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Bicentennial Review

Sedimentary basin and detrital zircon record along East Laurentia and Baltica during assembly and breakup of Rodinia

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Abstract: Tectonic processes associated with supercontinent cycles result in a variety of basin types, and the isotopic dating of detrital minerals within sedimentary sequences assists palaeogeographical reconstructions. Basins located along the Laurentia–Baltica margin prior to assembly of Rodinia at 1.2–1.0 Ga are dominated by zircon detritus derived from contemporaneous magmatic arcs. Basins formed during assembly are also dominated by zircon detritus with ages similar to that of sediment accumulation, reflecting syn-collisional magmatism and rapid exhumation of the developing Grenville–Sveconorwegian orogen. Post-collision intracratonic basins lack input from syn-depositional magmatism, and are dominated by significantly older detritus derived from the mountain range as well as its foreland. Basins formed during late Neoproterozoic to Cambrian breakup of Rodinia are divisible into two types. Those within the Caledonides lie on the Grenville–Sveconorwegian foreland and incorporate Archaean and Palaeoproterozoic detritus derived from the cratonic interior and Mesoproterozoic detritus derived from the eroded remnants of the orogen. In the Appalachian orogen, such basins are dominated by Mesoproterozoic detritus with older detritus forming only a minor component, suggesting restricted input from the cratonic interior as a result of either the Grenville orogen still forming a drainage divide or the formation of rift shoulders.

The detrital zircon record of clastic sediments represents a link between sedimentary basins and potential source regions (see Dickinson 1974; Ingersoll & Busby 1995). In ancient orogens, where basins and sources may be physically disconnected by tectonic processes, analysis of detrital zircons can facilitate reconstructing this link, to test tectonic models, palaeogeographical settings and continental reconstructions. A first-order constraint in detrital zircon provenance studies is the relation between the age of detritus and the age of sediment deposition. The youngest detrital zircon within an analysed sample constrains the maximum age of sedimentation. Generally, basins in convergent margin settings are likely to have igneous activity close to the time of deposition whereas divergent margin settings may show a considerable age gap between the youngest grain and the time of sediment accumulation (Cawood *et al*. 1999; Cawood & Nemchin 2001). More specifically, basins formed in accretionary orogens, during continuing subduction of oceanic lithosphere, will have much of their detritus close to time of deposition, whereas those in collisional orogens, formed during final closure of the ocean basin, will be dominated by reworking of older material (such as the Grenville orogen *sensu stricto*, Alps, Caledonides) and may produce significantly older detritus in addition to a component of syn-orogenic magmatic or metamorphic detritus. In extensional settings, rift basins with active rift-shoulder uplift tend to have zircon populations that reflect the small hinterland close to the basin itself. In contrast, intracontinental or sag basins and some passive margin sequences with large drainage areas can source their detritus from a very wide area and may have complicated 'multi-spike' zircon populations.

In this review, we outline the temporal and spatial record of sedimentary basins and their detrital zircon provenance record from East Laurentia and Baltica during a complete Wilson Cycle, from the Mesoproterozoic assembly to early Palaeozoic dispersal of the supercontinent Rodinia (Fig. 1). We concentrate on those units for which detrital zircon data are available and outline temporal and spatial trends in zircon age data and their implications in constraining source terrains and tectonic processes.

Geological framework

Pre-Mesozoic Laurentia and Baltica consist of Archaean cratons sutured along late Palaeoproterozoic collisional orogens (Figs 2 and 3; Hoffman 1989; Gorbatschev & Bogdanova 1993). The two are inferred to have formed a single landmass, termed Nena (Northern Europe–North America; Gower *et al*. 1990) that existed from the late Palaeoproterozoic until opening of the northern segment of the Iapetus ocean in the late Neoproterozoic to early Palaeozoic (Bingen *et al*. 1998; Cawood *et al*. 2001). During the end Palaeoproterozoic and Mesoproterozoic, a series

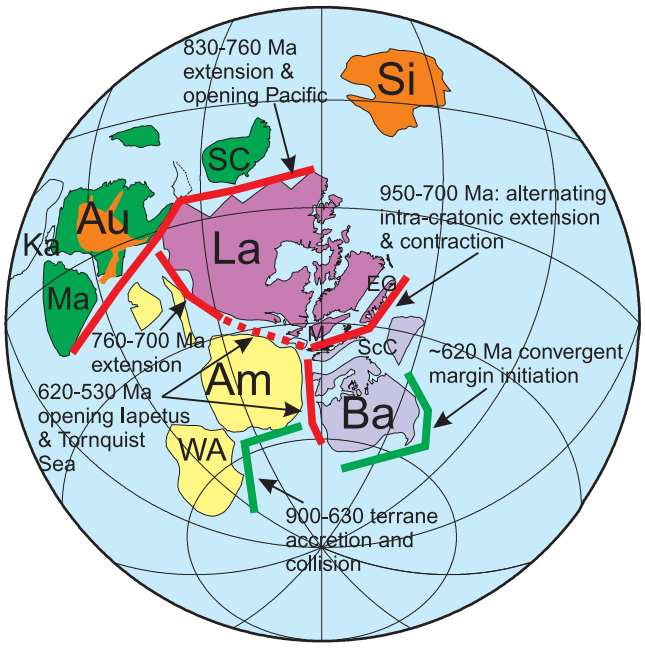


Fig. 1. Reconstruction of Rodinia at *c*. 870 Ma showing location of inferred Neoproterozoic convergent (green lines) and extension (red lines) plate boundaries. Am, Amazonia; Au, Australia; Ba, Baltica; Ka, Kalahari; EG, East Greenland Caledonides; Ma, Mawson; M, Moine; ScC, Scandinavian Caledonides; SC, South China; Si, Siberia; WA, West Africa. East Greenland and Scandinavian Caledonides shown in outboard positions with respect to Greenland and Scandinavian margins to reflect effects of Palaeozoic foreshortening within the Caledonides. Position of Siberia, Australia and Mawson and Baltica and Amazonia with respect to Laurentia based on palaeomagnetic work of Pisarevsky & Natapov (2003), Wingate *et al*. (2002) and Weil *et al*. (1998), respectively.

of predominantly magmatic arc accretionary orogens developed along the eastern and southern margins of Nena; these include the Yavapai, Matzatal and Ketilidian orogens in North America, the Rhinnian Complex in Scotland and the Sveco-Fennian, Trans-Scandinavian and Gothian belts in Baltica (Gower *et al*. 1990; Gower & Tucker 1994; Connelly & Åhäll 1996; Gower 1996; Åhäll & Gower 1997; Åhall & Connelly 1998; Holm *et al*. 2005). These arc systems terminated during inferred collision of Nena with Amazonia during Grenville, Sveconorwegian, and Sunsas orogenesis (*c*. 1200–980 Ma), which constituted a key event in the assembly of the supercontinent Rodinia (Hoffman 1991; Tohver *et al*. 2004*b*). The subsequent breakout of Laurentia and Baltica from within Rodinia (Hoffman 1991) resulted in the formation of the Iapetus Ocean (Fig. 1; 620–530 Ma), which is divided into northern and southern segments through the rifting from East Laurentia of the inferred conjugate margins of west Baltica and Amazonia, respectively (Dalziel 1997; Cawood *et al*. 2001; Cawood & Pisarevsky 2006).

Detrital zircon data sources and methods

Some 4400 detrital zircon U–Pb analyses from almost 130 samples distributed along East Laurentia and West Baltica have been compiled for this study. The sample set covers a depositional age range from around 1550 Ma to 520 Ma and extends some 6500 km along the entire length of East Laurentia and West Baltica. Analytical methods are documented in the source publications and were largely produced by ion microprobe (e.g. sensitive high-resolution ion microprobe; SHRIMP), although thermal ionization mass spectrometry (TIMS) was used for some of the older studies and induced coupled plasma mass spectrometry (ICP-MS) is increasingly used in recent studies. Data were replotted in standard 1D probability density distribution diagrams using the technique outlined by Nemchin & Cawood (2005). Combining datasets obtained using three different methods can potentially create some biasing in distribution diagrams. However, the analytical set is dominated by the SHRIMP and ICP-MS data, and the TIMS analyses are a minor (although very precise) component that is not likely to change the overall age distribution pattern. In addition, the applied mechanism of data treatment (Nemchin & Cawood 2005), which involves double weighing of the data based on the probability of concordance and errors, evens out, to some extent, the difference in precision of the datasets. Nevertheless, some precise but discordant ages, which may represent distinct age sources, do not form a notable peak on the probability plots. Also, the early Neoproterozoic shoulder on some late Mesoproterozoic peaks reflects minor lead loss and resultant displacement parallel to concordia towards younger apparent ages. To facilitate presentation, spatially associated rock units with similar detrital zircon signatures were merged.

Lithotectonic assemblages

Sedimentary basins in East Laurentia and Baltica reflect the cycle of Rodinian supercontinent assembly and breakup. They can be divided into four temporal assemblages (Fig. 3): (1) basins that predate Rodinian assembly; (2) basins formed synchronous with collisional orogeny and Rodinian assembly; (3) intracratonic basins that developed within an assembled Rodinia; (4) late to post-Rodinian basins related to supercontinent rifting and breakup. The following is a summary of the character of the four lithotectonic assemblages and the available detrital zircon data for each assemblage.

Assemblage 1: Pre-Rodinian basins

Active continental margin and marginal sea basins: East Laurentia and Baltica

Late Palaeoproterozoic to Mesoproterozoic sedimentary successions can be traced discontinuously from the Llano uplift of Texas, through the Grenville Inliers in the Appalachian orogen, into the Composite Arc Belt of the Canadian Grenville and then across into the Telemarkia and Idefjorden terranes of the Sveconorwegian orogen (Fig. 2). Sedimentary lithologies include a range of siliciclastic units intruded by mafic to felsic igneous rocks. Deformation and metamorphism occurred during arc-related accretionary orogenies such as the Pinwarian (Fig. 3; 1495–1445 Ma), and Elzevirian (1250–1190 Ma), and during the collisional-related Grenville–Sveconorwegian Orogeny (1100–980 Ma) (Tucker & Gower 1994; Rivers 1997; Rivers & Corrigan 2000; Gower & Krogh 2002; Bingen *et al*. 2003, 2005*b*). Detrital zircon data are largely lacking from the arc systems on the Grenville foreland (e.g. the Yavapai, Mazatzal and Granite–Rhyolite belts) and restricted to disrupted and isolated sequences within the Grenville and Sveconorwegian orogens.

In the Grenville orogen, supracrustal sequences include the *c*. 1500 Ma Wakeham Group in Quebec (Fig. 4, and equivalent units; Rivers & Corrigan 2000; Gower & Krogh 2002; van Breemen & Corriveau 2005), the *c*. 1450 Ma Montauban Group

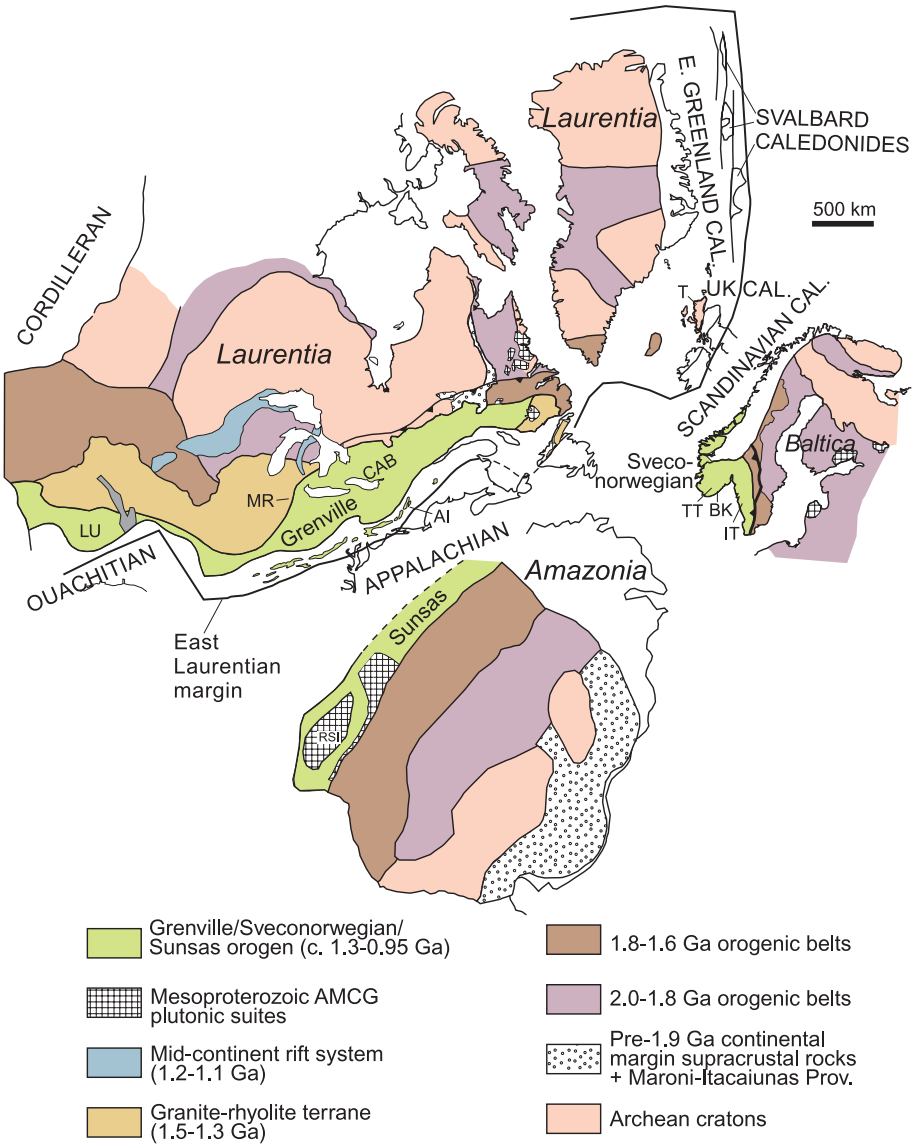


Fig. 2. Laurentia–Baltica–Amazonia reconstruction at around 600 Ma, immediately prior to opening of the Iapetus Ocean, showing ages of major Archaean, Palaeoproterozoic and Mesoproterozoic tectonic elements. The position of Baltica with respect to East Laurentia is based on geological and palaeomagnetic constraints as outlined by Cawood & Pisarevsky (2006). The position of Amazonia is not well constrained and it is placed south of Baltica and opposite the central and southern Appalachians (see Loewy *et al*. 2003, 2004; Tohver *et al*. 2004*b*). AI, Appalachian Inliers; BK, Bamble–Kongsberg sector; CAB, Composite Arc Belt; IT, Idefjorden terrane; LU, Llano Uplift; MR, Middle Run Formation; T, Torridonian; TT, Telemarkia terrane. AMCG, anorthosite–mangerite–charnockite–granite.

of central Quebec (MacLean *et al*. 1982; Corrigan & van Breemen 1997), and the *c*. 1360 Ma metasedimentary Sandy Bay gneiss (Slagstad *et al*. 2004). Detrital zircons from the Wakeham Group show a multimodal range extending from 2950 to 1520 Ma with the main peak on the probability plot at 1950–1750 Ma and subsidiary peaks at around 2500 and 1520 Ma (Fig. 5). Sedimentation is constrained by the youngest detrital zircons at *c*. 1520 Ma and intrusion into the sequence of granitoids dated at 1510–1496 Ma (Madore *et al*. 1997; Wodicka *et al*. 2003; van Breemen & Corriveau 2005). Sediment basin formation and associated igneous activity are part of the 1520–1460 Ma Pinware Orogeny, which is related to an Andean-style continental margin magmatic arc (Gower 1996; Rivers & Corrigan 2000). In the Sandy Bay gneiss, detrital zircons range in age from around 2000 Ma to 1364 Ma (T. E. Krogh, unpubl. data, cited by Culshaw & Dostal 1997).

Of the various sedimentary successions associated with the Elzevirian and younger history of the Grenville, detrital zircon data are available only for the Composite Arc Belt (Easton 1992; Rivers & Corrigan 2000), and the Grenville inliers of the Appalachian orogen (Sinha & Bartholomew 1984; Rankin *et al*. 1989; Burton & Southworth 2004; Ownby *et al*. 2004; Stelten-pohl *et al*. 2004; Volkert 2004). In the Composite Arc Belt, detrital zircons are variably discordant and range in age from around 3200 to 1250 Ma with the bulk of the concordant analyses at the younger end of this spectrum (Fig. 5) and a secondary concentration around 1800 Ma, which does not appear on the probability plot because of discordance of analyses (Sager-Kinsman & Parrish 1993; Friedman & Martingnole 1995; Wodicka *et al*. 1996; Corriveau & Morin 2000; Davidson *et al*. 2002). Detrital zircons from paragneisses of Grenville basement inliers within the Appalachian orogen are dominated by ages in the range 1350–1175 Ma (Fig. 5) with minor peaks at 2050 and 1500 Ma (Gates *et al*. 2004; Ownby *et al*. 2004).

In the Sveconorwegian orogen, pre-Rodinian supracrustal sequences are widespread in the Idefjorden and Telemarkia terranes and intervening Bamble–Kongsberg sector (Sigmond *et al*. 1997; de Haas *et al*. 1999; Bingen *et al*. 2001, 2002, 2003, 2005*b*). The Idefjorden terrane consists of supracrustal rocks and coeval suprasubduction-zone plutonic suites ranging in age from

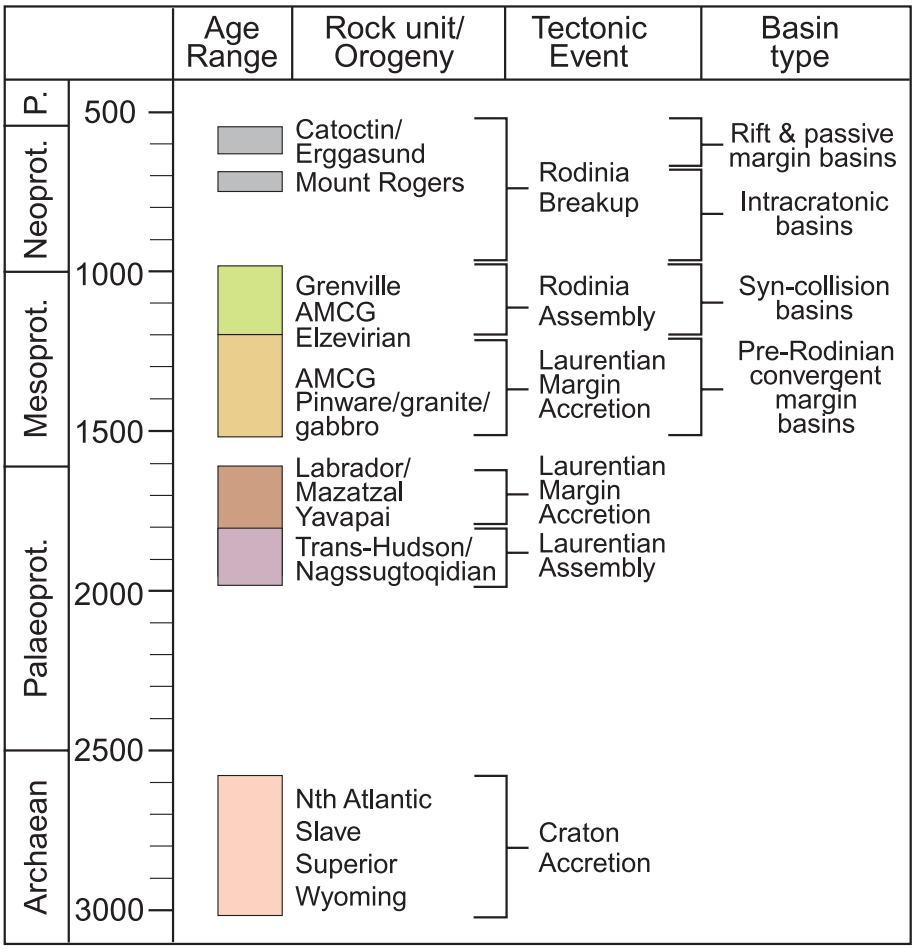


Fig. 3. Age range of major Archaean and Proterozoic events during craton accretion, Laurentian assembly and subsequent East Laurentian margin accretion, and the assembly and breakup of Rodinia. The Neoproterozoic igneous activity associated with intracratonic extension (Mount Rogers) and rifting (Catoctin) related to Rodinia breakup is also shown. Colours of Archaean to Mesoproterozoic events are tied to the scheme used in Figure 2. Baltica records a similar temporal sequence of crust generation events. Neoprot., Neoproterozoic; Mesoprot., Mesoproterozoic; Palaeoprot., Palaeoproterozoic; P., Palaeozoic.

1660 to 1520 Ma (Fig. 4). The bulk of the detrital zircon ages overlap with, and are inferred to be derived from, the coeval magmatic arc (Fig. 5; Åhall *et al*. 1998; Bingen *et al*. 2001, 2005*b*). However some (discordant) detrital ages extend back to almost 2000 Ma, suggesting input from continental sources and indicating that at least part of the magmatic arc was adjacent to, or built on, a continental margin such as Fennoscandia (Andersen *et al*. 2004*a*).

The oldest units in the Telemarkia terrane, SW Norway, are the early Mesoproterozoic quartzite-dominated Hallingdal complex and possible correlatives (Fig. 4; Bingen *et al*. 2005*b*). Three samples contain Archaean to Palaeoproterozoic zircons, the youngest ranging from 1710 to 1540 Ma (Fig. 5). The frequency maximum at 1900–1850 Ma suggests derivation of detritus from Svecofennian magmatic rocks exposed on the Fennoscandian shield (Bingen *et al*. 2001). Widespread Pinwarian magmatism at 1500 Ma includes the 10 km thick rhyolite and clastic Rjukan Group (Fig. 4). Detrital zircons from the unconformably overlying Vindeggen Group (Laajoki *et al*. 2002; Laajoki & Lamminen 2006) yield ages predominantly in the range 2000–1470 Ma (Fig. 5) with minor late Archaean grains (2770 Ma) (de Haas *et al*. 1999; Andersen & Laajoki 2003; Bingen *et al*. 2005*b*). Stratigraphic relations constrain the age of the group only to early to mid-Mesoproterozoic but it is generally assumed to have accumulated around 1400 Ma (Fig. 4; Andersen & Laajoki 2003).

The Bamble–Kongsberg sector of the Sveconorwegian orogen contains early Mesoproterozoic supracrustal rocks and a series of late Mesoproterozoic plutons. Lithologies show similarities to both the Telemarkia and Idefjorden terranes and are inferred to record the collisional interaction between these terranes as they were juxtaposed along the Fennoscandian margin (Bingen *et al*. 2005*b*). Detrital zircons show a similar age signature dominated by a main population between 2000 and 1450 Ma (Fig. 5) with peaks at 1890, 1840, 1720 and 1460 Ma and a subsidiary set of Archaean ages between 3130 and 2450 Ma with a prominent peak at 2780 Ma (Åhall *et al*. 1998; de Haas *et al*. 1999; Bingen *et al*. 2001). The metasediments are interpreted as part of a quartz-rich cover succession deposited after 1470 Ma (Bingen *et al*. 2001).

Inboard rift (extension-related) basins

Inboard of the main trace of the Grenville–Sveconorwegian orogen on Laurentia is the alluvial to lacustrine Mesoproterozoic Stoer Group of NW Scotland (Fig. 2). The timing of sedimentation is approximated by a Pb–Pb age of 1199 ± 70 Ma from a limestone horizon, interpreted as dating early diagenesis (Turnbull *et al*. 1996). Detrital zircons are predominantly Archaean, ranging between 3115 and 2460 Ma (Fig. 5), but also include a few Palaeoproterozoic grains with ages scattered between 2000 and 1740 Ma (Rainbird *et al*. 2001; Kinnaird *et al*. 2007). Provenance, palaeocurrent and sedimentological data suggest that the Stoer Group was derived from nearby Lewisian basement and accumulated on the flanks of an active fault-bounded rift basin (Stewart 1982, 1991*a*, *b*; Van de Kamp & Leake 1997; Rainbird *et al*. 2001). The rift was oriented approximately north–south at a high angle to the contemporary plate margin (present coordi-

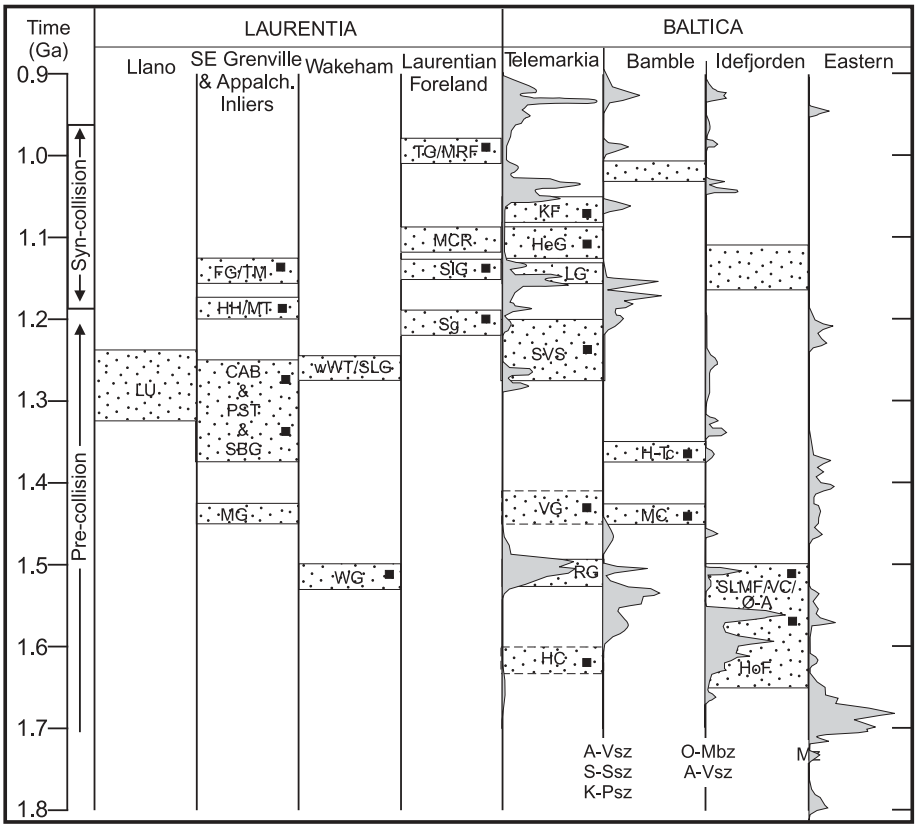


Fig. 4. Age range of principal latest Palaeoproterozoic and Mesoproterozoic metasedimentary units within the Sveconorwegian and Grenville orogens and the adjoining Laurentia–Baltica foreland. Also shown are relative probability curves for magmatic events in Baltica (from Bingen *et al*. 2005*b*). Black squares highlight sequences containing detrital zircon data. Ages given in billions of years (Ga). Data complied from Turnbull *et al*. (1996), Rivers & Corrigan (2000, and references therein), Bingen *et al*. (2002, 2003, 2005*b*, and references therein) and Santos *et al*. (2002). Appalch., Appalachian; CAB, Composite Arc Belt; FG, Flinton Group; HC, Hallingdal Complex; HeG, Heddal Group and correlatives; HoF, Horred Formation and related units; HH, Hudson Highlands; H-Tc, Hisøy–Torungen complex and correlatives; KF, Kalhovd Formation; LG, Lifjell Group and correlatives; LU, Llano Uplift; MC Modum Complex and correlatives; MCR, Mid-Continent Rift; MG, Montauban Group; MRF, Middle Run Formation; MT, Mars Hill terrane, Ø-A, Østfold–Akershus sector metasedimentary units; PST, Perry Sound terrane; RG, Rjukan Group; SBG, Sandy Bay Gneiss; SG, Stoer Group; SLM, Stora Le–Marstrand belt; SVS, Sæsvatn–Valldal supracrustal sequence; TG, Torridon Group; TM, Twelve Mile Quartzite; SlG, Sleat Group; SLG, Seal Lake Group; VG, Vindeggen Group; VC, Veme Complex; WG, Wakeham Group and correlatives; wWT, western Wakeham terrane; Shear zone abbreviations: MZ, mylonite zone; O-Mbz, Ostfold–Marstrand boundary zone; A-Vsz, Åmot–Vardefjell shear zone; S-Ssz, Saggrenda–Sokna shear zone; K-Psz, Kristiansand–Porsgrunn shear zone.

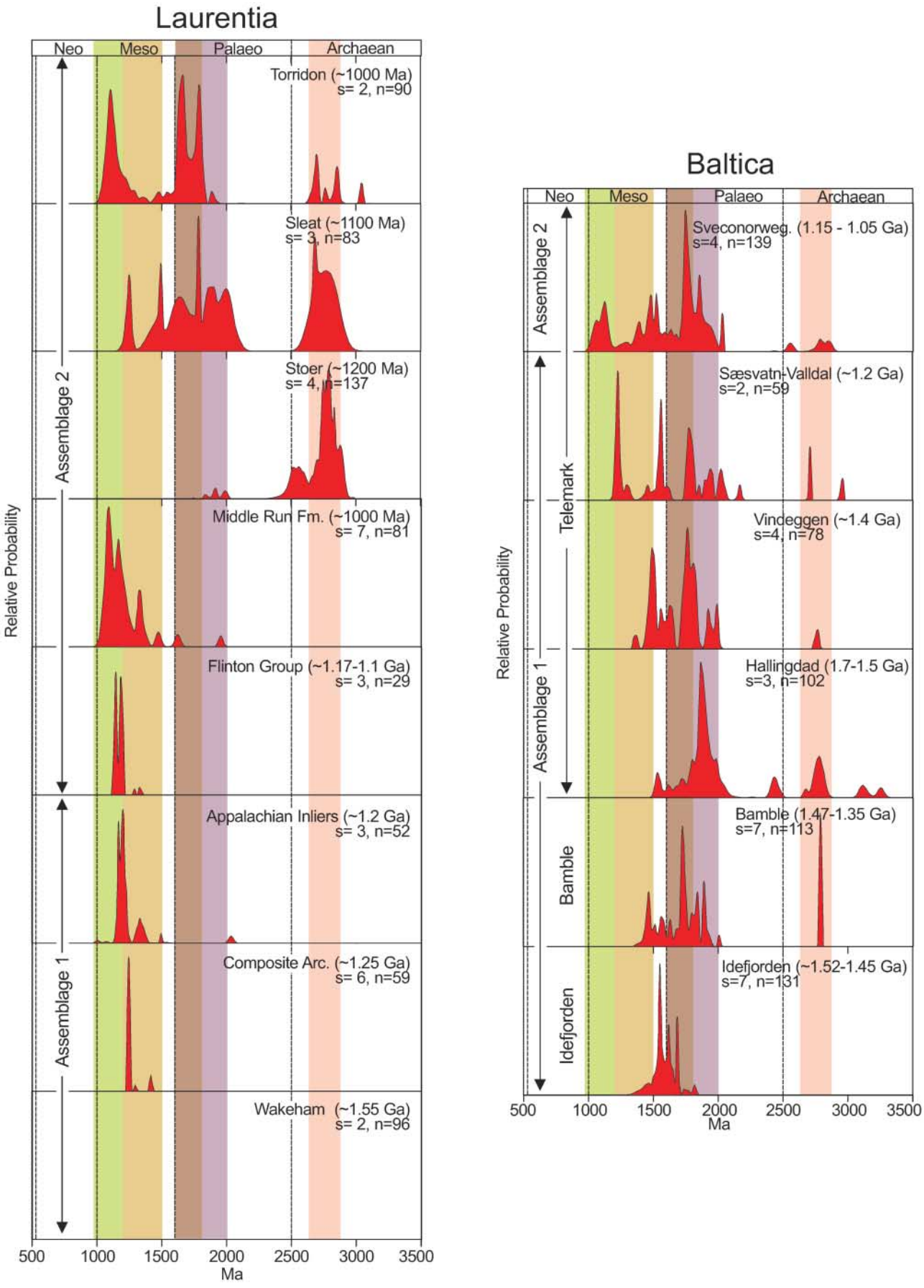
nates) and may have formed as a result of dextral transtension (Beacom *et al*. 1999). Although the cause of rifting is uncertain, it could plausibly relate to terrane accretion and collision during the Elzevirian Orogeny.

Late Mesoproterozoic sedimentary and volcanic successions within the Telemarkia terrane include the 1.27–1.2 Ga Sæsvatn–Valldal rift basin sequence and equivalent units (de Haas *et al*. 1999; Bingen *et al*. 2002). Detrital zircons have ages ranging from 2.96 to 1.21 Ga with maxima at 1.79, 1.56 and 1.22 Ga (Fig. 5; Bingen *et al*. 2002). The youngest grains are interpreted to have been derived from coeval felsic volcanic rocks (Bingen *et al*. 2002). The age range of the detritus within these late Mesoproterozoic basins indicates input not only from units within the Telemarkia terrane, such as the Rjukan Group for *c*. 1.5 Ga detritus, but also the Idefjorden terrane for the 1.64–1.54 Ga detritus and Transscandinavian Igneous Belt for 1.85–1.65 Ga age material and the main Fennoscandian shield for Archaean detritus (Figs 4 and 5). These data link the Telemarkia terrane to the Baltic shield at this time (Andersen *et al*. 2004*a*; Bingen *et al*. 2005*b*).

Although the Rjukan and Vindaggen groups of the Telemarkia terrane are included in the active continental margin and marginal sea type basins of Assemblage 1, their tectonic setting is disputed and accumulation in an inboard rift environment is also possible. Geochemical data on the volcanic rocks within the Rjukan Group suggest a continental, within-plate rift (Menuge & Brewer 1996; Sigmond *et al*. 1997), although data for time-equivalent strata in the Suldal sector of the Telemarkia terrane suggest an active continental margin setting (Bingen *et al*. 2005*b*). The Rjukan Group, and possibly the Vindaggen Group, is of similar age to the Pinware magmatic arc of Canadian Grenville (Tucker & Gower 1994; Wasteneys *et al*. 1997) but the lack of clear evidence of a convergent margin setting suggests that it may have lain well inboard of the active plate margin (Gower 1996; Åhall & Connelly 1998).

Assemblage 2: Rodinia assembly, syn-collisional basins

Active accretionary margin tectonism along the East Laurentia–Baltica margin terminated in the late Mesoproterozoic through


Laurentia
Neo
Meso
Palaeo
Archaean
Torridon (~1000 Ma)
s= 2, n=90
Sleat (~1100 Ma)
s= 3, n=83
Stoer (~1200 Ma)
s= 4, n=137
Middle Run Fm. (~1000 Ma)
s= 7, n=81
Flinton Group (~1.17-1.1 Ga)
s= 3, n=29
Appalachian Inliers (~1.2 Ga)
s= 3, n=52
Composite Arc. (~1.25 Ga)
s= 6, n=59
Wakeham (~1.55 Ga)
s= 2, n=96
Assemblage 2
Assemblage 1
Relative Probability
500
1000
1500
2000
2500
3000
3500
Ma
Baltica
Neo
Meso
Palaeo
Archaean
Sveconorweg. (1.15 - 1.05 Ga)
s=4, n=139
Sæsvatn-Valldal (~1.2 Ga)
s=2, n=59
Vindeggen (~1.4 Ga)
s=4, n=78
Hallingdad (1.7-1.5 Ga)
s=3, n=102
Bamble (1.47-1.35 Ga)
s=7, n=113
Idefjorden (~1.52-1.45 Ga)
s=7, n=131
Assemblage 2
Assemblage 1
Telemark
Bamble
Idefjorden
Relative Probability
500
1000
1500
2000
2500
3000
3500
Ma

inferred continent–continent collision with the Amazonia craton, resulting in Grenville–Sveconorwegian–Sunsas orogenesis (Rivers 1997; Tassinari *et al*. 2000; Bingen *et al*. 2003; Tohver *et al*. 2004*a*). Tectonothermal activity occurred between 1190 and 950 Ma and involved discrete pulses of compression alternating with extension and collapse of the over-thickened crust. Magmatic activity associated with orogenesis includes A-type plutons and anorthosites (Corrigan & Hanmer 1997; Corrigan & van Breemen 1997; Bingen *et al*. 2003). Basins developed during collisional orogenesis reveal an early history between around 1190 and 1100 Ma, sometimes associated with bimodal igneous activity, and deposition of later cover sequences between 1120 and 1010 Ma (Rivers & Corrigan 2000; Bingen *et al*. 2003).

In East Laurentia, several sedimentary successions accumulated within the Grenville orogen during the early phases of collisional orogeny. The Flinton Group (Fig. 4) is a largely clastic metasedimentary sequence that unconformably overlies igneous and metavolcanic rocks deformed during the 1250–1200 Ma Elzevirian Orogeny (Moore & Thompson 1980; Davidson 1986; Van Breemen & Davidson 1988). Detrital zircons from the Flinton Group, along with those from the Twelve Mile and St. Boniface quartzites, fall largely in the age range 1350–1150 Ma but with some variably discordant late Archaean grains (Fig. 5; Sager-Kinsman & Parrish 1993; Wodicka *et al*. 1996; Corrigan & van Breemen 1997). Subsequent high-grade metamorphism and granite intrusion constrain the age of these units to between 1150 and 1090 Ma.

In Baltica, Sveconorwegian syn-collisional basins in the Telemarkia terrane include several groups generally separated by unconformities and collectively referred to as the Sveconorwegian succession by Laajoki & Lamminen (2006). They include a lower sequence (Oftefjell, Høydalsmo, Lifjell groups) associated with 1180–1140 Ma metavolcanic rocks of continental affinity and an upper cover sequence deposited after 1140 Ma and made up of immature clastic sediment (Heddal Group, Eidsborg, Kalhovd formations). Both are affected by metamorphism at 1010 ± 5 Ma (Bingen *et al*. 2001). Samples from the upper cover sequence display a multimodal detrital zircon pattern including a few late Archaean to earliest Palaeoproterozoic grains with ages between 2.85 and 2.41 Ga but with the majority between 2.07 and 1.05 Ga with peaks at 1.95–1.82, 1.75, 1.65, 1.5–1.45 and 1.12–1.05 Ga (de Haas *et al*. 1999; Bingen *et al*. 2003; Andersen *et al*. 2004*a*). Detrital ages younger than about 1.7 Ga correspond well to those in the Telemarkia terrane and adjacent units whereas older grains require input from the Baltic–Laurentian cratonic foreland.

Basins on the Laurentian foreland

A series of syn-collisional basins developed on the Laurentian craton, inboard of the Grenville orogen. They appear to include both basins formed during phases of extension, perhaps in response to relaxation following a convergent pulse, and foreland basins, which developed in response to the increasing orogenic load.

The Midcontinent Rift system comprises a narrow hook-shaped belt of *c*. 1100 Ma sedimentary and volcanic rocks (Fig. 2, Sims *et al*. 1993; Hanson *et al*. 2004) that attain a total combined thickness of up to 30 km (Reed *et al*. 1993) and appear to be truncated and perhaps overridden by thrusts of the Grenville orogen (Rankin *et al*. 1993). The thickness of the rift fill and its hooked shape that does not parallel the Grenville front suggests that it is unrelated to foreland loading from the Grenville orogen.

The Torridon Group of NW Scotland (Fig. 2) consists of arkosic sandstone up to 6 km thick derived predominantly from the west (Williams 2001; Park *et al*. 2002; Stewart 2002). The group lies in marked angular discordance to the Stoer Group (Lawson 1965; Stewart 1966, 1969, 1991*b*; Park *et al*. 2002). It is unconformably overlain by the Cambrian Ardvreck Group. The Torridon Group has generally been considered to conformably overlie the Sleat Group (e.g. Park *et al*. 2002; Stewart 2002), which is preserved only in the Caledonian Kishorn nappe, but Kinnaird *et al*. (2007) have suggested a slight angular discordance across the contact. Detrital zircons from Torridon Group samples range in age from 3094 to 1050 Ma with distinct modes at 1800, 1660 and 1100 Ma (Rainbird *et al*. 2001). A maximum age for sedimentation of the group is provided by a detrital zircon U–Pb age of 1060 ± 18 Ma (Rainbird *et al*. 2001) and detrital muscovites as young as 997 Ma (errors not given, T. J. Dempster *et al*. unpubl. data, cited by Bluck *et al*. 1997). Rb–Sr whole-rock ages of 994 ± 48 Ma and 977 ± 39 Ma from shales from the lower parts of the Torridon Group are interpreted as diagenetic ages (Turnbull *et al*. 1996), and provide a possible minimum age for deposition.

The Sleat Group consists of probable non-marine sandstone and shale up to 3.5 km thick interpreted to be deposited in local rifts beneath the Torridon Group with a sediment source to the WSW (Stewart 2002). Detrital zircons have an age range of 2850–2500 Ma and 2000–1250 Ma with peaks in the probability distribution plot at around 2700, 1800, 1650, 1500 and 1250 Ma (Fig. 5; Kinnaird *et al*. 2007). Archaean detritus decreases in frequency up-section whereas the component of Mesoproterozoic detritus increases. The youngest near-concordant detrital zircon yielded a $^{207}Pb/^{206}Pb$ age of 1247 ± 35 Ma. Although relations with the Stoer Group are not preserved it is considered to be younger than this unit (Stewart 2002; Kinnaird *et al*. 2007).

The Torridon and Sleat data are consistent with derivation from Laurentian and/or Baltica, more specifically the Superior Craton for the 2700 Ma detritus, as well as Ketilidian (1800 Ma), Labradorian–TransScandinavian Igneous Complex (1650 Ma), Pinwarian–Rjukan Group (1500 Ma) and Grenvillian–Sveconorwegian (1250 and 1100 Ma) sources (see Rainbird *et al*. 2001). Sleat sources contained a much greater component of Archaean

Fig. 5. Probability plots of latest Palaeoproterozoic and Mesoproterozoic metasedimentary units within the Sveconorwegian and Grenville orogens. Sources of data: Appalachian Inliers, Carrigan *et al*. (2003), Gates *et al*. (2004) and Ownby *et al*. (2004); Bamble–Kongsberg Sector, Knudsen *et al*. (1997), Åhall *et al*. (1998), de Haas *et al*. (1999) and Bingen *et al*. (2001); Composite Arc Belt, Sager-Kinsman & Parrish (1993), Friedman & Martignole (1995), Wodicka *et al*. (1996) and Corrigan & van Breemen (1997); Flinton Group and correlatives, Sager-Kinsman & Parrish (1993), Wodicka *et al*. (1996) and Corrigan & van Breemen (1997); Hallingdal complex and correlatives, Bingen *et al*. (2001); Idefjorden terrane, Åhall *et al*. (1998), Bingen *et al*. (2001) and Andersen *et al*. (2004*a*); Middle Run Formation, Santos *et al*. (2002); Sævatn–Valldal supercrustals and correlatives, de Haas *et al*. (1999) and Bingen *et al*. (2001); Sleat Group, Kinnaird *et al*. (2007); Stoer Group, Rainbird *et al*. (2001) and Kinnaird *et al*. (2007); Sveconorwegian succession, de Haas *et al*. (1999), Bingen *et al*. (2003) and Andersen *et al*. (2004*b*); Torridon Group, Rainbird *et al*. (2001); Vindeggen Group, de Haas *et al*. (1999) and Andersen & Laajoki (2003); Wakeham Group, Madore *et al*. (1997) and van Breemen & Corriveau (2005). Sveconorweg., Sveconorwegian; s, number of samples; n, number of analyses.

detritus and lack the main Grenville signature, possibly indicative of deposition prior to Grenville orogenesis (Kinnaird *et al*. 2007).

The Middle Run Formation of the East Continent Rift Basin (Fig. 2) lies between the Grenville orogen and Granite Rhyolite Province in the eastern Midwest, USA (Fig. 2; Drahovzal *et al*. 1992; Santos *et al*. 2002) and consists of fining-upward fluvial sequences over 8 km in thickness (Drahovzal *et al*. 1992). In a seismic section from Kentucky, the formation appears to be overthrust by the Grenville orogen (Drahovzal *et al*. 1992) whereas in another from Ohio it overlaps the Grenville rocks (Richard *et al*. 1997), suggesting that sediment accumulation may have been coeval with orogenic activity. A volcanic flow intersected in drill core in Kentucky is geochemically similar to those of the Keweenawan Supergroup (Drahovzal *et al*. 1992). The formation is unconformably overlain by Middle Cambrian strata. Zircon fission-track data show that the Middle Run Formation is older than about 700 Ma (Roden-Tice & Shrake 1998). SHRIMP U–Pb analyses on detrital zircon grains range in age from 1964 ± 22 Ma to 1048 ± 22 Ma with modes at 1960, 1630, 1470, 1340, 1150 and 1080 Ma with the majority of the detritus at the younger end of this age spectrum (Fig. 5), consistent with derivation largely from the Grenville orogen but with some input from the Laurentian hinterland (Santos *et al*. 2002). The formation accumulated sometime between 1048 Ma, the youngest detrital grain, and 700 Ma, the zircon fission-track cooling age, and has been interpreted as a foreland basin to the Grenville orogen (Hauser 1993, 1996). It is overlain unconformably by Middle Cambrian strata.

Assemblage 3: intracratonic basins within an assembled Rodinia

During the Neoproterozoic, East Laurentia and Baltica underwent a complex intracratonic history prior to final breakout from Rodinia through opening of the Iapetus Ocean. Evidence summarized below implies two periods of extension and basin development between 1000 and 700 Ma, each followed by crustal thickening and orogeny. This was immediately followed by regional extension that lasted until the Cambrian (520 Ma) and resulted in successful opening of the Iapetus Ocean (Cawood *et al*. 2001, 2004).

The first cycle of intracratonic sedimentation and orogeny spanned the period *c*. 1000–950 Ma and is represented by the Krummedal succession of East Greenland, the Brennevinsfjorden Group and Helvetesflya Formation of Svalbard, and the Svaerholt succession in Finnmark, Norway. The Krummedal succession (Fig. 6) mainly comprises pelitic to psammitic gneisses (Watt & Thrane 2001; Higgins *et al*. 2004) that are locally unconformable on Archaean to Palaeoproterozoic basement. We consider the Krummedal succession to post-date the main Grenville orogenic pulse and occupy an inboard, intra-cratonic position within an assembled Rodinia (Cawood *et al*. 2004). Detrital zircons yield ages in the range 1900–1100 Ma (Fig. 7; Strachan *et al*. 1995; Kalsbeek *et al*. 2000; Watt *et al*. 2000; Watt & Thrane 2001; Leslie & Nutman 2003). Archaean grains are rare or absent. The youngest detrital zircons from the Krummedal equivalents in Smallefjord yield ages of *c*. 1035 Ma with metamorphic rims giving a pooled $^{206}Pb/^{238}U$ age of 955 ± 13 Ma (Strachan *et al*. 1995). A series of S-type augen granites that intrude the Krummedal yield emplacement ages of 940–910 Ma (Kalsbeek *et al*. 2000; Watt & Thrane 2001; Leslie & Nutman 2003).

On Svalbard, the Brennevinsfjorden Group and Helvetesflya Formation (Gee & Tebenkov 2004) consist of deep-water siliciclastic deposits, metamorphosed to greenschist facies and intruded by granites dated at around 950 Ma (Gee *et al*. 1995; Johansson *et al*. 2000). Detrital zircons are dominantly Mesoproterozoic with little evidence of older material (A. Larionov, pers. comm., cited by Gee & Tebenkov 2004). Basement to the Brennevinsfjorden Group and Helvetesflya Formation is not observed. An angular unconformity separates these units from overlying felsic volcanic rocks of the Kapp Hansteen Group, but all three units were folded together during intrusion of *c*. 950 Ma granites (Tebenkov *et al*. 2002; Gee & Tebenkov 2004). The Svaerholt Succession within the lower part of the Kalak Nappe Complex of northern Norway is dominated by late Palaeoproterozoic and Mesoproterozoic grains, and accumulated between 1030 and 980 Ma on the basis of the constraints provided by the youngest detrital grains and the oldest intrusive granites (Kirkland *et al*. 2006).

The Moine Supergroup of Scotland and the Sørøy Succession of the upper Kalak Nappe Complex of northern Norway are, at least in part, probable correlative units that have similar provenance and apparently represent the result of a second cycle of basin development and sedimentation that was initiated after *c*. 910–900 Ma (Fig. 6; e.g. Cawood *et al*. 2004; Kirkland *et al*. 2006). The Moine is a metasedimentary sequence of predominantly psammite and pelite (Holdsworth *et al*. 1994; Soper *et al*. 1998; Strachan *et al*. 2002, and references therein). Facies analysis implies deposition in a mainly marine setting, and palaeocurrent data indicate a general direction of flow from south to north parallel to the inferred axis of the basin(s) (Strachan 1986; Glendinning 1988). The westerly Morar Group is separated from the overlying Glenfinnan and Loch Eil groups by the Sgurr Beag Thrust, although original sedimentary continuity between the Morar and Glenfinnan groups has been proposed within the Moine inlier on the Ross of Mull (Holdsworth *et al*. 1987). The youngest detrital zircon grain within the Morar Group has been dated at 980 ± 4 Ma (Peers 2001, sample 9615), and a maximum age for upper parts of the Moine succession is provided by the youngest detrital grain, dated at *c*. 900 Ma, from the Glenfinnan Group of the Sgurr Beag Nappe (Emery 2005). The Glenfinnan and Loch Eil groups are intruded by the 870 Ma West Highland Granite Gneiss (Friend *et al*. 1997; Rogers *et al*. 2001) and associated metabasic sheets (Millar 1999). Within the available age constraints we cannot preclude absolutely correlation of the Morar Group with the *c*. 1000–950 Ma Torridon Group of the Laurentian foreland (Peach & Horne 1930; Kennedy 1951; Sutton 1963). However, the Glenfinnan and Loch Eil groups appear to represent a distinctively younger succession deposited after *c*. 900 Ma. U–Pb detrital zircon ages from the Moine Supergroup as a whole are predominantly in the range *c*. 1900–1000 Ma with age peaks at *c*. 1650, 1500, 1400 and 1100 Ma (Fig. 7; Friend *et al*. 2003; Cawood *et al*. 2004). Archaean to early Palaeoproterozoic grains are rare or absent. The Moine succession underwent a series of tectonothermal events between about 820 and 700 Ma that are grouped together under the general term ‘Knoydartian’ but that consist of distinct orogenic pulses at around 820, 730 and possibly 700 Ma (Fig. 6; P. A. Cawood *et al*., unpubl. data; Piasecki & van Breemen 1983; Piasecki 1984; Rogers *et al*. 1998; Vance *et al*. 1998; Tanner & Evans 2003; Storey *et al*. 2004). The Sørøy Succession accumulated between *c*. 910 and 840 Ma (Kirkland *et al*. 2006), based on the age of the youngest detrital grains, and the age of deformation of the succession during the Porsanger Orogeny. It was affected by multiple subsequent late Neoproterozoic to Palaeozoic tectonothermal events at around 710, 670, 560 and 520 Ma (Fig. 6; Corfu *et al*. 2006; Kirkland *et al*. 2006). It shows

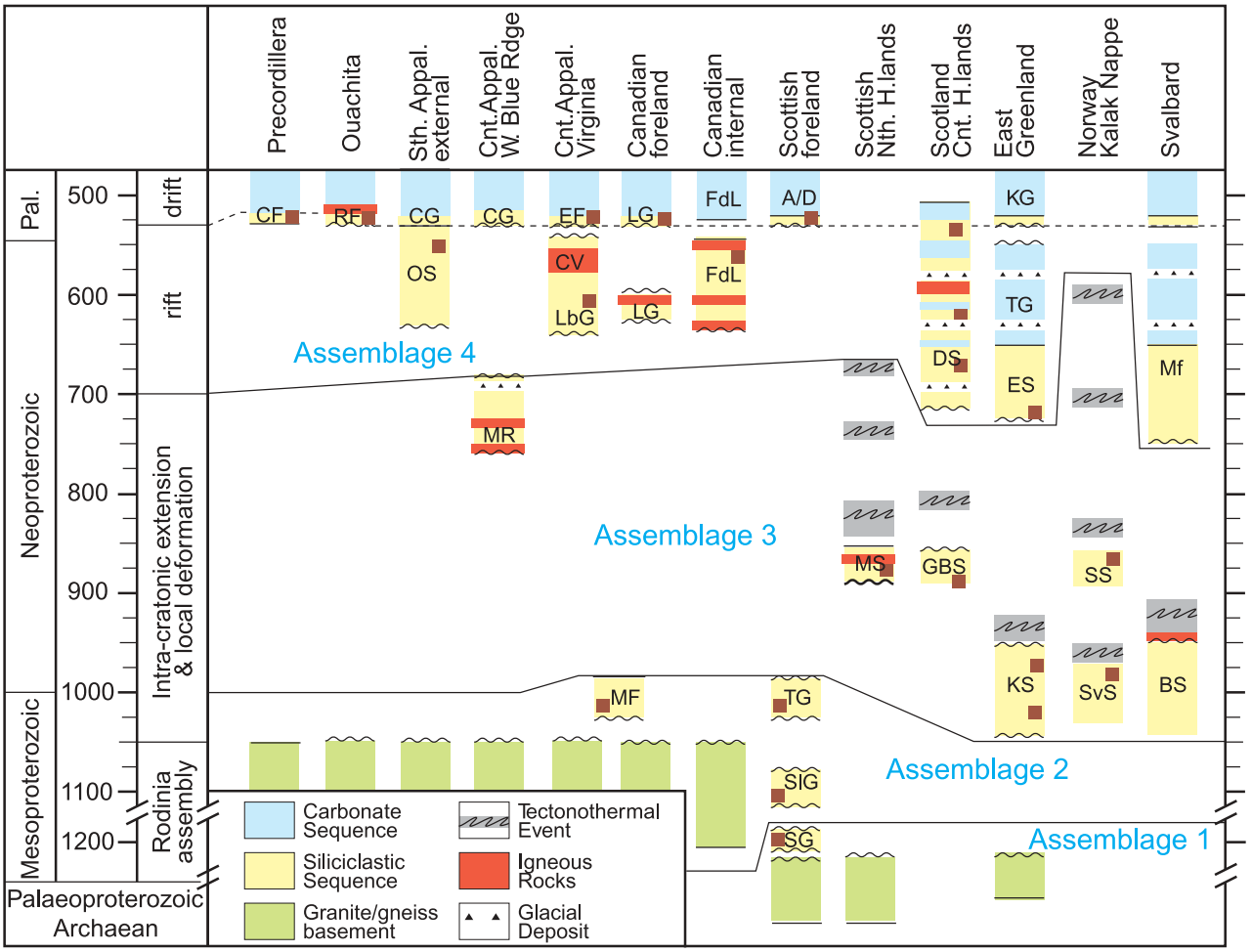


Fig. 6. Age range of principal latest Mesoproterozoic to earliest Palaeozoic metasedimentary units within the Appalachian and Caledonian orogens, including the Argentine Precordillera. A/D, Ardvreck and Durness groups; BS, Brennevinsfjorden Group; CG, Chilhowie Group; CF, Cerro Totora Formation; Cnt. H.lands, Central Highlands; CV, Catoctin Formation; DS, Dalradian Supergroup; EF, Erwin Formation; ES, Eleonore Bay Supergroup; FdL, Fleur de Lys Succession; GBS, Glen Banchor Succession; KG, Kong Oscar Fjord Group; KS, Krummedal succession; LbG, Lynchburg Group; LG, Labrador Group; MR, Mount Rogers Formation; MS, Moine Supergroup; Mf, Murchisonfjorden Group; MF, Middle Run Formation; OS, Ocoee succession; Nth. H.lands, Northern Highlands; Pal., Palaeozoic; RF, Rome Formation; SG, Stoer Group; SlG, Sleat Group; SS, Sørøy Succession; Sth. Appal., Southern Appalachians; SvS, Svaerholt; TG, Torridon Group; TiG, Tillite Group; W., West. Brown square indicates units with detrital zircon data.

a multimodal spectrum of late Palaeoproterozoic to Mesoproterozoic detrital ages, and Archaean and early Palaeoproterozoic material is rare.

Early to mid-Neoproterozoic clastic rocks crop out in the Blue Ridge Province of the Appalachian orogen and in East Greenland of the Caledonian orogen and are related to a failed rifting episode predating Iapetus opening but overlapping the timing of rifting in West Laurentia and opening of the proto-Pacific Ocean (see Dalziel & Soper 2001). The Blue Ridge succession includes extensive plutonic and volcanic units that unconformably overlie or were emplaced into Grenville basement. The igneous units have U–Pb ages in the range 760–680 Ma and show A-type peralkaline, rift-related affinities (Aleinikoff *et al*. 1995; Fetter & Goldberg 1995; Cawood *et al*. 2001; Novak & Rankin 2004; Tollo *et al*. 2004). Glaciogenic strata, correlated with the *c*. 720 Ma Sturtian glaciation (Evans 2000), occur at the top of the succession. The Greenland succession is siliciclastic dominated and includes the Hagen Fjord and Rivieradal groups. The succession is poorly dated and could extend into the late Mesoproterozoic (Higgins *et al*. 2001; Smith *et al*. 2004*a*).

Assemblage 4: rift basins and passive continental margins during Rodinia breakup

Opening of the Iapetus Ocean is recorded by late Neoproterozoic to early Cambrian rift and passive margin strata that can be traced along the length of the Appalachian–Caledonian orogen in East Laurentia and Baltica (Anderton 1982; Hatcher *et al*. 1989; Higgins 1995; Williams 1995; Hibbard *et al*. 2006). Rift facies units are characterized by siliciclastic-dominated successions with varying amounts of volcanic rocks and their intrusive equivalents, and show facies and thickness variations consistent with accumulation in a tectonically unstable environment. In contrast, passive margin strata are mainly carbonate-rich successions with minor siliciclastic input (notably at the base), except for the deep-water siliciclastic-dominated Southern Highlands Group in Scotland, and are characterized by lateral continuity of facies and relatively uniform stratigraphic thickness (Cawood *et al*. 2001). The base of the drift cycle is marked by transgressive sandstones (e.g. Bradore, Chilhowie, Eriboll), which show a relatively uniform Early Cambrian transgression along the length of the East Laurentian margin; they are overlain by Middle

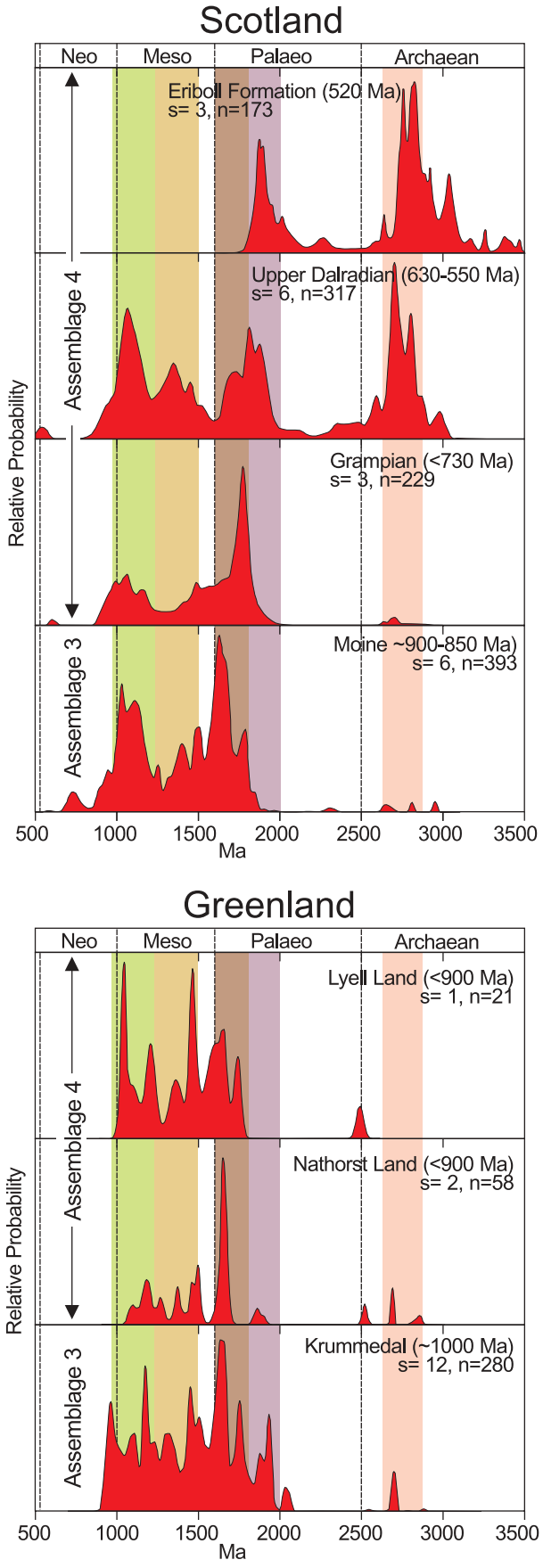
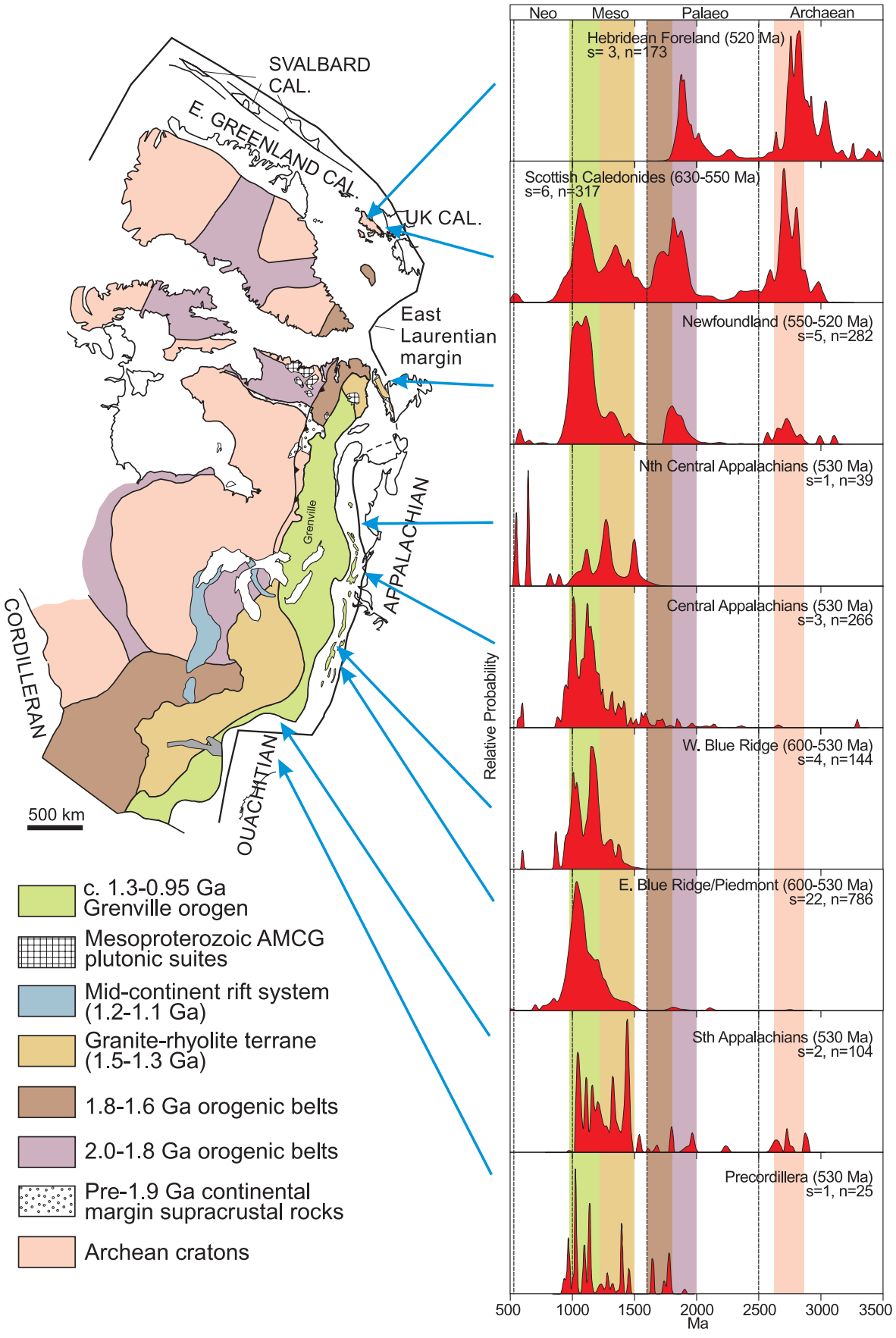


Fig. 7. Probability plots of Neoproterozoic and early Palaeozoic metasedimentary units within the Caledonian orogen in Scotland and Greenland. Sources of data: Krummedal, Strachan *et al*. (1995), Kalsbeek *et al*. (2000), Watt *et al*. (2000), Leslie & Nutman (2003), K. Thrane (unpubl. data) and G. R. Watt & P. D. Kinny (unpubl. data); Nathorst Land, Watt *et al*. (2000); Lyell Land, G. R. Watt & P. D. Kinny (unpubl. data); Moine, Friend *et al*. (2003) and Cawood *et al*. (2004); Grampian Group, Cawood *et al*. (2003); upper Dalradian Group, Cawood *et al*. (2003); Eriboll Formation (Ardvreck Group), P. A. Cawood *et al*. (unpubl. data). s, number of samples; n, number of analyses.

Cambrian to Ordovician carbonates (Williams & Hiscott 1987; Simpson & Eriksson 1989; Waldron *et al*. 1998; Cawood *et al*. 2001; Smith *et al*. 2004*b*). They vary from essentially flat-lying, little-deformed sedimentary strata unconformable on Proterozoic and Archaean basement within the foreland to the Appalachian–Caledonian orogen, to intensely deformed and high-grade metamorphic assemblages occurring within thrust sheets in the internal zones of the orogen (Hibbard 1983; Hatcher *et al*. 1989; Williams 1995; Cawood *et al*. 1996; Cawood & van Gool 1998). Segments of the continental margin succession form continental ribbons or plateaux that developed outboard of the margin and were re-accreted to the margin during closure of the Iapetus Ocean (Dashwoods, Piedmont; Cawood *et al*. 2001; Waldron & van Staal 2001; Hatcher *et al*. 2004) or transferred to Gondwana through drift across the ocean or through collisional interaction (Precordillera; Thomas & Astini 1996; Dalziel 1997).

The oldest sedimentary sequences associated with Assemblage 4 occur in the Caledonides and include the siliciclastic-dominated Nathorst Land and Lyell Land groups of the Eleonore Bay Supergroup and the Grampian Group of the Dalradian Supergroup (Fig. 6). Ages of these units are not well constrained but they conformably underlie established late Neoproterozoic and early Palaeozoic strata (Sonderholm & Tirsgaard 1993; Strachan *et al*. 2002). The detrital zircon population of these mid-Neoproterozoic units is similar to the older Krummedal and Moine successions with Archaean detritus only a minor component and dominated by late Palaeoproterozoic and Mesoproterozoic material (Fig. 7). In contrast, overlying strata, at least in Scotland where data are available from the upper Dalradian, contain a significant component of Archaean detritus (Fig. 7; Cawood *et al*. 2003). In the Nathorst Land Group, B. Dhuime (pers. comm.) has noted that Palaeoproterozoic detritus is present throughout the group but that Archaean grains increase, and Mesoproterozoic detritus decreases, up-section.

Fig. 8. Probability plots of latest Neoproterozoic to early Palaeozoic metasedimentary units from along the Appalachian–Caledonian orogen in East Laurentia. Sources of data: Central Appalachians (Unicoi, Erwin, Hardystron formations), Eriksson *et al*. (2004); Eastern Blue Ridge–Piedmont (including Eastern and Central Blue Ridge, Dahlonega gold belt, Sauratown Mountains window and Smith River Allochthon), Bream *et al*. (2004) and Carter *et al*. (2006); Hebridean Foreland (Eriboll Formation, Ardvreck Group), P. A. Cawood *et al*. (unpubl. data); Newfoundland (Bradore, Hawke Bay, Summerside, South Brook, Blow-Me-Down Brook formations), Cawood & Nemchin (2001); North Central Appalachians (Poughquag Quartzite), McLennan *et al*. (2001); Precordillera (Cerro Totora Formation), Thomas *et al*. (2004); Scottish Caledonides (Upper Dalradian Supergroup including Appin, Argyll and Southern Highlands groups), Cawood *et al*. (2003); Southern Appalachians (Rome Formation), Thomas *et al*. (2004); Western Blue Ridge, Bream *et al*. (2004). s, number of samples; n, number of analyses.


SVALBARD
CAL.
E. GREENLAND CAL.
UK CAL.
East
Laurentian
margin
Grenville
APPALACHIAN
CORDILLERAN
OUACHITIAN
500 km
c. 1.3-0.95 Ga
Grenville orogen
Mesoproterozoic AMCG
plutonic suites
Mid-continent rift system
(1.2-1.1 Ga)
Granite-rhyolite terrane
(1.5-1.3 Ga)
1.8-1.6 Ga orogenic belts
2.0-1.8 Ga orogenic belts
Pre-1.9 Ga continental
margin supracrustal rocks
Archean cratons
Neo
Meso
Palaeo
Archaean
Hebridean Foreland (520 Ma)
s= 3, n=173
Scottish Caledonides (630-550 Ma)
s=6, n=317
Newfoundland (550-520 Ma)
s=5, n=282
Nth Central Appalachians (530 Ma)
s=1, n=39
Central Appalachians (530 Ma)
s=3, n=266
W. Blue Ridge (600-530 Ma)
s=4, n=144
E. Blue Ridge/Piedmont (600-530 Ma)
s=22, n=786
Sth Appalachians (530 Ma)
s=2, n=104
Precordillera (530 Ma)
s=1, n=25
Relative Probability
500
1000
1500
2000
2500
3000
3500
Ma

Late Neoproterozoic to early Palaeozoic sedimentary rocks associated with the later stages of Iapetus opening can be traced along the eastern margin of Laurentia. The provenance of this age grouping changes dramatically along the strike of the Appalachian–Caledonian orogen. Those in the US Appalachians, and including the Argentine Precordillera (Thomas & Astini 1996), are dominated by Mesoproterozoic zircon detritus, particularly late Mesoproterozoic ages (Fig. 8). In contrast, those in the north, including the Caledonides and Canadian Appalachians, also include significant Archaean and Palaeoproterozoic detritus. Late Neoproterozoic zircon grains are present in minor amounts in samples north of the Blue Ridge, with ages around 620–570 Ma, consistent with the timing of rift-related magmatism along the Laurentian margin (see Cawood *et al*. 2001). Samples from the Rome Formation in the southern Appalachians, and to a lesser extent those from the Argentine Precordillera, show evidence for input of an increased component of early Mesoproterozoic and older grains, suggesting a drainage system that is tapping into the interior of the continent (Thomas *et al*. 2004).

The Lower to Middle Cambrian Ardvreck Group accumulated on the Hebridean foreland, unconformably on Torridonian and Lewisian units, and is time equivalent to the uppermost Southern Highlands Group of the Dalradian (Strachan & Holdsworth 2000). Detrital zircons from the Eriboll Formation are solely of Archaean and Palaeoproterozoic age, with the latter increasing up-section (Fig. 8; P. A. Cawood *et al*., unpubl. data). The Zebra series of East Greenland occupies a similar position to the Eriboll Formation, lying inboard of Caledonian orogenic activity, and limited detrital zircon data suggest that it shows a similar provenance, dominated by Archaean detritus (Tucker *et al*. 1993). The absence of Mesoproterozoic (Grenville) detritus distinguishes these units from time-equivalent units that lie within the Caledonian segment of the orogen. This implies that the drainage system sourced detritus from the west, consistent with available palaeocurrent data, and did not extend into currently structurally juxtaposed and temporally equivalent units such as the Dalradian, which continued to receive an axial supply of detritus from the south to account for the significant Grenville age detrital component. Development of a rift shoulder related to Iapetus opening provides a probable structural and drainage divide to separate these two basin types.

Detrital zircon data from Baltica during the interval of Rodinia breakup are limited to the late Neoproterozoic sandstone underlying the Moelv Tillite. Zircon detritus mainly yields late Palaeoproterozoic to Mesoproterozoic ages (1800–985 Ma) but with late Neoproterozoic grains as young as 620 ± 14 Ma (Bingen *et al*. 2005*a*). The tillite is correlated with the *c*. 580 Ma Gaskiers glacial event (Bowring *et al*. 2003; Halverson *et al*. 2005).

Amazonia

The inferred collision of Amazonia with Laurentia–Baltica (Loewy *et al*. 2003*a*; Tohver *et al*. 2004*b*) terminated Assemblage 1 type basins and resulted in the development of Assemblage 2 and 3 type basins within Rodinia before breakup of the supercontinent and formation of type 4 basins during opening of the Iapetus ocean. In the SW Amazon Craton, thick sequences were deposited in a marginal basin predating the collision to Laurentia at *c*. 1100 Ma (Santos 2003). These immature units, termed the Nova Brasilândia Group and Colorado do Oeste and Fortuna formations, are comparable with the Piraparaná Formation (1100 Ma, Rb–Sr whole-rock isochron, Priem *et al*. 1982) of NW Amazonia (SE Colombia), suggesting the existence of a much larger basin now almost totally covered by Andean-derived Cenozoic deposits. S-type leucogranites derived from the partial melt of the metasedimentary rocks are dated at *c*. 1100 Ma (Rizzotto *et al*. 1999), marking peak metamorphism and constraining the minimum age of the basins. Detrital zircons from Nova Brasilândia Group and Fortuna Formation (Santos 2003) produced four main peaks at 1560, 1450, 1320 and 1170 Ma. Zircons in the 1450–1170 Ma range are derived from the Sunsás orogen to the west and the 1560 Ma zircons correlate to the Serra Providência rapakivi suite, which occurs to the north and east of the basins. Unpublished detrital zircon U–Pb data from the Aguapeí Group in Bolívia (J. O. S. Santos, pers. comm.) indicate that the basin is almost entirely derived from the older orogenic rocks within the Sunsás Belt (47 grains out of 49). The two main peaks on cumulative plots mark the duration of the Candeias (1380–1312 Ma; 61% of the detritus) and Santa Helena (1458–1416 Ma; 20% of the detritus) orogenies.

Three syn-collisional basins developed on the Amazonia foreland, to the east of the of the Sunsás front, in response to orogenic uplift. They are named Palmeiral, Pacaás–Novos and Apiacás, and consist of flat-lying fluvial deposits having a dominantly arkosic composition. Detrital zircon grains as young as 1050 Ma constrain the maximum age for the Palmeiral Basin (Santos 2003).

Detrital zircons from rift and passive margin basins formed during Iapetus opening are restricted to the Punocoviscana Formation and correlative units (e.g. Sierras de Córdoba). Zircons are mainly Neoproterozoic (760–570 Ma) and early Neoproteroozic to late Mesoproterozoic (1100–880 Ma) with minor Palaeoproterozoic (*c*. 1900–1800 Ma) and late Archaean grains (*c*. 2700 Ma) (Schwartz & Gromet 2004; Adams *et al*. 2005). Age patterns are consistent with derivation from cratonic South America or contiguous regions of SW Africa.

Discussion

Source terranes

The detrital zircon record of Mesoproterozoic to early Palaeozoic sedimentary successions from along the eastern margin of Laurentia and Baltica shows a remarkably similar pattern for ages of the main sediment pulses. Major age peaks within the sample set (Figs 5, 7 and 8) occur in the late Archaean (*c*. 2.7 Ga), late Palaeoproterozoic (2.0–1.75 Ga), early Mesoproterozoic (*c*. 1.5 Ga), and late Mesoproterozoic to earliest Neoproterozoic (1.2–0.95 Ga). Latest Palaeoproterozoic to mid-Mesoproterozoic material is variably present and early Palaeoproterozoic (2.5–2.0 Ga) and Neoproterozoic detritus is rare or absent. The amplitude of the age peaks varies between sample groups. The overall age patterns are consistent with derivation of the majority of the samples from the cratonic interior of Laurentia and Baltica (Figs 2 and 3), which records the following events: (1) accretion of cratonic nuclei in the late Archaean (*c*. 2.7 Ga); (2) relative quiescence until assembly of these cratonic fragments at around 2.0–1.8 Ga; (3) convergent margin tectonism along the eastern and southern margins of Laurentia and Baltica; (4) final collisional insertion within the supercontinent of Rodinia at the end of the Mesoproterozoic (1.2–0.95 Ga). Detritus from the northern Appalachians and Caledonides often shows age modes at 1.65 and 1.5 Ga, consistent with input from NE Laurentia and Baltica sources such as the Trans-Labrador batholith and Pinware arc (and correlative units) (Cawood *et al*. 2003, 2004; Friend *et al*. 2003; Banks *et al*. 2007; Kirkland *et al*. 2006).

The evidence for Neoproterozoic tectonothermal events affecting strata of the northern Caledonides in Scotland and Norway has been cited (e.g. Bluck *et al*. 1997; Corfu *et al*. 2006) as evidence for a non-Laurentian–Baltica origin that requires input from a Gondwana 'Pan-African' source. In the classic Gondwana sequences, Neoproterozoic detritus reflects the effects of arc accretion and assembly events leading ultimately to continental collision and Gondwana assembly (e.g. Stern 1994; Veevers 2000). This contrasts with the Neoproterozoic history of the northern Caledonides, where there is no record of any calc-alkaline magmatism that might be related to development of active plate margins, and contemporaneous detritus is conspicuously absent. Importantly, the provenance of these units (Krummedal, Moine, Sørøy) clearly ties them to a Laurentian source and excludes an exotic origin (Cawood *et al*. 2004; Kirkland *et al*. 2006). Cawood *et al*. (2004) integrated the detrital zircon data for these units with palaeogeographical reconstructions (Fig. 1) to argue that the Neoproterozoic sequences in the Caledonides accumulated in an intra-cratonic setting and deformation was driven by far-field effects around the margins of Rodinia.

Establishing if detritus is first or multi-cycle is a primary concern in any provenance study, particularly for a resistant and stable mineral phase such as zircon. Reworked detritus is likely to be an issue where basins unconformably overlie older sedimentary sequences such as the Dalradian and Eleonore Bay supergroups of Assemblage 4, which overlie Assemblage 3 basins. The lower Dalradian Grampian Group contains Palaeoproterozoic and Mesoproterozoic age material similar to the underlying Moines (Fig. 6). The Nathorst Land and Lyell Land groups of the Eleonore Bay Supergroup show a similar compositional relation to the underlying Krummedal Group. Surrounding basement source terranes are of Archaean and Palaeoproterozoic age, and Mesoproterozoic sources currently lie a considerable distance to the south (Fig. 2). The Grampian rocks are medium- to coarse-grained rift-fill sediments with evidence for syn-sedimentary faulting and block uplift (Smith *et al*. 1999), so it is likely that rift-shoulder uplift was pronounced and at least parts of the Grampian Group were sourced locally (see Cawood *et al*. 2003, sample 516, Glen Buck psammite). At that time, the Moine (and Torridon Group) would have covered much of the hinterland and could have formed the immediate source. The upper Dalradian shows an influx of Archaean detritus (Fig. 7) and this could reflect erosion through the Neoproterozoic and Mesoproterozoic sedimentary cover into underlying Archaean basement or regional subsidence and enlargement of the source region to include Archaean terranes. Recently however, Banks *et al*. (2007) have shown variation in the provenance of the Grampian Group reflecting local palaeogeographical effects, with westerly derived sedimentary systems dominated by voluminous 1.8 Ga detritus and easterly derived material dominated by 1.0–0.9 Ga sources. This observation requires either changes in the nature and composition of the inferred reworked sedimentary basins either side of the Grampian Group or, as favoured by Banks *et al*. (2007) and consistent with basement outcrop patterns, changes in the primary source component.

Spatial and temporal trends in provenance

The 1000 Ma age range and 6000 km along-strike spread of sedimentary units from East Laurentia and Baltica provide an opportunity to establish temporal and spatial trends in zircon age patterns. However, as noted above, the lateral continuity and discrete age pulses of tectonostratigraphic events associated with assembly of Laurentia and Baltica have resulted in relatively simple age patterns in source regions (Figs 2 and 3) and in resultant detrital age signatures in the variety of basin types that developed within this broad temporal and spatial framework (Figs 5, 6 and 8). Furthermore, structural disruption within the various aged orogenic belts means that the original physical proximity of currently juxtaposed sedimentary sequences that cover a variety of depositional ages is uncertain and the preservation of time-equivalent units throughout the region is variable and generally becomes more fragmentary for older units. Within these limits, available data show that temporal trends are best observed in the NE Laurentia and west Baltica segments and spatial trends are limited to the late Neoproterozoic to early Palaeozoic time period.

The youngest detrital zircon grains in the Mesoproterozoic sedimentary units that accumulated either pre- and/or syn-assembly of Rodinia (Assemblages 1 and 2) approximate the inferred time of sediment accumulation (Fig. 5), and the youngest peak is a prominent or dominant component of the age spectrum. This is consistent with the inferred tectonic setting along active convergent plate margins. The Stoer Group is an exception to this pattern, consistent with its site of accumulation well inboard of the margin in a rift setting dominated by locally derived detritus. In general, the pre-assembly strata from northern Laurentia show a more restricted age signature than those from Baltica, which is again consistent with the accumulation of Laurentian units within an arc setting whereas the broader age spectrum of units from Baltica suggest greater input from the cratonic hinterland through accumulation inboard of the main arc. In contrast, the Neoproterozoic to early Palaeozoic sediments that accumulated after Rodinia assembly (Assemblages 3 and 4) generally lack evidence for input from contemporaneous igneous sources. In fact, some of the younger Palaeozoic units showing an age gap of almost 500 Ma between sedimentation age and the youngest detrital component (Grenvillian, Fig. 8). This observation is also consistent with the inferred intraplate and divergent plate tectonic setting of these assemblages.

Figure 9 is a series of schematic cross-sections across East Laurentia–Baltica covering the time frame from pre-collision with Amazonia to continental breakup and Iapetus opening, showing the setting of the main sedimentary units. This figure emphasizes the changing regional drainage patterns for sediment accumulation. During Assemblage 1, prior to supercontinent assembly, drainage patterns extended from the continental interior towards the margins, which included active arc systems. By the latter stages of Assemblage 2, the previous continental margin assemblages were located within the continental interior and were being reworked within a major collisional mountain chain, which constituted a drainage divide. In the early to mid-Neoproterozoic (Assemblage 3), the Grenville mountain range subsided and locally underwent extension and basin development (intermontane, successor or intracratonic basins). However, it still formed a significant sediment source for basins developed inboard of the mountain range (e.g. Krummedal and Moine and related units). Finally, in the late Neoproterozoic to early Palaeozoic, Assemblage 4 time, associated with extension leading to continental breakup and Iapetus opening, drainage was re-established from the interior of Laurentia and Baltica, but in a divergent rather than convergent plate setting.

Although opening of the Iapetus Ocean is generally envisaged as following older inherited zones of weakness associated with the Grenville–Sveconorwegian orogen (Williams 1995), it is clear from palaeogeographical reconstructions (Fig. 2) that opening of the northern Iapetus Ocean (Caledonides) cut directly across the deformational front of this old orogen. In the

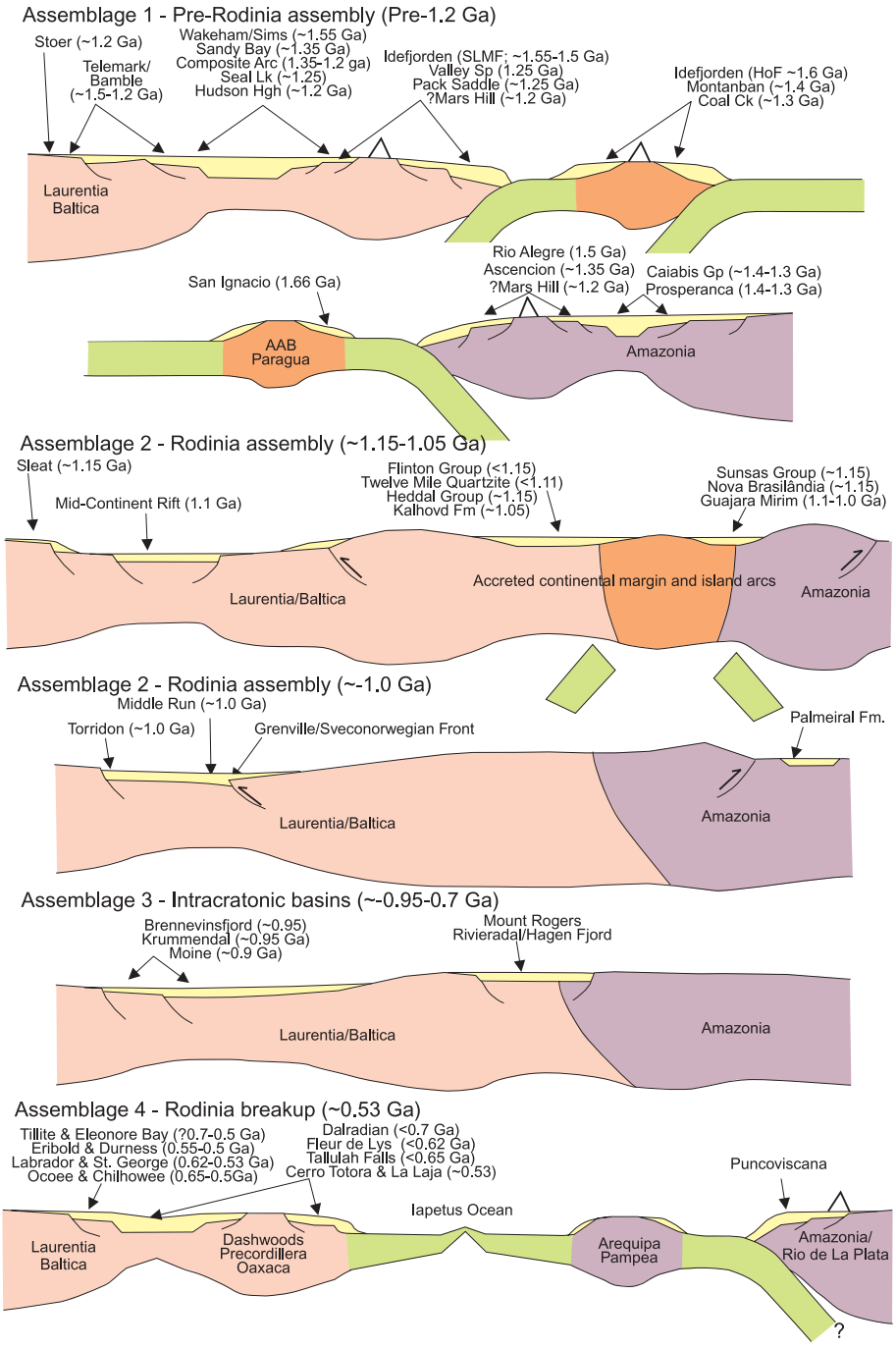


Fig. 9. Schematic cross-sections from Laurentia–Baltica and Amazonia showing positions of sedimentary basins pre-, syn- and post-Rodinian supercontinent cycle. For simplicity, subduction zones associated with Assemblage 1 basins are show as dipping towards the craton (see Mosher 1998) but changes in subduction direction and subduction away from the craton have been invoked during final collision (e.g. Gower 1996; McLelland *et al*. 1996).

Appalachians, Iapetus opening followed the overall trend of the Grenville orogen. However, north of Newfoundland, Iapetus rifting occurred to the north of the Grenville–Sveconorwegian belt, lying almost orthogonal to the trend in Laurentia, and opening of the northern Iapetus Ocean cut across older Proterozoic and Archaean structural trends (Fig. 2; Cawood & Pisarevsky 2006). Thus the Iapetan rift basins and subsequent Caledonides in Scotland lie largely on the cratonic foreland of the Grenville–Sveconorwegian orogen. The effect of this divergence in orogen trends is significant in understanding temporal trends in the provenance of sediments associated with the Iapetan-related rift and passive margin sequences (Assemblage 4, Fig. 8). Sediments that accumulated within the central and southern Appalachians lay within the pre-existing Grenville orogen and detrital zircon age signatures are dominated by late Mesoproterozoic detritus. Older detritus, which would come from the continental interior, is rare. This observation indicates that the western margin of the Grenville orogen acted as a drainage divide, either a relict of the mountain range related to Rodinia assembly or, perhaps more likely, reflecting the development of rift shoulders, related to lithospheric extension during Iapetan opening. In the northern Appalachians and north into the Caledonides, the proportion of Archaean to early Mesoproterozoic detritus within the rift and drift sediments increases (Fig. 8).

These regions lie close to, or inboard of, the older orogenic front and even if a rift shoulder was developed they would receive sediment derived from the older cratonic elements of Laurentia–Baltica as well as remnants of the Grenville mountain front. The most inboard units, however, such as the Ardvreck and Zebra successions, did not receive Mesoproterozoic detritus, again perhaps isolated from that source by lying in-board of a rift shoulder.

Conclusions

A supercontinent cycle involving assembly and dispersal of continental fragments through closure and opening of ocean basins is the consequence of a range of contractional and extensional tectonic settings and therefore results in a variety of basin types. These include basins formed in convergent settings such as continental margin and island arc basins, collision-related basins including collision, foreland and successor basins, intracratonic basins, and basins in divergent settings such as rift basins and passive continental margins (e.g. Ingersoll & Busby 1995). Basins forming at plate margins, whether in contractional or extensional settings (e.g. arc-related basins, rift and foreland basins) will tend to be disrupted by faulting and compartmentalized because of the tectonically unstable environment, resulting in along-strike changes in facies and sediment thickness. In contrast, basins that develop away from plate margins will tend to be larger and characterized by lateral continuity of facies and stratal thickness as a result of overall tectonic stability. Syn-sedimentary igneous activity, developed in convergent margin basins and some rift basin settings, will further affect basin character and at least in settings involving explosive igneous activity (arcs) or rapid uplift and erosion (collision) will also strongly influence sediment composition. Sedimentary facies within basins and the extent of their drainage systems will be a function of these tectonic settings and, combined with source region character, will ultimately control sediment composition.

The record of sedimentary basins associated with assembly and breakup of Rodinia conforms well to this view of basin type and the supercontinent cycle. Assemblage 1 basins lying along the margin of Laurentia and Baltica in the Mesoproterozoic prior to Rodinia assembly formed in an overall convergent margin environment associated with, or inboard of, magmatic arcs. Zircon detritus is dominated by material that approximates the time of sediment accumulation, with the proportion of older, cratonic aged detritus dependent on the position of the basin with respect to the hinterland source; those basins inferred to lie inboard of the arc containing a greater proportion of older detritus. Assemblage 2 basins, which formed during end Mesoproterozoic Rodinia assembly, are also dominated by zircon detritus with ages similar to the inferred age of sediment accumulation, reflecting syn-collisional magmatism and rapid exhumation of the developing mountain range. The zircon detritus reflects strong uplift of specific source areas in the Grenville–Sveconorwegian orogen. This resulted in sharp peaks of either syn-Grenville magmatic zircons or of older zircons from rocks reworked and uplifted within the Grenville Orogeny (e.g. 1650 Ma peak originating from uplifted Trans-Labrador Batholith in NE Laurentian basins). Archaean material was largely unexposed within the Grenville–Sveconorwegian orogen, so that Archaean material is rare to absent in Assemblage 2 basins. Assemblage 3 intracratonic basins lack input from syn-depositional magmatic activity, resulting in an increasing gap between age of sediment accumulation and the youngest detrital grain. Although some approximately syn-sedimentary igneous activity is recorded in these basins (Millar 1999; Rogers *et al*. 2001), it was either intrusive or non-explosive so that, even though these basins were subsequently inverted during tectonothermal events, igneous material does not appear to have been reworked into younger deposits. This basin type is best developed in the Caledonides and is dominated by Palaeoproterozoic and Mesoproterozoic detritus along with only a minor component of Archaean detritus. This compositional character is despite the fact that these units currently lie up to thousands of kilometres from Mesoproterozoic sources but are proximal to Archaean sources. Thus, although localized tectonothermal activity and associated uplift and exhumation occurred within and around these intracratonic basins (e.g. Knoydartian, Porsanger orogenic events), the immediate hinterland was relatively subdued, whereas the Grenville–Sveconorwegian mountain range, assuming first cycle input, was still a significant palaeogeographical element with a well-developed drainage system. Hoffman & Grotzinger (1993) argued that the deep erosion of the Grenville orogen and the extensive dispersal of derived detritus on the Laurentian foreland resulted from the orogenic front being favourably oriented to receive trade winds, which resulted in high orographic precipitation. The extensive Grenville-aged detritus developed within Assemblage 3 basins is consistent with this inference but the absence of data from the conjugate, hinterland in Amazonia makes it difficult to critically establish the lee and windward sides of the orogen. Assemblage 4 rift basins and passive margin sequences formed during breakup of the Rodinian supercontinent and are divisible into two basic types on the basis of detrital zircon age profiles, which relate to differences with respect to the Grenville–Sveconorwegian mountain front and drainage divide. Assemblage 4 basins within the Caledonian orogen lie on the foreland of the Grenville–Sveconorwegian mountain front and incorporate both Archaean and Palaeoproterozoic detritus, presumably derived from the cratonic interior, with Mesoproterozoic detritus derived from the orogenic front. In the Appalachian orogen, Assemblage 4 basins are dominated by Mesoproterozoic detritus with older detritus forming only a minor component, suggesting restricted input from the cratonic interior as a result of either the Grenville orogen still forming a drainage divide or formation of rift shoulders associated with Iapetus opening restricting input from the continental interior. Although magmatic activity is developed along the Appalachian–Caledonian orogen during Iapetus opening, syn-depositional igneous detritus is very limited (Fig. 8), reflecting the non-explosive or intrusive nature of this type of magmatic activity as well as its often mafic, zircon-poor character; for example, in the Dalradian Supergroup, syn-depositional magmatic detritus occurs in the Green Beds and Tayvallich volcanic rocks but there is little magmatic-aged zircon.

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