Ancient Laurentian detrital zircon in the closing Iapetus Ocean, Southern Uplands terrane, Scotland

John W.F. Waldron
Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada
James D. Floyd
British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, Scotland
Antonio Simonetti
Larry M. Heaman
Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada

ABSTRACT

Early Paleozoic sandstones in the Southern Uplands terrane of Scotland were deposited during closure of the Iapetus Ocean between Laurentia and Avalonia. Their tectonic setting and sources are controversial, and different authors have supported subduction-accretion, extensional continental-margin development, or back-arc basin settings. We report new U-Pb detrital zircon ages from five Late Ordovician sandstones from the Northern Belt of the Southern Uplands and test models of their tectonic setting. The U-Pb zircon age distributions are dominated by peaks characteristic of sources in Laurentia and include grains as old as 3.6 Ga, older than any previously recorded in the British Caledonides SE of the Laurentian foreland. Discordant grains in one sample suggest derivation via erosion of metasedimentary rocks incorporated in the Grampian-Taconian orogen. Rare Neoproterozoic grains, previously interpreted as originating from a peri-Gondwanan terrane, may be derived from igneous rocks associated with Iapetan rifting. Only rare zircons are contemporary with the depositional ages. The results are difficult to reconcile with extensional continental-margin and back-arc models, but they support an active continental-margin subduction-accretion model. Close similarities with distributions from the Newfoundland Appalachians are consistent with sinistral transpression during closing of the Iapetus Ocean.

Keywords: tectonics, Caledonides, Southern Uplands, detrital zircon geochronology, provenance.

INTRODUCTION AND GEOLOGIC SETTING

The Southern Uplands terrane (Fig. 1) records the last zone of major convergence during the building of the British Caledonides, which occurred between Laurentia- and Gondwana-derived terranes, including the microcontinent Avalonia and the Leinster-Lakesman terrane on its northern margin. The terrane has been interpreted (Leggett et al., 1979; McKerrow et al., 1977) as an accretionary complex formed at a subduction zone along the Laurentian margin of Iapetus. However, other authors (e.g., Morris, 1987; Stone et al., 1987) have suggested that part of the stratigraphy represents a back-arc basin that was subsequently deformed in a foreland fold-and-thrust belt. In another hypothesis (Armstrong and Owen, 2001; Armstrong et al., 1996), the northern part of the terrane is interpreted as an extensional continental margin, in which major normal faults were inverted during later collision.

The Southern Uplands terrane is dominated by Ordovician and Silurian turbiditic sandstones that occur in tracts bounded by faults that strike NE-SW (Fig. 1B). Strata within tracts young predominantly NW (e.g., Leggett et al., 1979), but overall depositional ages become younger to the SE (Fig. 1C). The terrane is divided into an Ordovician Northern Belt, a Central Belt with interleaved Ordovician and Silurian units, and a Silurian Southern Belt (Fig. 1B). Inliers of graptolitic shale and radiolarian chert, locally associated with basaltic volcanics, occur at the base of many of the sandstone successions. Stratigraphic correlations of basal graptolitic shales, together with rarer fossils in the sandstones, show that the onset of sandstone deposition becomes progressively younger in each tract toward the SE. Cleavage and fold relationships indicate deformation initially under orthogonal convergence but later dominated by sinistral transpression as the Laurentian and Avalonian plates docked obliquely (Barnes et al., 1989).

Petrographically and sedimentologically distinct suites of sandstone are recognized within the Northern Belt (Fig. 1C). The Kirkcolm, Shinnel, and Glenlee Formations are characterized by quartzofeldspathic detritus with abundant heavy minerals characteristic of metamorphic sources (Mange et al., 2005). Other units contain abundant ferromagnesian minerals, including pyroxenes and amphiboles indicative of andesitic arc sources (Styles et al., 1989). These include the Galdenoch Formation, which interfingers with the Kirkcolm Formation, and the Portpatrick Formation to the south; the Portpatrick Formation itself contains more quartzose intercalations assigned to the Glenwhargen Formation (Fig. 1C). In addition to andesitic material, these units contain rare fragments of lawsonite and sodic amphibole, suggesting a subduction-zone origin (Mange et al., 2005). Felsic material has generally been attributed to sources in the Grampian orogen of Scotland and Ireland, though Elders (1987) suggested sources in Newfoundland, requiring 1500 km of sinistral strike-slip motion between the terrane and Laurentia, and/or along-margin transport of sediment. The arc-derived units rich in andesitic detritus have been the focus of debate. Proponents of the back-arc model (Morris, 1987; Stone et al., 1987) suggest derivation from the SE. Some paleocurrent observations support this inference, although paleocurrent directions in all formations are highly variable, with a predominance of "axial" directions from the NE or SW. Transverse flow from either the NW or SE is seen in most formations locally; in some localities, even felsic units show flow from the SE (e.g., Stone, 1995, their Fig. 12B). A previous attempt (Phillips et al., 2003) to determine the provenance of the andesite-bearing Portpatrick Formation using detrital zircon geochronology produced unexpected results; contemporary (Late Ordovician) detrital zircon grains were not identified. Instead, a predominance of ca. 550 Ma and 1 Ga zircons was

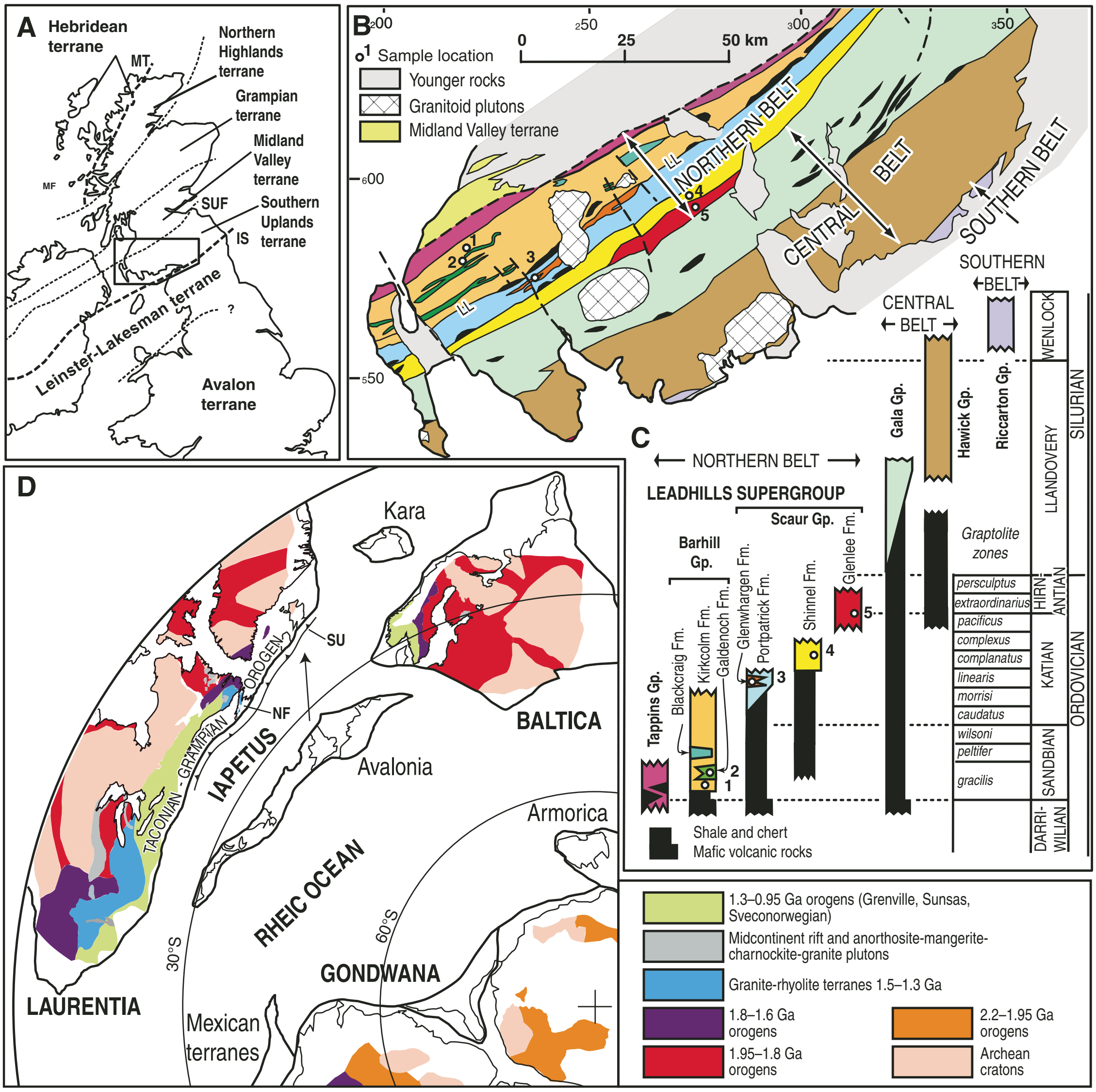

Figure 1. (A) Map of northern Britain, showing principal terranes. MT—Moine thrust; SUF—Southern Upland fault; IS—Iapetus suture. (B) Map of western Southern Uplands terrane, showing principal lithologic units. LL—Leadhills Line. (C) Schematic stratigraphic columns after Floyd (2001) showing progressive SE-younging of sandstone-dominated units (wider columns), colored to correspond to map in B. (D) Paleocontinental reconstruction at 450 Ma, interpolated from reconstructions of Cocks and Torsvik (2002), but with Laurentia displaced 10°W to allow sinistral transpression (arrow) as Avalonia approaches Laurentia. Location of Southern Uplands is marked SU, and western Newfoundland is marked NF. Shadings show principal crustal ages in Laurentia, Baltica, and NW Gondwana (after Bingen et al., 2001; Cawood et al., 2007; Rocci et al., 1991), approximately mapped onto a Schmidt projection.

interpreted to indicate a source in an Avalonian arc fragment to the south (Phillips et al., 2003).

These tectonic hypotheses lead to different predictions of sandstone provenance. Under the back-arc hypothesis, units with andesitic detritus would be expected to show distinct provenance. An extensional rifted margin might be expected to show evolution from local sources to more broadly distributed sources as rift margins subsided (e.g., Cawood et al., 2007). In contrast, an accretionary complex would be expected to show progressive change in sources during denudation of the Grampian-Taconian orogen on the Laurentian margin.

DETRITAL ZIRCON GEOCHRONOLOGY

Samples were collected from five sandstones located in the Ordovician Northern Belt (Fig. 1B). Approximately 100 zircon grains from each sample were mounted, polished, imaged optically and by electron backscatter, and analyzed for their U and Pb isotopic composition using a Nu Plasma multicollector–inductively coupled plasma–mass spectrometer (MC-ICP-MS) coupled to a New Wave Research UP213 laser-ablation system (Simonetti et al., 2005). A spot diameter of 40 µm was used, except for grains that yielded low Pb counts, in which case a 60 µm spot was used. Age uncertainties are reported at 2σ; either the $^{207}Pb/^{206}Pb$ or $^{206}Pb/^{238}U$ age is reported depending on which value gives the lower uncertainty. Probability distribution plots for all grains with <10% discordancy are shown in Figure 2. Full tables of results appear in the GSA Data Repository.[1]

The Kirkcolm Formation, of Sandbian (Caradocian) age, shows the widest range of detrital zircon ages. One Paleoarchean grain yields an age of 3595 ± 16 Ma, the oldest recorded from the British Caledonides SE of the Moine thrust (Fig. 1). Approximately 35% of the grains are Archean, mainly Neoarchean (2.8–2.5 Ga). A second large group (~25%) is Paleoproterozoic (2.0–1.7 Ga). A third large population (~40%) is Mesoproterozoic, from ca. 1.55 to 1.0 Ga, with a large peak at ca. 1.05 Ga. A single Paleozoic age, 459 ± 15 Ma, is consistent with the depositional age.

The Galdenoch Formation, representing andesite-sourced intercalations within the Kirkcolm Formation, shows a more restricted distribution of Neoarchean ages (~22%) and contains much less Paleoproterozoic detritus (~6%). The Mesoproterozoic and earliest Neoproterozoic detritus shows an age distribution resembling the Kirkcolm Formation (Fig. 2). Two late Neoproterozoic grains (567 ± 38 and 619 ± 20 Ma) are comparable to the ages reported from the andesite-

[1]GSA Data Repository item 2008130, detrital zircon analyses, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

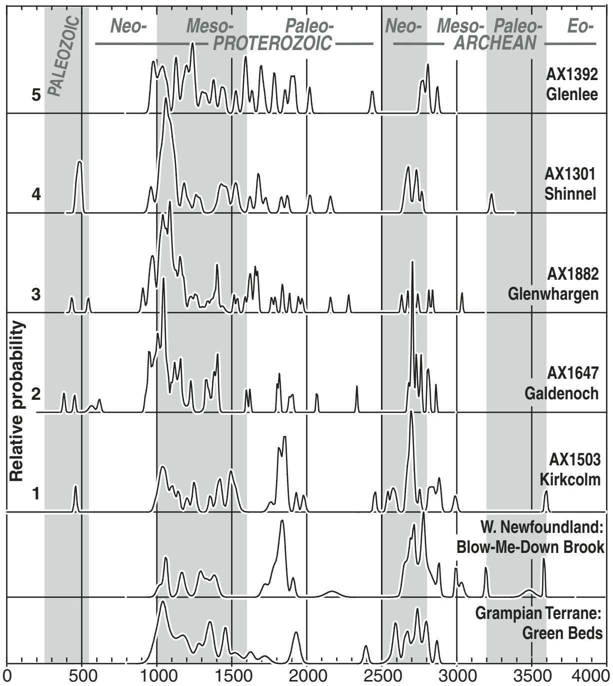

Figure 2. U-Pb detrital zircon relative probability distribution plots for sandstone samples from the Southern Uplands. Sample 2 (Galdenoch Formation) displays andesitic provenance; other samples are felsic. The lower two panels show comparisons with samples from the Blow-Me-Down Brook Formation of Western Newfoundland (after Cawood and Nemchin, 2001), and the Green Beds, Dalradian Supergroup, from the Grampian terrane of Scotland (after Cawood et al., 2003). Plots were generated by ISOPLOT (Ludwig, 2003).

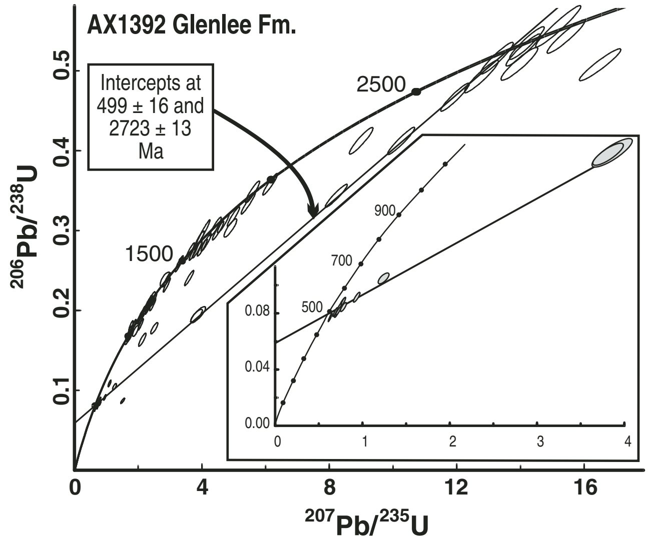

Figure 3. Concordia plot for Glenlee sample AX1392 showing 2σ error ellipses. Inset shows lower intercept of discordia line.

sourced Portpatrick Formation (Phillips et al., 2003). A 446 ± 15 Ma grain is consistent with the depositional age.

Felsic-sourced samples from the Glenwhargen and Shinnel Formations show broad similarities with the preceding units. The Glenwhargen contains 8% Archean and 16% Paleoproterozoic grains. The bulk of the sample (71%) is Mesoproterozoic to earliest Neoproterozoic, with a strong peak at 1.05 Ga. A single grain at 545 ± 15 Ma records the late Neoproterozoic source prominent in the interleaved Portpatrick Formation. A single grain is contemporary, within error, with the inferred depositional age. In the Shinnel Formation, a single Paleoarchean grain is again present (3240 ± 19 Ma). The rest of the Precambrian distribution strongly resembles the Glenwhargen Formation. Four Early Ordovician grains (500–475 Ma) indicate a source not recorded in the other samples. The youngest grain, at 462 ± 14 Ma, may represent a member of this cluster, or could, within error, be contemporary with the depositional age.

The Glenlee Formation contains less (11%) Archean material and more (27%) late Paleoproterozoic material than the other formations. Mesoproterozoic and oldest Neoproterozoic grains form a large majority (62%) of the grains, but the population is more evenly distributed, and the higher peak occurs at ca. 1.24 Ga. No zircons (<10% discordant) younger than 950 Ma are present. However, of 26 discordant grains, 16 fall close to a discordia line with an upper intercept at 2723 ± 23 Ma and a lower intercept at 499 ± 13 Ma (Fig. 3).

DISCUSSION

The striking result of this study is the similarity in the U-Pb detrital zircon provenance obtained for five sandstone samples collected across multiple tracts in the Northern Belt. This similarity strongly supports a progressive unitary model for the development of this belt, as opposed to models in which tracts are assigned to different tectonic environments (Morris, 1987), or in which they are correlated with distinct terranes (van Staal et al., 1998). Primary derivation from Laurentia is supported by detrital zircon age peaks at 2.7, 1.8, and 1.1 Ga, which coincide with major episodes of Laurentian crust formation (e.g., Hoffman, 1989). Sources for the Paleoarchean grains are absent in peri-Gondwanan terranes that form the SE margin of the Caledonide-Appalachian system, whereas Laurentia contains several potential sources, including the North Atlantic craton of Greenland and Labrador. Possible Paleoproterozoic (1.9–1.8 Ga) and early Mesoproterozoic (1.6 Ga) sources are abundant in Laurentia, whereas these ages are rare in Avalonia. The Grenville orogen, fringing the Laurentian continent, is a likely source of the ca. 1.0 Ga detritus, which is abundant in all the samples. Zircons in the range 2.0–2.5 Ga are rare in all the samples (another characteristic shared with Laurentian populations).

In Figure 2 (lowest two panels), we compare our detrital zircon age distributions with selected populations from units in the Grampian and Taconian orogens of Scotland and Canada (Cawood and Nemchin, 2001; Cawood et al., 2003). Striking similarities exist with units in the Dalradian Supergroup of Scotland and the Blow Me Down Brook Formation of western Newfoundland (which contains rare 3.6 Ga zircon). Cawood et al. (2003) noted that Newfoundland zircon populations show a distinct gap around 1600 Ma (see also Ross and Villeneuve, 2003); this gap is not seen in Dalradian detrital zircon age distributions. In this respect, our oldest sample (Kirkcolm Formation) resembles those from Newfoundland, whereas other samples more closely resemble Dalradian distributions.

Derivation from within a Paleozoic orogen, rather than by direct erosion of Precambrian crystalline units, is supported by discordant zircons from the Glenlee Formation, which suggest thermal reworking at 499 ± 13 Ma (Fig. 3). This age is somewhat older than peak metamorphism and deformation in the Dalradian (470 Ma; Soper et al., 1999), but it is consistent, within error, with isotopic ages for early stages of Taconian collision in Canada (Waldron and van Staal, 2001).

A sandstone unit (Galdenoch Formation) dominated by andesitic detritus shows a small component of grains with ages around 550 and 615 Ma, consistent with previous work (Phillips et al., 2003). These ages have been interpreted as suggesting that peri-Gondwanan terranes such as Avalonia, or a rifted-arc fragment such as the Popelogan–Victoria Arc–Grangegeeth terrane (Armstrong and Owen, 2001; van Staal et al., 1998), drifted rapidly toward Laurentia in the Late Ordovician. However, this detritus could also be derived from intrusions in Laurentia associated with late Proterozoic Iapetan rifting (e.g., Cawood et al., 2001). Whatever the origin, the sample shows that this material was thoroughly mixed with older zircon from Laurentia. Local northward paleoflow is therefore best explained by meandering of axial turbidite channels, and not necessarily by distinct southern sources. The consistent southward migration of sandstone deposition through time and the overwhelmingly Laurentian zircon populations provide the best indication of overall provenance.

Paleozoic zircons are scarce in all samples, suggesting that contemporary volcanic sources were minor. Late Cambrian to Early Ordovician zircon in the Shinnel Formation may have been derived from a source similar to volcanics dated at 490 ± 14 Ma (McKerrow et al., 1985) exposed along the Leadhills Line (LL: Fig. 1) to the NW. Other potential sources for this material include: ophiolites in the Grampian-Taconian orogen or the Midland Valley terrane; "scraped-off" seamounts or arc remnants that entered a trench; and peri-Gondwanan arcs such as the Popelogan–Victoria Arc–Grangegeeth terrane.

CONCLUSIONS

Overall, felsic detritus, including the oldest material yet recorded in the British Caledonides SE of the Moine thrust, was dominantly derived from the Precambrian of Laurentia. Our results provide no clear support for a contemporary arc terrane oceanward of the site of deposition, which would be required by the back-arc basin hypothesis. An extensional rifted-margin hypothesis would predict an evolution from more restricted to more broadly distributed sources (e.g., Cawood et al., 2007). In contrast, we observe the largest detrital age diversity in the older formations. The observed detrital zircon age distributions are entirely consistent with deposition in an active-margin trench environment. Derivation was predominantly from rapid erosion of metamorphosed continental-margin sediments in the Grampian-Taconian orogen. Detrital zircon age populations show the closest match with sources in Canada, consistent with along-margin sinistral transpression during accretion.

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