Chapter 31

A Palaeozoic NW Passage and the Timanian, Caledonian and Uralian connections of some exotic terranes in the North American Cordillera

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Abstract: Exotic terranes of inferred Arctic affinity form an outer belt within the North American Cordillera extending from Alaska to northern California. The geological history, fossil and detrital zircon data for these terranes show strong correlations and linkages among them, and many features in common with the northern Caledonides, the Timanide orogen and the Urals. They probably occupied an intermediate position between Baltica, Laurentia and Siberia, in proximity to the northern Caledonides in Early Palaeozoic time. Westward dispersion of these terranes is interpreted to result from development of a Scotia-style subduction system between Laurentia–Baltica and Siberia in Mid-Palaeozoic time – the NW Passage – following closure of the Iapetus ocean. Diachronous orogenic activity from Late Silurian in Arctic Canada to Early Devonian in north Yukon and Alaska records passage of some of these terranes. Westward propagation of a narrow subduction zone coupled with a global change in plate motion, linked to closure of the Rheic Ocean are proposed to have led to initiation of subduction along the western margin of Laurentia. This is recorded by the Late Devonian initiation of arc magmatism along western Laurentia, and the Late Devonian–Early Mississippian Antler orogeny in the western US and Ellesmerian orogeny in the Canadian Arctic.

The North American Cordillera is an accretionary orogen that extends from Mexico northward to the Arctic Ocean, where it intersects the Palaeozoic Ellesmerian orogen along northern Laurentia and merges with younger orogens bordering Siberia (Figs 31.1 & 31.2). It developed as a result of the convergence of terranes – mobile crustal blocks with a variety of origins, including continental fragments, pieces of island arc crust and oceanic tracts – with the western margin of the Laurentian craton beginning in Late Palaeozoic time and continuing today.

Detailed mapping coupled with application of analytical tools (Nd, Hf, Sr isotopes; geochemistry; U–Pb geochronology, particularly of detrital zircon suites; palaeomagnetism) and the fossil evidence have provided a sound basis for understanding the geological history and geodynamic affinities of the Cordilleran accreted terranes. It is now recognized that a group of terranes that generally occupy the core of the orogen (Yukon–Tanana, Quesnellia, Stikinia and related terranes) were generated along the western margin of Laurentia as a series of rifted continental fragments, superposed arcs and marginal ocean basin(s) in Mid-Palaeozoic to Early Mesozoic time (Fig. 31.1; Monger & Nokleberg 1996; Nokleberg *et al.* 2000, 2005; Nelson *et al.* 2006; Colpron *et al.* 2007). These terranes tectonically enclose the Cache Creek terrane (Fig. 31.1), a tract of oceanic rocks with Palaeozoic faunal elements of Tethyan (Asian) affinity that were incorporated during the Early Mesozoic development of the Cordilleran orogen (Mihalynuk *et al.* 1994).

By contrast, terranes that generally occupy more outboard positions in the orogen, the Arctic realm of Colpron *et al.* (2007), have been recognized by a growing consensus as manifesting Palaeozoic and older affinities with northern Baltica (Alexander; Bazard *et al.* 1995; Gehrels *et al.* 1996; Soja & Antoshkina 1997; Antoshkina & Soja 2006), Siberia (e.g. Farewell; Blodgett *et al.* 2002; Dumoulin *et al.* 2002; Bradley *et al.* 2003, 2007), the northern Caledonides (part of Arctic Alaska; Nilsen 1981; Sweeney 1982; Moore *et al.* 1994; Macdonald *et al.* 2009), or tectonic interleaving or transitional affinities between Arctic and northern Laurentian elements (e.g. Arctic Alaska, Eastern Klamath, Northern Sierra and others; Dumoulin *et al.* 2002; Wright & Wyld 2006; Lindsley-Griffin *et al.* 2008; Fig. 31.1). Equally important, shared faunas, igneous and deformational events, and similar detrital zircon populations suggest that all of these terranes developed in some proximity to each other, and therefore constitute elements of a single, albeit complex, tectonic system.

In a recent review of Cordilleran terranes, we have proposed a geodynamic model that explains many aspects of the Palaeozoic evolution of northern and western Laurentia and provides a mechanism for the transport of exotic terranes into eastern Panthalassa, the Palaeozoic proto-Pacific Ocean (Colpron & Nelson 2009). In this paper, we focus our attention on the Cordilleran terranes of Arctic affinities in Palaeozoic time, their tectonic history, and their probable sites of origin. We first summarize the main characteristics of proposed source regions for these terranes – the Circum-Arctic Precambrian cratons of Laurentia, Baltica and Siberia, and their bordering Neoproterozoic–Palaeozoic orogens – and then review the main lines of evidence that link Cordilleran terranes to these source regions. We place particular emphasis on the growing global database of detrital zircon ages that continues to refine previous interpretations derived mainly from the fossil and palaeomagnetic record. We then review our hypothesis that accounts for the incursion of crustal fragments of inferred Timanian, Caledonian and Uralian affinities into eastern Panthalassa via a Caribbean/Scotia-style subduction system – the NW Passage – that developed between Laurentia–Baltica and Siberia in Mid to Late Palaeozoic time as the Iapetus and Rheic oceans closed and Pangaea was being amalgamated (Colpron & Nelson 2009). This hypothesis also provides an explanation for the enigmatic Mid-Palaeozoic compressional (transpressional) deformational events documented along the northern and western continental margin of Laurentia, as well as the rapid onset of subduction along its western margin in Devonian time.

The Circum-Arctic Precambrian cratons

The Precambrian cratons Laurentia, Baltica and Siberia, that now occupy the core of the modern Circum-Arctic continents, evolved independently from the Gondwana supercontinent for much of Palaeozoic time. Although separated by oceans (e.g. Iapetus, Aegir, Uralian), their evolution was apparently geodynamically linked until their end Permian convergence to form northern Pangaea (e.g. Dalziel 1997; Scotese 2002; Golonka *et al.* 2003;

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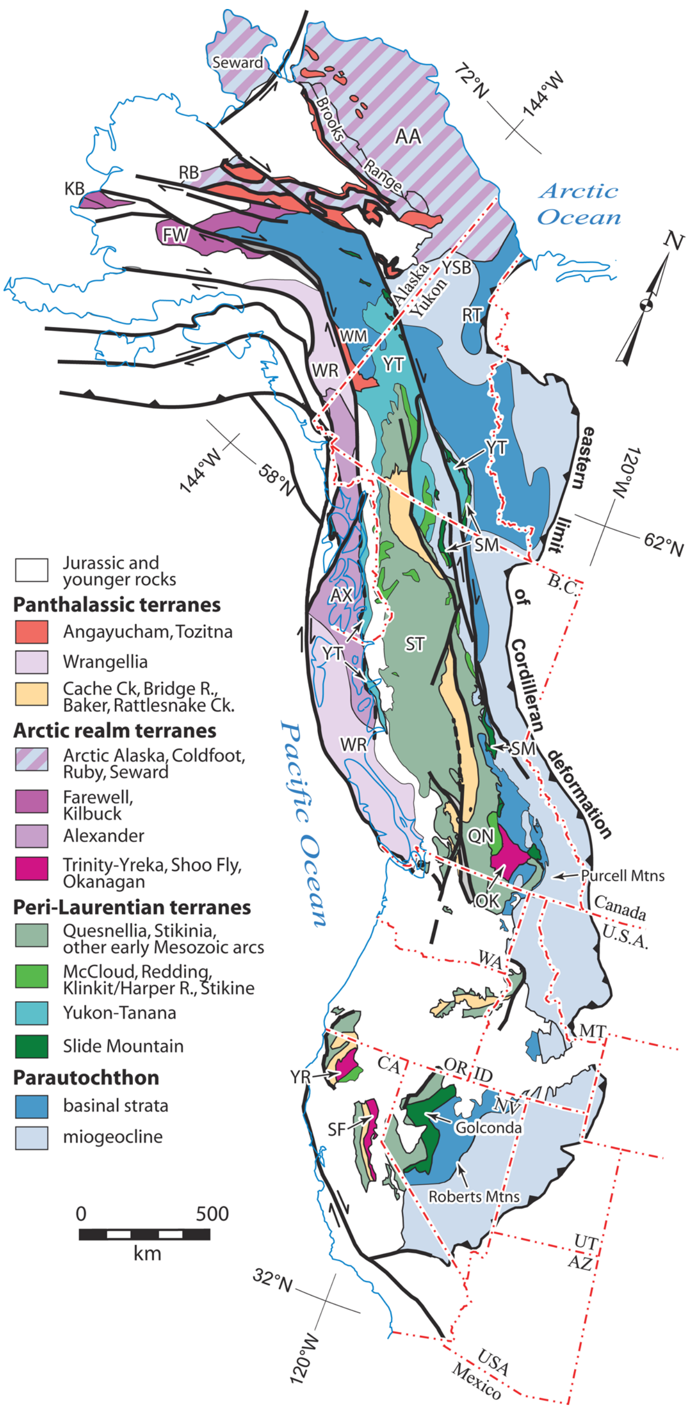

Fig. 31.1. Palaeozoic to Early Mesozoic terranes of the North American Cordillera. Terranes are grouped according to faunal affinity and/or source region in Early Palaeozoic time. Terrane abbreviations: AA, Arctic Alaska; AX, Alexander; KB, Kilbuck; OK, Okanagan; QN, Quesnellia; RB, Ruby; RT, Richardson trough; SF, Shoo Fly complex; SM, Slide Mountain; ST, Stikinia; WM, Windy–McKinley; WR, Wrangellia; YR, Yreka and Trinity; YSB, Yukon Stable Block; YT, Yukon–Tanana terrane. Other abbreviations: B.C., British Columbia; CA, California; NV, Nevada; OR, Oregon; USA, United States of America.

Cocks & Torsvik 2006), as suggested by the shared Palaeozoic histories of many of their margins as outlined later in this paper. The Precambrian makeup of these cratons shows distinct superposition of geological events, that in some cases provide unique fingerprints for the source region of detrital minerals, in a number of significant instances pointing to a specific part of a craton. We summarize below the main characteristics of the three Circum-Arctic cratons.

Laurentia

The Laurentian craton is characterized by Archaean cores (e.g. Slave, Superior, Wyoming), predominance of Palaeoproterozoic magmatic arcs in the northern and western parts of the craton (e.g. Hottah, Great Bear, Fort Simpson), and of Mesoproterozoic crust, including the Yavapai–Mazatzal and Grenville orogens, in its southern and eastern parts (Fig. 31.2; Hoffman 1988; Ross & Villeneuve 2003). This distribution of Precambrian basement domains is reflected in the detrital zircon populations of Neoproterozoic–Palaeozoic strata that were deposited along the Laurentian continental margins, with detrital zircon signatures that typically correspond with nearby Precambrian domains. For instance, Neoproterozoic–Palaeozoic siliciclastic rocks deposited along the Cordilleran margin near northwestern Laurentia have detrital signatures dominated by Archaean (>2.6 Ga) and Palaeoproterozoic (*c.* 2.0–1.8 Ga) zircons, with a subordinate population in the 2.4–2.2 Ga range, derived from the Slave, Great Bear and Hottah domains, respectively (Figs 31.2 & 31.3b; Gehrels *et al.* 1995; Gehrels & Ross 1998; Gehrels 2000). In contrast, rocks deposited along the Appalachian margin are dominated by zircons derived from the Grenville orogen (*c.* 1.4–1.0 Ga) with only minor contributions from Palaeoproterozoic and Archaean domains (Figs 31.2 & 31.3d, e; Cawood *et al.* 2007). And those deposited along the northeastern margin of Laurentia, now preserved in Scotland and Greenland, show a mixed Archaean, Palaeoproterozoic and Mesoproterozoic signature (Figs 31.2 & 31.3f, g; Cawood *et al.* 2007).

Along the western Laurentian margin, significant Grenvillian (*c.* 1.4–1.0 Ga) detrital zircon populations are restricted to the southermost and northernmost parts of the Cordillera (Fig. 31.3a, c; Gehrels *et al.* 1995; Gehrels 2000). In the southwestern USA, they are derived from local basement sources, namely the southwestern extension of the Grenville orogen into Texas and Mexico (Gehrels *et al.* 1995; Whitmeyer & Karlstrom 2007). Their more unexpected northern occurrence is accounted for by Rainbird *et al.* (1997), who hypothesize that they were initially introduced into lower Neoproterozoic strata (*c.* 800 Ma) via cross-continental fluvial transport from the then-high-standing Grenville orogen. These older strata probably provided a local source for minor populations of Grenvillian zircons occurring in younger sedimentary rocks along the western Laurentian margin (Fig. 31.3a–c). An important characteristic of Laurentia is the paucity of magmatic ages in the 1.61–1.49 Ga range, coined the ‘North American magmatic gap’ by Ross & Villeneuve (2003; Van Schmus *et al.* 1993; hatched area in Fig. 31.3). Magmatism of this age is only known locally in the eastermost Grenville province of Canada (Pinware terrane; Fig. 31.2; Gower *et al.* 2008).

Baltica

Baltica also has a distinct Precambrian makeup, with Archaean domains occupying mainly its northeastern part (Karelian, Vulgo–Uralia), and progressively younger Palaeoproterozoic (Svecofennian) and Mesoproterozoic (Gothian, Telemarkian, Sveconorwegian) domains towards the SW (Fig. 31.2; Gee & Stephenson 2006). Palaeoproterozoic crust in the 2.2–2.0 Ga range is restricted to southern Baltica (Sarmatia), near the Black Sea. An important feature of Baltica is the belt of *c.* 1.65–1.50 Ga Rapakivi granite magmatism that intrudes the central part of the Svecofennian domain (Fig. 31.2) and records a period of intracratonic extension unique to Baltica (Bingen *et al.* 2008). Together with the Gothian (*c.* 1.64–1.52 Ga) and Telemarkian magmatism (*c.* 1.52–1.48 Ga), the Rapakivi magmatism constitutes an important source of Mesoproterozoic zircons that fall within the ‘North American magmatic gap’ (*c.* 1.61–1.49 Ga) and thus provide a unique fingerprint for western Baltica. Detrital zircons from the Neoproterozoic–Early Palaeozoic western margin of Baltica are

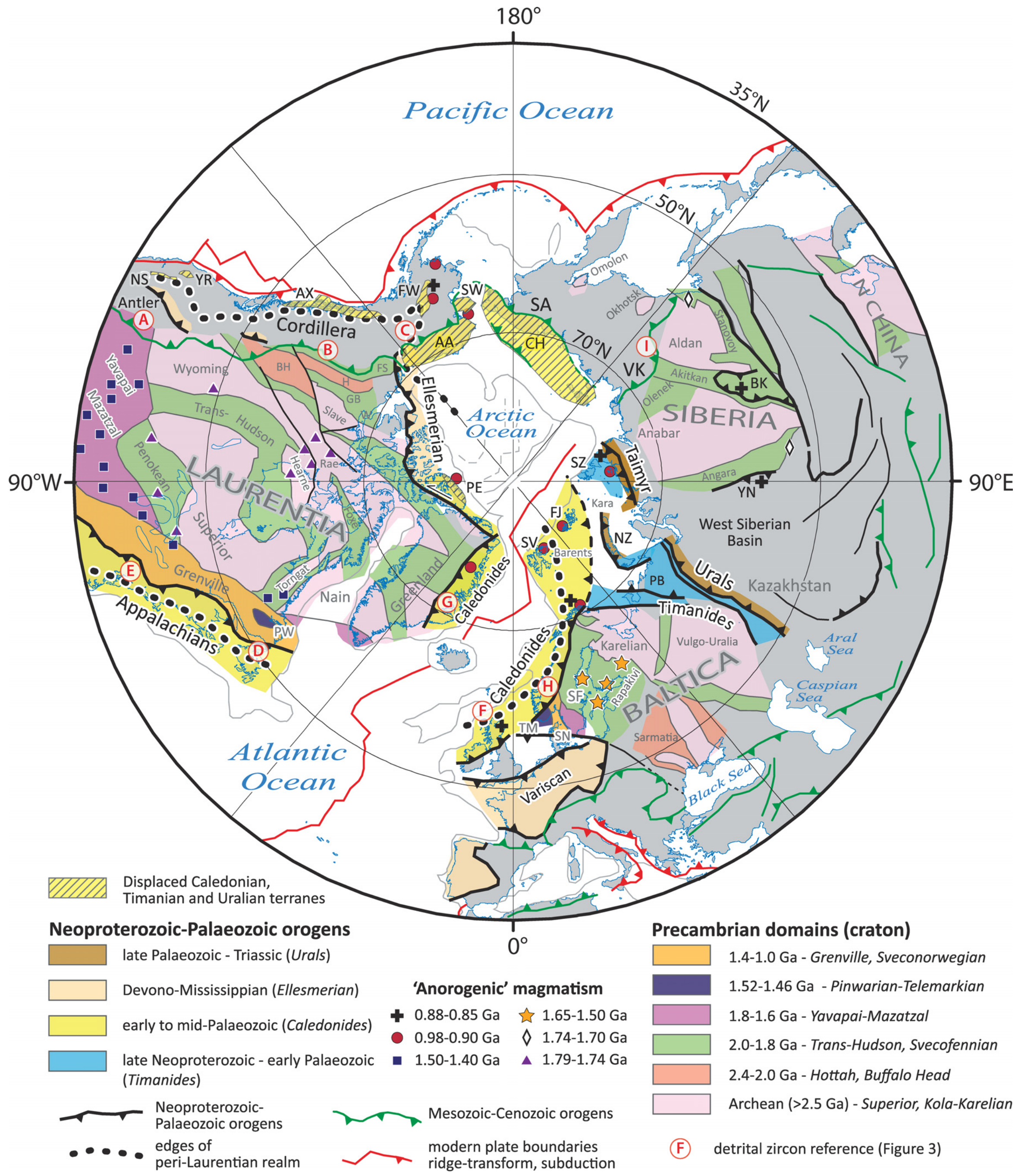

Fig. 31.2. Cratons and orogens of the Circum-Arctic region; polar stereographic projection. Precambrian basement domains of Laurentia after Hoffman (1988) and Ross & Villeneuve (2003); Baltica after Gee & Stephenson (2006); and Siberia after Rosen *et al.* (1994) and Khudoley *et al.* (2007). Grey areas are Palaeozoic and younger cover rocks and Mesozoic–Cenozoic orogens. Abbreviations: Precambrian cratons – BH, Buffalo Head; FS, Fort Simpson; GB, Great Bear; H, Hottah; PW, Pinware; SF, Svecofennian; SN, Sveconorwegian; TM, Telemark. Other abbreviations: AA, Arctic–Alaska terrane; AX, Alexander terrane; BK, Baikal–Vitim orogen; CH, Chukotka; FJ, Franz Josef Land; FW, Farewell terrane; NS, Northern Sierra terrane; NZ, Novaya Zemlya; PB, Pechora basin; PE, Pearya; SA, South Anyui zone; SV, Svalbard; SW, Seward Peninsula; SZ, Severneya Zemlya; VK, Verkhoyansk orogen; YN, Yenisey Ridge; YR, Yreka terrane.

indeed dominated by Palaeoproterozoic and Mesoproterozoic (*c.* 2.0–1.0 Ga) ages, with only rare Archaean zircons (Fig. 31.3h; Knudsen *et al.* 1997; Åhäll *et al.* 1998; de Haas *et al.* 1999; Bingen *et al.* 2005).

Siberia

The Precambrian makeup of the Siberian craton is not as well established as the other Circum-Arctic cratons, because it is mostly covered by Mesoproterozoic to Cenozoic sedimentary rocks up to 10 km thick (Zonenshain *et al.* 1990; Khudoley *et al.* 2007). It comprises two Archaean cores (Aldan, Anabar) separated and surrounded by Palaeoproterozoic orogens, but apparently devoid of Mesoproterozoic magmatic rocks (Fig. 31.2; Rosen *et al.* 1994; Khudoley *et al.* 2007). U–Pb ages from the Siberian craton are mainly distributed in three peaks at 3.05–2.95, 2.00–1.85 and 1.74–1.70 Ga (Khudoley *et al.* 2007). Detrital zircons from Neoproterozoic sandstone along the SE margin of Siberia are mostly in the range of 2.1–1.8 Ga, with a few Mesoproterozoic ages (*c.* 1.7–1.5 and *c.* 1.3 Ga) and rare Archaean zircons (Fig. 31.3i; Khudoley *et al.* 2001). Precambrian zircons in younger,

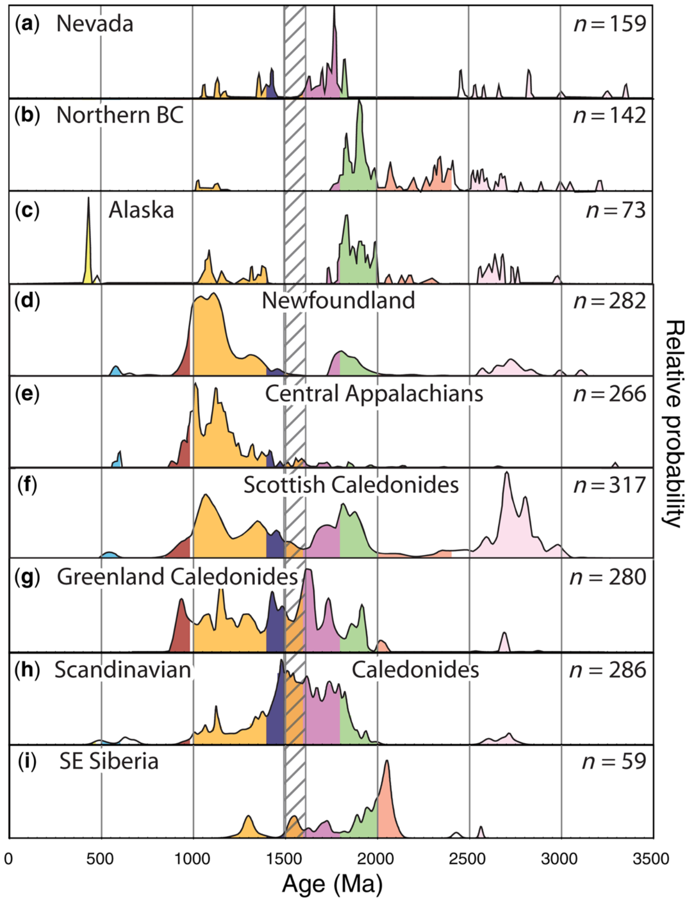

Fig. 31.3. Representative detrital zircon reference spectra for sandstone deposited along the Neoproterozoic–Early Palaeozoic continental margins of the Circum-Arctic cratons. (**a–c**) Western Laurentian reference data of Gehrels *et al.* (1995) and Gehrels & Ross (1998) for Neoproterozoic–Palaeozoic sandstones of the Cordilleran miogeocline (after Gehrels 2000). The Alaska reference data (c) is a composite of two samples including a Devonian sandstone that likely received Silurian–Devonian detritus of Caledonian origins during development of the NW Passage (Colpron & Nelson 2009). (**d–g**) Reference data for Neoproterozoic–Palaeozoic sandstones deposited along the eastern and northeastern margins of Laurentia in the central and northern Appalachians, and the Scottish and Greenland Caledonides (after Cawood *et al.* 2007, and sources cited therein). Data from the Greenland Caledonides (g) are composites of several samples from sandstones of Early Neoproterozoic age (after Cawood *et al.* 2007, and sources cited therein). (**h**) Data from Neoproterozoic–lower Palaeozoic sandstones from western Baltica (Scandinavian Caledonides; data from Knudsen *et al.* 1997; Åhäll *et al.* 1998; de Haas *et al.* 1999; Bingen *et al.* 2005). (**i**) Data for Meso- and Neoproterozoic sandstones of the eastern Siberian platform (after Khudoley *et al.* 2001). Hatched area represents the *c.* 1.61–1.49 Ga North American magmatic gap (Van Schmus *et al.* 1993; Ross & Villeneuve 2003).

upper Palaeozoic to lower Mesozoic sandstone are mostly *c.* 1.9–1.8 Ga with minor contribution from *c.* 2.9–2.3 Ga sources (Prokopiev *et al.* 2008). Khudoley *et al.* (2001) interpreted the Mesoproterozoic zircons in Neoproterozoic sandstone from SE Siberia to be related to similar sandstone in northern Laurentia (Rainbird *et al.* 1997) and favoured a connection with that margin in the Rodinia supercontinent. The southern margin of the Siberian craton was apparently an active margin in Early Neoproterozoic time as indicated by *c.* 900–812 Ma ophiolite and arc magmatism of the Baikal-Vitim belt (Fig. 31.2; Vernikovsky *et al.* 2004).

In summary each of the three Precambrian cratons surrounding the present-day Arctic Ocean have distinct characteristics that are readily identified in the detrital zircon populations from siliciclastic units deposited along their respective continental margins (Figs 31.2 & 31.3).

Neoproterozoic–Palaeozoic orogens of the Circum-Arctic region

The Circum-Arctic cratons are surrounded by a number of Neoproterozoic–Palaeozoic orogens that record their progressive amalgamation into northern Pangaea. Many of these orogenic belts project into the modern Arctic ocean where in some cases they overlap each other (Fig. 31.2). Major Neoproterozoic–Palaeozoic orogens include the Timanides, the Caledonides (Appalachians), the Ellesmerian and the Urals. Many aspects of these orogens are suspected to be represented in some of the Cordilleran terranes (e.g. Sweeney 1982; Moore *et al.* 1994; Bradley *et al.* 2003; Soja & Krutikov 2008; Colpron & Nelson 2009). We briefly summarize here the main characteristics of the major Circum-Arctic Neoproterozoic–Palaeozoic orogens with the aim to establish their 'fingerprints' to facilitate comparison with exotic terranes of the North American Cordillera.

The Timanides

The Timanide is an accretionary orogen that developed along the northeastern and eastern margins of Baltica in Neoproterozoic–Early Palaeozoic time. It extends for more than 2000 km from the southern Urals northwestward to the Varanger Peninsula of Norway, and can be traced northeastward below the thick Phanerozoic sedimentary cover of the Pechora Basin and Barents Shelf, to the Polar Urals and southern Novaya Zemlya (Fig. 31.2; Roberts & Siedlecka 2002; Gee & Pease 2004; Korago *et al.* 2004). Along NE Baltica, the Timanian deformation is generally characterized by SW-verging folds, a NE-dipping cleavage, and sub-greenschist to lower greenschist facies metamorphism related to SW-verging thrusting of basinal continental margin strata over shelf carbonate in Ediacaran–Early Cambrian time (Roberts & Siedlecka 2002; Roberts & Olovyanishnikov 2004). Amphibolite facies metamorphism is only locally known in northwestern Russia (Lorenz *et al.* 2004). Neoproterozoic arc magmatism (*c.* 610–550 Ma) is widespread in the basement to the Pechora Basin, in the Polar Urals and on Novaya Zemlya (Gee *et al.* 2000; Remizov & Pease 2004; Korago *et al.* 2004; Kuznetsov *et al.* 2007). It has been interpreted to record SW subduction beneath Baltica in Ediacaran time (Pease *et al.* 2004; Kuznetsov *et al.* 2007).

Neoproterozoic to Cambrian (<500 Ma), greenschist-facies turbiditic sandstone on Novaya Zemlya, Severnaya Zemlya and northern Taimyr are interpreted to have been derived from the Timanide orogen (Korago *et al.* 2004; Lorenz *et al.* 2008; Pease & Scott 2009). These form part of the North Kara terrane, a complex tract of rocks that has been interpreted either as a microcontinent that evolved independently between Siberia and Baltica in Palaeozoic time (Cocks & Torsvik 2005; Metelkin *et al.* 2005), or an extension of the Baltican Timanides (Gee *et al.* 2006; Pease & Scott 2009). It comprises local evidence of reworked Mesoproterozoic (Grenvillian) basement, a Neoproterozoic to Cambrian succession of turbidite and shale with *c.* 750–505 Ma detrital zircons (Pease & Scott 2009), evidence for latest Cambrian–earliest Ordovician deformation, and a lower Palaeozoic succession that includes a Lower Devonian Old Red Sandstone unit with a western, Caledonian source (Gee *et al.* 2006; Lorenz *et al.* 2008).

The timing of Timanian deformation is everywhere constrained by a regional sub-Early Ordovician angular unconformity that marks the onset of passive margin sedimentation following opening of the Uralian Ocean (Bogolepova & Gee 2004; Lorenz *et al.* 2007, 2008; Pease & Scott 2009). The Timanian deformation and metamorphism are generally estimated to be of late Neoproterozoic age (*c.* 600–550 Ma; Roberts & Olovyanishnikov 2004; Lorenz *et al.* 2004), but folding of strata as young as Middle Cambrian in Severnaya Zemlya and northern Taimyr suggests younger, perhaps diachronous deformation in the northeastern part of the orogen (Kuznetsov *et al.* 2007; Pease & Scott 2009).

Neoproterozoic arc magmatism and development of the Timanide orogen has been interpreted either as an extension of the Avalonian–Cadomian arc (Scarrow *et al.* 2001; Roberts & Siedlecka 2002) or as the result of convergence and eventual collision between Arctida (including the North Kara terrane) and Baltica in Ediacaran–Middle Cambrian time (Kuznetsov *et al.* 2007).

The northwestern extension of the Timanides is locally overprinted by the Caledonian deformation front in northern Norway (Fig. 31.2; Roberts & Siedlecka 2002). Gee *et al.* (2006) summarize evidence that suggest that a Timanian basement reworked by Caledonian deformation underlies much of the Barents Shelf as far north as Franz Josef Land (Fig. 31.2). Local evidence for Neoproterozoic amphibolite-facies metamorphism in southwestern Svalbard also suggests incorporation of Timanian rocks in the northern Caledonides (Majka *et al.* 2008). The Timanian deformation is overprinted by Carboniferous–Early Mesozoic Uralian tectonism in the Urals, Novaya Zemlya, and northern Taimyr (Gee *et al.* 2006; Pease & Scott 2009).

The northern Caledonides

The Caledonides of Scandinavia, Greenland and the British Isles, and their southern extension in the northern Appalachians (Fig. 31.2), record the closure of the Iapetus Ocean and the oblique convergence of Baltica and Avalonia with Laurentia in Silurian to Early Devonian time (van Staal *et al.* 1998; McKerrow *et al.* 2000; Roberts 2003; Gee *et al.* 2008). In Scandinavia, the Caledonides comprise a series of east-verging thrust sheets that can be subdivided into Lower, Middle, Upper and Uppermost allochthons, each recording greater transport with higher structural level in the orogen (Roberts 2003; Gee *et al.* 2008). The Lower and Middle allochthons are composed of telescoped, Neoproterozoic–Early Palaeozoic continental margin strata of western Baltica and locally include slices of *c.* 1.70–1.45 Ga crystalline basement. The Upper allochthon comprises mainly ophiolitic complexes, magmatic arcs and basinal sedimentary rocks deposited within and along the margins of the Iapetus Ocean. Arc magmatism in the Upper allochthon spans the period of *c.* 500–430 Ma, with a peak at *c.* 450–430 Ma (Gee *et al.* 2008). The Uppermost allochthon consists mainly of exotic, amphibolite-facies continental margin strata of inferred Laurentian affinity, that were emplaced at high levels in the orogen during the main, Scandian phase of the Caledonides (Roberts *et al.* 2002). These Laurentian rocks experienced an early phase of Middle Ordovician, NW-verging deformation that is unique in the Scandinavian Caledonides and has been related to the arc-continent Taconian collision of the northern Appalachians (Roberts *et al.* 2002; Roberts 2003).

In northern Norway, an early phase of Caledonian deformation – the Late Cambrian to earliest Ordovician Finnmarkian phase – affects the basal Upper allochthon (Seve-Kalak Nappe Complexes) and parts of the Middle allochthon (Roberts 2003). It has been related to arc–continent collision along the northern margin of Baltica. Eclogite facies metamorphism (*c.* 500 Ma) is locally preserved in the Seve Nappe Complex (Dallmeyer *et al.* 1991; Essex *et al.* 1997). However, recent studies suggest that some of the inferred Finnmarkian deformation is older and may in part be related to Grenvillian–Sveconorwegian orogenesis (Kirkland *et al.* 2006). Alternatively, this Late Cambrian–earliest Ordovician deformation could be related to late Timanian deformation recorded in the North Kara terrane of Arctic Russia (Pease & Scott 2009).

The main phase of Caledonian deformation, the Late Silurian–Early Devonian Scandian phase (Wenlock-Emsian; *c.* 430–398 Ma; Gee 1975; Roberts 2003), is related to final closure of the Iapetus Ocean, oblique convergence and collision of Baltica and Laurentia. It involved westward subduction of Baltica beneath Laurentia, to depths of *c.* 125 km at *c.* 407 Ma, and produced the overall present geometry of the Scandinavian Caledonides. Scandian deformation ended with a late phase of Early to Middle Devonian ductile extension followed by younger, Late Devonian–Carboniferous(?) sinistral transtension (Roberts 2003, and references therein).

In East Greenland, the Caledonides involve thrust imbrication and westward translation of Neoproterozoic–Middle Ordovician Laurentian continental margin strata during the Scandian phase of deformation (Gee *et al.* 2008; Higgins & Leslie 2008). In this region, there is no evidence for older deformation corresponding to the Finnmarkian phase in Scandinavia. The East Greenland Caledonides comprises a series of well-defined thrust sheets that record progressively greater transport and increasing metamorphic grade with higher structural levels to the east (Gilotti *et al.* 2008; Higgins & Leslie 2008). The youngest foreland rocks involved in Caledonian deformation are turbidites of Middle Silurian age (Middle Wenlock, *c.* 426 Ma), and deformation is thought to have continued until Mississippian time, as suggested by *c.* 360–350 Ma ultrahigh-pressure metamorphism in the highest thrust sheet in the northern part of the orogen (McClelland *et al.* 2006*a*; Higgins & Leslie 2008). The earliest Caledonian magmatism comprises *c.* 466–432 Ma calc-alkaline granitoids in the southern part of the upper thrust sheet. It probably represents continental arc magmatism related to subduction of Iapetus lithosphere beneath Laurentia and coeval with the Taconian–Grampian phase of arc accretion further south in the Caledonides–Appalachians (Kalsbeek *et al.* 2008). S-type leucogranite and augen gneiss (*c.* 435–425 Ma) are prominent near the base of the upper thrust sheet in the southern part of the East Greenland Caledonides, where they occur within a midcrustal-level migmatite complex. The Caledonian leucogranites were emplaced both before and during deformation. They are commonly difficult to distinguish in the field from similar Late Grenvillian (*c.* 950–900 Ma) granite and migmatites that occur at the same structural level in the orogen (Kalsbeek *et al.* 2000, 2008). The late-stage Caledonian deformation was characterized by Middle to Late Devonian regional extension, in part coeval with thrusting and in part related to north–south sinistral wrench faulting that controlled basin development and deposition of Old Red Sandstone in East Greenland (Gilotti & McClelland 2008; Higgins & Leslie 2008; Larsen *et al.* 2008).

Evidence of Caledonian orogenesis occurs in four fault-bounded terranes in the Svalbard Archipelago and is thought to affect much of the adjacent Barents Shelf in the Eurasian Arctic (Fig. 31.1; Gee & Teben'kov 2004; Gee *et al.* 2006, 2008). In NE Svalbard, the Nordaustlandet terrane is characterized by a Late 'Grenvillian' metasedimentary and metavolcanic basement, intruded by *c.* 960–940 Ma augen granites, and overlain by a Neoproterozoic to Early Palaeozoic sedimentary succession, including Ediacaran tillites (Harland 1997; Halverson *et al.* 2004). These rocks were deformed by west-verging folds during the Scandian phase of the Caledonides. Superposed Late Grenvillian (*c.* 960–940 Ma*)* and Caledonian (*c.* 450–410 Ma) magmatic and metamorphic events, and the overall Neoproterozoic to Early Palaeozoic stratigraphy of the Nordaustlandet terrane, support correlations with East Greenland (Gee & Teben'kov 2004; Johansson *et al.* 2004, 2005).

In north-central Svalbard, the West Ny Friesland terrane comprises mainly Late Palaeoproterozoic orthogneiss (*c.* 1750 Ma) imbricated with amphibolite–facies metasedimentary schist along west-verging Caledonian thrusts (Johansson *et al.* 2005; Gee *et al.* 2008). This north-central terrane is separated from the northeastern terrane by a north-trending normal fault that probably has earlier components of significant sinistral stike-slip displacement and possibly originated as a west-verging thrust fault (Gee *et al.* 2008). The West Ny Friesland terrane lacks evidence of Grenvillian tectonism present in terranes to the east and west.

Svalbard's northwestern terrane is separated from the West Ny Friesland terrane by two north-trending grabens filled by Devonian Old Red Sandstone. It is dominated by a Late Mesoproterozoic to

Neoproterozoic succession of schist and marble, intruded by *c.* 960 Ma granitoids, and later deformed, extensively intruded and migmatized during Caledonian orogenesis (*c.* 435–420 Ma; Gee & Teben'kov 2004; Gee *et al.* 2008; Pettersson *et al.* 2009). This superposition of Late Grenvillian and Caledonian tectonism suggests possible correlation with the Nordaustlandet terrane to the east and the East Greenland Caledonides (Pettersson *et al.* 2009). Ordovician (*c.* 460–450 Ma) amphibolite to eclogite metamorphism locally occurs in the northernmost part of the northwestern terrane (Gromet & Gee 1998; Labrousse *et al.* 2008).

The Caledonian history of the southwestern terrane is largely obscured by the Cenozoic deformation of the West Spitzbergen fold and thrust belt (Gee *et al.* 2008). Its Late Mesoproterozoic, Neoproterozoic and Early Palaeozoic successions differ from the other Svalbard terranes and an affinity with the Pearya terrane of northern Ellesmere Island has been proposed (e.g. Trettin 1987; Ohta 1994; Harland 1997). The greenschist–facies metasedimentary succession is dominated by siliciclastic rocks and includes probable Ediacaran diamictite units (Gee & Teben'kov 2004). To the north, a metamorphic complex that includes Ordovician (*c.* 470 Ma) blueschist and eclogite is thrust over the Ediacaran diamictite unit and is unconformably overlain by Middle Ordovician conglomerate and limestone, and Upper Ordovician to Lower Silurian turbidites (Gee & Teben'kov 2004; Labrousse *et al.* 2008). Further south in the southwestern terrane, evidence of Neoproterozoic (*c.* 640 Ma) amphibolite–facies metamorphism suggests a possible affinity with the Timanides of NE Baltica (Majka *et al.* 2008).

Assembly of the Svalbard terranes is generally considered to have occurred along Late Silurian to Devonian sinistral faults, that locally controlled basin development and deposition of Old Red Sandstone facies (Gee & Page 1994; Ohta 1994; McCann 2000; Gee & Teben'kov 2004). These syn- to post-orogenic clastic rocks are widely distributed across the northern Caledonides, possibly extending as far east as Severnaya Zemlya in Arctic Russia and the Canadian Arctic Islands to the west (Fig. 31.1; McCann 2000; Gee *et al.* 2006; Lorenz *et al.* 2008). Old Red Sandstone facies span Late Silurian to Early Carboniferous time. They were derived from erosion of the Caledonides and limited provenance studies of detrital mica suggest local derivation from metamorphic basement with $^{40}Ar/^{39}Ar$ cooling ages of *c.* 470–390 Ma (Sherlock *et al.* 2002; Eide *et al.* 2005).

Pearya and the Ellesmerian Orogen

Evidence of Mid-Palaeozoic tectonism is widespread along northern Laurentia, from the North Greenland fold belt westward to the Ellesmerian orogen of Arctic Canada (Fig. 31.2). Influx of Silurian (Llandovery) turbidites derived from the rising Caledonides to the east marks the onset of tectonic activity along northern Laurentia. This was followed by Late Silurian–Early Devonian sinistral transpression and the emplacement of the Pearya terrane along northern Ellesmere and Axel Heiberg Islands, Late Silurian–Early Devonian west-verging thrusting along the north-trending Boothia Uplift, and Early Devonian SW-directed compression (Romanzov orogeny) in the western Arctic (Fig. 31.4; Trettin 1987; Trettin *et al.* 1991*a*; Lane 2007). The main phase of Ellesmerian deformation occurred in Late Devonian to Early Mississippian time and involved development of a SSE-directed fold and thrust belt and deposition of a foreland clastic wedge to the south (Thorsteinsson & Tozer 1970; Trettin *et al.* 1991*a*; Lane 2007).

Pearya is the only exotic, accreted terrane exposed in Arctic Canada along the northern Laurentian margin (Figs 31.2 & 31.4), although related crustal fragments may also form part of the Arctic Ocean seafloor. Pearya lies on the northern side of Ellesmere and Axel Heiberg Islands, juxtaposed against lower Palaeozoic miogeoclinal strata and Silurian–Lower Devonian flysch deposits of the Clements Markham fold belt (Trettin 1987; Trettin *et al.* 1991*b*). Pearya is a composite terrane. The oldest rocks in it, Succession I of Trettin (1987), are schists and gneisses of Grenvillian age (*c.* 965 Ma), based on limited U–Pb zircon dating (Trettin *et al.* 1992). The crystalline rocks are overlain by Succession II, a Neoproterozoic to Lower Ordovician rift-related and passive margin sequence. The Lower to Middle Ordovician, suprasubduction zone-related Maskell Inlet assemblage was juxtaposed with the continental margin rocks during the Middle Ordovician M'Clintock orogeny (Trettin 1987). This tectonic event is age-equivalent to the Taconic orogeny in the peri-Laurentian terranes of the Canadian Appalachians, and similarly juxtaposes intra-oceanic arc and Grenvillian continent-margin crustal blocks (van Staal 2007). The characteristic features of Pearya, in particular the evidence for Early Ordovician subduction and Middle Ordovician tectonism, are strikingly similar to the southwestern terrane of Svalbard, thus suggesting a derivation of Pearya from the northern end of the Caledonian orogen (Trettin 1987; Ohta 1994; Gee & Teben'kov 2004). The Middle Ordovician to Upper Silurian strata of Succession IV represent a successor basin and arc sequence developed across the M'Clintock orogen. Late Ordovician faunas have diagnostic elements in common with faunas from Siberia, northern Greenland and the Arctic platform (Trettin 1987).

The initial approach of Pearya to the present Arctic Islands is suggested by quartzite and marble clasts in coarse Upper Silurian conglomerates of the Danish River Formation in central Ellesmere

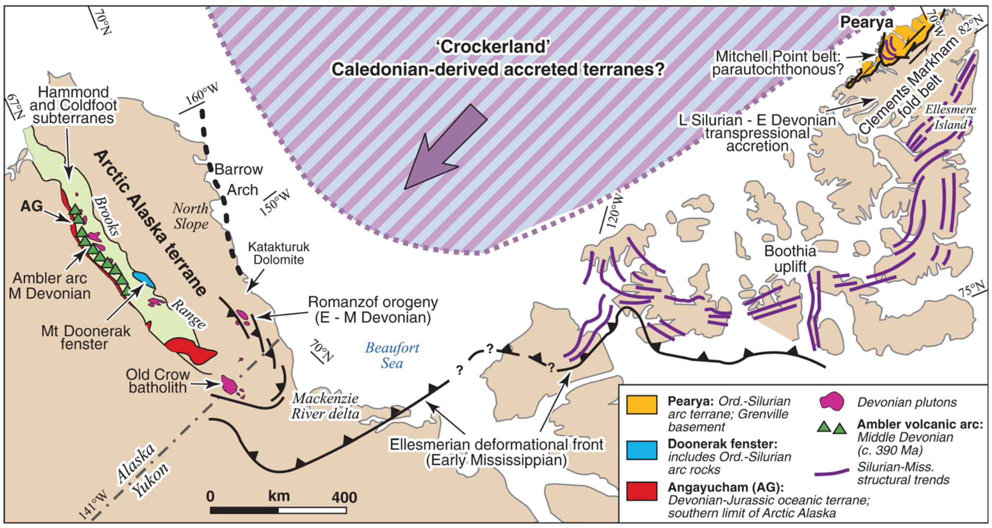

Fig. 31.4. Distribution of the main Mid-Palaeozoic tectonic elements of northern Canada and adjacent Alaska (after Moore *et al.* 1994; and Lane 2007).

Island (Trettin *et al.* 1991*a*). Its actual emplacement is probably marked by the sub-Middle Devonian unconformity that overlies strata as young as Silurian (and possibly Lower Devonian) in the Clements Markham fold belt (Trettin *et al.* 1991*a*). A *c.* 390 Ma post-tectonic pluton cuts rocks of the terrane. The southern boundary of Pearya is a high-angle, sinistral fault, that curves northward near its western end into a thrust (Fig. 31.4). Along its northwestern extent, Pearya has been dissected into a set of slivers, possibly structurally interleaved with parautochthonous strata. Trettin *et al.* (1991*a*) favoured a model of westward transpressional emplacement. Sinistral transcurrent motion dominated in Silurian time, with Pearya acting as an indentor or indentors into the continental margin (Trettin *et al.* 1991*a*; see their fig. 12*B*.2). This was succeeded by a more widespread shortening event in latest Devonian and Early Mississippian time: the Ellesmerian orogeny, which produced a broad, south-verging fold-and-thrust belt and an extensive clastic wedge in the Canadian Arctic region (Thorsteinsson & Tozer 1970; Lane 2007). The Ellesmerian orogeny was caused by collision with an enigmatic crustal block to the north – the mythical Crockerland of Arctic explorers – in the region presently occupied by the Arctic Ocean (Fig. 31.2; Trettin *et al.* 1991*a*). This landmass apparently shed sediments into Sverdrup Basin to the south intermittently until Mid-Mesozoic time (Davies & Nassichuk 1991; Embry 1993, 2009).

The Urals and Taimyr

Late Palaeozoic deformation related to the Uralian orogeny is recognized over a distance of approximately 4000 km, from near the Aral Sea in the south to the Taimyr Peninsula of Arctic Russia in the north (Fig. 31.2). The Urals record the Palaeozoic collision of at least two intra-oceanic arcs with the eastern margin of Baltica and its subsequent continent–continent collision with the Kazakhstan and Siberian plates during final assembly of Pangaea (Zonenshain *et al.* 1990; Sengör *et al.* 1993; Puchkov 1997; Brown *et al.* 2006*a*, *b*). Over much of its length, the Uralian deformation is superposed on the Late Neoproterozoic Timanide orogen of eastern Baltica (Fig. 31.2). In mainland Russia, only the western (Baltican margin) and interior parts (ophiolite and arc complexes) of the Uralian orogen are preserved; parts of Kazakhstan and Siberia involved in the Late Palaeozoic deformation are concealed beneath the West Siberian Basin (Fig. 31.2). To the north, along the Russian Arctic coast, the belt of Uralian tectonism is offset by approximately 600 km to the west where it continues on the Novaya Zemlya archipelago and extends eastward to the Taimyr Peninsula (Inger *et al.* 1999; Gee *et al.* 2006; Pease & Scott 2009). In this region, ophiolites and arc complexes that are prominent in the Southern and Middle Urals are absent. Elements of the Siberian margin that were deformed during the Uralian orogeny are exposed in central and southern Taimyr (Inger *et al.* 1999; Pease & Scott 2009).

The first indications of Uralian tectonism correspond to Silurian to Middle Devonian arc magmatism and subsequent Late Devonian to Early Mississippian arc–continent collision in the Southern and Middle Urals (Brown *et al.* 2006*a*, *b*). This has been related to east-directed subduction of the Baltican plate beneath Uralian oceanic lithosphere and development of an intra-oceanic arc. A west-verging accretionary complex developed along the eastern margin of Baltica from Middle to Late Devonian time (*c.* 390–360 Ma). It involved imbrication of continental margin strata with Devonian flysch, ophiolitic and arc crust, and locally Late Devonian (*c.* 380–370 Ma) blueschist and eclogites (Brown *et al.* 2006*a*). During most of Carboniferous time, the Baltican margin of the Southern Urals was tectonically quiescent while, to the east, east-directed subduction of Uralian oceanic lithosphere was ongoing beneath the Kazakhstan plate. Arc magmatism occurred there in two main phases at *c.* 370–350 and *c.* 335–315 Ma (Brown *et al.* 2006*a*).

The main phase of Uralian tectonism began with collision of the Kazakhstan plate in Late Pennsylvanian time (*c.* 300 Ma) and culminated with development of a west-verging fold and thrust belt and foreland basin along the Baltican margin to the west (Brown *et al.* 2006*a*). Amphibolite-facies metamorphism in the hinterland (East Uralian Zone) spans the period of *c.* 305–291 Ma (based on K–Ar dates on amphibole and mica). Deformation in the East Uralian Zone progressed from NW-verging folds and thrust to an intense phase of late-stage sinistral strike-slip faulting in Permian–Triassic time. This late orogenic sinistral wrench fault system was extensively intruded by granite–gneiss complexes of *c.* 292–280 Ma in the Southern Urals and *c.* 270–250 Ma in the north (Brown *et al.* 2006*a*; Görz *et al.* 2009). In this region, Uralian tectonism is thought to have ended in Early Triassic time.

On the Novaya Zemlya archipelago, NW-directed foreland folds and thrusts related to the Uralian orogeny affect a sedimentary succession of Neoproterozoic to Early Triassic age (Korago *et al.* 2004; Gee *et al.* 2006; Pease & Scott 2009). The Ordovician to Permian stratigraphy was accumulated along the eastern passive margin of Baltica. It lies unconformably on Neoproterozoic–Cambrian succession of turbidites derived from the Timanide orogen (Korago *et al.* 2004; Pease & Scott 2009). Uralian deformation on Novaya Zemlya is of lower intensity and somewhat younger than in the Southern and Middle Urals; it occurred in Middle to Late Triassic time (Gee *et al.* 2006).

The Taimyr Peninsula comprises three NE–SW-trending tectonostratigraphic domains (Zonenshain *et al.* 1990). Southern Taimyr contains an Ordovician to Mississippian carbonate-dominated shelf succession that was deposited along the Siberian passive margin (Inger *et al.* 1999; Pease & Scott 2009). This succession is overlain by Pennsylvanian to Lower Triassic siliciclastic rocks that are intercalated with Permian–Triassic mafic extrusive and intrusive rocks of the Taimyr igneous suite (Inger *et al.* 1999; Walderhaug *et al.* 2005). This siliciclastic succession may be derived from the Uralian orogen to the north and west, a hypothesis that awaits testing (Inger *et al.* 1999). Late Palaeozoic deformation in Southern Taimyr is limited to rare SSE-verging thrust faults developed in the Palaeozoic carbonate succession (Inger *et al.* 1999). Triassic and older rocks of Southern Taimyr are all affected by Late Triassic–earliest Jurassic dextral transpression (Inger *et al.* 1999; Torsvik & Andersen 2002; Walderhaug *et al.* 2005).

Central Taimyr contains a Neoproterozoic (Ediacaran) to Early Palaeozoic deepwater continental margin succession, interpreted to have been contiguous with the shelf succession of Southern Taimyr and deposited along the continental slope of Siberia (Inger *et al.* 1999). This succession unconformably overlies a variety of Precambrian rocks. The oldest comprises Mesoproterozoic to Early Neoproterozoic amphibolite–facies metasedimentary rocks that are intruded by *c.* 900 Ma granites and probably represent continental crust that is otherwise exotic to northern Siberia (Pease *et al.* 2001). These exotic rocks are in turn unconformably overlain by a Neoproterozoic greenschist–facies, volcano–sedimentary succession with felsic volcanic rocks dated at *c.* 630–600 Ma (Pease & Vernikovsky 1998; Pease & Scott 2009). Occurrence of dismembered ophiolites and island–arc complexes in the Neoproterozoic succession and the Late Neoproterozoic metamorphism affecting the Precambrian rocks suggest that exotic crustal elements of Central Taimyr were accreted to northern Siberia before deposition of Ediacaran and younger shelf and slope facies of the Siberian passive margin in Central and Southern Taimyr (Pease & Scott 2009), an event that may have coincided with the Timanide orogeny.

Northern Taimyr comprises a local basement of *c.* 700 Ma arc volcanism overlain by an extensive turbidite succession of Neoproterozoic to Cambrian age (Pease & Scott 2009). The turbidite are thought to have been derived from the Timanide orogen and Northern Taimyr is considered a part of the North Kara terrane – a terrane of Baltican affinity accreted to northern Siberia in Late Palaeozoic time (Gee *et al.* 2006; Pease & Scott 2009). Both

Central and Northern Taimyr experienced SSE-directed folding and thrusting, along with migmatization and intrusion of syn- to post-tectonic granitoids between *c.* 305–264 Ma (Lorenz *et al.* 2008). Late-stage dextral transpression also occurred in Central and Northern Taimyr where it may initially have been associated with the SSE-directed deformation (Inger *et al.* 1999).

Summary

The Neoproterozoic–Palaeozoic orogens that border the Circum-Arctic cratons all have distinct tectonic and magmatic events that may serve as 'fingerprints' in evaluating displaced terranes and/or detrital zircon populations. The Timanide orogen is generally characterized by low metamorphic grades and arc magmatism of *c.* 610–550 Ma (Gee *et al.* 2000), and possibly as old as *c.* 700 Ma if arc magmatism in Northern Taimyr is related to the Timanides (Pease & Scott 2009). The Caledonides are best characterized by widespread granitic magmatism, migmatization and high-grade metamorphism of *c.* 450–420 Ma (Roberts 2003; Johansson *et al.* 2005; Higgins & Leslie 2008; Kalsbeek *et al.* 2008). In the Urals and in Northern and Central Taimyr, the peak Uralian metamorphism and magmatism occurred at *c.* 290–260 Ma, but arc magmatic rocks of Devonian age are also common in the southern parts of the orogen (Brown *et al.* 2006*a*; Görz *et al.* 2009). The Ellesmerian orogen of Arctic Canada lacks significant volume of magmatic rocks and is typically of low metamorphic grade. It comprises elements of probable Caledonian origins and was probably kinematically linked to the northern Caledonides (Trettin 1987; Ohta 1994; Gee & Teben'kov 2004).

The superposition of Palaeozoic orogenic events is evident in various parts of the Eurasian Arctic (Fig. 31.2). Late Palaeozoic Uralian deformation is superposed on the older Timanide orogen along most of eastern Baltica, and possibly in Central and Northern Taimyr (Gee *et al.* 2006; Pease & Scott 2009). The Timanides are clearly overprinted by Caledonian structures in northern Norway (Roberts & Siedlecka 2002), and possibly in the Barents Shelf region and SW Svalbard (Gee *et al.* 2006; Majka *et al.* 2008). The northern Caledonides are also characterized by superposition of Mid-Palaeozoic metamorphic and magmatic events on Late 'Grenvillian' (*c.* 950 Ma) orogenic crust; this is particularly evident on Svalbard and in NE Greenland (Fig. 31.2; Kalsbeek *et al.* 2000, 2008; Johansson *et al.* 2004, 2005; Pettersson *et al.* 2009). Similar ages in the basement of Central Taimyr suggest that Late 'Grenvillian' crust may also have been reworked by Late Palaeozoic Uralian orogenesis, and possibly the Neoproterozoic–Cambrian Timanide orogen as well (Pease *et al.* 2001; Pease & Scott 2009). The occurrence of Late 'Grenvillian' crust overprinted by Palaeozoic orogenic activity is a common feature of Pearya and many exotic terranes in the North American Cordillera.

Cordilleran terranes with Timanian, Caledonian and/or Uralian affinities

Northern Cordilleran terranes with Palaeozoic and older elements that are exotic with respect to western Laurentia include Arctic Alaska, Farewell, and the Alexander terranes (Fig. 31.2). Farther south, parts of the pre-Devonian basement of the Eastern Klamath and Northern Sierra terranes are also included in this group, as is, provisionally, the Okanagan terrane that forms part of the basement of Quesnellia of southern British Columbia. The Palaeozoic and older parts of these terranes present tectonic histories, detrital zircon populations and fossil assemblages that differ profoundly from western Laurentia and the peri-Laurentian terranes. Instead, recent studies of these terranes strongly favour linkages with northern elements of the Caledonides in NE Laurentia and western Baltica as the closest match for some, and Siberia and Taimyr for others. The main lines of evidence include:

(1) affinities of Early Palaeozoic macro- and microfossils with those in Siberia, and in some cases Baltica, as well as endemic species common between terranes;
(2) for terranes of inferred Baltican and Caledonian affinities, detrital zircon signatures reflect a heterogeneous basement with multiple sources between 2.0 and 1.0 Ga, including significant populations in the 1.61–1.49 Ga North American magmatic gap (Van Schmus *et al.* 1993), and only minor Archaean and Palaeoproterozoic source terranes;
(3) evidence of Grenvillian magmatism, both direct and reflected in robust detrital zircon populations;
(4) Late Neoproterozoic magmatism and arc development (700–540 Ma);
(5) Ordovician–Silurian arc development;
(6) Early Permian orogeny, similar to the Urals and Taimyr.

In the following sections, we first describe the Cordilleran terranes of inferred Siberian affinity, and then the terranes with Baltican and/or Caledonian affinities. We focus on the characteristics that identify their palaeogeographic affinities, and also their early relationships to each other.

Terranes of Siberian affinity in Alaska: Arctic Alaska–Seward–Chukotka, Farewell and Kilbuck

The Arctic Alaska terrane forms a sinuous belt extending from far northern Yukon, through the Brooks Range and North Slope, with correlatives in the Seward Peninsula and the Chukotka Peninsula and Wrangel Island of northeastern Russia (Figs 31.1 & 31.2; Moore *et al.* 1994; Nokleberg *et al.* 2000, 2005; Amato *et al.* 2009). To the south, the Farewell terrane, subdivided into the Nixon Fork, Dillinger and parts of the Mystic terrane, comprises Proterozoic basement overlain by Palaeozoic shelf and slope strata and a Permian clastic wedge (Fig. 31.1; Bradley *et al.* 2003).

Detrital zircons and basement ages. Evidence for the oldest basement rocks in the Arctic Alaska and Farewell terranes comes from detrital zircon populations in sandstones. The Nuka Formation, a coarse, immature Mississippian–Pennsylvanian(?) arkose in the southernmost of the Brooks Range allochthons, contains 2.1–2.0 Ga detrital zircons (Moore *et al.* 1994, 1997*a*). It indicates the presence of a Palaeoproterozoic basement block to the south (present coordinates), similar in age to basement rocks of the Kilbuck terrane of far western Alaska (2.07–2.04 Ga; Box *et al.* 1990; Fig. 31.1). Detrital zircons from the Farewell terrane show a strong peak at *c.* 2050 Ma, and minor peaks at *c.* 1375 and *c.* 950 Ma (Fig. 31.5a; Bradley *et al.* 2007). Moore *et al.* (2007) report significant populations of *c.* 1.7–1.5 and 1.2–1.0 Ga in Proterozoic and younger sandstones from all but far eastern Arctic Alaska, which they interpret as derived from sources related to the northern Caledonides. Metasedimentary rocks on Seward Peninsula contain predominantly Neoproterozoic–Early Palaeozoic detrital zircons (*c.* 720–540, *c.* 430 Ma) with subordinate populations of Mesoproterozoic–Palaeoproterozoic grains (Fig. 31.5b; Amato *et al.* 2009). In the southern Brooks Range, limited detrital zircon data show a predominance of Palaeozoic grains (*c.* 370–360 Ma) but also grains with ages of *c.* 2.8, 2.5–2.3, 2.0–1.8 and 1.3 Ga (Fig. 31.5c; Moore *et al.* 1997*b*). In eastern Arctic Alaska, detrital zircon from clastic rocks below the Cryogenian Katakturuk Dolomite yielded zircons as young as *c.* 760 Ma and peaks in ages at *c.* 2.74–2.68, 2.07–2.03, 1.98–1.88, 1.47–1.38 and 0.89–0.85 Ga (Fig. 31.5d; Macdonald *et al.* 2009). A significant number of grains in the *c.* 1.2–1.0 Ga range are also reported from one sample of a diamictite unit below the Katakturuk Dolomite (Fig. 31.5d).

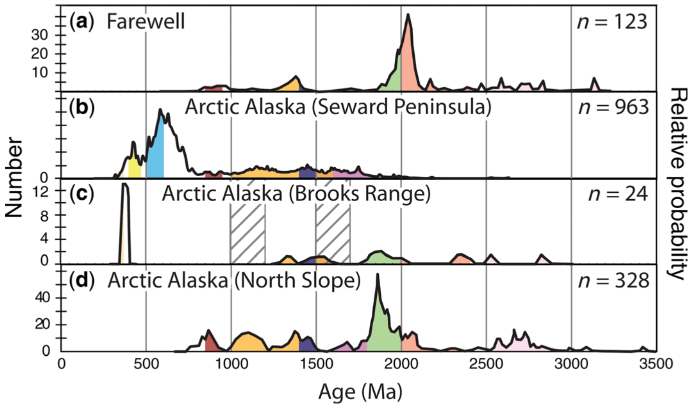

Fig. 31.5. Detrital zircon data for terranes of Siberian affinities in Alaska. (**a**) Farewell terrane quartzites, central Alaska (composite of 3 samples; data from Bradley *et al.* 2007). (**b**) Metasedimentary rocks from Seward Peninsula, western Alaska (composite of 11 samples; Amato *et al.* 2009). (**c**) Limited data from the Marion Schist of the Coldfoot terrane, Brooks Range, southern Arctic Alaska terrane (Moore *et al.* 1997*a*). The Coldfoot data is dominated by Late Devonian grains derived from coeval arc magmatism to the south. Hatch areas show range of significant detrital zircon populations reported by Moore *et al.* (2007) from other sandstone units in the Brooks Range. (**d**) Clastic rocks beneath the Katakturuk Dolomite, North Slope, eastern Arctic Alaska terrane (composite of three samples; data from Macdonald *et al.* 2009).

Sources for the Mesoproterozoic (*c.* 1.40–0.95 Ga) and Early Neoproterozoic (*c.* 850 Ma) zircons may be found in basement units of Arctic Alaska and Farewell terranes. A U–Pb age on metarhyolite of *c.* 970 Ma has been obtained from the southern Brooks Range (McClelland *et al.* 2006*b*). Amato *et al.* (2009) report U–Pb dates of *c.* 870 Ma from metavolcanic rocks on Seward Peninsula. The oldest rocks in the Farewell terrane include metasedimentary rocks with *c.* 1200 Ma detrital zircons, 980–920 Ma rhyolites and *c.* 850 Ma orthogneiss (Bradley *et al.* 2003, 2007; McClelland *et al.* 2006*b*). These basement ages and detrital zircon populations are not characteristic of NW Laurentia (Figs 31.2 & 31.3; Box *et al.* 1990; Bradley *et al.* 2003, 2007).

Neoproterozoic–Cambrian rocks. Neoproterozoic to Cambrian magmatic rocks are reported from several localities in Arctic Alaska–Chukotka. Metamorphosed basement units include orthogneiss and metavolcanic units of *c.* 750–540 Ma in the southern Brooks Range (Hammond and Coldfoot subterranes; Amato *et al.* 2006; McClelland *et al.* 2006*b*), *c.* 680–670 and *c.* 560–540 Ma on the Seward Peninsula (Patrick & McClelland 1995; Amato & Wright 1998; Amato *et al.* 2009) and *c.* 700–630 Ma on Wrangel Island (Cecile *et al.* 1991). Detrital zircon populations of *c.* 700–540 Ma are reported from clastic units in the Brooks Range and on Seward Peninsula (Moore *et al.* 2007; Amato *et al.* 2009).

Early Palaeozoic stratigraphy. In most of Arctic Alaska, the Early Palaeozoic was a period of tectonic quiescence, characterized by platformal to basinal deposition. Lane (2007) points out that Proterozoic to Silurian strata in the far eastern part of the terrane show lithologic linkages to autochthonous Laurentian elements such as the Richardson Trough and Yukon Stable Block (Fig. 31.1). In the Farewell terrane, carbonate and siliciclastic strata were deposited on an Ediacaran to Devonian continental platform and slope like that of Arctic Alaska–Chukotka; minor Silurian tuffs suggest nearby arc activity (Fig. 31.4; Bradley *et al.* 2007). Dumoulin *et al.* (2002) point out that the overall pattern of lithofacies correlates closely with that in Arctic Alaska, both consisting of Ediacaran ooid-rich dolostones, Middle Cambrian outer shelf deposits and Ordovician to Devonian platform and basin facies.

Sub-Ordovician unconformities have been noted only in the western part of Arctic Alaska. On Wrangel Island, *c.* 540 Ma and older igneous rocks are unconformably overlain by a lower Palaeozoic platformal cover sequence (Kos'ko *et al.* 1993; Amato *et al.* 2006). On the Seward Peninsula, Ediacaran and older metamorphic and igneous rocks are presumably unconformably overlain by strata including immature sandstone with detrital zircons of *c.* 700–540 Ma and locally *c.* 440–420 Ma, and fossiliferous Lower Ordovician carbonate (Amato *et al.* 2009).

Faunal affinities. Palaeozoic strata of Arctic Alaska terrane contain macrofaunal and microfaunal assemblages with Siberian and Siberian–Laurentian affinities (Blodgett *et al.* 2002; Dumoulin *et al.* 2002). Megafossils with Siberian affinities include Middle Cambrian trilobites in the central Brooks Range, Ordovician trilobites from the Seward Peninsula and Late Ordovician brachiopods and gastropods from the Seward Peninsula and Brooks Range. Characteristic Laurentian forms include Early and Late Cambrian trilobites from the eastern Brooks Range and Late Ordovician corals, stromatoporoids and brachiopods from the Seward Peninsula and central Brooks Range. Faunal components with Siberian affinities, including Ordovician conodonts, decrease markedly from west to east across northern Alaska (Dumoulin *et al.* 2002). They proposed that in Early Palaeozoic time, the Arctic Alaska terrane developed as an isolated crustal fragment originally located between the Siberian and Laurentian cratons.

Early Palaeozoic faunas of the Farewell terrane similarly show the influence of both Siberian and Laurentian provinces (Blodgett *et al.* 2002; Dumoulin *et al.* 2002). Middle Cambrian trilobites are of Siberian aspect, like those in the central Brooks Range. Identical species of Ordovician brachiopods (*Tsherkidium*) and gastropods are found in both terranes; Ordovician conodont faunas with mixed Siberian–Laurentian affinities characterize both as well (Dumoulin *et al.* 2002). Silurian stromatolite–sphinctozoan reefs in the Farewell terrane resemble those in the Ural Mountains, as well as those in the Alexander terrane (Soja & Antoshkina 1997; Antoshkina & Soja 2006). Combined with the other faunal evidence, these data favour an Early Palaeozoic palaeogeography in which the Farewell and Arctic Alaska crustal fragments were proximal to each other, in a position between Laurentia and Siberia.

Early Palaeozoic oceanic and arc assemblages. There are several occurrences of lower Palaeozoic oceanic and arc-related assemblages in the Arctic Alaska terrane (Moore *et al.* 1994). In the Mt Doonerak fenster, a structural window in the central Brooks Range (Fig. 31.4), a metasedimentary assemblage occupying a high structural level consists of Middle Cambrian limestone containing trilobites of Siberian affinity, along with Ordovician and Silurian basinal strata. A structurally lower volcanic assemblage has a supra-subduction zone geochemical signature and has yielded a K–Ar age of *c.* 470 Ma (Dutro *et al.* 1976). The palaeogeographic and palaeotectonic setting of the Ordovician arc rocks are uncertain. They were probably incorporated into the Arctic Alaska terrane in Devonian time, as the Palaeozoic rocks in the Mt. Doonerak fenster are unconformably overlain by Lower Mississippian clastic rocks of the Endicott Group, which blankets the terrane as a whole. Lower Palaeozoic rocks of oceanic character are also recognized in the Romanzof Mountains in the eastern Brooks Range, in a disrupted assemblage that may structurally overlie miogeoclinal facies (Moore *et al.* 1994). The deformed oceanic rocks are truncated by an angular unconformity, which is overlain by Middle Devonian chert-rich sandstone. The presence of these oceanic assemblages, along with the Proterozoic to Cambrian magmatic suites in the southern Brooks Range, and strong Siberian faunal affinities in the western Brooks Range, all support the concept of Moore *et al.* (1994) that much of the Arctic Alaska terrane evolved apart from western Laurentia in the Early Palaeozoic, prior to Devonian time.

Middle and Late Palaeozoic orogenic events. Eastern Arctic Alaska was affected by the late Early to earliest Middle Devonian (*c.* 400 Ma) Romanzof orogeny, which caused shortening in the Romanzof and British–Barn Mountains near the Alaska–Yukon border (Fig. 31.4; Lane 2007). Thrust fault displacement was to the NE and east, but the decreasing intensity of deformation to the south and the southward progradation of Lower Devonian turbidites suggest that the responsible collision took place in what is now the Beaufort Sea (Fig. 31.4). The Romanzof orogeny was followed by widespread Late Devonian granitic plutonism, including the *c.* 367 Ma Old Crow batholith (Fig. 31.4).

In the Mackenzie Delta region of northern Yukon, the Early Mississippian Ellesmerian orogeny is expressed as a southerly to southeasterly vergent fold and thrust belt that apparently terminates near the eastern limit of rocks assigned to the Arctic Alaska terrane, and east of rocks affected by the older Romanzof orogeny (Fig. 31.4; Lane 2007). The opposing vergences, differing ages and distinct geographic distribution of Ellesmerian and Romanzof structures suggests that they represent two discrete tectonic events formed as a result of Mid-Palaeozoic terrane interactions in the Arctic region (Lane 2007).

A sub-Mississippian unconformity is present throughout much of Arctic Alaska, overlain by northward-transgressive and coarsening quartz- and chert-rich marine and nonmarine clastic rocks of the Endicott Group (Moore *et al.* 1994). Prominent redbeds in this sequence more closely resemble the thick syn- and post-orogenic Devonian–Mississippian Old Red Sandstone of the Franklinian Basin (northern Laurentia), the Caledonides and Appalachians rather than the abundant Upper Devonian and Lower Mississippian flysch of the adjacent western Laurentian margin to the south (Nilsen 1981).

Although the Farewell terrane shows many early similarities to Arctic Alaska, in the later Palaeozoic their tectonic histories diverged strongly. There is no evidence for Devonian or Mississippian tectonism in the Farewell terrane; no expression of the Romanzof or Ellesmerian orogeny; no Devonian or Mississippian clastic wedge. Instead, it was affected by the Early Permian (*c.* 285 Ma) Browns Fork orogeny, with deformation, metamorphism and deposition of a clastic wedge (Bradley *et al.* 2003), an event that is not recognized in Arctic Alaska.

Terranes of Northern Caledonian–Baltican affinity: Alexander, Eastern Klamath (Trinity and Yreka) and Northern Sierra (Sierra City mélange, Shoo Fly complex)

The Alexander terrane occupies a broad belt in the western Cordillera, in close spatial association with Wrangellia (Fig. 31.1). Together they make up the Insular superterrane. Alexander itself is probably a composite terrane. Stratigraphic successions in various parts of it indicate widely differing, coeval tectonic environments, including a succession of Neoproterozoic to lower Palaeozoic arc-related rocks in southeastern Alaska (Gehrels & Saleeby 1987; Gehrels 1990; Gehrels *et al.* 1996), but also a thick Proterozoic–lower Palaeozoic continental platform sequence in the northern part of the terrane near the Tatshenshini River in northwestern British Columbia (Fig. 31.4; Mihalynuk *et al.* 1993). The latter is poorly documented at present; it may have more affinity with the Farewell terrane than with the southern Alexander terrane (Colpron & Nelson 2009).

Pre-Devonian basement rocks in the Eastern Klamath Mountains of southern Oregon and northern California comprise two terranes, the Trinity and Yreka (Fig. 31.1; summarized by Lindsley-Griffin *et al.* 2006; 2008; Wright & Wyld 2006). The Trinity terrane is a composite Neoproterozoic and Cambro-Ordovician (?) ophiolitic complex (Lindsley-Griffin *et al.* 2008). The Yreka terrane, which structurally overlies the Trinity ophiolite, consists of numerous tectonic slivers and mélanges, and is interpreted by Lindsley-Griffin *et al.* (2008) as an Ordovician and Siluro-Devonian forearc complex.

The lower Palaeozoic Shoo Fly complex forms the basement for Late Devonian to Permian arc and related strata of the Northern Sierra terrane (Fig. 31.2; Girty *et al.* 1990). It is composed of four allochthons. The three structurally lower allochthons within it contain siliciclastic and basinal strata; detrital zircon signatures are consistent with the northwestern Laurentian margin in British Columbia and Yukon (Harding *et al.* 2000). The Sierra City mélange, the structurally highest and the most easterly unit within the Shoo Fly complex, differs radically from the underlying allochthons but shows striking similarities to the Yreka terrane of the Eastern Klamaths. It contains blocks of both ophiolitic affinity and sedimentary origin, within a sheared matrix of slate, chert and sandstone (Schweickert *et al.* 1984).

Neoproterozoic and Early Palaeozoic arc and orogenic events. The oldest known rocks in the southern Alexander terrane, the Wales Group, represent an Ediacaran arc-building event (U–Pb ages of *c.* 595 and *c.* 554 Ma; Gehrels *et al.* 1996). These strata were deformed in the pre-Early Ordovician Wales orogeny. Arc magmatism resumed in Early Ordovician–Early Silurian time, represented by the Descon Formation. It was followed by clastic and carbonate sedimentation and pluton emplacement later in the Silurian. The second important orogenic event, the Middle Silurian to Early Devonian Klakas orogeny, was marked by thrust imbrication, metamorphism, ductile deformation, and deposition of the Lower Devonian Karheen Formation clastic wedge.

Ediacaran (*c.* 570–565 Ma) and Cambro-Ordovician (?) ophiolite of the Trinity terrane in the eastern Klamath Mountains (Lindsley-Griffin *et al.* 2008) is coeval with the Wales Group. It is crosscut by post-tectonic Ordovician plagiogranites, and also by a suite of Silurian to Early Devonian suprasubduction zone plutons with related basalt flows (*c.* 435–412 Ma). The Ordovician and Siluro-Devonian forearc complex that makes up the Yreka terrane consists of tectonic slivers and mélanges, including Late Ordovician blueschist slivers (*c.* 454 Ma; Grove *et al.* 2008). Mélange units near its structural base carry Ediacaran tonalite blocks (*c.* 570–560 Ma). Most of the terrane consists of imbricated Upper Silurian to Lower Devonian sedimentary strata and sediment-matrix mélange units with mixed siliciclastic and volcaniclastic provenance, interpreted as forearc and/or trench sedimentary deposits.

The Sierra City mélange contains blocks of ophiolitic affinity (serpentinite, gabbro, plagiogranite, basalt), and of sedimentary origin (chert, limestone, sandstone) within a sheared matrix of slate, chert and sandstone; it is interpreted as a combination of tectonic mélange and olistostrome (Schweickert *et al.* 1984). A plagiogranite block in the mélange has yielded a Neoproterozoic (*c.* 600 Ma) U–Pb zircon age, and a felsic body – either a tuff or a dyke – is Silurian (*c.* 423 Ma; Saleeby *et al.* 1987; Saleeby 1990). Detrital zircon populations are predominantly Ediacaran in age (*c.* 600–550 Ma), corresponding to the age of the single dated igneous block (Fig. 31.6f; Harding *et al.* 2000; Grove *et al.* 2008).

The Ediacaran plagiogranite and tonalite in the Yreka and Sierra City mélanges could have been derived from granitoid bodies like those associated with the Wales Group in the Alexander terrane. Ordovician through Early Devonian development of subduction-zone and accretionary complexes in both Yreka and Sierra City mélanges was coeval with the Descon arc. Thus, the Yreka and Sierra City mélanges could be reasonably modelled as the forearc complexes related to arc development in the southern Alexander terrane, given additional evidence for geographic proximity as described below.

Detrital zircon signatures. Detrital zircon ages from the Karheen Formation show a strong population between 500 and 400 Ma, corresponding to Descon magmatic ages, a scatter of Proterozoic ages

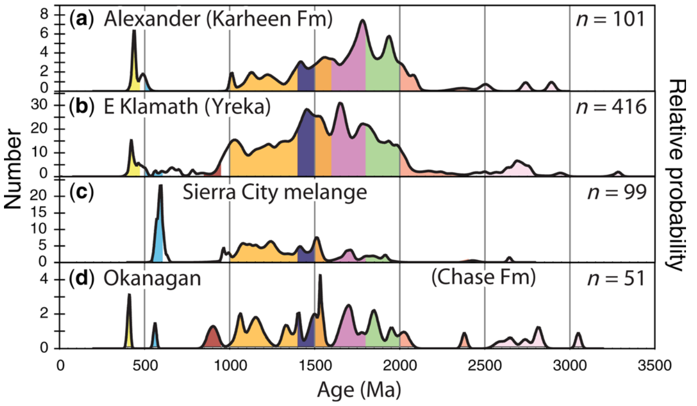

Fig. 31.6. Detrital zircon data for terranes of northern Caledonian and Baltican affinities. (**a**) Karheen Formation, Alexander terrane (after Gehrels *et al.* 1996; Grove *et al.* 2008). (**b**) Yreka terrane, Eastern Klamaths (after Grove *et al.* 2008). (**c**) Sierra City mélange, Northern Sierra terrane (after Grove *et al.* 2008). (**d**) Chase Formation, Okanagan terrane, southern British Columbia (composite of three samples from Lemieux *et al.* 2007; see Colpron & Nelson 2009 for discussion).

between 2.1 and 1.0 Ga, and a few Archaean grains (Fig. 31.6a; Bazard *et al.* 1995; Gehrels *et al.* 1996; Grove *et al.* 2008). Detrital zircon populations in the Yreka blueschist and in crustally derived Lower Devonian units show broad, multipeaked distributions from 2.0 to 1.0 Ga, including significant peaks within the 1.61–1.49 Ga North American magmatic gap of Van Schmus *et al.* (1993) (Fig. 31.6b; Grove *et al.* 2008). Other arc-derived clastic units contain mostly Early Palaeozoic zircons, with predominant ages from 476 to 381 Ma, and a few 560–550 Ma grains that match those of tonalite blocks in the mélange. The detrital zircon signature from sandstone blocks within the Sierra City mélange shows a spread of Mesoproterozoic–Palaeoproterozoic ages, including Grenvillian zircons (*c.* 1.30–0.96 Ga) and grains with ages in the range 1.61–1.49 Ga, as well as abundant Ediacaran grains (*c.* 635–540 Ma, Fig. 31.6c; Grove *et al.* 2008). As pointed out by Grove *et al.* (2008), these patterns are very unlike northwestern Laurentia (Fig. 31.6c; compare with Fig. 31.3b, c).

Faunal and palaeomagnetic evidence. Silurian stromatolite-sphinctozoan reef faunas in the Heceta Limestone of southern Alexander terrane resemble those in the Ural Mountains, as well as in the Farewell terrane (Soja & Antoshkina 1997; Antoshkina & Soja 2006). Early Devonian (Pragian–Early Emsian) rugose corals from Alexander terrane show strong similarities with those of Siberia, Omulevka and Baltica (Pedder 2006). An Early Devonian palaeopole, integrated with the geological record of igneous and orogenic events, fossil affinities and detrital zircon signatures, led Bazard *et al.* (1995) to favour a Mid-Palaeozoic location for Alexander terrane near eastern Siberia and Baltica.

Macrofossils from Ordovician and Silurian limestone blocks in the Yreka mélanges comprise both endemic species and species linked to faunas of Laurentia, Siberia, Baltica, Kazakhstan, Scotland, Australia and China (Lindsley-Griffin *et al.* 2008). Late Ordovician sphinctozoan sponges are part of a rare fauna that is only known in Australia, the Farewell terrane, autochthonous rocks of northern Yukon/east-central Alaska (Potter *et al.* 1990*a*), the Alexander terrane and limestone blocks in olistostromes within the Sierra City mélange (Rigby *et al.* 2005). Upper Ordovician faunas of the Sierra City mélange contain brachiopods, conodonts, rugose and tabulate corals, and sphinctozoan sponges (Potter *et al.* 1990*b*). Most of the brachiopod, coral and sponge genera are also present within the Yreka terrane mélanges. In particular, the sponges include *Amblysiphonolella* sp., *Corymbospongia adnata* and *Girtyocoelia* sp. that the Sierra City mélange shares with the Yreka terrane (Potter *et al.* 1990*a*), as well as with an Ordovician limestone block in the Alexander terrane (Rigby *et al.* 2005). *Cystothalamiella* sp. and *Girtyocoelia epiporata* and *Rigbyetia obconica* occur in limestones of the Sierra City mélange and the Farewell terrane (Potter *et al.* 1990*b*). Brachiopod faunas are similar to those in the Yreka terrane and also the autochthon of northern Yukon. A rugosan coral, *Grewingkia penobscotensis*, is only known from the Sierra City mélange, the Yreka terrane, and northern Maine (eastern Laurentia; Potter *et al.* 1990*b*). Other faunas are less provincial.

Devonian fossils from mixed siliciclastic/volcaniclastic units, and clasts and matrix in mélange units of the Yreka terrane, include corals, brachiopods and conodonts. Like older Yreka terrane faunas, some are very restricted in occurrence, while others have more widespread correlatives. Brachiopods in one of the mélange units, are similar to those in Nevada and northern Canada; some conodonts and corals are only found in the Yreka terrane and in Nevada (Lindsley-Griffin *et al.* 2008). Compared with older faunas, these exhibit a greater connection to western Laurentia, as opposed to northern Laurentia–Baltica–Siberia. A Middle Devonian palaeopole from the Eastern Klamath terranes places them at 31° either north or south latitude (Mankinen *et al.* 2002); combined with faunal linkages the terrane probably lay near northwestern Laurentia at that time (Lindsley-Griffin *et al.* 2008, their figure 11). This pole, however, is only based on two sites, and should be considered preliminary.

Limited data from the Okanagan terrane of southern British Columbia (Fig. 31.1), including detrital zircons from Devonian sandstone (Fig. 31.6d; Lemieux *et al.* 2007), Grenvillian and Ediacaran granitoid cobbles, and enigmatic Ordovician limestone blocks in a probable mélange unit, also support a possible association with the Alexander, Yreka-Trinity and Sierra City terranes in Early Palaeozoic time (Colpron & Nelson 2009, and references therein).

Early Palaeozoic 'Circum-Arctic homelands'

The overall stratigraphic and faunal affinities of the Arctic Alaska and Farewell terranes suggest ties with Siberia and a position near Laurentia in Neoproterozoic–Early Palaeozoic time (Blodgett *et al.* 2002; Dumoulin *et al.* 2002; Macdonald *et al.* 2009). Early Palaeozoic faunas from the Alexander, Yreka and Sierra City terranes also suggest shared provinciality between these terranes and affinities with northern Laurentia, Siberia, Baltica, Kazakhstan, Scotland, Australia and China (Lindsley–Griffin *et al.* 2008). Some endemic species, particularly Silurian sponges, are common to both groups of terranes. The combination of highly endemic and shared faunas is suggestive of an intra-oceanic setting, perhaps as a chain of islands and micro-continents in the palaeo-Arctic ocean between northern Laurentia, Baltica and Siberia (Fig. 31.7).

Detrital zircon signatures from these terranes are completely at odds with northwestern Laurentian basement sources (Fig. 31.2), and completely unlike the patterns seen in sandstones from the northern miogeocline (Fig. 31.3b, c). Detrital zircons from the Farewell terrane (Fig. 31.5a; Bradley *et al.* 2007) closely resemble those from Proterozoic sandstones from the southeastern Siberian platform (Fig. 31.3i; Khudoley *et al.* 2001) with a predominance of zircons in the 2.1–1.8 Ga range and a strong peak at *c.* 2.05 Ga. Those from Arctic Alaska terrane show similar Archaean–Palaeoproterozoic zircons but with a peak in ages at *c.* 1.88 Ga (Fig. 31.5c, d), zircon populations that are compatible with a Siberian source region (Fig. 31.2; Khudoley *et al.* 2007; Prokopiev *et al.* 2008) but also resemble reference data for the northwestern Laurentian Palaeozoic margin in eastern Alaska (Fig. 31.3c; Gehrels *et al.* 1999). Occurrences of Mesoproterozoic and Early Neoproterozoic detrital zircons are atypical of either NW Laurentian or Siberian sources (Fig. 31.2). 'Grenvillian' zircons (*c.* 1.4–1.0 Ga) are present as minor populations in Alaskan and SE Siberian reference data (Fig. 31.3c, i); they are generally interpreted as

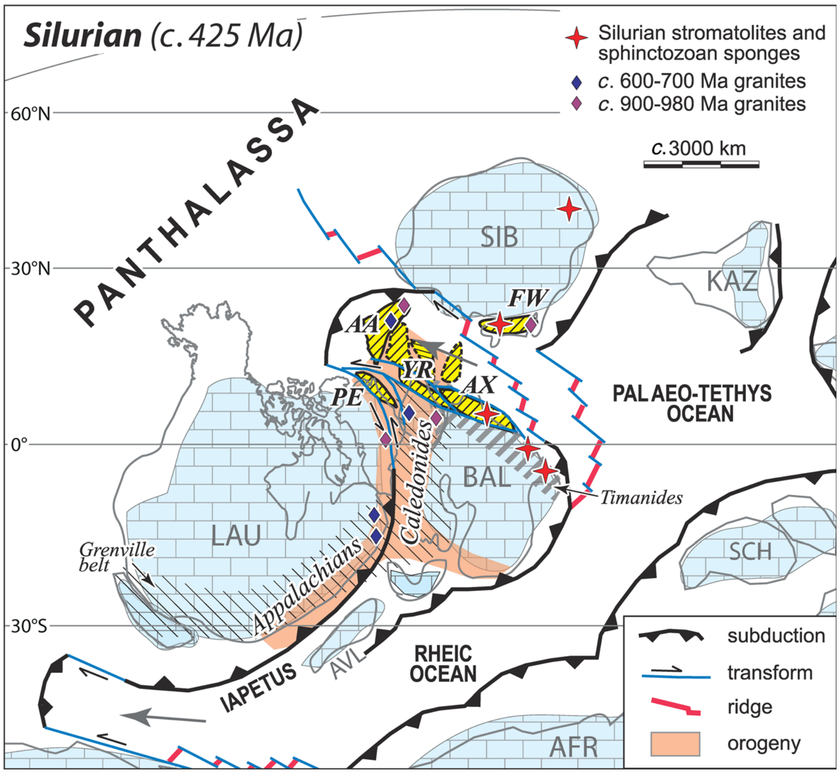

Fig. 31.7. Palaeogeographical setting of Cordilleran exotic terranes of 'Arctic' affinities in Silurian time. Continental reconstructions in this and subsequent figures are modified after Scotese (2002). Mollweide projection; approximate scale. Generalized outline of displaced Caledonian, Timanian and Uralian terranes are shown by yellow polygons with hatch pattern. Terranes with dashed outline schematically represent possible additional crustal fragments that either now form part of larger composite terranes (e.g. Alexander, Arctic Alaska, Chukotka, Ruby) or are submerged in the Arctic Ocean (e.g. Crockerland). Continent abbreviations: AFR, Africa; AVL, Avalonia; BAL, Baltica; KAZ, Kazakhstania; LAU, Laurentia; SCH, South China; SIB, Siberia. Terrane abbreviations: AA, Arctic Alaska; AX, Alexander; FW, Farewell; PE, Pearya; YR, Yreka (including Trinity, and parts of Shoo Fly and Okanagan).

recycling of lower Neoproterozoic strata that contain distal Grenvillian detritus (Rainbird *et al.* 1997; Khudoley *et al.* 2001). Vigorous populations of *c.* 1.2–1.0 Ga detrital zircons in samples from Arctic Alaska terrane, and the presences of Early Neoproterozoic (*c.* 980–900 and *c.* 850 Ma) igneous rocks and detrital zircons in Arctic Alaska, Farewell and Kilbuck terranes cannot easily be matched with NW Laurentia. Granitoids of *c.* 950–900 Ma intruding Mesoproterozoic–Early Neoproterozoic basement units are common features of the northern Caledonides and occur locally in central Taimyr (Fig. 31.2; Kalsbeek *et al.* 2000; Pease *et al.* 2001; Johansson *et al.* 2005). The predominance of Late Neoproterozoic–Early Palaeozoic detrital zircons in metasedimentary rocks of Seward Peninsula (Fig. 31.5b) suggests affinities with the Timanide orogen or the Avalonian–Cadomian terranes and the Caledonides (Amato *et al.* 2009).

Possible correlatives for the *c.* 850 Ma granitoids in the Farewell and Kilbuck terranes are more limited in the Circum-Arctic region (Fig. 31.2). A few isolated granites in the northern Caledonides have yielded ages of *c.* 870–850 Ma; these have been related either to anatectic melts associated with alkalic mafic igneous complexes emplaced during early stages of Rodinia breakup (Millar 1999; Paulsson & Andréasson 2002) or an intrusive event associated with the Early Neoproterozoic Porsanger orogeny (*c.* 850 Ma) in northern Scandinavia (Kirkland *et al.* 2008). Calc-alkaline granite gneisses of *c.* 880–850 Ma are reported locally from Central Taimyr along the northern Siberian margin, and also in the Yenisey Ridge fold-and-thrust belt along western Siberia (Fig. 31.2; Vernikovsky *et al.* 2004). In southern Siberia, *c.* 900–812 Ma syn-tectonic granitoids also occur with an ophiolitic complex in the Baikal–Vitim belt (Vernikovsky *et al.* 2004).

Detrital zircons from the Alexander, Yreka and Sierra City terranes show multiple sources between 2.0 and 1.0 Ga, including significant populations in the 1.61–1.49 Ga North American magmatic gap (Fig. 31.6a–c; Grove *et al.* 2008). Limited data from the Okanagan terrane of southern British Columbia suggest a possible link to these terranes as well (Figs 31.1 & 31.6d; Lemieux *et al.* 2007). Grove *et al.* (2008) have pointed out the similarities of these detrital zircon patterns to those of Neoproterozoic–Early Palaeozoic sandstones from the western (Caledonian) margin of Baltica (Figs 31.3h & 31.6). They also bear similarities with detrital zircon patterns from Neoproterozoic sandstones of the Greenland Caledonides (NE Laurentia; Fig. 31.3g; Cawood *et al.* 2007; Colpron & Nelson 2009).

Late Neoproterozoic arc magmatism (*c.* 700–540 Ma) is documented in the western and southern Arctic Alaska and Alexander terranes, and attested to by detritus in the Yreka and Sierra City mélanges. Arc activity of this age is not only absent along the western Laurentian margin, but is unlikely to have occurred, given that the open margin itself is a *c.* 700–540 Ma feature (e.g. Colpron *et al.* 2002). In Alexander terrane, this arc development was followed by pre-Ordovician orogenesis (Gehrels *et al.* 1996). On Seward Peninsula and Wrangel Island (Chukotka), Neoproterozoic arc magmatism occurs below inferred sub-Ordovician unconformities (Amato *et al.* 2009). This combination of Neoproterozoic magmatism, Neoproterozoic–Cambrian deformation and sub-Ordovician unconformity is reminiscent of the Timanide orogen in the Eurasian Arctic (Fig. 31.2; Bogolepova & Gee 2004; Gee *et al.* 2006; Lorenz *et al.* 2007, 2008; Pease & Scott 2009).

Ordovician–Silurian arc activity flourished in the southern Alexander terrane (Descon Formation); Ordovician arc-related strata also occur in the Doonerak fenster in the Arctic Alaska terrane. Ordovician blueschist in the Yreka terrane and Ordovician–Devonian mélanges in the Yreka and Sierra City terranes represent a forearc tectonic environment that was broadly coeval with development of the Descon arc in the Alexander terrane. Arc development of this age is unknown on the western Laurentian margin, but it is common in the northern Appalachians and Caledonides (van Staal *et al.* 1998; Gee *et al.* 2008). In Alexander terrane, Ordovician arc buildup was followed by Siluro-Devonian orogeny and deposition of the coarse clastic rocks of the Karheen Formation, a redbed unit that has been compared with the Old Red Sandstone of northern Europe (Bazard *et al.* 1995; Gehrels *et al.* 1996; Soja & Krutikov 2008). The *c.* 500–400 Ma detrital zircon population in the Karheen Formation (Fig. 31.6a) matches well the ages of intrusive and metamorphic events in the northern

Caledonides (Roberts 2003; Gee *et al.* 2008; Higgins & Leslie 2008), and resembles detrital mica $^{40}Ar/^{39}Ar$ ages from the Old Red Sandstone (Sherlock *et al.* 2002; Eide *et al.* 2005). Similar peak in ages for detrital zircons from the Yreka and Okanagan terranes (Fig. 31.6b, d) suggest similar Caledonian sources for these terranes as well.

Linkages between the Eastern Klamath basement (Yreka and Trinity terranes), the Sierra City mélange and the Alexander terrane are suggested based on their overall characteristics and detrital zircon signatures (Wright & Wyld 2006), and also with terranes of the northern Caledonian orogen (Grove *et al.* 2008). The favoured palaeogeographic position for these terranes during Neoproterozoic through Early Devonian time was offshore near the Baltican end of the Caledonides (Fig. 31.7; Bazard *et al.* 1995; Soja & Antoshkina 1997; Pedder 2006; Lindsley-Griffin *et al.* 2008; Soja & Krutikov 2008). An alternative 'southern' location between Laurentia and Gondwana in Silurian time (Wright & Wyld 2006) seems unlikely, because of the lack of faunal similarities between the Yreka terrane and Gondwana (Lindsley-Griffin *et al.* 2008).

A northern Caledonian connection for parts of the Arctic Alaska terrane has long been proposed based on the local occurrences of lower Palaeozoic oceanic rocks and the character of Mid-Palaeozoic clastic rocks (Nilsen 1981; Sweeney 1982), an interpretation that finds strenght in more recent detrital zircon and detailed stratigraphic studies (Moore *et al.* 2007; Macdonald *et al.* 2009). These models proposed westward emplacement of Caledonian elements of Arctic Alaska terrane in Devonian time, prior to deposition of the Lower Mississippian Endicott Group clastic rocks (Moore *et al.* 1994).

The superposition of Neoproterozoic–Cambrian and Ordovician–Early Devonian arcs and orogenic belts in the southern Alexander terrane, combined with Silurian Siberian–Baltican faunas, suggests that it most likely originated near the present-day Barents Shelf (Fig. 31.2), where the Siluro-Devonian Caledonian deformation is inferred to overprint the Neoproterozoic Timanide orogen (Roberts & Siedlecka 2002; Gee *et al.* 2006).

The Farewell terrane, although it has early faunal similarities to southern Alexander, has a completely different Palaeozoic tectonic history. It contains no evidence of Neoproterozoic–Cambrian or Ordovician–Devonian arc magmatism or orogenesis. Instead, quiet platformal conditions prevailed until the onset of Early Permian orogeny. The Browns Fork orogeny is coeval and similar in style to Uralian orogenesis related to Permian collision between Baltica and the Kazakhstan–Siberian plate (Bradley *et al.* 2003; Brown *et al.* 2006*a*). This constraint, along with the evidence that Arctic Alaska was interacting with the northwestern margin of Laurentia in Devonian time, suggests that at this time Farewell and Arctic Alaska had separated, with Farewell remaining near the Arctic end of the Uralian orogen near Taimyr until the end of the Palaeozoic. The similarities between Farewell terrane and central Taimyr are striking: composite Mesoproterozoic–Early Neoproterozoic basement overlain by miogeoclinal strata containing Siberian faunas and derived from Siberian sources, including abundant *c.* 2.0 Ga detritus. An episode of Triassic–Jurassic dextral transpression that affected Taimyr (Inger *et al.* 1999; Torsvik & Andersen 2002; Walderhaug *et al.* 2005) offers a possible mechanism for westerly displacement of Farewell terrane towards its present location.

A Palaeozoic NW Passage

The westerward migration of these 'Arctic' terranes – from their sites of origins along extensions of the Timanian, Caledonian and Uralian orogens in Early Palaeozoic time to their progressive accretion to the Cordilleran margin of Laurentia between Mid-Palaeozoic and Mesozoic time – is inferred to have occurred as a Caribbean/Scotia-style subduction system developed between Laurentia–Baltica and Siberia in Mid to Late Palaeozoic time (Fig. 31.7; Colpron & Nelson 2009). Dispersion of these terranes and their westward travel around northern Laurentia began as the Iapetus and Rheic oceans closed and the Appalachian–Caledonian orogen developed between eastern Laurentia and western Baltica in Mid-Palaeozoic time (Fig. 31.7). We have postulated that upper mantle flow out of the shrinking Iapetus–Rheic oceans opened a Mid-Palaeozoic 'gateway' between Laurentia and Siberia, termed the NW Passage (Colpron & Nelson 2009), similar to the Miocene to recent development of the Scotia Sea through Drake Passage between South America and Antarctica (Pearce *et al.* 2001). Initial rifting and rapid westward migration of a narrow subduction zone (Schellart *et al.* 2007) led to dispersion of the crustal fragments that once lay between Baltica, Siberia and northeastern Laurentia (Fig. 31.7). The southern boundary of the NW Passage developed as a sinistral transpressive zone along which Pearya, the least displaced of these terranes, was emplaced along the northern Laurentian margin in Late Silurian–Early Devonian time (Figs 31.7 & 31.8). This sinistral transpressive zone was probably kinematically linked with Silurian to Devonian sinistral transpression that characterized the Late Caledonian deformation of Svalbard and NE Greenland (Gee & Page 1994; Ohta 1994; Gee & Teben'kov 2004; Higgins & Leslie 2008).

Early record of a Scotia-style arc is probably preserved in the Early to Middle Devonian magmatism of the southern Brooks Range and the Seward Peninsula. Arc magmatism spans the period of *c.* 402–366 Ma in the southern Brooks Range and probably reflects north-dipping (present-day coordinates) subduction beneath the Arctic Alaska terrane (Moore *et al.* 1994; McClelland *et al.* 2006*b*). By late Early Devonian, the Arctic Alaska terrane was accreted to the northwestern margin of Laurentia during the Romanzof orogeny (Fig. 31.8; Lane 2007; Moore *et al.* 2007). Arctic Alaska is thought to have been part of a single continent-scale terrane, which included Pearya in the Canadian Arctic Islands, and once linked up with the northern Caledonides (Sweeney 1982; Moore *et al.* 2007). A tectonic highland persisted north of present-day Arctic Alaska (and Sverdrup Basin in Arctic Canada) from Early Mississippian through Early Mesozoic time, based on successive onlaps and northward-coarsening of siliciclastic strata (Embry 1993, 2009; Moore *et al.* 1994), and Ediacaran and Ordovician detrital zircons from northerly derived Triassic units (Miller *et al.* 2006).

Both the Eastern Klamath and Northern Sierra (Shoo Fly complex) terranes include siliciclastic units with detrital zircons that are consistent with a northwestern Laurentian source, and that were structurally interleaved with their Caledonian elements in Devonian time (Harding *et al.* 2000; Wallin *et al.* 2000; Colpron & Nelson 2009, and references therein). We speculate that the Caledonian-derived elements of the Eastern Klamath and Northern Sierra terranes also came into contact with their northwestern Laurentian counterparts during the Romanzof orogeny, and later migrated southward along western Laurentia as composite terranes (Figs 31.8 & 31.9; Wallin *et al.* 2000; Colpron & Nelson 2009). This southward transport of terranes most probably occurred along a sinistral transform fault system that developed along the western edge of Laurentia in Middle Devonian time (Fig. 31.9). The southward propagation of this transpressional fault system is possibly recorded by progressively younger deformation along the western Laurentian continental margin, starting with the late Early Devonian Romanzof orogeny in northern Yukon and Alaska (Lane 2007), progressing to early Middle Devonian (Eifelian) folding and faulting in the Purcell Mountains of southeastern British Columbia (Root 2001), and ending with the Late Devonian to Early Mississippian Antler orogeny in the SW USA (Johnson & Pendergast 1981; Figs 31.1, 31.8–31.10). The Okanagan terrane appears to have been emplaced against the western Kootenay terrane by Late Devonian time (Thompson *et al.* 2006), an event that could relate to

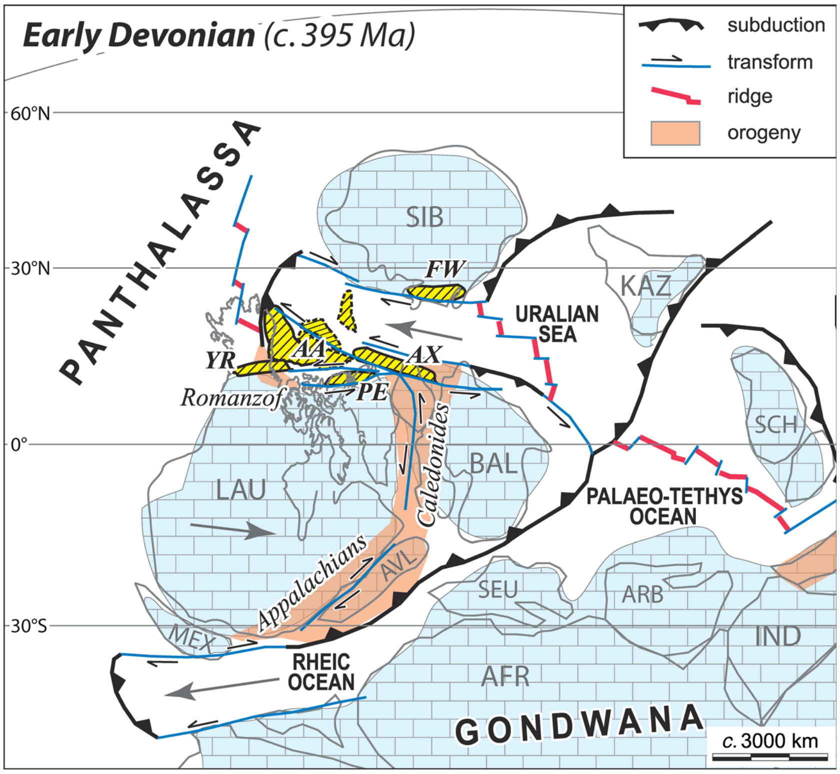

Fig. 31.8. Early Devonian palaeogeography and development of the NW Passage between Laurentia–Baltica and Siberia. Continent abbreviations: ARB, Arabia; IND, India; MEX, Mexico; SEU, southern Europe. Other abbreviations as in Figure 31.7.

enigmatic Middle Devonian deformation in the Purcell Mountains to the east (Colpron & Nelson 2009). Arrival of the Northern Sierra terrane before intrusion of the *c*. 364 Ma Bowman Lake batholith could have triggered the east-directed emplacement of the Roberts Mountains allochthons (western Laurentia continental slope deposits) and deposition of a clastic wedge during the Antler orogeny.

Both the Eastern Klamath and Northern Sierra terranes contain peri-Laurentian Devonian to Jurassic arc-related suites that developed on top of previously imbricated basement units of Caledonian affinity (Potter *et al.* 1990*a*; Miller & Harwood 1990; Grove *et al.* 2008). Facies transitions have been inferred between these and basinal strata farther east in the Golconda allochthon, which in turn show ties with the local continental margin. Thus, by Middle to Late Devonian time, the inferred Caledonian terranes had been displaced considerably southwards along the western Laurentian margin and incorporated into its evolving, highly mobile borderlands (Colpron & Nelson 2009). This proposed scenario would require passage of the Shoo Fly Complex (Northern Sierra) and the Eastern Klamath terrane from a site of

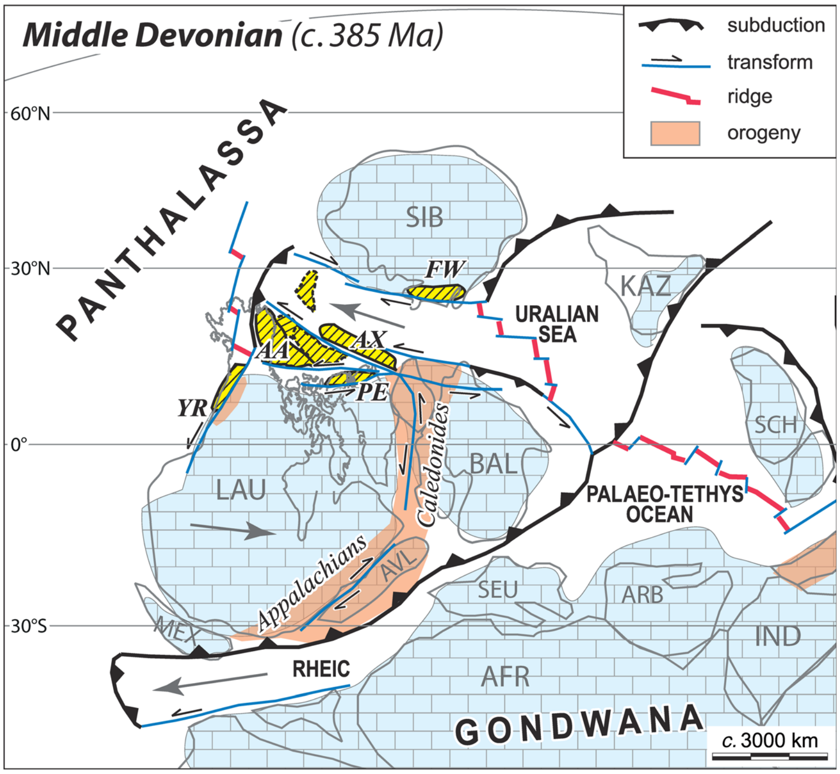

Fig. 31.9. Middle Devonian palaeogeography and development of a transform margin along western Laurentia. Abbreviations as in Figures 31.7 and 31.8.

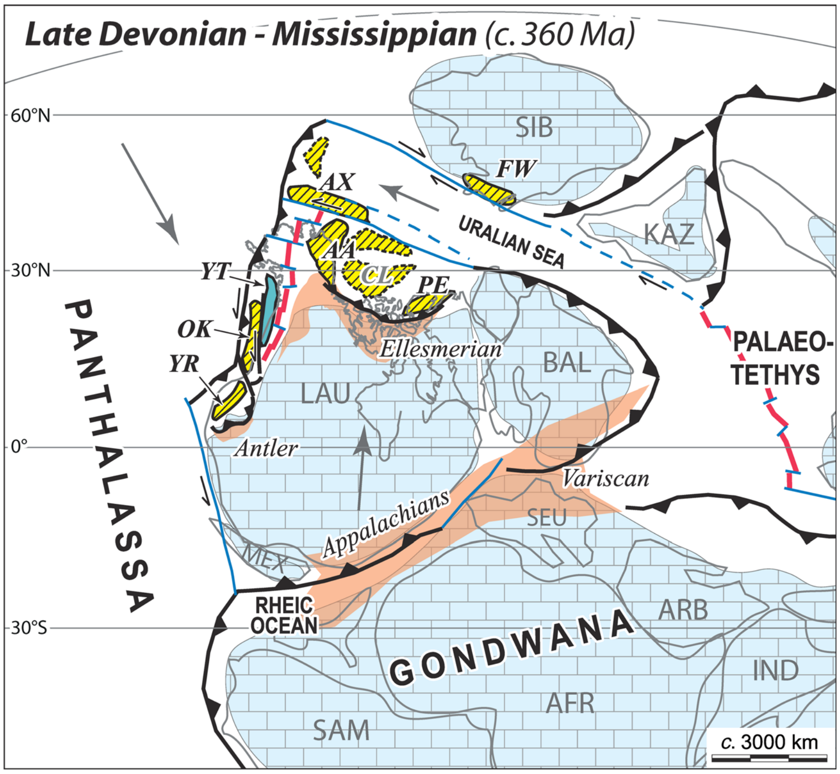

Fig. 31.10. Late Devonian to Early Mississippian palaeogeography. Development of the Antler and Ellesmerian orogens, initiation of subduction along western Laurentia and onset of rifting in the backarc region. The Yukon–Tanana terrane (YT; green) represents a rifted fragment of western Laurentia upon which an active arc developed in Mid to Late Palaeozoic time (Nelson *et al.* 2006; Colpron *et al.* 2007). The Okanagan terrane (OK) has affinities with the Yreka terrane and may represent fragments of this terrane in southern British Columbia (Colpron & Nelson 2009). Abbreviations: CL, 'Crockerland'; SAM, South America. Other abbreviations as in Figures 31.7 and 31.8.

collision with northwestern Laurentia to a location nearer southwestern Laurentia as a Devonian event, a maximum possible interval of 58 Ma and probably less (time scale of Gradstein *et al.* 2004). In this case average motion would need to be about 5 cm/year, comparable to rates of advance of short modern arc segments such as the Scotia and New Hebrides arcs (Schellart *et al.* 2007).

Subduction was initiated along the entire western margin of Laurentia in Late Devonian time (Monger & Nokleberg 1996; Monger & Price 2002). Propagation of a sinistral transform fault that apparently nucleated out of the NW Passage in Middle Devonian time could have provided the weakness along which the oceanic lithosphere collapsed and subduction propagated southward (Figs 31.9 & 31.10). Onset of subduction and its southward propagation is recorded by magmatism of 400–380 Ma in Arctic Alaska terrane, 390–380 Ma in Yukon–Tanana terrane of the Coast Mountains (which probably restored near present-day Alaska in Palaeozoic time; Mihalynuk *et al.* 1994), 370–360 Ma in parautochthonous continental margin of eastern Alaska and Yukon, and *c.* 360 Ma along the entire margin of western Laurentia (Nelson *et al.* 2006). These events were probably the result of a global plate reorganization that followed the Middle Devonian Acadian orogeny in the Appalachians and continued with the Carboniferous collision of Gondwana (Figs 31.9–31.11). A narrow subduction zone that propagated westward through the NW Passage in Silurian–Devonian time could have provided the seed point from which to initiate subduction along western Laurentia (Figs 31.8–31.10).

Along northern Laurentia, this change in plate motion led to a collision with an enigmatic crustal block (Crockerland) and development of the Late Devonian–Early Mississippian Ellesmerian orogeny as Laurentia apparently tracked north during collision with Gondwana (Fig. 31.10). Crockerland was possibly one of the Caledonian crustal fragments associated with the Alexander and other terranes (Fig. 31.4). It apparently supplied sediments intermittently to Sverdrup basin to the south until Mid-Mesozoic time (Davies & Nassichuk 1991; Embry 1993, 2009) and was probably removed or submerged during Jurassic–Cretaceous opening of the Arctic Ocean. This interpretation differs from that of Golonka *et al.* (2003), who postulated that a collision with Siberia was the driver behind the Ellesmerian orogeny. Detrital zircons in rocks of the Ellesmerian clastic wedge and Sverdrup basin are consistent with sources in the Caledonides, Timanides and Laurentia (Beranek 2009) rather than cratonal Siberia.

Shortly after initiation of subduction along western Laurentia, slab rollback is thought to have caused extension in the backarc region, which led to rifting of parts of the distal continental margin which became basement to peri-Laurentian arc terranes such as Yukon–Tanana, Stikinia and Quesnellia in the northern Cordillera, and the Eastern Klamath and Northern Sierra terranes in the SW USA (Fig. 31.10; Monger & Nokleberg 1996; Nokleberg *et al.* 2000; Nelson *et al.* 2006; Colpron *et al.* 2007; Colpron & Nelson 2009). This rifting culminated in opening of the Slide Mountain ocean in Early Mississippian time and hence migration of the Late Palaeozoic peri-Laurentian arcs away from the continental margin (Figs 31.10 & 31.11). The Yukon–Tanana terrane shares Late Devonian to earliest Mississippian (370–355 Ma) magmatism with the Laurentian margin, but younger Carboniferous to Permian arc magmatism is unique to the terrane (Nelson *et al.* 2006). The Slide Mountain ocean apparently reached its maximum width in Early Permian time (Fig. 31.11; Nelson *et al.* 2006; Colpron *et al.* 2007). Permian limestones common in the peri-Laurentian arc terranes contain fusulinids and corals defining the McCloud faunal belt, an endemic fauna only found in the peri-Laurentian terranes and autochthonous strata of western Texas (Miller 1988; Stevens 1995). Based on statistical analysis, Belasky *et al.* (2002) have suggested that the McCloud belt probably lay 2000–3000 km west of the continental margin, providing a maximum estimate for the width of the Slide Mountain ocean. By Middle Permian time (*c.* 270 Ma), subduction polarity was reversed and the Slide Mountain lithosphere was being subducted beneath the Yukon–Tanana and related terranes. This is recorded in the Yukon–Tanana terrane by paired belts of blueschists and eclogites to the east and Middle to Upper Permian arc rocks to the west (Nelson *et al.* 2006). By Triassic time, the Slide Mountain ocean had closed and the Late Palaeozoic peri-Laurentian arcs were accreted to western Laurentia, by then a part of Pangaea, during the Sonoma orogeny (Fig. 31.12). Triassic synorogenic clastic rocks overlying

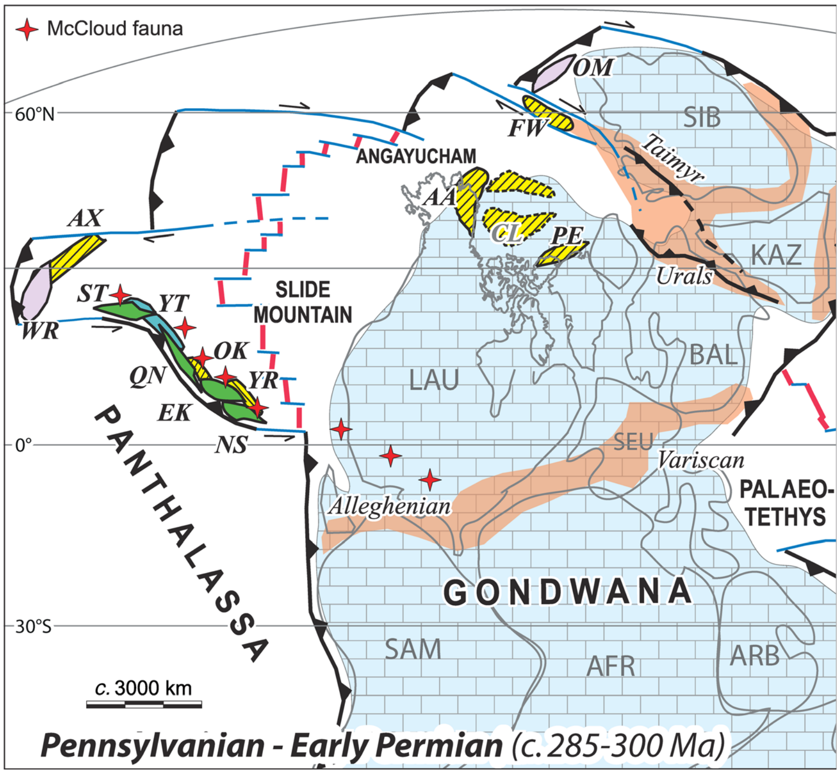

Fig. 31.11. Pennsylvanian to Early Permian palaeogeography. By this time, the Slide Mountain ocean had reached its maximum width and volcanic arcs of the McCloud belt (Late Palaeozoic sequences of Stikinia (ST), Quesnellia (QN), Eastern Klamaths (EK) and Northern Sierra (NS) terranes) were developing on top of pericratonic Mid-Palaeozoic and older fragments of Yukon–Tanana (YT), Yreka-Trinity (YR), Shoo Fly and Okanagan (OK) terranes. Onset of Uralian tectonism along northern Baltica, Kazakhstania and Siberia, and inferred expulsion of the Farewell terrane (FW) from the Siberian margin. Wrangellia (WR) is a Late Palaeozoic arc terrane of Panthalassic affinity that is in part tied to Alexander terrane. OM, Omulevka ridge. Other abbreviations as in Figures 31.7–31.10.

the Yukon–Tanana and Slide Mountain terranes, as well as the Laurentian continental margin, and amphibolite–facies metamorphism in the Yukon–Tanana terrane provide records of the Sonoman event in the northern Cordillera (Berman *et al.* 2007; Beranek 2009).

Unlike the Eastern Klamath and Northern Sierra terranes, there is no evidence that the Alexander terrane interacted directly with either the western Laurentian margins or with the peri-Laurentian terranes until its Mid-Jurassic accretion to the Yukon–Tanana terrane in southeastern Alaska (Gehrels 2001, 2002). Late Devonian and Mississippian corals in the Alexander terrane resemble those from western Laurentia suggesting that this terrane had migrated into eastern Panthalassa by that time (Fig. 31.10; Pedder 2006). By Pennsylvanian time, the Alexander terrane was intruded by a *c.* 309 Ma pluton that also intrudes part of Wrangellia (Gardner *et al.* 1988) and is inferred to be comagmatic with arc volcanism in this Devonian–Triassic arc terrane (Fig. 31.1). Wrangellia and Alexander terrane apparently evolved together in an

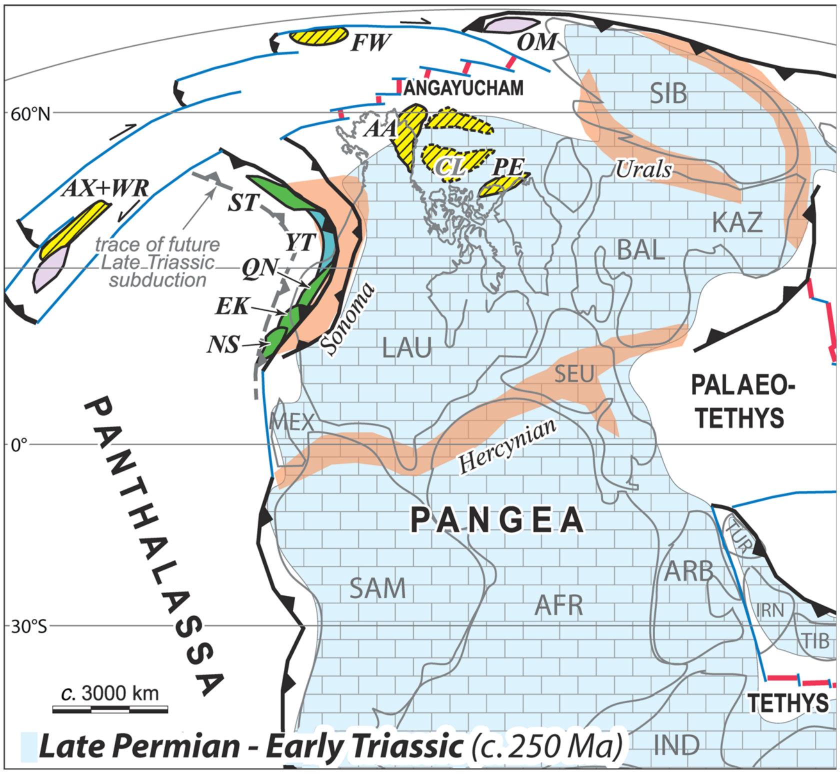

Fig. 31.12. Late Permian to Early Triassic palaeogeography. By then, all Caledonian, Baltican and Siberian terranes now found in the North American Cordillera had entered Panthalassa. The Slide Mountain ocean was closing and the Late Palaeozoic peri-Laurentian arcs were accreted to western Laurentia, by then a part of Pangaea. IRN, Iran; TIB, Tibet; TUR, Turkey. Other abbreviations as in Figures 31.7–31.11.

isolated intra-oceanic setting in northern Panthalassa from Carboniferous until their Middle Jurassic accretion (Fig. 31.12).

The Farewell terrane is thought to have originated from the northern margin of the NW Passage, where it originally evolved as part of the Siberian Platform until at least Early Permian time, when it was deformed during the *c.* 285 Ma Browns Fork orogeny, an event related to development of the Uralian and Taimyr fold belts (Figs 31.8–31.11; Bradley *et al.* 2003). Details of its Mesozoic history are sparse. The Farewell terrane may have been expelled from its site of origin during or following Uralian tectonism (Figs 31.11 & 31.12).

By Middle to Late Triassic time, east-dipping subduction was re-established along the entire western margin of Laurentia (now part of Pangaea; Fig. 31.12), giving rise to voluminous Triassic–Jurassic arc magmatism of Stikinia, Quesnellia and related terranes of the western USA, which were in part built upon Palaeozoic basements of the Yukon–Tanana, Okanagan, Eastern Klamath and Northern Sierra terranes. This more stable, wide slab geometry (Schellart *et al.* 2007) has apparently persisted more or less in its original form along western North America until at least Early Cenozoic time. Convergence between the North American plate and the various oceanic plates that succeeded Panthalassa (e.g. Farallon, Kula and Pacific) began with the Jurassic opening of the North Atlantic Ocean and the westward drift of North America over its western subduction zone (Monger & Price 2002).

Conclusions

A number of the exotic terranes that generally occupy outboard positions in the North American Cordillera apparently originated in Palaeozoic time from sites now found in the Eurasian Arctic region. Comparison of their Neoproterozoic–Early Palaeozoic histories, detrital zircon signatures, faunal assemblages and palaeomagnetic data to features of the Circum-Arctic cratons and their bordering Palaeozoic orogens brings refinement to previous palaeogeographic interpretations for these terranes. Cordilleran Arctic terranes share a number of features amongst them that indicate interactions in a common source region, occupying an intermediate position between NE Laurentia, Baltica and Siberia (Figs 31.2 & 31.7). Neoproterozoic–Palaeozoic tectonic and magmatic events in these terranes can be matched specifically with elements that characterize the Arctic extensions of the Timanian, Caledonian and/or Uralian orogenic belts.

Dispersion of the northern Caledonian–Siberian terranes and their westward migration into eastern Panthalassa is interpreted to result from development of a Caribbean/Scotia-style subduction system between northern Laurentia–Baltica and Siberia in Mid-Palaeozoic time: the NW Passage. This system was probably driven by upper mantle outflow from the closing Iapetus–Rheic oceans along eastern Laurentia, as Pangaea was being amalgamated (Figs 31.7–31.10). The rapid westward migration of a narrow subduction zone through the NW Passage entrained northern Caledonian and Siberian terranes into eastern Panthalassa and provided a seed point for propagation of subduction along western Laurentia in Late Devonian–Early Mississippian time. The westward and subsequent southward migration of these terranes around Laurentia is recorded by a series of 'enigmatic' Mid-Palaeozoic orogenic events including the Romanzof, Ellesmerian and Antler orogens. Subduction along western Laurentia is inferred to have been initiated as a result of a global plate reorganization related to Devonian convergence in the Appalachian orogen of eastern Laurentia and Carboniferous collision with Gondwana. By Early Mesozoic time, this subduction system had evolved to a stable, wide-slab geometry that persisted along western North America at least until Early Cenozoic time.

The NW Passage hypothesis emerged from a growing body of evidence that consistently points to 'Arctic' origins for some Cordilleran terranes. However, this knowledge base is in many cases derived from studies of geographically limited regions within otherwise vast terranes with complex geology. Further studies of the exotic terranes of the North American Cordillera and their postulated source regions in the Eurasian Arctic are required to test and refine this hypothesis. Critical advances are expected to be made with further mapping and geochronological studies tied to stratigraphic controls, particularly of detrital zircon suites, in Palaeozoic and older terranes of the Circum-Arctic region and the northern Cordillera. More specific tests could include:

(1) Resolving the relationships between older parts of large, composite terranes such as Alexander and Arctic Alaska. Both these terranes comprise Neoproterozoic–Early Palaeozoic elements that apparently originated along distinct parts of the present Eurasian Arctic. At present, these are at best sparsely documented and their times of amalgamation are poorly understood but probably Palaeozoic in age.

(2) Establishing the potential role of other terranes in the northern Cordillera (e.g. Ruby, Windy–McKinley; Fig. 31.1) in the Palaeozoic–Early Mesozoic evolution of northwestern Laurentia. The Ruby terrane of central Alaska in particular remains largely unknown. Limited information available from this terrane suggests possible affinity with Arctic Alaska, Farewell, and possibly northwestern Laurentia (Roeske *et al.* 2006; Bradley *et al.* 2007). The Ruby terrane probably played a role in the evolution of the NW Passage, but the current lack of information from it prevents integration into a geodynamic model.

(3) Improving the detrital zircon database for both displaced terranes and Circum-Arctic continental margins. Although this dataset is rapidly growing, at present detrital zircon data is most commonly available for limited stratigraphical and geographical extents. More complete characterization of stratigraphical sections and their lateral extents within terranes are necessary to refine the evolution of these terranes. Systematic analyses of Palaeozoic sandstone deposited along the Arctic margins should reveal increasing contributions from Timanian, Caledonian and Uralian sources as terranes progressed westward through the NW Passage. Reference detrital zircon data are particularly lacking from the Siberian margins. Future detrital zircon studies should also integrate Hf and Nd isotopic analyses in order to better characterize potential source regions.

(4) The NW Passage hypothesis requires that the northern margin of Siberia was a dextral transform margin in Mid to Late Palaeozoic time. Early Mesozoic dextral transpression is documented in Taimyr. Could this transcurrent deformational regime have been initiated in Palaeozoic time?

(5) Finally, palaeomagnetic studies of the Palaeozoic sections of inferred displaced terranes should be attempted in order to reconstruct their travels.

Discussions with many of our colleagues on topics of Cordilleran and Arctic tectonic evolution since our initial proposal of the NW Passage hypothesis have helped refine our interpretations. Recent exchanges with J. Amato, R. Blodgett, D. Bradley, J. Dumoulin, A. Embry, S. Karl, F. Macdonald, J. Monger, E. Miller, V. Pease and A. Till were particularly influential. Thanks to A. Embry for inviting this external view of Circum-Arctic tectonics to this volume. We thank J. Golonka, T. F. Redfield and A. Spencer for their comments. This is Yukon Geological Survey Contribution no. 005.

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