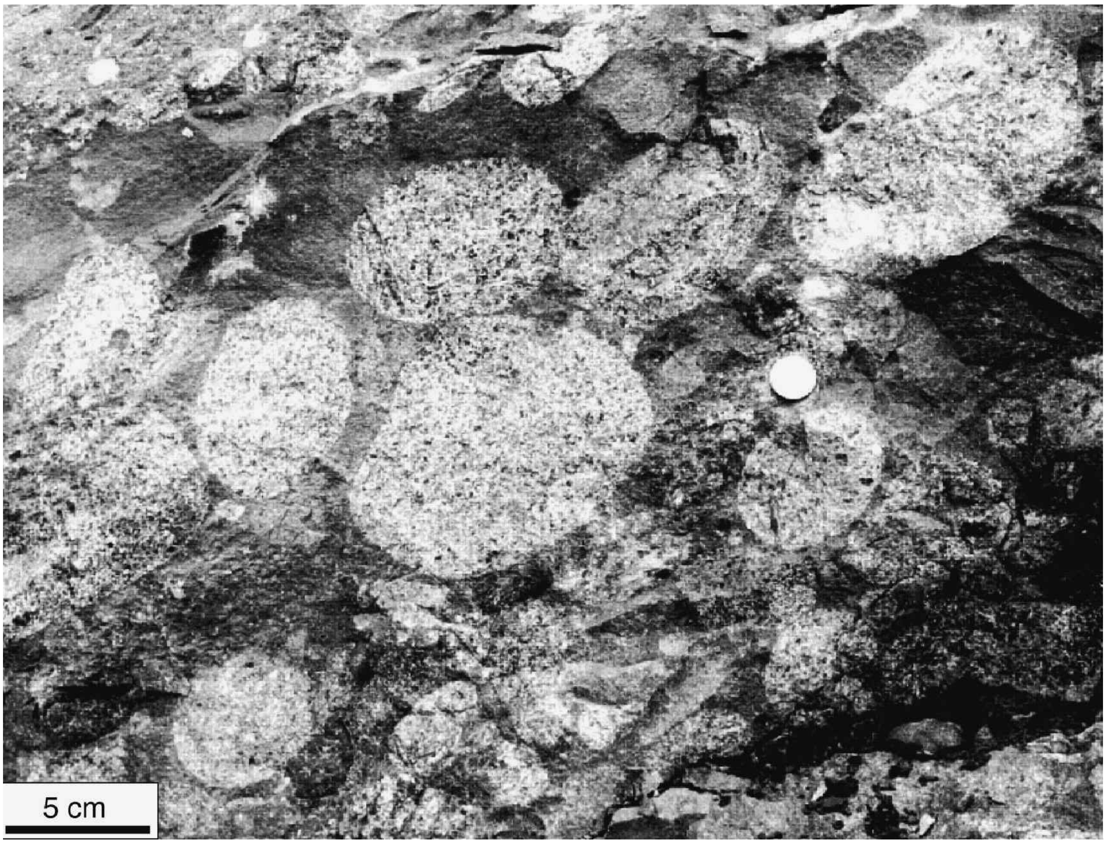

Figure 3 Photograph of a typical exposure of conglomerate from the Rosroe Formation exposed along the southern shore of Killary Harbour, 2 km from Leenane; the exposure shows the large, rounded granite boulders that dominate.

the Derrylea Formation, although these values drop in the middle of this unit. Dewey & Mange (1999) correlated this drop to the first appearance of high-grade metamorphic minerals (garnet, hornblende and sillimanite) in the middle of the Rosroe and Derrylea Formations. They suggested that this was the first pulse of erosion from a newly exposed Dalradian terrane located to the N, now exposed in North Mayo.

2. Palaeo-current indicators

Palaeo-flow directions within the Rosroe Formation can be determined through study of sedimentary structures. In this sequence we measured the elongation direction of cobbles in conglomerate beds, as well as cross-bedding in the sandstones. The former criterion constrains the axis of flow without limiting the direction, which can be seen in the cross-bedding. Paleocurrent measurements were made in the Rosroe Formation at Rosroe, at Leenane and at Lough Nafooey. In addition, we measured current data in the laterally equivalent Maumtrasna and Derrylea formations. The data shown in Figure 4 are consistent with sediment flow from the N and E, with some indication of flow from the S at Rosroe. Although we recognise that some flow is from the S along the southern edge of the basin, as proposed by Archer (1977), we record a dominant axial flow, with major contributions of granitic debris from the NE seen in the Maumtrasna Formation and at Leenane. It is noteworthy that our data broadly agree with the work of Archer (1977), who showed a NE–SW axis of sediment transport based on 20 readings. The presence of abundant volcanic clasts in the Rosroe close to Lough Nafooey, where flow is to the NNW, indicates that more than one source is involved in the provenance of the Rosroe Formation. Although the general fining of the sediments from S to N across the South Mayo Trough appears to argue against a northerly source, the significance of this trend is less apparent in a dominantly axial flowing basin. In that scenario the accumulation of coarse clastic material on the southern limb of the trough may simply reflect preferential subsidence in that region during Rosroe times.

The palaeo-current indicators from the Rosroe Formation are in contrast with the flow seen in the Derryveeny Conglomerate. Pebble orientations and imbrications imply strong SE to NW flow. This is in accord with the concept that a Dalradian metamorphic source, presumably Connemara, was located to the SE of the South Mayo Trough by Derryveeny times (460–443 Ma).

3. Trace element chemistry of granite clasts

The trace element chemistry of magma has long been recognised to vary, depending on the tectonic setting in which the melt is generated, because of differing mantle source compositions and varying degrees of contamination by the continental lithosphere. The relationship is best known for primitive liquids because the fractional crystallisation process obscures the relationship between source chemistry and whole-rock composition. Nonetheless, Pearce *et al.* (1984) demonstrated that certain trace elements could be used to resolve granites emplaced in different tectonic settings. Ten granite clasts were therefore extracted from Rosroe Formation conglomerates and their trace element chemistry was determined. An additional three samples were taken from the younger Derryveeny Formation (Figs 1 and 2) for comparison, as well as two from the 462 Ma Oughterard Granite and five from the syn-collisional quartz diorites of southern Connemara, because

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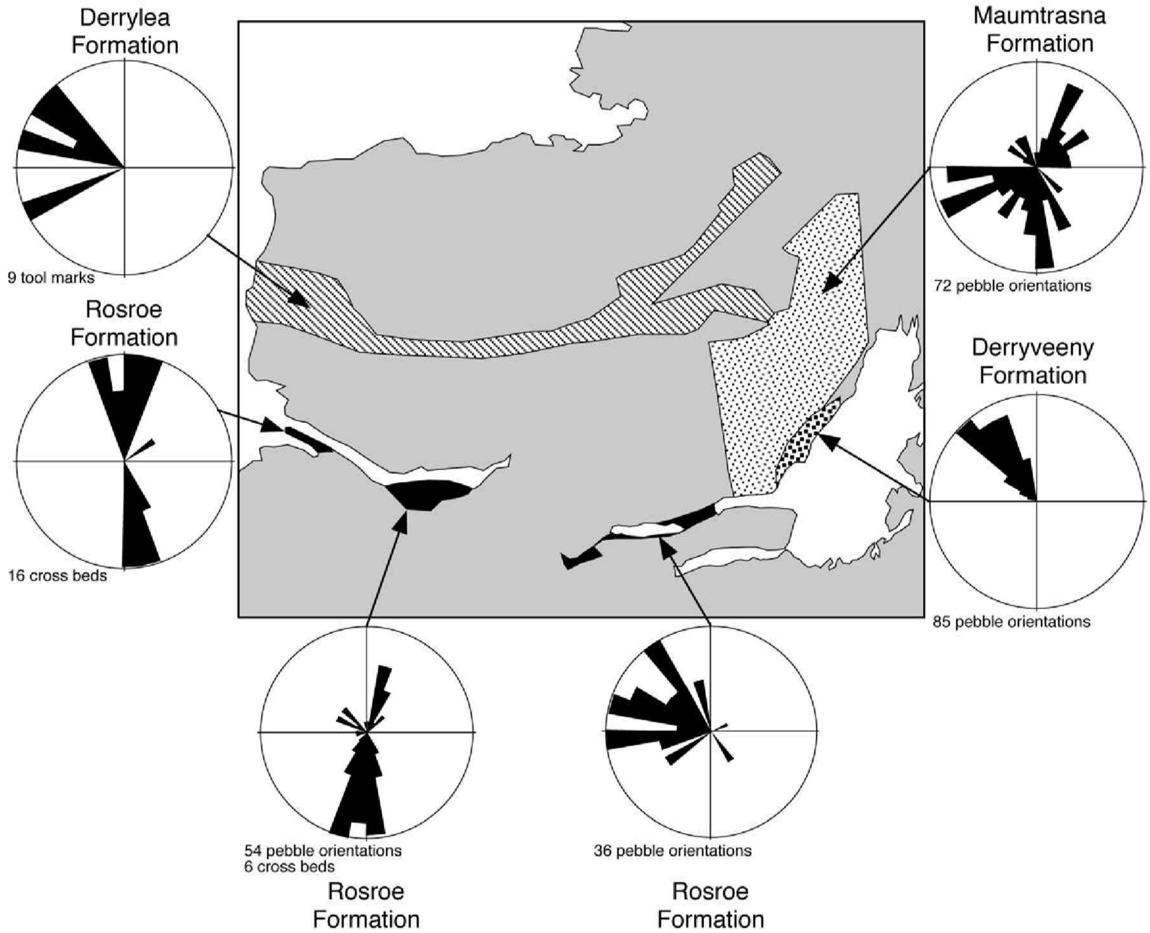

Figure 4 Rose diagrams showing the palaeo-flow directions in the South Mayo Trough during deposition of the Rosroe and Maumtrasna formations on the basis of conglomerate cobble orientations and cross-bedding. Although cobble orientation only specifies the axis of flow, we infer the direction of flow from cross-bedding and pebble imbrication. The dominant southerly and westerly flow contrasts with the NNW-flow in the latter Derryveeny Conglomerate.

these are uncharacterised but possible sources for the sediment. Samples were powdered and dissolved prior to rare earth element analysis by inductively coupled plasma mass spectrometry (ICP-MS) at the Woods Hole Oceanographic Institution (WHOI). Analytical uncertainties are $<2\%$, determined by analysis of USGS standard BCR-2. The results are shown in Table 1.

Figure 5 shows one of the granite discrimination plots of Pearce *et al.* (1984), with eight of the Rosroe cobbles showing a dominant affiliation to within-plate continental granites. Two granite cobbles are closer to the range of syn-collisional granites. The boulders from the Derryveeny Conglomerate are not significantly different from the Rosroe Formation in terms of their trace element character. The Rosroe Formation was deposited immediately after peak metamorphism in Connemara (Draut & Clift 2001), but does not appear to be dominated by granites of arc character. Instead the formation appears to reflect erosion of granites that intruded continental crust prior to or during collision. Because the Lough Nafooey Arc is an oceanic feature (Ryan *et al.* 1980; Clift & Ryan 1994) the source of these clasts must be Laurentia.

The Rosroe samples may be compared to existing analyses of Caledonian granites. The analyses from the Oughterard Granite lie close to the clast analyses from both the Rosroe and Derryveeny formations, although the same cannot be said of the late syn-collisional Connemara quartz diorites. In addition, we compare our analyses with those of Precambrian granites and granitic gneisses from the Scottish Dalradian (unpublished data of J. Mendum 2001), as well as the late orogenic Younger Granites of the Grampian Highlands (Stephens & Halliday 1984). The older granite analyses are from the Keith–Portsoy region of the Scottish Highlands. No comparable data sets are published for the Irish Dalradian, although the close proximity and identical tectonic setting would suggest that similar rocks should be present in that sector too. The Younger Granites are emplaced into the metamorphic stack of the Dalradian after deposition of the Rosroe Formation, and the mismatch between the groups is clear (Fig. 5). In contrast, the older Precambrian granites provide a good fit to the clast chemistry. The chemistry of the Younger Granites shows that there is compositional variability in granites intruded into the Dalradian and that geochemical discriminants are useful in this environment.

In summary, the trace element composition of the Rosroe cobbles is inconsistent with patterns known from modern volcanic arc granites. They are also unlike the Grampian Younger Granites, but are indistinguishable from the older granites that intrude the Laurentian margin, and whose ages suggest emplacement during rifting of the Iapetus Ocean. They also lie close to the values of the latest syn-collisional Oughterard Granite, which was intruded at 462·5 Ma (Friedrich *et al.* 1999a), just post-dating the age of Rosroe sedimentation. Although this particular intrusion cannot have been the source of clasts in the Rosroe Formation, it is possible that similar, slightly older syn-collisional granite could have provided detritus to the basin. Indeed, two of the Rosroe clasts

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Table 1 Trace element composition for granite boulders extracted from the Rosroe Formation, 2 miles W of Leenane on the southern shore of Killary Harbour; analysis measured by ICP-MS.

Sample	Formation	Sr	Rb	Nb	Zr	Y	La	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu
RR-92-9	Rosroe	452	314·0	53·9	247	46·3	33·5	8·76	29·3	5·01	1·10	4·24	0·49	2·86	0·52	1·48	1·36	0·12
RR-92-7	Rosroe	621	93·7	59·7	209	54·3	24·8	7·11	23·9	4·69	0·63	3·97	0·53	3·51	0·69	2·09	2·40	0·30
RR-92-3	Rosroe	155	314·4	63·4	187	54·8	9·1	2·82	10·3	2·61	0·57	2·65	0·46	3·36	0·70	2·14	2·27	0·26
Okr-9	Rosroe	370	221·2	8·6	194	9·0	14·8	3·80	12·4	1·94	0·81	2·11	0·19	1·31	0·25	0·86	1·08	0·09
Okr-10	Rosroe	428	292·4	27·9	119	16·2	35·1	7·03	19·8	2·74	0·80	2·71	0·25	1·54	0·28	0·91	1·14	0·10
Okr-11	Rosroe	340	161·2	21·6	218	35·0	33·1	8·45	28·6	4·75	1·37	4·50	0·53	3·24	0·61	1·80	1·76	0·18
Okr-12	Rosroe	146	264·0	52·6	112	47·7	13·3	4·53	17·0	4·05	0·56	4·09	0·67	4·72	0·96	2·97	3·22	0·38
Okr-13	Rosroe	96·6	158·5	26·44	354·4	62·26	95·90	22·36	79·44	14·80	3·343	13·02	2·095	11·04	2·355	6·773	6·844	1·083
Okr-15	Rosroe	91·4	252·0	20·97	48·02	53·89	56·80	11·85	45·18	10·31	1·961	9·045	1·566	9·774	2·524	7·167	7·677	1·186
Okr-17	Rosroe	112	324·1	27·36	70·66	57·04	79·07	19·01	67·34	13·73	2·547	11·18	1·672	8·148	1·874	5·664	5·522	0·831
DV-00-1	Derryveeny	124	417·6	17·50	63·44	47·63	99·64	21·33	73·98	12·67	3·000	8·126	1·362	8·133	1·766	4·672	4·928	0·735
DV-00-2	Derryveeny	160	408·5	81·4	383·1	44·44	165·9	34·66	123·6	21·86	4·787	17·56	2·214	10·14	2·169	5·180	4·639	0·639
DV-00-4	Derryveeny	98·7	170·0	18·46	178·2	39·69	173·7	37·85	132·5	22·10	4·793	12·97	1·707	8·454	1·549	4·247	4·356	0·690
OG-00-2	Oughterard	327	542·4	36·19	108·5	36·27	60·56	14·4	49·65	9·161	2·407	7·964	1·128	6·979	1·790	5·484	6·559	1·079
OG-00-3	Oughterard	222	271·9	21·16	515·5	19·09	44·02	11·13	38·22	7·051	2·502	5·483	0·604	3·077	0·747	2·032	2·330	0·403
QD-00-1	Qtz. Diorite	85·6	91·08	3·859	24·19	12·33	35·50	7·138	25·39	4·424	2·209	3·403	0·495	2·332	0·347	0·987	0·776	0·090
QD-00-3	Qtz. Diorite	69·7	89·35	13·45	9·3	9·534	24·47	5·370	19·33	3·211	1·533	2·633	0·277	1·687	0·309	0·774	0·683	0·106
QD-00-5	Qtz. Diorite	26·9	49·17	5·972	8·375	10·32	25·30	5·799	20·89	4·030	0·890	3·020	0·366	2·129	0·396	0·853	0·514	0·067
QD-00-6	Qtz. Diorite	23·3	30·34	5·126	6·213	17·18	15·21	4·798	19·64	4·107	0·980	3·482	0·523	2·695	0·595	1·483	1·509	0·219
QD-00-7	Qtz. Diorite	9·02	25·74	1·807	14·89	7·189	5·317	1·891	7·730	1·619	0·427	1·728	0·228	1·305	0·294	0·775	0·814	0·128

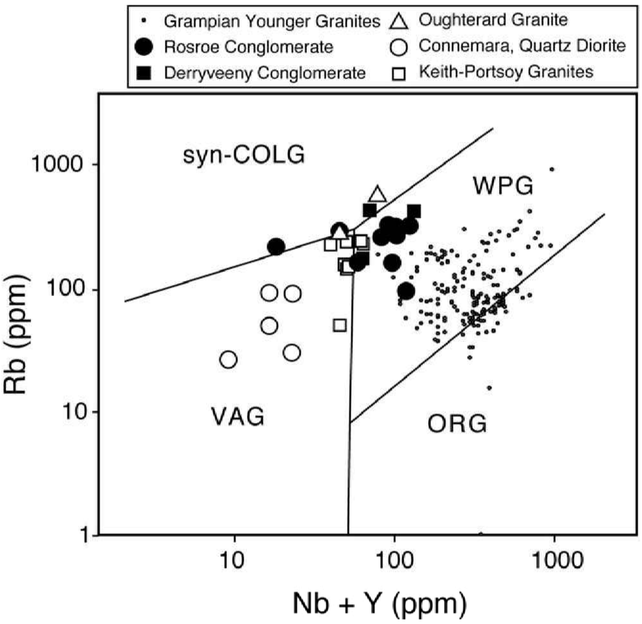

Figure 5 Granite tectonic discrimination diagram after Pearce *et al.* (1984), showing the within-plate associations of the Rosroe and Derryveeny Conglomerate boulders and their similarity to Precambrian granites of the Dalradian Highlands (data from J. Mendum, unpublished). The contrast with the younger granites of the Grampian Orogeny (Stephens & Halliday 1984) is striking. WPG = within-plate granites, ORG = orogenic granites, syn-COLG = syn-collisional granites, VAG = volcanic arc granites.

are suggestive of erosion from granites emplaced early during the collisional cycle, possibly intrusive equivalents of the silicic syn-collisional Tourmakeady Volcanic Group (Draut & Clift 2001). The trace element chemistry argues against erosion of the clasts from an unroofing colliding oceanic island arc and instead suggests derivation from the deformed Laurentian margin. There is no significant difference noted between the clasts of the Rosroe and Derryveeny formations.

4. Pb isotopic constraints

The provenance of the Rosroe clastic sediments was further investigated using the Pb isotopic character of detrital K-feldspar grains extracted from the rock. This technique is based on the different isotopic character of the possible source terranes and the concept that K-feldspar is rich in Pb but contains almost no U, so that Pb isotopic ratios measured in the grains have not changed significantly since that crystal first formed, i.e. K-feldspar does not suffer from in-growth of radiogenic Pb. The method has been demonstrated as being an effective provenance tool using either conventional thermal ionisation mass spectrometry (TIMS; e.g. Dickin 1984; McDaniel *et al.* 1994) or ion microprobe (secondary ion mass spectrometry, SIMS; Clift *et al.* 2001). The latter approach exploits new analytical methods that permit the PB isotope character of single grains to be examined (Layne & Shimizu 1998). Normally only the largest sedimentary grains are big enough for TIMS work to be considered. In an igneous rock where all the grains have the same origin, Pb isotope work can be done by analysing several grains at one time. However, this assumption is invalid for detrital grains. SIMS analysis of the small grain-size fraction is important because analysing only the large grains can bias the result through preferentially considering only the most proximal sources.

A large sandstone sample from the section two miles W of Leenane was disaggregated and sieved. K-feldspar grains were then picked and mounted in epoxy and polished using aluminium oxide abrasives. After gold coating, the grains were analysed using the Cameca IMS 1270 ion microprobe at the US Northeast National Ion Microprobe Facility (NENIMF) at WHOL. A beam of negatively charged oxygen ions (O^-) was focused to a spot as small as 15–20 μm. Analytical uncertainties are principally a reflection of the counting statistics, typically averaging $2\sigma < 0{\cdot}5\%$. In order to avoid contamination by secondary Pb, analysis was made in grain centres, away from cracks.

Selected granite boulders were chosen for analysis by TIMS. These grains were first leached in hot 6M HCl following the procedure of Gariepy *et al.* (1985), in order to remove secondary Pb contamination coating the surface of the grains. The grains were then washed, dried and powdered before dissolution and extraction of the Pb using standard column techniques. The isotopic analysis was performed at WHOI using a VG354 5-collector mass spectrometer. The analytical results of both TIMS and SIMS work are shown in Table 2.

The results are plotted together with the previously defined range of values for the various possible source terranes in order to constrain provenance. In this work we compare detrital K-feldspar analyses with source K-feldspar analyses. The Avalon field is defined by the work of Hampton & Taylor (1983) in southern Britain. The NW Highlands, i.e. Lewisian and cover sequences, are defined by Chapman & Moorbath (1977), Blaxland *et al.* (1979), Walters *et al.* (1990) and Whitehouse (1990). The Dalradian field is defined by work of Blaxland *et al.* (1979). The oceanic end member is constrained by both the work of Doe *et al.* (1985) and the measurement of Ordovocian arc lithologies in NW Ireland by Dixon *et al.* (1990). The arc and mantle values plot close together on Figure 6, indicating that the arc material is not significantly contaminated by crustal material. The Lough Nafooey Arc might be anticipated to have a strongly oceanic Pb character given its clearly oceanic trace element character (Clift & Ryan 1994) and Nd isotopic values (Draut & Clift 2001).

The Rosroe K-feldspar grains show a clear association with the Laurentian field of composition, overlapping both the NW Highland (Lewisian) and Dalradian fields. Although some of the grains yielded isotopic ratios that do not overlap

Table 2 Measured Pb isotopic ratios for detrital K-feldspar grains extracted from the Rosroe Formation.

Analytical method	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{204}Pb$ σ(%)	$^{207}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$ σ(%)	$^{208}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$ σ (%)
SIMS	17·4872	0·36	0·8797	0·27	2·1430	0·19
SIMS	17·4800	0·88	0·8717	0·49	2·1656	0·46
SIMS	16·8023	0·58	0·9103	0·31	2·2008	0·25
SIMS	17·3936	0·20	0·8321	0·13	1·9970	1·16
SIMS	18·3373	0·55	0·8365	0·33	2·0300	0·31
TIMS	17·7380	0·10	0·8652	0·03	2·1427	0·08
TIMS	17·7890	0·10	0·8640	0·03	2·1344	0·08

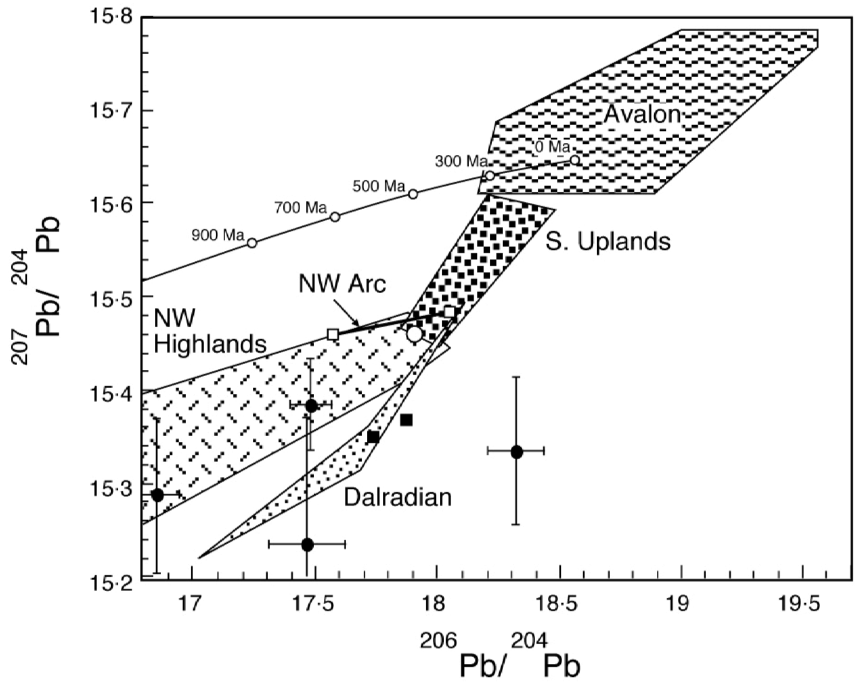

Figure 6 Pb isotopic diagram showing the ratios for detrital K-feldspars measured by SIMS (solid circles) and TIMS (solid squares), compared to known values for basement terrains in the North Atlantic Caledonides; open circle is mantle value of Doe *et al.* (1985); growth curve is that of Stacey & Kramers (1975); error bars show 1σ uncertainty.

with any previously measured values from the Laurentian basement, it is noteworthy that measured ratios in detrital grains are lower than either arc or Avalonian sources, making a Laurentian source most likely. The scatter in measured ratios from detrital grains probably reflects undocumented isotopic heterogeneity within the Laurentian margin. The oceanic island arc values of Dixon *et al.* (1990) do not appear to be represented in the grains analysed as part of this study. The SIMS and TIMS data both fall in this Laurentian range, but the SIMS shows much more scatter. This is interpreted to reflect a relatively restricted, local source for the conglomerate boulders and a wider spread of more distal sources for the sand-grade fraction of the sediment. We conclude that the Pb isotopic data are suggestive of the bulk of Rosroe sediment being eroded from the deformed margin of Laurentia, and not from an accreted oceanic arc.

5. Discussion

The trace element and isotopic data presented above provide an image of the Rosroe Formation being derived from the erosion of granites and metamorphic rocks of distinctively Laurentian character. This conclusion is consistent with the work of Dewey & Mange (1999), who suggested that the upper part of the formation is influenced by erosion of a newly exhumed Dalradian terrane. The presence of some pinkish-coloured volcanic clasts in the Lough Nafooey area does support the model of Archer (1977) of erosion from an arc source, but the new data would suggest that this is a limited part of the total sediment budget. Critically, the new palaeo-current data also support the Dewey & Mange (1999) model for sediment flow from a source located N of the present outcrop, i.e. the North Mayo Dalradian. This latter inference is important because if the Connemara Dalradian block had been present towards the S in Rosroe (early Llanvirn) times, then it might be expected to have been a major, if not dominant, sediment source, given the proximity of the Rosroe basin to Connemara (Fig. 1).

Unroofing of the Dalradian metamorphic and intrusive units is required to expose the source of the Rosroe sediments. Rapid cooling of the Dalradian metamorphic block was probably accomplished mostly by tectonic means rather than erosion, through motion along the Renvyle-Bofin Slide, as proposed by Wellings (1998), by low-angle extensional faults S of Connemara (Williams & Rice 1989), or by other as yet unidentified structures. Such extensional faulting appears to have been synchronous with low-angle thrusting along the Mannin Thrust (Cliff *et al.* 1996; Draut & Clift 2002). The Mannin Thrust is deformed by a D4 age structure, and this phase of Dalradian folding is constrained to being pre-462 Ma by the known age of the Oughterard Granite (Friedrich *et al.* 1999a). Exhumation is also constrained to being pre-462 Ma, broadly consistent with the rapid cooling at 468–460 Ma measured in the Connemara Dalradian (Friedrich *et al.* 1999a, b). Slightly younger cooling and exhumation ages of 460–450 Ma recorded from North Mayo (Flowerdew *et al.* 2000) are incompatible with these rocks being the source of the Rosroe Formation because this is older than 464 Ma. This mismatch indicates either an error in dating, or an age progression in orogenic collapse along the Caledonian Orogen, and the along-strike delivery of sediment from the NE into the South Mayo Trough during sedimentation of the Rosroe Formation. The latter scenario is supported by the palaeo-current data. If the Rosroe source was similar to the Connemara Dalradian in its cooling history, then it follows that exhumation of the source and its erosion was accomplished in no more than 4 m.y. (448–464 Ma), confirming recent evidence that the Grampian Orogeny was a short-lived event (e.g. Friedrich *et al.* 1990a, b; Draut & Clift 2001).

Rapid unroofing of the Dalradian source terrains by low-angle detachment faulting would generate topographic uplift

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as a result of the flexural response to unloading, and these mountains would be affected by erosion. We consider it unlikely that significant Dalradian mountains existed S of the South Mayo Trough in Rosroe times (Llanvirn) but contributed no sediment, while tectonically similar mountains further away in North Mayo, or further NE in the Grampian Highlands, were sending large amounts of sediment into the basin.

This study thus suggests that the Connemara Dalradian was not displaced laterally into its present location along high-angle strike-slip faults until after the end of the Rosroe sedimentation, i.e. post-464 Ma, and after the low-angle faulting that exhumed the orogenic core. Because the Derryveeny Conglomerate, deposited after Connemara reached its present location, is dated at 460–443 Ma (Graham *et al.* 1991), the lateral motion of Connemara can be constrained to have occurred over a period of 4–21 m.y. The lack of a significant geochemical difference between Rosroe and Derryveeny clasts means that the use of the Derryveeny Formation to constrain the emplacement of Connemara S of South Mayo rests entirely on the palaeo-current information from this unit (Fig. 4). The geochemical similarity is not surprising given that both are eroding Dalradian (Laurentian) source terrains.

6. Conclusions

New chemical and isotopic provenance data from the Rosroe Formation show that although these sediments lie within the South Mayo Trough, the forearc basin to the Lough Nafooey Arc, much of the sediment is not derived from that arc but instead from the Laurentian margin, with which the Lough Nafooey Arc had collided after ~480 Ma. The derivation of the coarse sediment from the NE precludes the presence of the Connemara Dalradian in its present location until after that time. In contrast, the Derryveeny Conlgomerate is eroded into the South Mayo Trough from a Dalradian source located to the SE. The similar ages of Rosroe sedimentation and exhumation of the Laurentian (Dalradian) sources require that the entire exhumation process lasted no more than ~4 m.y.

The consistency of Pb isotopic measurements made by ion microprobe and conventional TIMS methods indicates that the former technique is an effective provenance tool, but also shows the need to examine both coarse and fine particles in sediments with potentially mixed sources, since these may not be identical. The spread of Pb isotopes measured by SIMS for the sand particles shows that measurement of batches of mixed detrital grains by TIMS would not yield geologically meaningful results.

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