TECTONICS AND METALLOGENY OF THE BRITISH COLUMBIA, YUKON AND ALASKAN CORDILLERA, 1.8 GA TO THE PRESENT

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Abstract

The northern Cordilleran Orogen of western Canada and Alaska comprises rocks that attest to over 1.8 billion years of tectonic history, from cratonization of the Laurentian continental core to current subduction and transform motion off the west coast today. Evolving tectonic styles, ranging from Proterozoic intracratonic basin formation through Paleozoic rifting through the construction of Mesozoic and younger intraoceanic and continent margin arcs, has led to the wide variety of metallogenetic styles that define the mineral wealth of the northern Cordillera.

The northern Cordillera is made up of five large-scale tectonic provinces: the Laurentian craton and its deformed margins; allochthonous terranes of the peri-Laurentian realm, that represent offshore rifted continental fragments, arcs, and ocean basins formed in a setting similar to the modern western Pacific province; the Arctic and Insular terranes, a group of crustal fragments that originated in the Arctic realm between Laurentia and Siberia and were transported separately southwards to impinge on the outer peri-Laurentian margin in Mesozoic time; and the late-accreted Pacific terranes, Mesozoic to Cenozoic accretionary prisms that developed along an active Pacific plate margin with a configuration much like the present one. Each tectonic province carries its own metallogenetic signature. Superimposed post-accretionary magmatic arcs and compressional and extensional tectonic regimes have also given rise to important mineral deposit suites. Seafloor hotspring deposits forming presently along the Juan de Fuca Ridge off the southwest coast of British Columbia show the continuation of Cordilleran metallogeny into the foreseeable future.

Résumé

La partie nord de l'orogène de la Cordillère, qui s'étire le long de la côte Ouest du Canada et en Alaska, comprend des roches témoignant d'une évolution tectonique longue de plus de 1,8 milliard d'années. Amorcée par la cratonisation du noyau continental laurentien, cette évolution se poursuit de nos jours par le déplacement de la côte Ouest par subduction et coulissage. Des styles tectoniques en évolution, depuis la formation de bassins intracratoniques au Protérozoïque jusqu'à la distension continentale au Paléozoïque puis à l'édification d'arcs intra-océaniques et d'arcs de marge continentale au Mésozoïque et plus récemment, ont engendré toute une gamme de styles métallogéniques déterminant la richesse minérale du nord de la Cordillère.

La Cordillère septentrionale comprend cinq grandes provinces tectoniques : le craton laurentien et ses marges déformées; les terranes allochtones du domaine péri-laurentien, constitués de fragments continentaux, qui se sont détachés par rifting et dispersés au large, d'arcs et de bassins océaniques formés dans un cadre similaire à celui de l'actuelle province du Pacifique occidental; les terranes arctiques et insulaires, un groupe de fragments crustaux émanant du domaine arctique entre la Laurentie et la Sibérie, transportés séparément vers le sud et poussés contre la marge péri-laurentienne au Mésozoïque; et les terranes du Pacifique d'accrétion tardive, constitués de prismes d'accrétion datant du Mésozoïque au Cénozoïque, qui se sont formés le long d'une marge active de la plaque du Pacifique présentant une configuration très semblable à la marge actuelle. Chacune de ces provinces présente une signature métallogénique qui lui est propre. Les arcs magmatiques post-accrétionnaires et les régimes tectoniques de compression et d'extension ont en outre engendré d'importantes successions de gîtes minéraux. Les dépôts de sources chaudes qui s'accumulent actuellement sur le fond marin le long de la dorsale Juan de Fuca, au large de la côte sud-ouest de la Colombie-Britannique, attestent de la continuation de la métallogénie cordillérienne dans l'avenir prévisible.

Introduction

This synthesis spans the northern Cordilleran Orogen of British Columbia, Yukon, and Alaska (Fig. 1). The modern Cordillera was founded upon the western margin of the Laurentian craton (later North America), a continental margin that has been tectonically active from its inception in Late Precambrian time up to the present. Because the northern Cordillera has evolved as an active belt over such a protracted period of time, through diverse tectonic styles and paleogeographic configurations, it provides an excellent case study of how metallogenesis is governed by tectonics. The purpose of this article is to weave the stories of metallic mineral deposits into the overall tectonic history of the northern Cordillera, and also to serve as a portal for more detailed sources of information, for instance Nokleberg et al. (2000, 2005).

Metallic mineral deposits preserved within the northern Cordillera range in age from 1.6 billion to less than 20 million years. The wide variety of deposit types reflects tectonic processes such as intra-continental and intra-arc extension, and the multistage development of pericratonic fringing magmatic arcs. Of most economic significance at present are SEDEX (sedimentary exhalative), VMS (volcanogenic massive sulphide), porphyry, and mesothermal (orogenic), epithermal and intrusion-related gold deposits. Many other deposit types, including Irish-type syngenetic sulphide, MVT (Mississippian Valley-type Pb-Zn), skarn, and iron-oxide copper-gold, are also well represented.

The northern Cordillera is a highly fertile metallogenetic environment that hosts world-class orebodies. The most notable mined examples include the 160 Mt Sullivan, the 142 Mt Red Dog, and the 120 Mt Anvil Range SEDEX

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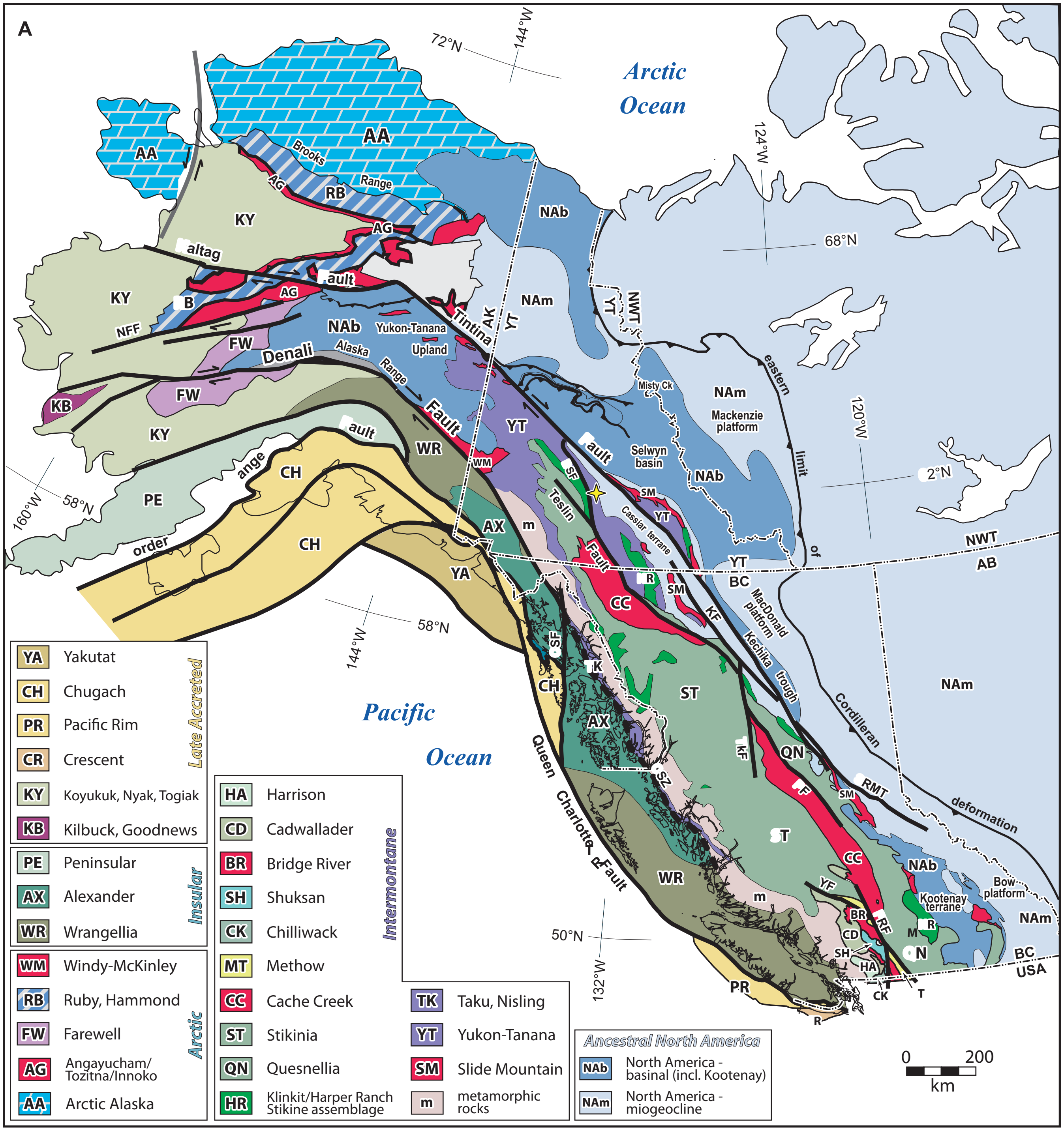

Figure 1. Terranes (**A**) and tectonic realms (**B** – facing page) of the Canadian-Alaskan Cordillera. Geological features/regions and major strike-slip fault systems discussed in the text and restored in Figure 2 are shown. Yellow star marks the location of Solitary Mountain in south-central Yukon. Fault abbreviations: BSF – Big Salmon fault; CSF – Chatham Strait fault; CSZ – Coast shear zone; FRF – Fraser River fault; KF – Kechika fault; NFF – Nixon Fork-Iditarod fault; PF – Pinchi fault; SMRT – southern Rocky Mountain trench; TkF – Takla-Finlay-Ingenika fault system; YK – Yalakom fault. Other abbreviations: AB – Alberta; AK – Alaska; BC – British Columbia; NWT – Northwest Territories; YT – Yukon Territory. Sources: Wheeler et al. (1991); Silberling et al. (1994); Colpron (2006).

deposits; the long-lived, billion-tonne Highland Valley Cu-Mo porphyry deposits; as well as a host of other producing or past-producing Cu±Au±Mo porphyries that are a vital part of the economy of interior British Columbia (location, grade, and tonnage data on all cited deposits are listed in Appendix 1). Other world-class prospects are moving towards mine stage at present. These include British Columbia‘s Galore Creek and Alaska’s Pebble porphyry deposits, which contain resources of 385 million and 1 billion tonnes, respectively.

The set of deposits included in this discussion is, of necessity, a small subset, slightly over 130 mines and major undeveloped mineral resources, of the 13 000 occurrences listed

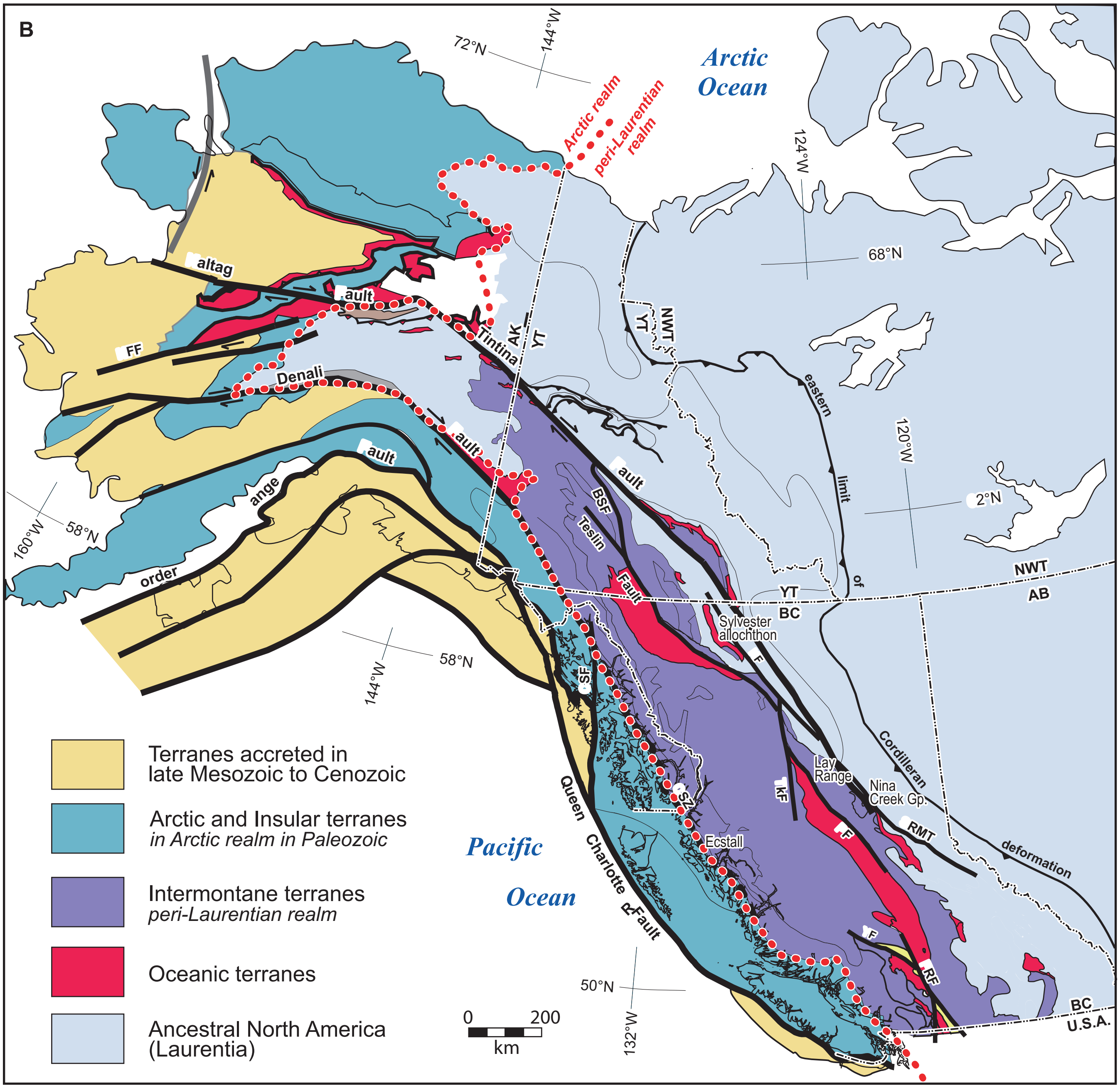

FIGURE 1 CONTINUED.

in British Columbia's Minfile, the over 2600 in Yukon's Minfile, the more than 7100 occurrences listed in the Alaska Resource Data File, and the 329 occurrences in the NORMIN database for the Mackenzie Mountains in Northwest Territories. The list was generated partly based on size and grade of individual deposits and of cumulative economic potential of belts and camps, but also on less easily quantifiable criteria, such as perceived economic potential and linkage to large-scale tectonic events. In the end, we have made a subjective selection; we thank our respective organizations for their input, but the ultimate choices were our own.

Overview of Cordilleran Tectonics

Within the northern Cordillera, Proterozoic to Triassic miogeoclinal, mainly sedimentary, platformal to basinal strata of the Laurentian continental margin (NAm and NAb on Fig. 1A) extend into eastern British Columbia and Yukon. These strata are incorporated into the fold and thrust belt of the eastern Cordillera. Farther west, most of British Columbia, Yukon, and Alaska are made up of Paleozoic to Mesozoic volcanic, plutonic, sedimentary, and metamorphic assemblages that represent magmatic arcs, microcontinents and ocean basins, accreted to western Laurentia in Mesozoic and younger time. These, along with the parautochthonous deformed belt and the undisturbed platform of Alberta, are overlain by syn- and post-accretionary clastic deposits. The western and inner parts of the orogen are pierced by post-accretionary plutons and in places overlain by thick accumulations of relatively young volcanic strata.

The variety of pre-accretionary assemblages, many of them juxtaposed across faults, led to the conceptualization of the Cordillera as a collage of tectonostratigraphic terranes – independent, fault-bounded entities with “suspect” or unspecified relationships to each other as well as to the continent (Coney et al., 1980; Jones et al., 1983). After a quarter of a century of subsequent research, the terranes on Figure 1A are remarkably similar in outline to those originally proposed – a testament to the insight and inspiration of that work. On the other hand, considerable progress has been made in refining the origins, relationships, and individual and collective histories of these entities. The result is an emerging image of Cordilleran evolution that is simpler, clearer, and more explicit in its historical implications.

Although the northern Cordillera has been subdivided into a multiplicity of terranes (Fig. 1A), it can be viewed more globally as consisting of five first-order tectonic entities: 1) Ancestral North America (Laurentia); 2) the allochthonous marginal pericratonic terranes (Intermontane terranes); 3) the exotic Insular and Farewell terranes; 4) Arctic Alaska; and 5) Mesozoic and younger arc and accretionary terranes that form a western and southern fringe to the older elements. These are shown on Figure 1B, which is a simplified and, in places, updated version of the terrane maps of Wheeler et al. (1991), Silberling et al. (1994), and Nokleberg et al. (2000).

Ancestral North America (or Laurentia) includes the western craton margin, the miogeocline with its platforms (Mackenzie, McDonald, and Bow) and basins (Selwyn, Kechika, and Misty Creek) and its fringing, parautochthonous pericratonic terranes (Cassiar and Kootenay) (Fig. 1A). The western, outboard boundary of this autochthonous to parautochthonous belt is marked by discontinuous slivers and slices of the Slide Mountain oceanic terrane, which were derived from a marginal rift basin of Late Devonian to Permian age that once lay between the continent and a mixed belt of rifted pericratonic and Devonian through Jurassic arc terranes (Yukon-Tanana, Quesnellia, and Stikinia). The belt of pericratonic terranes was originally bounded on its outer, oceanward margin by an accretionary zone comprised by what is now referred to as the Cache Creek terrane, a relict fore-arc assemblage that includes slivers of high-pressure metamorphic assemblages, as well as blocks containing Permian fusulinid and coral faunas of very exotic, Tethyan (Asian) affinity (Ross and Ross, 1983). The terranes of the Intermontane belt have been referred to as the Intermontane superterrane by Monger et al. (1982), who regarded them as a product of Triassic-Jurassic tectonic amalgamation. In this discussion, we describe initial and ongoing relationships that span the entire period of the existence of these terranes. In keeping with Appalachian terminology (Zagorevsky et al., 2006), these terranes could be said to constitute the peri-Laurentian realm (Fig. 1B). The position of the exotic Cache Creek terrane, enclosed within the pericratonic belt, is a constructional anomaly that may be best explained by oroclinal enclosure that developed as the Intermontane terranes amalgamated and accreted to the continent (Mihalynuk et al., 1994a).

In contrast to the Intermontane terranes, the Insular terranes (Wrangellia and Alexander) and the Farewell terrane of central Alaska, although long-lived (Precambrian to Triassic) and in part of pericratonic origin, show no evidence of early relationships to the western margin of North America. Instead, their early faunal and isotopic affinities are with Siberia and Barentia (Bazard et al., 1995; Nokleberg et al., 2000; Bradley et al., 2003). The Arctic Alaska composite terrane, although continental to pericratonic, is anomalous with respect to adjacent western North America (Patrick and McClelland, 1995; Amato, 2004), and it is commonly considered displaced and/or rotated; it too was probably mobile within the Arctic realm in pre-Cretaceous time. It bears stratigraphic similarities to the Chukotka peninsula of the Russian Far East and it has been proposed that they were contiguous throughout most of their history (Natal’in, 2004; Amato et al., 2006). Together, these terranes constitute an original set of detached crustal fragments, along with subsequent Paleozoic and Mesozoic arcs and basins, which developed mainly within the Arctic realm: they are referred to here collectively as the Arctic/Insular terranes (Fig. 1B).

Early in the history of Wrangellia, a Pennsylvanian pluton linked it to the Alexander terrane (Gardner et al., 1988). By Late Triassic to Early Jurassic time, at least Wrangellia seems to have been transported to a more southerly paleolatitude west of the North American margin, prior to mid-Jurassic accretion with the Intermontane terranes (Aberhan, 1999; Smith et al., 2001). After accretion, but prior to 430 km of Eocene dextral displacement on the Tintina fault (Gabrielse et al., 2006), this set of terranes bounded the combined North American margin and Intermontane terranes to the west (Fig. 2).

The outermost belt of terranes contains relatively young, Mesozoic to Paleogene assemblages, including the accreted Yukon-Koyukuk and Talkeetna arcs, the accreted Paleocene-Eocene seamounts of the Crescent terrane, and the Chugach, Pacific Rim, and Yakutat terranes, which are accretionary complexes dominated by trench sediments. Older crustal fragments, such as the Precambrian Kilbuck terrane (Box et al., 1990), are also involved in this mass of late-accreted crustal material. These arc and accretionary assemblages developed within the eastern Pacific realm near or on the developing Cordilleran margin.

Realm Boundaries

If the major realms of the Cordillera – the autochthonous North American, the peri-Laurentian, and Arctic realms – are first-order tectonic features, then the nature of the boundaries between them becomes of particular interest in understanding Cordilleran evolution. The boundary between the edge of ancestral North America and the Intermontane (peri-Laurentian) terranes lies within the Slide Mountain terrane (Fig. 1A,B), a Late Devonian to Middle Permian oceanic assemblage of subtly expressed pericratonic affinity (Nelson, 1993). The Slide Mountain terrane exhibits Paleozoic stratigraphic linkages both to North America (Klepacki and Wheeler, 1985) and to the Yukon-Tanana terrane (Murphy et al., 2006); it contains interbedded MORB (mid-ocean ridge) basalts and Mississippian chert-quartz sandstones and conglomerates that contain Precambrian detrital zircons (Nelson, 1993, and unpublished data).

The boundary between the Intermontane and Arctic/Insular terranes (peri-Laurentian and Arctic realms) is more variable in nature and is marked by very few oceanic

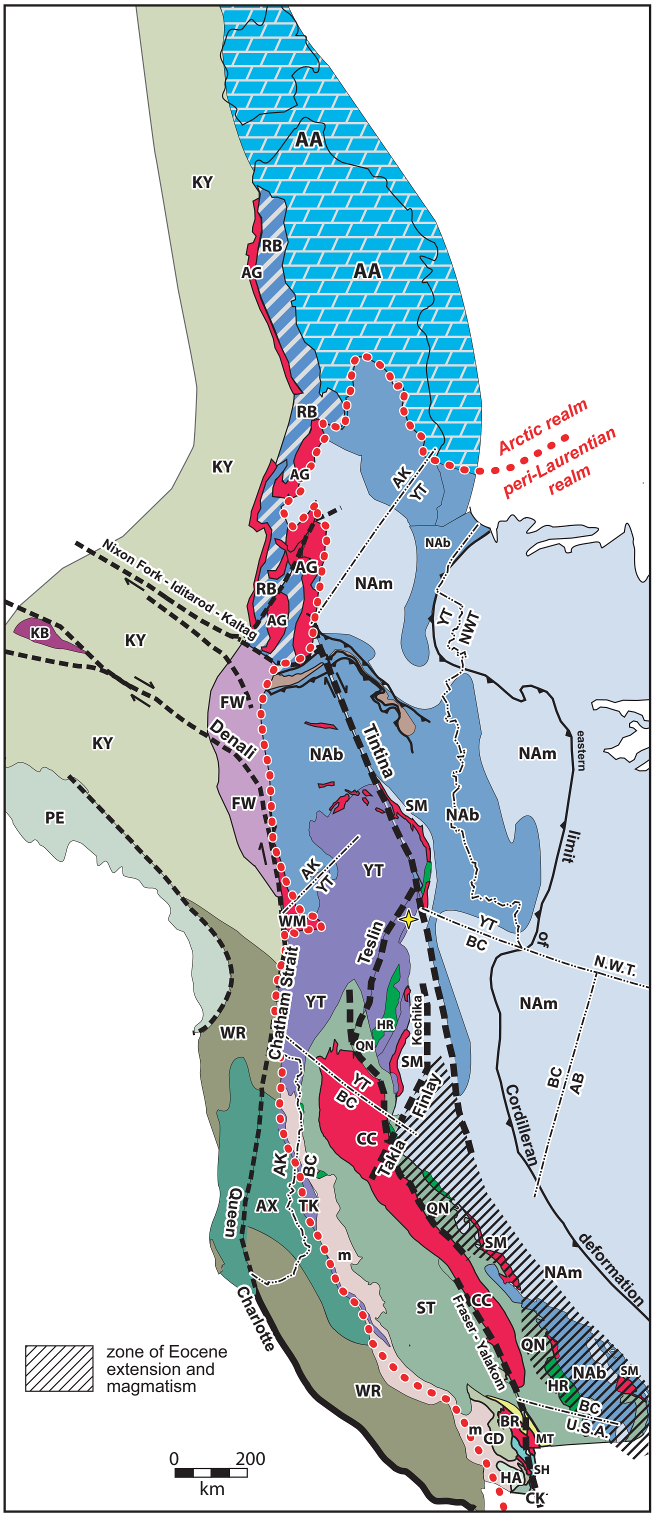

Figure 2. An approximate pre-Late Cretaceous restoration of the Canadian-Alaskan Cordillera. Constraints on the restoration of the dextral strike-slip faults are discussed in the text (e.g. 430 km on Tintina [Gabrielse et al., 2006]; 370 km on Denali [Lowey, 1998]; 150 to 200 km on Chatham Strait [Hudson et al., 1982]; 130 km on Kaltag/Tozitna [Patton and Tailleur, 1977]). Southward projections of the Tintina fault are assumed to lie between Stikinia and southern Quesnellia. Additional motion on the Teslin and related faults is required to restore the two "halves" of the Cache Creek terrane (Gabrielse, 1985). Southern projection of the Denali fault is located on the Chatham Strait fault. Restoration of this bend results in considerable clockwise rotation. To compensate, the Insular terrane block has been rotated counterclockwise to lie adjacent to the Coast Mountains. The Brooks Range is rotated clockwise 30°, and the Seward Peninsula is aligned with it. In general, only rigid-body displacements have been restored. For instance, Eocene extension related to dextral transtension in central and southern British Columbia has not been restored in this diagram. Terranes of the Pacific realm are not shown, as their locations at this time are poorly constrained. Terrane legend as in Figure 1A. Yellow star marks the approximate location of Solitary Mountain.

remnants. In the Coast Mountains of British Columbia and southeast Alaska, it is a collisional suture between the Alexander/Wrangellia terranes and the Yukon-Tanana terrane, onlapped by the Gravina belt, a mid-Jurassic to Cretaceous arc and clastic sequence (Gehrels, 2001). In western Yukon, the intervening oceanic Windy-McKinley terrane shows intriguing similarities with the Alexander terrane (Mortensen and Israel, 2006): it may be a fragment of intervening oceanic crust. In central Alaska, the Livengood belt of the Farewell terrane is in thrust contact with western North American strata with intervening Jurassic-Cretaceous flysch and minor ultramafic rocks (Beaver Creek belt of Dover, 1994). This structural setting is complicated by displacement on the Tintina fault and its splays, and the Z-shaped Alaska orocline (Patton and Tailleur, 1977; Churkin et al., 1980; Moore et al., 1987; Coe et al., 1989; Stone, 1989; Dover, 1994, among many others); a feature related both to northerly motion of the block west of the Tintina fault and, in many models, to counterclockwise rotation of the Brooks Range (compare Figs. 1 and 2).

The Ruby terrane is presently an enigma. It is pericratonic, and intruded by Devonian plutons. It may be a North American salient, or it could be affiliated with the Hammond terrane in the southern Brooks Range, a part of the Arctic Alaska terrane that also contains Late Devonian plutons. The Arctic Alaska composite terrane in the Brooks Range is separated from western North America to the east by a thrust belt that involves Cretaceous overlap strata (Dover, 1994; Gordey and Makepeace, 2001). Its outer (southern) margin is in the footwall of a thrust fault that carries the Devonian to Jurassic Angayucham oceanic terrane in its hanging wall. Cretaceous blueschists within the footwall of this fault zone are evidence for subduction of the Arctic Alaska terrane beneath the Angayucham Ocean and the Jurassic-Cretaceous Yukon-Koyukuk arc (Moore et al., 2004). The Ruby terrane exhibits similar structural relationships and timing; however, it faces northwest. The pericratonic Hammond and Ruby terranes, coupled with the Angayucham oceanic terrane, presently enclose the Yukon-Koyukuk terrane in a west-facing V-shaped frame (Fig. 1A,B).

Structure of this Paper

As a prologue to the tectonic/metallogenetic histories presented here, we lay out the existing constraints for historical reconstruction of the evolving Cordillera, starting with the restoration of estimated Late Cretaceous to Eocene strike-slip displacements and their consequences (Fig. 2). This reconstruction emphasizes the integrity of the fundamental components of the Cordillera: the amalgamated Intermontane terranes, the Insular and Farewell terranes as micro-continental blocks; the continuity of the Ruby and Arctic Alaska terranes; the not-yet-accreted Pacific terranes. Figure 2 incorporates the best available estimates and interpretations of displacements and is offered as a reasonable post-accretion, pre-strike-slip dismemberment interpretation of the Cordillera and the large-scale entities within it.

The main part of the paper is a chronological treatment of tectonics and metallogeny of western North America (Laurentia) and the peri-Laurentian realm; the Arctic/Insular realm; and then syn- and post-accretionary events and deposits. We first describe the development of Paleoproterozoic to Neoproterozoic intracratonic basins of Laurentia and their contained deposits, which are mostly older than and unrelated to the opening of the western margin of the continent during the breakup of Rodinia. Second, we describe, starting with that rift event, the tectonic development and metallogeny of the combined western North American (Laurentian) margin and Intermontane terranes, as an evolving southwest Pacific-style active margin. Its timeline spans Late Proterozoic time through the last Early Jurassic manifestation of pre-accretionary arc development in offshore Quesnellia and Stikinia. Third, we separately describe the tectonic development and metallogeny of the Arctic/Insular terranes. As their origins and "terrane trajectories" are less well understood, and each may well have developed independent of the others, this treatment is of necessity more piecemeal.

Finally, we cover Late Jurassic and younger tectonic patterns and metallogeny, which developed during and after accretion of the Arctic/Insular terranes to the Intermontane terranes and continent fringes, when a simple west-facing subduction system was imposed on the new, amalgamated, and much broader western continent margin. The Mesozoic and younger arcs of the outer terranes are considered as intra-oceanic extensions of those superimposed on the growing Cordillera. This approach was first applied successfully by Nokleberg et al. (2000), who emphasized the role of paired belts (arcs and their accretionary complexes) in interpreting the evolution of the circum-Pacific region.

Reconstructing the Pre-Late Cretaceous Cordillera: Faults, Cut-offs, and Transverse Features versus Stipulations of Paleomagnetic Data

Throughout this paper, the present-day distribution of terranes on Figures 1A and 1B is used as a framework for locating mineral deposits and districts. However, it is useful first to visualize the different sets of terranes as they were just after accretion but prior to their dismemberment by Cretaceous and younger transcurrent faults. Figure 2 represents a graphical re-organization of the present distribution of terranes on Figure 1A. It follows the same lines as the reconstruction of Pavlis (1989), with added constraints from recently published geological evidence and revised interpretations. Its configuration in mid-Cretaceous time is largely constrained by:

1. Restoration of 430 to 490 km of Eocene dextral motion on the Tintina fault, most of which occurred in Eocene time (Gabrielse et al., 2006). The amount and timing of this displacement is constrained by the following: offset of the northeastern section of Yukon-Tanana terrane from its main exposures southwest of the fault; offset of a set of Cretaceous thrust imbricates north of Fairbanks, which are considered equivalent to the Robert Service and Tombstone thrusts in Yukon (Fig. 1A); offset of the ca. 92 to 90 Ma Tombstone plutonic suite from its Alaskan equivalent, the Livengood suite; and offset of Late Cretaceous (70-65 Ma) Sn-bearing peraluminous intrusions (McQuesten plutonic suite in Yukon). North of Fairbanks, the Tintina fault abruptly bends and splays into the Kaltag, Tozitna, and other faults that have a cumulative dextral displacement of approximately 130 km (Patton and Tailleur, 1977). The remaining displacement was probably taken up in compression and rotation.
2. Restoration of approximately 100 km of Eocene dextral motion on the Fraser and Yalakom faults, to restore offset imbricate fault panels (Umhoeffer and Schiarizza, 1996). As Price and Carmichael (1986) pointed out, the amount of Eocene dextral fault offset is far less in the southern Cordillera than it is on the Tintina fault and much of the relative motion was probably expressed as extension.
3. Restoration of approximately 370 km of Eocene and younger dextral motion on the Denali fault (Lowey, 1998). In this reconstruction, we use the Chatham Strait fault as a southern continuation of the Denali fault (Hudson et al., 1982). This results in an overall shortening and widening of the pre-displacement Insular terrane.
4. Rotation of Arctic Alaska 30°+ clockwise and restoration of the Seward Peninsula to align with the Brooks Range (Patton and Tailleur, 1977). The motion history of Arctic Alaska during Cretaceous opening of the Canada Basin is controversial, with models ranging from extreme counterclockwise rotations up 66 degrees from an original position against the Canadian Arctic Islands (Grantz et al., 1990; Toro et al., 2004), to a complex opening history of the Arctic Ocean that involved spreading in several senses, as well as strike-slip displacement (Lane, 1992, 1997). Our restoration represents a compromise. In its favour, we point out that this restoration, in concert with back-rotation of the Ruby terrane as displacement along Tintina fault is restored, results in a fairly straight continental margin, and eliminates the anomalous V-shaped enclosure of the Yukon-Koyukuk arc.

Figure 2, although a cartoon and not unique, is a more coherent image of the Cordillera than the current one (Fig. 1A,B), which has been shaped by post-accretionary strike-slip tectonics, development of the arcuate southern Alaska orocline (Coe et al., 1989), the contortion of Alaskan tectonic trends into the Z-shaped present day configuration (Patton and Tailleur, 1977; Pavlis, 1989), and the extrusion of terranes into the Bering Sea region (Scholl, 1991; Redfield et al., 2005). In Figure 2, the two offset parts of the Yukon-Tanana terrane are joined, as are the two separate belts of the Cache Creek terrane. The northwestern tip of the ancestral North American continent is gently curvilinear and in part bounded by a Cretaceous thrust complex. The Farewell and Insular terranes are depicted as separate accreted micro-continents.

The key message embodied in Figure 2 is that the Cordillera can be viewed as a set of very few, large-scale tectonic entities – the realms – of which individual, smaller terranes form a part. The history of each of these entities involves interaction between its components over a long period of time, except in the case of the very young, outermost Pacific terranes. In each of these histories, metallogeny closely follows on tectonic developments, particularly rift zone development and the growth of superimposed magmatic arcs.

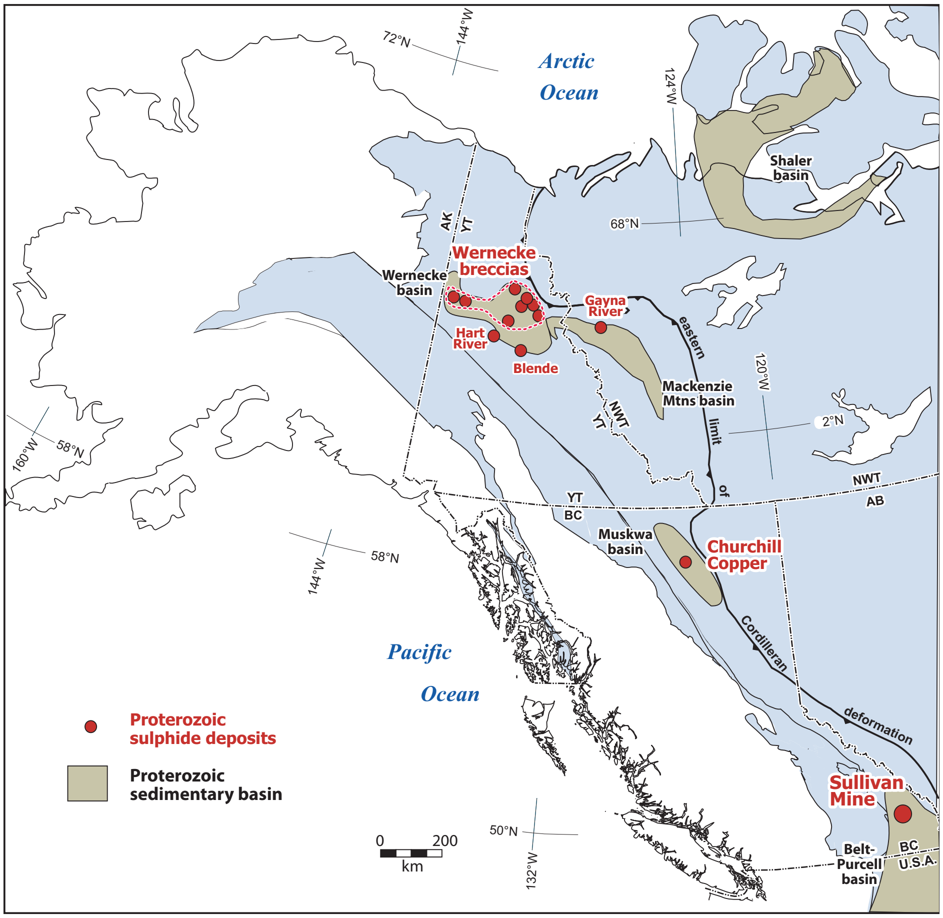

Figure 3. Proterozoic basins and mineral deposits of northwestern Laurentia. The basins are generalized from Wheeler and McFeely (1991); Wernecke deposits are from Lefebure et al. (2005).

Assessment of Cretaceous Paleomagnetic Data and Its Relevance to Tectonic Reconstructions

The geologically based reconstructions that underlie the configuration shown in Figure 2 are at odds with a literal paleogeographic interpretation of the Cretaceous paleomagnetic data set for the Canadian and Alaskan Cordillera (Enkin, 2006, and references therein). In this latest, well considered synthesis, ten high-quality poles from bedded rocks between 95 and 65 Ma, and one from a batholith (Mt. Stuart) in which post-crystallization tilting is demonstrably minimal, are overall about 15° far-sided (shallower inclination) compared to the North American reference pole. The difference is ascribed to 2000 km of post-Cretaceous northward translation of the entire Cordillera, as far inboard as the Rocky Mountain fold and thrust belt (Enkin, 2006). The involvement of the entire width of the Cordillera in mega-translation contrasts with earlier models, in which the western Cordilleran terranes were seen as more paleomagnetically discordant than those of the central Cordillera (cf. Irving and Wynne, 1990).

This new, more radical translational model is dictated by the discordant paleomagnetic results from a recent study on comparatively young volcanic rocks, the 70 Ma Carmacks Group, which overlie the easternmost Yukon-Tanana terrane at Solitary Mountain in south-central Yukon, next to the Tummel fault – a steeply dipping fault zone juxtaposing Yukon-Tanana and Cassiar terranes (Figs. 1A, 2; Enkin et al., 2006). Detailed geological mapping in this area has shown that the contact aureole of the mid-Cretaceous (ca. 105 Ma) Glenlyon batholith, which intrudes Cassiar terrane east of the fault, overprints the Tummel fault and eastern Yukon-Tanana terrane, thereby limiting the amount of possible Late Cretaceous dextral displacement along this fault (Colpron et al., 2005). This constraint effectively disqualifies the Tummel fault as a candidate for continent-scale displacement younger than 70 Ma. The nearby Tintina fault has a well supported Eocene offset that falls some 1500 km short of that apparently required by the paleomagnetic data. One is then forced to seek a cumulative dextral offset three times that on the Tintina, within the parautochthonous Selwyn Basin and Mackenzie/Rocky Mountains – regions that are dominated by well defined, regionally discontinuous thrust faults and related folds and where cross-structures such as the east-west-trending southern margin of the Selwyn Basin and associated northeast-trending lineaments (Liard and Fort Norman lines of Cecile et al., 1997), the west-northwest trend of the mid-Cretaceous Tombstone-Tungsten plutonic suites (Hart et al., 2004), and the inferred projection of northeast-trending Proterozoic and Archean domains from the Alberta basement into the Cordilleran Orogen of southern British Columbia and northern Idaho (Malton, Monashee, and Priest River complexes; Crowley, 1999) apparently defeat any possible location for continent-scale transcurrent faults (e.g. Gabrielse et al., 2006). A definitive presentation and evaluation of the geological constraints on large-scale transcurrent motions is urgently needed.

In the end, it may be more productive to re-examine the assumptions behind a strict paleogeographic interpretation of the anomalously shallow Cretaceous paleomagnetic inclinations, as did Butler et al. (2001). Their careful analysis suggests that a combination of moderate translation with minor tilting and sedimentary and/or tectonic compaction could account for the inclination anomalies, which average about 15 degrees. Since the original magnetic inclinations are very steep, almost any tectonic effect would result in flattening. Because paleolatitude is related to inclination

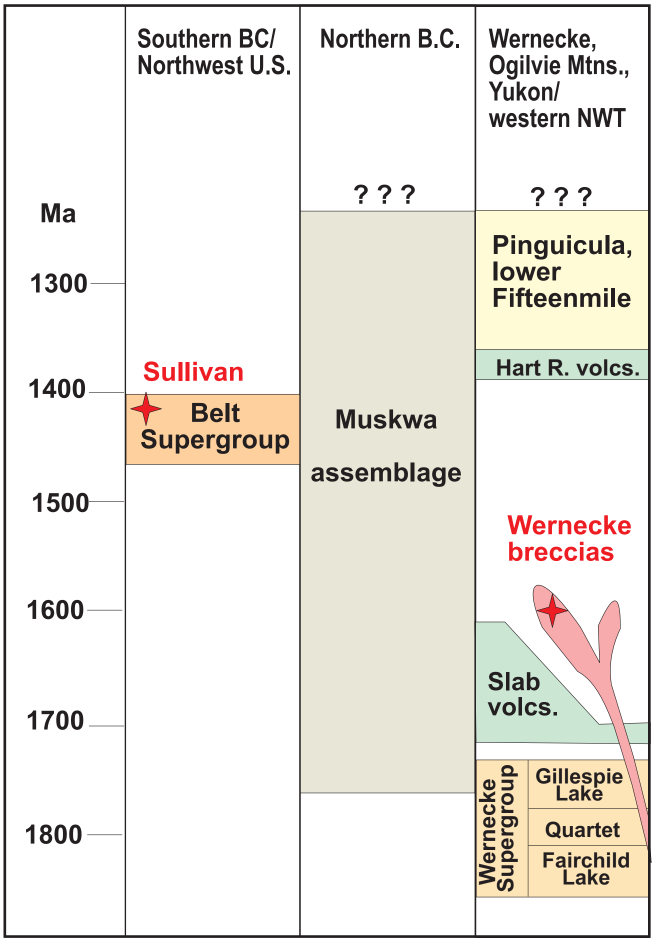

Figure 4. Stratigraphy of the Wernecke, Muskwa, and Belt-Purcell basins. From Thorkelson et al. (2001a).

through a tangent function (tan I = 2 tan L), the proximity of the northern Cordillera to the Cretaceous paleopole means that each degree of inclination difference results in more than a degree of apparent latitudinal translation. This kind of compromise probably points towards the direction in which the long-standing "Baja BC" controversy will eventually be resolved; however, a full treatment is outside the scope of this paper.

Ancestral North America (Laurentia) and Its Fringing Terranes

Proterozoic Basins of Western Laurentia (1.84 to 0.78 Ga)

Within the deformed belt of the parautochthonous continental margin are a series of separate sedimentary basins that developed after regional cratonization at ca. 1850 Ma, but well prior to formation of the open western margin of Laurentia at ca. 750 to 570 Ma. They occur in three main depocentres which are, from north to south, the Wernecke-Mackenzie Mountains, and the Muskwa and Belt-Purcell basins (Fig. 3; see also Fig. 9 in Thorkelson et al., 2001a). All three areas contain significant mineral deposits, each of distinct types (Nokleberg et al., 2005). The Belt-Purcell Basin contains the giant Sullivan SEDEX deposit; rocks of the Muskwa Basin are host to the Churchill Copper vein systems; and the Cu-Au-U-Co-enriched Wernecke breccias crosscut older strata of the Wernecke Supergoup. Mississippi Valley-type mineralization occurs in younger strata of the Mackenzie Mountains Supergroup (Gayna River deposits).

The northernmost of these Proterozoic depocentres, in the Wernecke and Mackenzie mountains, records multiple episodes of basinal sedimentation punctuated by orogenesis, magmatism, and prolonged subaerial exposure (Thorkelson et al., 2005). During deposition of the 13 km thick Wernecke Supergroup (post-1.84, pre-1.71 Ga; Thorkelson et al., 2001a; Fig. 4), the Wernecke basin was a broadly subsiding marine basin built on extending crystalline basement. The hydrothermal Wernecke breccias were emplaced ca. 1.6 Ga into the sequence after it was deformed by the southeast-verging Racklan Orogeny (Thorkelson et al., 2001b). The breccias (Fig. 3, Appendix 1) form an extensive, curvilinear, east-west-trending province that corresponds to Wernecke Supergroup exposures in the Wernecke and Ogilvie mountains of north-central Yukon (Fig. 3); they are considered IOCG-type (iron-oxide copper-gold; Lefebure et al., 2005; Corriveau, 2007). Their tectonic setting was certainly post-orogenic and probably anorogenic. The precursor Racklan Orogeny is seen as a farfield effect of a remote orogeny, perhaps localized and focused in the relatively thin crust below the basin (Thorkelson et al., 2001a), and their proximity to continental margins is not known. Significant parallels can be drawn between the Wernecke breccias and the giant Olympic Dam deposit in Australia, and Thorkelson et al. (2001b) offer an intriguing pre-Rodinia continental reconstruction that places them less than 1000 km from each other in a single, contiguous Mesoproterozoic province. However, pre-Rodinian and Rodinian reconstructions are contentious and poorly constrained (see below); and in contrast to the Wernecke breccias, the Olympic Dam deposit formed in an active tectonic setting associated with continental arc magmatism (Ferris and Schwartz, 2003).

Following an approximately 220 m.y. hiatus, marine sedimentation resumed in northern Yukon with deposition of the 3.5 km thick Pinguicula Group and associated intrusion of the ca. 1.38 Ga Hart River sills and eruption of volcanic equivalents (Abbott, 1997; Thorkelson et al., 2005). The Hart River massive sulphide deposit (Fig. 3, Appendix 1) is the only known significant occurrence associated with this phase of deposition. The youngest of the precursor Proterozoic basins of the northern Cordillera, the Mackenzie Mountains Supergroup (1.0-0.78 Ga; up to 4 km-thick), forms part of a widespread Neoproterozoic depocentre in northwestern Laurentia (e.g. Rainbird et al., 1996). The lower part of the Mackenzie Mountains Supergroup consists of shallow marine to fluvial mudstone, siltstone, and quartz arenite, which contains abundant Mesoproterozoic detrital zircons (1.25-1.0 Ga); these strata are interpreted to form part of a pan-continental braided-river system with sources in the Grenville Orogen of southeastern Laurentia (Rainbird et al., 1997). Overlying carbonates and minor evaporites of the Little Dal Group record deposition in an epicratonic basin. Reef mounds in the basinal facies of the Little Dal contain the only known significant mineralization in the Mackenzie Mountains Supergroup, the Gayna River deposits, a cluster of MVT deposits totalling some 50 Mt averaging 4.7% Zn (Fig. 3, Appendix 1). The age of the Gayna River deposits is not well constrained. Kesler (2002) relates their formation to penecontemporaneous basinal fluids, in which case mineralization would have been early Neoproterozoic.

The age of the westward-thickening sedimentary prism in the Muskwa basin is loosely constrained between 1766 Ma, the age of its youngest detrital zircons, and cross-cutting 780 Ma diabase dykes (Ross et al., 2001). Its detrital zircon signature allies it with the Wernecke Supergroup, although their stratigraphies do not directly correspond. Like the Wernecke basin, it has been interpreted as an intracontinental rift basin (Long et al., 1999). The Churchill Cu-bearing quartz-ankerite veins (Appendix 1) are associated with abundant diabase dykes in a generally northeast-striking array that postdates a phase of northeast-vergent folding. It is suggested that both veins and dykes relate to the onset of Neoproterozoic rifting that fragmented Rodinia.

The Belt-Purcell Basin is host to one of Canada's stellar deposits, the 160 Mt Sullivan Pb-Zn-Ag orebody (Fig. 3, Appendix 1), which was mined continuously from 1914 until closure in 2001. At 1.47 to 1.40 Ga (Ross and Villeneuve, 2003), or more broadly 1.50 to 1.32 Ga (Lydon, 2007), the Belt Supergroup is significantly younger than the Wernecke Supergroup (Fig. 4). It also shows a much more active style of extension than the Wernecke and Muskwa basins, with rapid rates of sedimentation (18-20 km thick; Lydon, 2007), mafic volcanic rocks and sill complexes, and well defined intrabasinal syndepositional faults (Ross and Villeneuve, 2003). Facies and paleocurrent indicators, as well as detrital zircon populations of 1.61 to 1.5 Ga that are not represented in the nearby Laurentian basement, are interpreted by Ross and Villeneuve (2003) to indicate the presence of non-North American western source terranes that were subsequently removed in Late Proterozoic or earlier continental rifting. The presence of detrital grains identical in age to sedimentation in the Belt Basin suggests that it may have abutted an active magmatic belt on its western side (Ross et al., 1992; Ross and Villeneuve, 2003). This intra-continental rift basin provided the tectonic setting for large-scale accumulation of syngenetic, sediment-hosted massive sulphide ore. Sullivan itself, which has been dated at 1.47 to 1.45 Ga by Sm-Nd methods (Jiang et al., 2000), is associated with a northeast-striking synsedimentary fault array, including the St. Mary, Kimberley, and Moyie faults (Höy et al., 2000), and with voluminous synsedimentary mafic sills, the Moyie sills. The northeast-striking faults parallel basement structures, at a high angle to the north-northwesterly-trending basin margin, as well as to trends of rift grabens. Lead-zinc-silver mineralization, with its characteristic associated tourmaline alteration, is localized where the cross-faults offset rift basins (Höy et al., 2000).

Worldwide, there are no other large SEDEX deposits comparable in age to Sullivan. Broken Hill, Mt. Isa, and HYC in Australia are ca. 1.69 to 1.67 Ga, 200 Ma older than the Belt-Purcell Basin. Sullivan, it seems, stands alone, not as part of a later fragmented global metallotect. The challenge of finding a western continuation of the Belt-Purcell Basin on some other continent, with its promise of prospective ground for the discovery of a second Sullivan, is part of a broader tectonic question: which continent or continents represent North America's missing twin(s), following the breakup of Rodinia? Four candidates have been proposed: Antarctica/Australia ("SWEAT" connection; Hoffman, 1991; Moores, 1991; Ross et al., 1992); Australia ("AUSWUS" connection; Burrett and Berry, 2000), Siberia (Sears and Price 2000, 2003a,b), and the Yangtze block (Li et al., 1995). The reconstruction of Sears and Price (2003b) is particularly appealing in that it aligns a ca. 1.5 Ga mafic sill/dyke swarm from the southern Wyoming craton, through the Moyie sills, and into the northern Siberian platform and shows the Taimyr trough as a western continuation of the Belt-Purcell Basin (Fig. 5A). If this is correct, then the continental rift zone that hosted the Sullivan orebody did not follow the later outline of the western North American margin, but instead cut across it at a fairly high angle. According to Sears and Price (2000, 2003b), the 1610 to 1500 Ma detrital zircons in the Belt-Purcell Basin were derived from southwestern Laurentia, but transported eastwards along the Udzha trough (Fig. 5A). In this reconstruction, the Wernecke basin in northern Laurentia is not assigned a counterpart (Sears and Price, 2003a,b, Fig. 1).

Tectonics and Metallogeny of the Rifted North American Continental Margin and Its Fringing Arcs (780 to 180 Ma)

Phase 1: Initial Rifting and After (Cambrian to Silurian)

Following rifting in the Belt-Purcell Basin and formation of the Sullivan deposit, a period of tectonic quiescence ensued throughout much of western Laurentia that would last for nearly 700 million years. There are hints of Grenvillian-age tectonism buried beneath the western Cordillera (cf. Anderson and Parrish, 2000; Doughty, 2004; Lund et al., 2004; Ross et al., 2005), but nothing to compare with the construction of the Grenville Orogen of eastern and southern Laurentia; there are no major episodes of contraction or extension. Then, in Neoproterozoic to Early Cambrian time, the cratonal nugget of Laurentia broke out of the Rodinia supercontinent, its western side opening first to initiate the formation of the ocean that would, in time, become Panthalassa – the world ocean (Scotese, 2002). The western Laurentian margin was born.

The creation of the margin involved at least two separate episodes of rifting (Fig. 5B; see Colpron et al., 2002). An earlier phase (younger than ca. 723 Ma) is shown in coarse, immature clastic facies of the Windermere Supergroup, and a later, final phase in the late Neoproterozoic to Early Cambrian Hamill/Gog Group of southeastern British Columbia. Rifting occurred concurrently with at least two global Neoproterozoic glaciations (Rapitan [Sturtian] and Ice Brook [Marinoan]; 'Snowball Earth' events of Hoffman et al., 1998; Hoffman and Schrag, 2002). In the south, thermal subsidence associated with the later rifting event began about 575 Ma (Bond and Kominz, 1984). The lower part of the Hamill/Gog Group lies unconformably on the Windermere, and strong facies/thickness variations along with significant local accumulations of basalt suggest that it was deposited in a series of north-trending rift grabens (Warren, 1997). A dyke related to this phase of magmatism is ca. 570 Ma, which dates the second pulse of rifting in the southern Cordillera (Colpron et al., 2002). During this time, the northern Cordillera was apparently the locus of passive margin sedimentation. Intermittent extension between these two major episodes of rifting is indicated by sporadic alka-

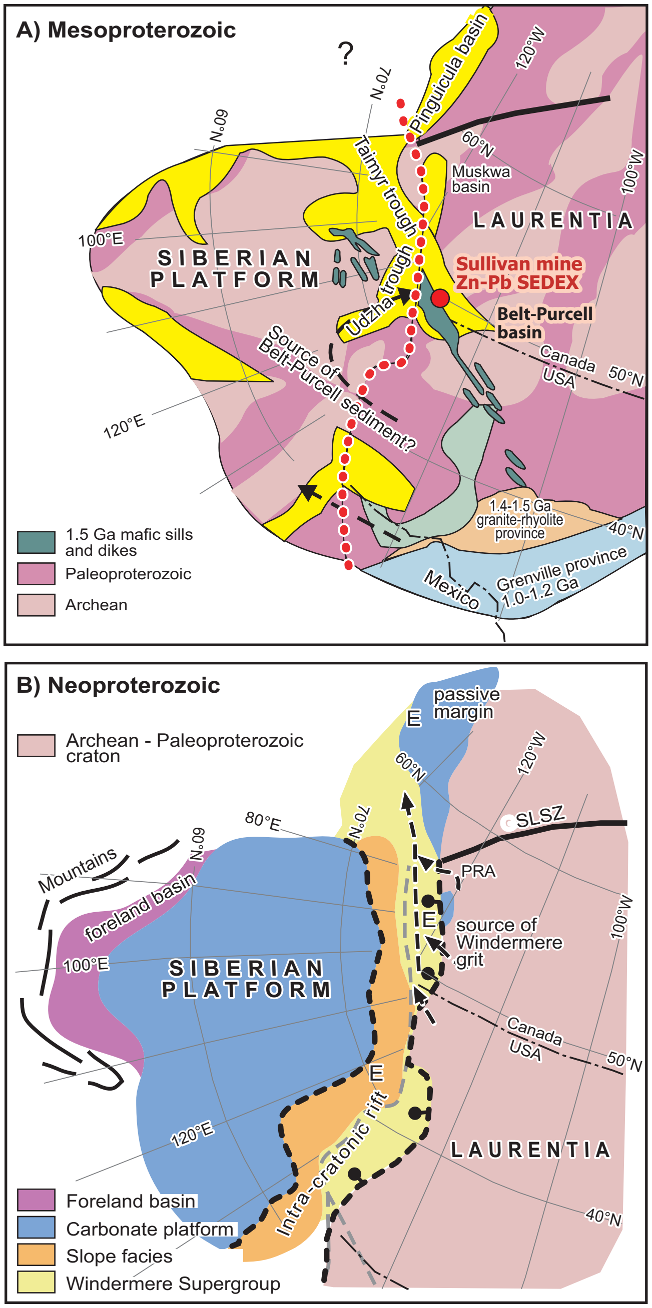

FIGURE 5. **(A)** Possible Mesoproterozoic reconstruction of western Laurentia and Siberia. From Lydon (2007); adapted from Sears and Price (2000, 2003a,b). **(B)** Neoproterozoic breakup of Rodinia according to the Sears and Price (2000, 2003) reconstruction. In this interpretation, coarse clastic sedimentation of the Windermere Supergroup occurred in an intracratonic rift between Laurentia and Siberia (see also Colpron et al., 2002). Final separation of Laurentia and Siberia took place in latest Neoproterozoic to Early Cambrian time. "E" marks ediacaran fauna localities. GSLSZ – Great Slave Lake shear zone; PRA – Peace River arch.

line magmatism along the length of the Cordilleran margin (Fig. 6; Lund et al., 2003; Pigage and Mortensen, 2004). To account for the differences in rift history between the northern and southern Canadian Cordillera, Colpron et al. (2002) offer two alternative scenarios that each depict the detachment of two separate continents from the North American margin. Figure 5B depicts the rifting scenario most compatible with the Rodinia reconstruction of Sears and Price (2000, 2003a,b) (Fig. 5A).

Although it marks a major continental rift event, the Windermere Supergroup hosts only limited syngenetic mineralization, all of which is located in the far northern Cordillera of Yukon and Northwest Territories. Mineralization in the Redstone copper belt, which includes the Coates Lake deposit (Fig. 6; Appendix 1) in the Mackenzie Mountains, is hosted by carbonate of the Coates Lake Group – a succession of evaporite, redbed (sandstone, conglomerate), and carbonate deposited in fault-bounded grabens that developed during the early stages of Windermere rifting (Jefferson and Ruelle, 1986). The copper mineralization is diagenetic in origin and concentrated at the transition zone between redbed and carbonate. The source of metal is inferred to be the volcanic-rich sedimentary rocks of the basal Coates Lake Group (Jefferson and Ruelle, 1986). Overlying glaciogenic strata of the Rapitan Group (diamictite, mudstone) are host to one of the largest and most unusual iron deposits in North America: the more than 5.5 billion tonne Crest deposit (Appendix 1; Yeo, 1986). The Rapitan banded iron formations consist of hematite-jasper rhythmites, locally with dropstones, that are interpreted as chemical precipitates during a major marine transgression in the aftermath of the Sturtian snowball event (Hoffman and Schrag, 2002). Iron was dissolved in the anoxic seawater that existed beneath the near-global sea-ice, and the iron formations were deposited at the end of glaciation by the oxidation of ferrous Fe, when ocean and atmosphere once again interacted.

In contrast with the Neoproterozoic, there are numerous syngenetic deposits of Cambrian age in both the northern and southern Canadian Cordillera. The Faro deposit, which was mined for nearly 30 years (1970-1998), is part of the Anvil district, a northwesterly belt of SEDEX Zn-Pb-Ag deposits hosted in the western Selwyn Basin (Fig. 6; Appendix 1). The Selwyn Basin was a persistent, rift-controlled deep-marine embayment in the northern continental margin throughout Paleozoic time, bounded to the west by the relatively high-standing McEvoy and Cassiar platforms that were probably contiguous prior to Eocene displacement on the Tintina fault. The Anvil deposits are of Cambrian age, hosted in siliceous graphitic units in the uppermost part of the Mt. Mye Formation and lowermost Vangorda Formation (Jennings and Jilson, 1986). Deposits are localized near the northeastern margin of the graphitic facies. Jennings and Jilson (1986) infer that the alignment of the deposits with the edge of the reduced sedimentary facies is due to control by a second-order extensional basin. Redox changes, due to the mixing of anoxic bottom waters, were probably important within it (Shanks et al., 1987).

In southeastern British Columbia, thick Lower Cambrian limestone of the Badshot Formation forms part of the outer continental margin succession in the Kootenay arc – a curvilinear belt that comprises the most westerly exposure of parautochthonous early Paleozoic strata. This limestone is host to a number of stratiform, stratabound, laminated to massive sulphide bodies (Fig. 6; Nelson, 1991). They have many features in common with Irish-type deposits and, like them, probably arose through fluid venting along seafloor growth faults. The presence of carbonate leads to much more extensive subsurface replacement mineralization than in typ-

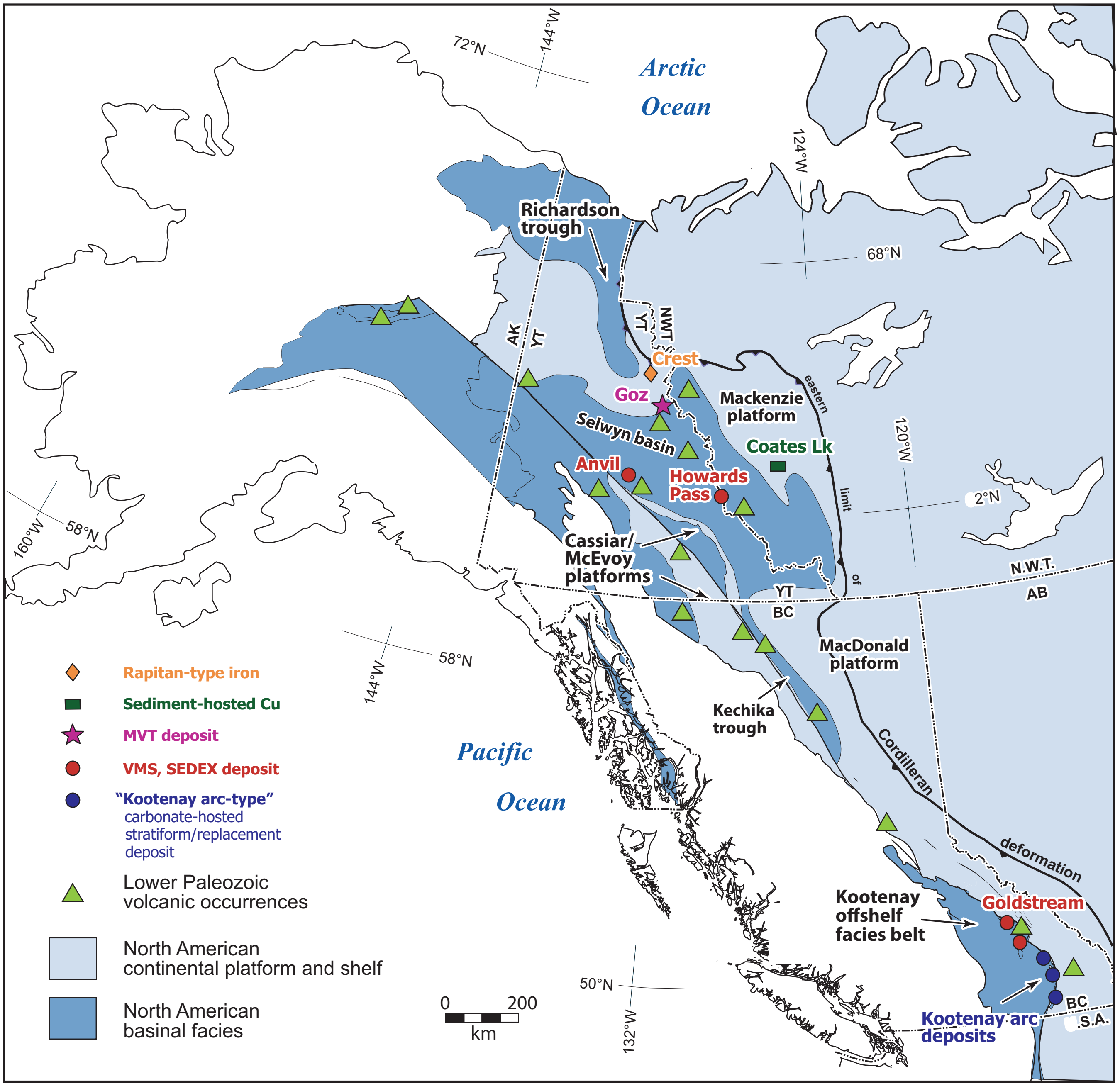

FIGURE 6. Distribution of early Paleozoic deposits and paleogeographic elements of the Laurentian margin. Volcanic occurrences from Goodfellow et al. (1995). Deposit locations from Abbott et al. (1986), Nelson (1991), Massey (2000a,b), and Logan and Colpron (2006).

ical SEDEX deposits. The Badshot limestone is overlain by the Lardeau Group, a >3.5 km-thick lower Paleozoic siliciclastic succession that does not correspond to coeval units of the continental shelf to the east and is thought to represent deposition in a deep trough along the outer continent margin (Logan and Colpron, 2006). In it, a belt of Cambro-Ordovician Besshi-type, Cu-Zn-rich VMS deposits are associated with fine-grained sedimentary and MORB-type mafic volcanic rocks, and laterally extensive manganese- and boron-enriched exhalative horizons (Fig. 6; Logan and Colpron, 2006). The most notable of these is the Goldstream deposit (Fig. 6; Appendix 1), which was mined in the early 1990s. Both the Lardeau Group itself and its contained deposits are thought to have formed within an intracontinental rift zone characterized by episodic rapid subsidence, OIB ("ocean island basalt" = enriched intraplate basalt) to MORB magmatism, and local hydrothermal activity (Logan and Colpron, 2006). The persistence of this strongly extensional tectonic style along the western Laurentian margin, long after its separation from adjoining continents, remains an outstanding mystery of Cordilleran development.

A further significant episode of extension of the so-called passive margin occurred in Ordovician time, as documented by the strongly alkalic Jowett Formation in the Lardeau Group (Logan and Colpron, 2006), as well as elsewhere in the Cordillera. Alkalic to ultrapotassic volcanic rocks occur throughout the Selwyn Basin and its southern extension, the

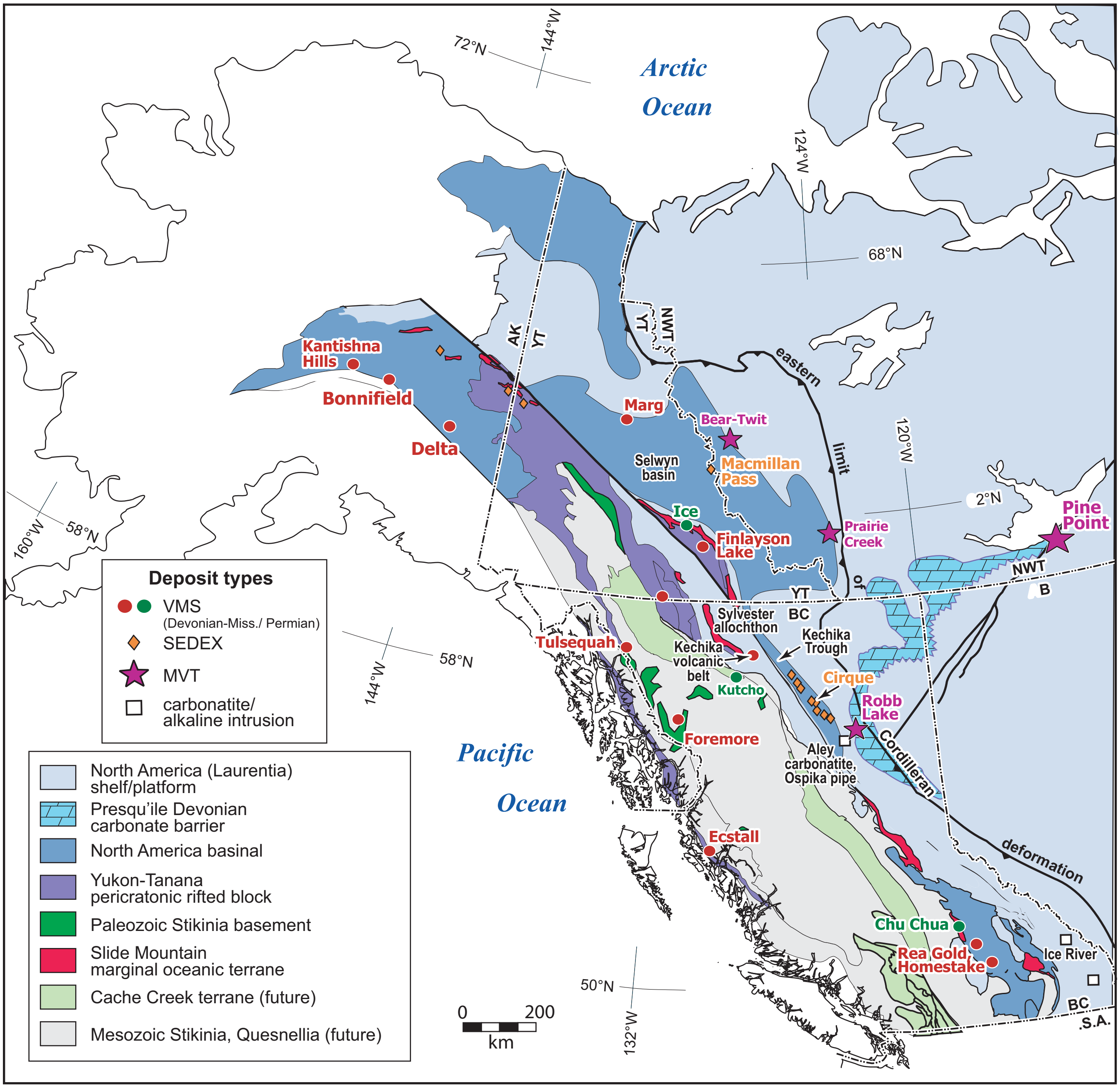

FIGURE 7. Devonian-Mississippian tectonics and metallogeny of the western Laurentian margin. From Nelson et al. (2002, 2006).

Kechika trough, and within basinal successions of northern Yukon (Fig. 6; Goodfellow et al., 1995). From their extensive compilation, these authors infer three major volcanic pulses, Cambrian, Early to Middle Ordovician, and Middle to Late Devonian. Silurian volcanic rocks and diatremes are also present. Ordovician to Early Devonian SEDEX-type deposits occur in the Selwyn Basin and Kechika trough, hosted by black shales of the Road River Group and other carbonaceous strata (Abbott et al., 1986; MacIntyre, 1991). Most are small; however, the very large Howards Pass district (Fig. 6; Appendix 1) is hosted by Early Silurian strata in the Selwyn Basin. In contrast with most other Cordilleran SEDEX deposits, those at Howards Pass did not apparently form in an active extensional regime. The deposits consist of laterally extensive, finely laminated sphalerite, galena, and pyrite associated with laminated limestone, cherty mudstone, and carbonaceous chert (Goodfellow and Jonasson, 1986). They infer a stable, starved, anoxic basinal setting, based on high $\delta^{34}S$ values in pyrite, low sedimentation rates, and the absence of local scarp-related facies or volcanic activity.

Phase 2: Establishment, Rifting, and Separation of the Continent-Margin Arc (Devonian to Mississippian)

There is very limited evidence for offshore or continent-margin arcs on the western side of Laurentia prior to Devonian time. The apparently long interval after initiation of the margin contrasts sharply with Appalachian history, where Laurentia was interacting with offshore arcs by

Middle Ordovician time (van Staal, 2007). Hints of Silurian arc activity are seen in the Trinity ophiolite/Yreka terrane in the western Klamath Mountains and the Shoofly Complex in the northern Sierras of California (Saleeby, 1990); there are a few documented Silurian plutons in the Yukon-Tanana terrane in the Coast Mountains of southeastern Alaska (Saleeby, 2000). How widespread and significant these early arcs were, and even where they were located with respect to the western margin of Laurentia, are unclear. Could the Silurian-Devonian deformation seen in the Shoofly Complex have been a factor in the initiation of margin-long subduction under the continent by Late Devonian time?

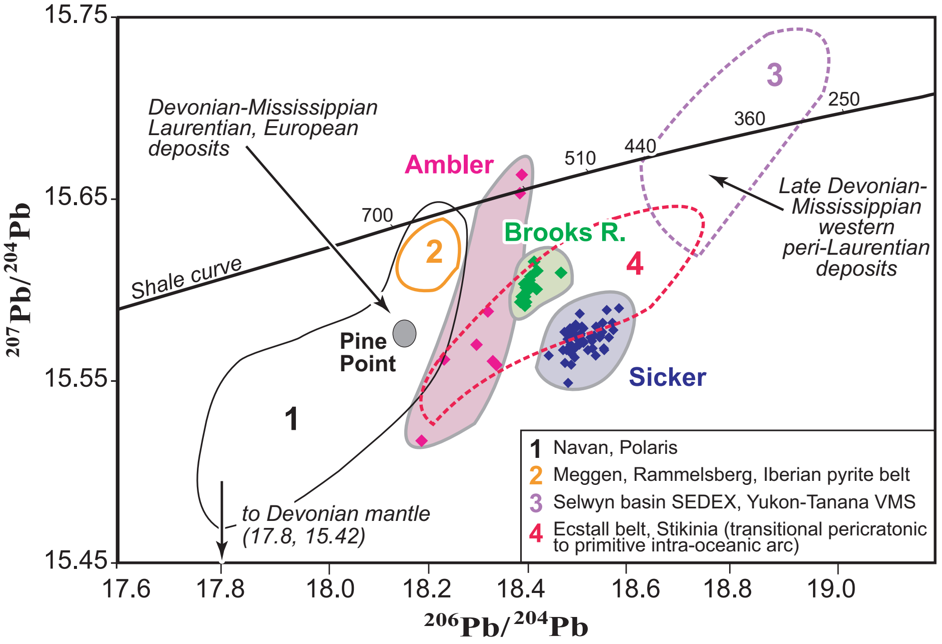

FIGURE 8. Pb isotopic signature of Devonian-Mississippian syngenetic deposits of the Cordillera compared with Arctic and European deposits. Data sources: Sicker from Robinson et al. (1996); Pine Point and European deposits from compilation of Nelson et al. (2002) and references therein; all other data from Mortensen et al. (2006).

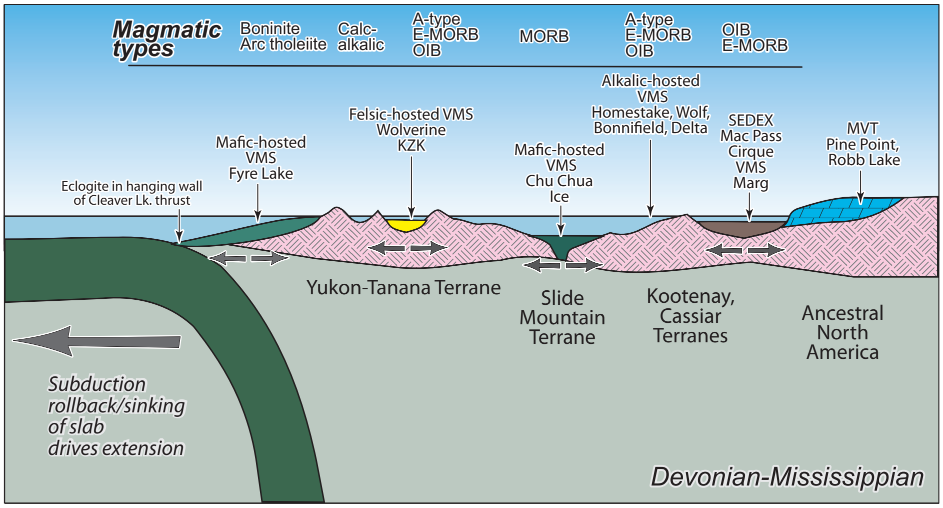

FIGURE 9. Schematic cross section of the western Laurentian margin in Devonian-Mississippian time with variation in magmatic styles and associated deposits. From Nelson et al. (2006). Although of Permian age, the mafic-volcanic-hosted VMS deposits of the Slide Mountain terrane (Chu Chua, Ice) are shown here in relation to other late Paleozoic geodynamic elements of the peri-Laurentian realm. Note that these deposits formed during the mature stage of the Slide Mountain Ocean; the nascent stage of this marginal basin is depicted here.

Whatever its precursors, the Middle to Late Devonian saw a flowering of arc-related magmatism along the length of the North American Cordillera that spanned both the autochthonous margin and the allochthonous peri-Laurentian realm (Rubin et al., 1990; Colpron et al., 2006). This event is well expressed in the western parautochthonous regions of the Canadian and Alaskan Cordillera, notably the Kootenay terrane and Yukon-Tanana upland, as well as the allochthonous Yukon-Tanana and Stikine terranes (Fig. 7; for redefinition of parts of the former Yukon-Tanana terrane as parautochthonous, see Dusel-Bacon et al., 2006; Nelson et al., 2006). High-quality U-Pb ages on volcanic and intrusive bodies range from ca. 390 to ca. 320 Ma, with the major magmatic peak at 360 to 350 Ma (Nelson et al., 2006). Throughout this interval, magmatism was strongly bimodal, with felsic components showing strong continental crustal influence and mafic components showing a broad compositional spectrum including arc tholeiite, calc-alkalic, MORB, E-MORB (enriched MORB), OIB, boninitic, and BABB (back-arc basin basalt) variants (Piercey et al., 2006). The pericratonic arcs were developed on attenuating Laurentian continental and adjacent crust, as shown by common detrital zircon and isotopic signatures (Fig. 8; Nelson et al., 2006). For instance, detrital zircon populations in the Yukon-Tanana terrane show dominant 1.8 to 2.0 Ga peaks that are comparable to the basement ages of northwestern Laurentia as well as to detrital zircon populations in autochthonous strata of the northwestern continental margin (Gehrels et al., 1995; Gehrels and Ross, 1998). During Early Mississippian time, the Slide Mountain Ocean opened to separate a large portion of the frontal arc from the continental margin: this rifted Laurentian sliver became the Yukon-Tanana terrane (Figs. 9, 10).

The Devonian-Mississippian development, attenuation, and detachment of pericontinental arcs gave rise to a wide variety of mineral deposits. Most important from this period are syngenetic sulphide deposits that range from volcanogenic in immediate back-arc and intra-arc settings, to

SEDEX styles in the more distant back-arc regions of the Selwyn Basin and Kechika trough (Fig. 7; Nelson et al., 2002). Notable VMS districts include the Finlayson Lake belt in the Yukon-Tanana terrane, Tulsequah Chief in far northwestern Stikinia, the Delta and Bonnifield districts in the parautochthonous Alaska Range, and the Eagle Bay deposits in Kootenay terrane of southeastern British Columbia (Dusel-Bacon et al., 2006; Murphy et al., 2006; Paradis et al., 2006a; Piercey et al., 2006). Of these, Tulsequah Chief, and Samatosum, Homestake, and Rea Gold in the Eagle Bay district have been producers; Wolverine in the Finlayson Lake district is currently in mine development stage (Fig. 7; Appendix 1). The largest and best known Devonian SEDEX deposits are those at Macmillan Pass in the eastern Selwyn Basin and Cirque in the Kechika trough. In 2005, drilling on the less explored Akie prospect, south of the Cirque, has returned some notable intersections, including 37 m at 11.3% Zn, 2.65% Pb, and 21 g/t Ag (Schroeter et al., 2006). All of these are hosted by black, carbonaceous, siliceous strata of the Earn Group. They are associated with facies transitions and synsedimentary faults related to an extensional tectonic regime that affected the entire continental margin in Middle to Late Devonian time. Yet farther inboard, Devonian MVT deposits, such as Robb Lake and even Pine Point, formed when relatively cool hydrothermal fluids interacted with carbonate strata (Fig. 7; Nelson et al., 2002). Prairie Creek is an Irish-type polymetallic deposit, located in a faulted basin-to-platform transitional setting on the eastern margin of the Selwyn Basin, partly carbonate-hosted and partly structurally controlled (Paradis et al., 2006b).

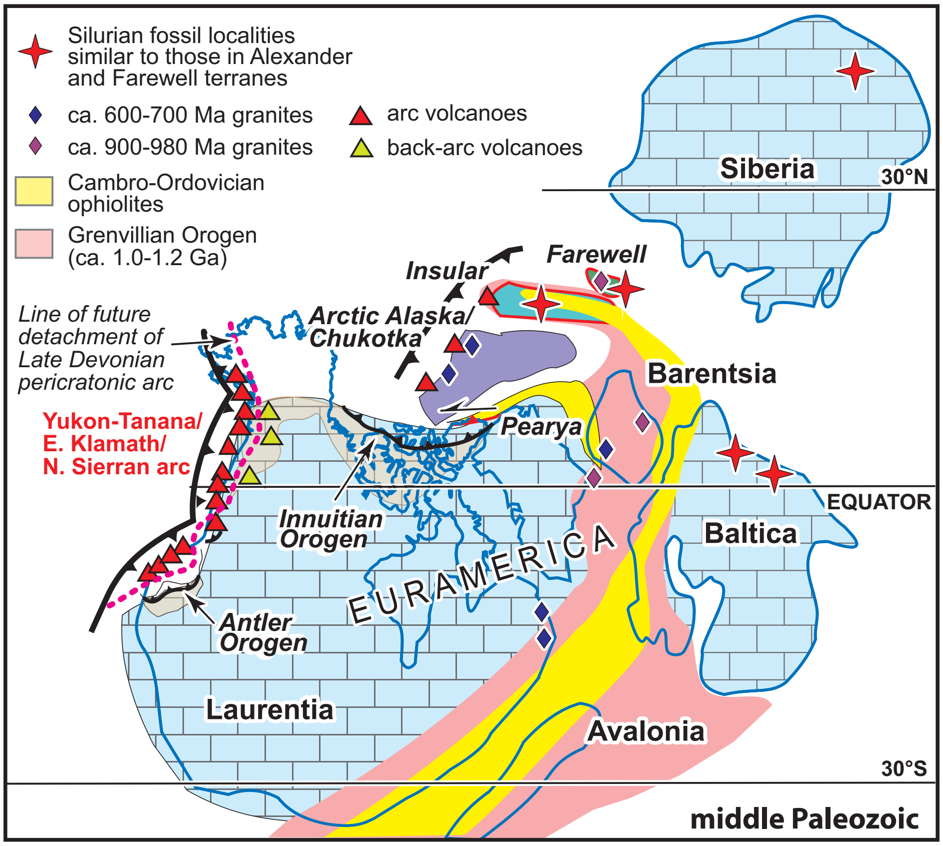

FIGURE 10. Schematic reconstruction of the peri-Laurentian and Arctic realm terranes in mid-Paleozoic time. Continental reconstruction is from Scotese (2002). Caledonides from Trettin (1987) and Gee (2005). Grenvillian basement from Trettin (1987). The locations of Precambrian granitoids are from Patrick and McClelland (1995) and Gee (2005). Silurian fossil localities are from Soja and Antoshkina (1997). The Farewell terrane is placed most proximal to the future Early Permian Uralian orogenic belt, which will affect it. The Alexander terrane is placed on trend with the Caledonian Orogeny and in the zone of ca. 1.0 Ga basement. Arctic Alaska/Chukotka is shown adjacent to the Arctic Islands. Red dashed line along the western Laurentia indicates the future site of the opening of the Slide Mountain Ocean.

Phase 3: Offshore Arcs, Quiet Margin (Pennsylvanian-Permian)

Arc-related sequences continued to build upon the rifted continental fragment of the Yukon-Tanana terrane throughout late Paleozoic time (Colpron et al., 2006; Nelson et al., 2006; Piercey et al., 2006). Extensions of these arcs may have been founded on oceanic substrates as well. The character of volcanism and sedimentation changed. Instead of widespread bimodal rhyolite-basalt volcanism associated with carbonaceous, basinal strata that characterized Devonian to Mississippian arcs, Pennsylvanian-Permian sequences were dominated by intermediate volcanic and volcaniclastic deposits and lesser enriched basalts, epiclastic beds, limestone, siliciclastic sedimentary strata, and chert (Simard et al., 2003; Gunning et al., 2006). These late Paleozoic units are depositionally linked both to older parts of the Yukon-Tanana terrane, and to Mesozoic strata of Stikine and Quesnel terranes (Read and Okulitch, 1977; Jackson et al., 1991; Mihalynuk et al., 1994b; Mihalynuk, 1999; Simard et al., 2003; Nelson and Friedman, 2004). Triassic/Jurassic intrusive suites are continuous across all three (Wheeler and McFeely, 1991). Together, the pericratonic Yukon-Tanana terrane and its overlying late Paleozoic cover form the underpinnings of the main Intermontane arc terranes.

Faunal affinities suggest that in Early to mid-Permian time, Stikine, Quesnel, and Eastern Klamath terranes probably lay 2000 to 3000 km west of North America (Belasky et al., 2002). Voluminous basalt – evidence of strong late Pennsylvanian-Early Permian spreading – and paucity of siliciclastic sedimentation in the Slide Mountain terrane are consistent with a broad ocean between the peri-Laurentian arc terranes and the continent at this time (Fig. 11; Nelson et al., 2006). Continental margin tectonics were more subdued during the late Paleozoic than at any time before or since: Permian strata are thin and dominated by limestone and chert, rather than siliciclastic sediments.

The late Paleozoic also saw a lull in formation of mineral deposits, which separated the previous era of widespread syngenetic sulphide mineralization from the subsequent flowering of porphyry and epigenetic mineralization that would dominate the Mesozoic. Tectonically, continental rifting in the peri-Laurentian realm was finished, and the crustal thickening that characterized Mesozoic arc history had not yet begun. The only deposits of significance that formed during this interval are modest Cyprus-type Cu-rich massive sulphide deposits such as Ice in the Finlayson belt and Chu Chua in southeastern British Columbia, both within the Slide Mountain ocean basin (shown on Fig. 7).

Phase 4: Marginal Basin Closure, Overlapping Arcs, and Accretionary Prisms (Middle Permian to Early Jurassic)

From its Devonian inception through the Early Permian, easterly dipping subduction took place under the western Laurentian margin, and later under its fringing pericratonic arc terranes. The Middle to Late Permian record in the Yukon-Tanana terrane documents reversal of this pattern. The Klondike assemblage, dominated by felsic, continentally influenced volcanic and intrusive rocks, is restricted to the eastern and northern side of the terrane; east of it lies a belt of coeval high-pressure metamorphic rocks and synorogenic clastic deposits (Fig. 12; Colpron et al., 2006; Nelson et al., 2006). Evidently, the Slide Mountain marginal ocean closed by westerly subduction beneath Yukon-Tanana terrane and remnants of the Slide Mountain Ocean that remained attached to Yukon-Tanana. Up to this point, there has been considerable controversy about which part of the continental margin the Yukon-Tanana and its affiliated terranes accreted to in Permo-Triassic time. A recent study by Beranek and Mortensen (2006) shows characteristic Yukon-Tanana detrital zircons in autochthonous Triassic strata in Yukon, including those derived from the spatially limited Klondike assemblage. These observations are strong evidence that the Yukon-

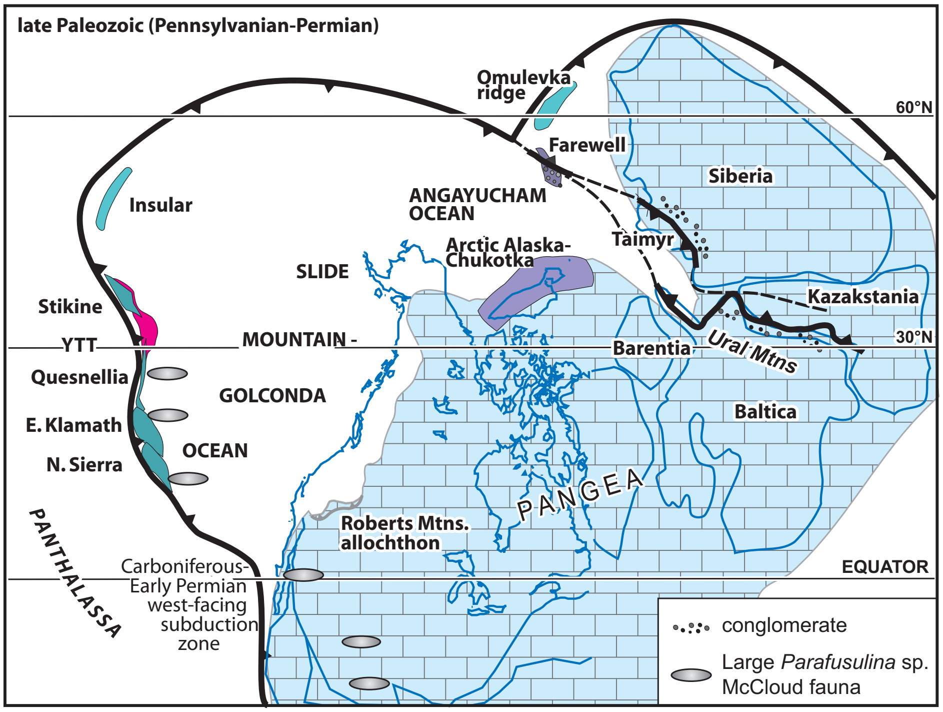

FIGURE 11. Late Paleozoic (Pennsylvanian-Early Permian) schematic reconstruction. Continents from Scotese (2002); northern continents and Uralian-Taimyr orogen from Bradley et al. (2003). Location of Insular and Intermontane terranes based largely on Belasky et al. (2002). Location of Farewell terrane based conceptually on Bradley et al. (2003). Omulevka Ridge from Nokleberg et al. (2005). YTT – Yukon-Tanana terrane.

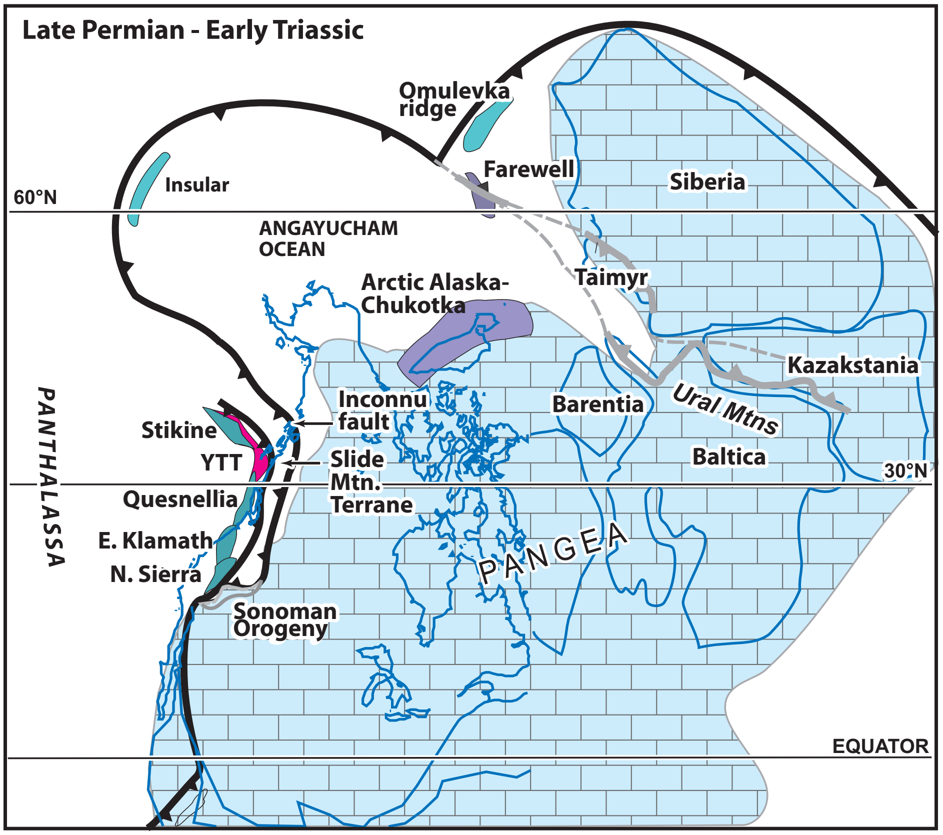

FIGURE 12. End Paleozoic (Late Permian – Early Triassic) schematic reconstruction. Sources as in Figure 11. YTT – Yukon-Tanana terrane.

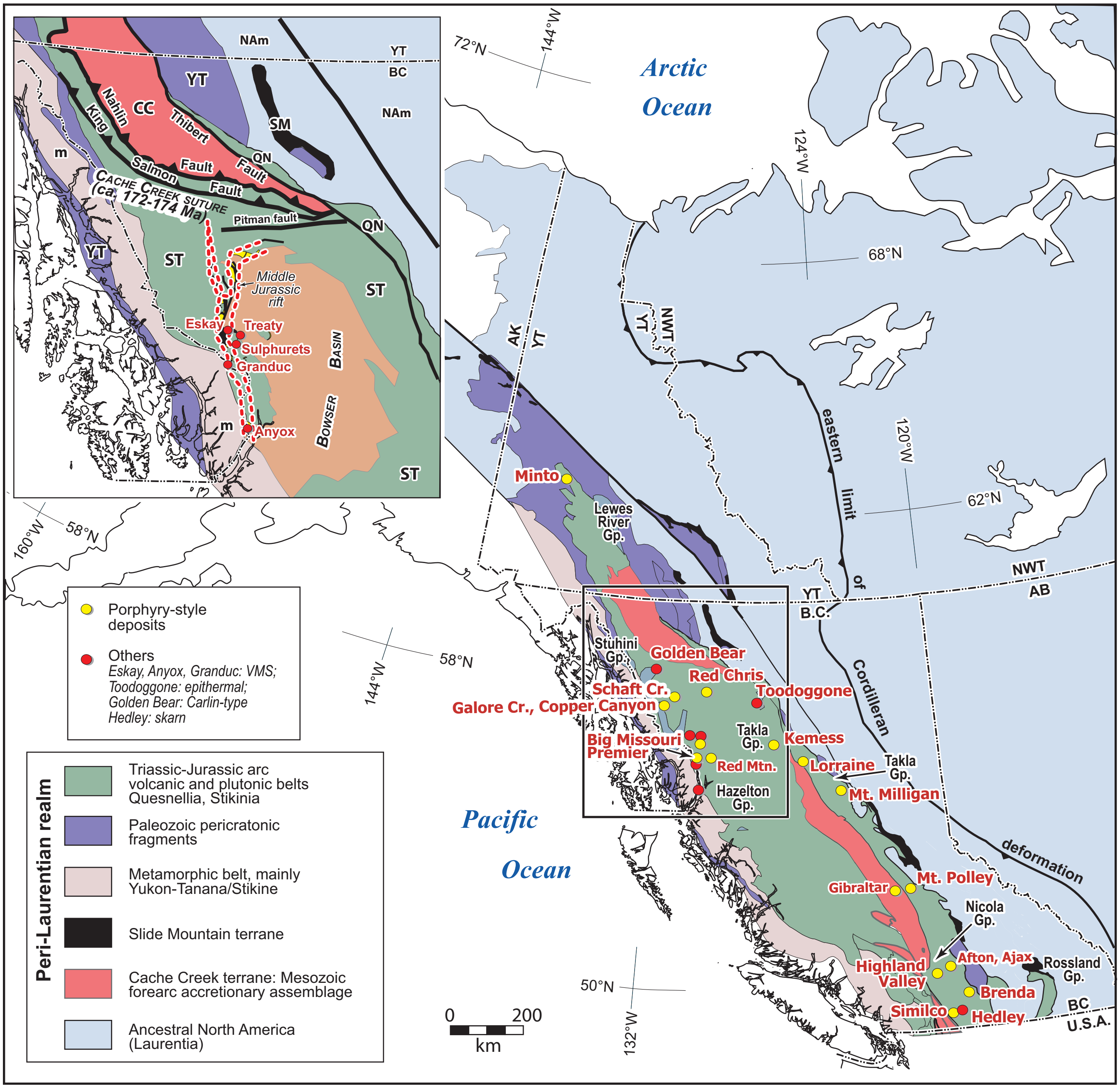

FIGURE 13. Triassic to Middle Jurassic magmatic belts and associated deposits of the Intermontane terranes. Deposit locations are from McMillan et al. (1995). Inset shows details of the mid-Jurassic Eskay rift and associated VMS deposits (from Alldrick et al., 2005; note that Granduc is Late Triassic but lies within the later rift zone). Bowser basin is the Middle Jurassic to Early Cretaceous foreland basin to the Cache Creek accretionary complex. Terrane labels as in Figure 1A.

Tanana terrane must have arrived near its present position in the Triassic (Fig. 12).

Permo-Triassic time marked a major tectonic, magmatic, and depositional break in the Intermontane, peri-Laurentian arc terranes. Except for the Klondike arc, Paleozoic arc magmatic activity was extinguished in the Intermontane terranes by Early (Gunning et al., 2006) to Middle Permian time.

The oldest Mesozoic volcanic and intrusive rocks in Quesnel and Stikine terranes are Middle Triassic, but voluminous arc-related buildups with coeval, cogenetic plutonism began in the Late Triassic (Fig. 13; Anderson, 1991). They include the Takla and Nicola groups northeast of the Cache Creek terrane and the Takla and Stuhini groups to the southwest (the oceanic, accretionary Cache Creek assemblage is used to demarcate between similar Mesozoic strata assigned to Quesnel and Stikine terranes; see Wheeler et al., 1991). Late Triassic, dominantly augite-(plagioclase-) phyric volcanogenic units on both sides of the Cache Creek assemblage are strongly similar in field characteristics, arc geochemistry, and primitive isotopic signatures (Dostal et al., 1999). In Quesnel terrane, the main Triassic volcanic accumulations lie west of the belt of Paleozoic pericratonic exposures, which are onlapped by thinner, volcanic-poor siliciclastic units with continentally influenced isotopic signatures (Unterschutz et al., 2002) that also overlie Yukon-Tanana terrane and the western continental margin. Following Permo-Triassic accretion of the innermost pericratonic terranes (Slide Mountain, Quesnel, and Yukon-Tanana), it is likely that the axis of the new west-facing arc migrated outboard from the collision zone. In the Stikine terrane, there is no evidence for a shift in the arc axis: the Stuhini and Takla groups are developed in a broad region on top of variably deformed Paleozoic arc units.

On both sides of the Cache Creek assemblage, newly configured Early Jurassic arcs were superimposed on Triassic architecture; contact relationships range regionally from disconformable to deeply unconformable on folded and thrust-faulted older strata. In Quesnel and Yukon-Tanana terranes, the Jurassic magmatic belt migrated eastwards towards the continent, as shown by abundant 200 to 185 Ma plutons in the Yukon-Tanana terrane, and volcanic strata of the Lower Jurassic Rossland Group, which lie well east of the Triassic Nicola Group in southern British Columbia (Fig. 13; Wheeler and McFeely, 1991). In the Stikine terrane, Lower Jurassic volcanogenic strata of the Hazelton Group are widespread and voluminous. The favoured tectonic model for this terrane in Early Jurassic time is a microplate with subduction under both east and west sides (present coordinates), which generated two arcs separated by a marine trough (Marsden and Thorkelson, 1992).

Late Triassic to Early Jurassic Cu-Au and Cu-Mo porphyry deposits of Stikine and Quesnel terranes (Fig. 13) are collectively the most important group of deposits in British Columbia; this belt extends into the Yukon-Tanana terrane of Yukon (Minto and Williams Creek; Tafti and Mortensen, 2004; Fig. 13). It includes long-time producers such as Highland Valley, Gibraltar, Copper Mountain, Brenda, and Afton; newer mines such as Mt. Polley and Kemess, probable future mines such as Galore, and unexploited large resources such as Mt. Milligan, Red Chris, and Schaft Creek (Appendix 1). Volumes, literally, have been written about these deposits – Canadian Institute of Mining and Metallurgy Special Volumes 15 (1976, edited by A. Sutherland Brown) and 46 (1995, edited by T.G. Schroeter) – a sign of their enduring significance. Host intrusions range from ca. 210 Ma (Galore, Highland Valley) to ca. 183 Ma (Mt. Milligan); most common ages are ca. 205 to 202 Ma (Mortensen et al., 1995), which corresponds to the end stage of Triassic arc activity and the pause before the onset of renewed Jurassic volcanism. The host intrusions tend to be high level, even subvolcanic (Nelson and Bellefontaine, 1996), except for those in the Yukon-Tanana terrane, which are deeply exhumed (Tafti and Mortensen, 2004). They range from calc-alkalic to mildly alkalic (shoshonitic) in affinity: this tendency is probably due to melting of upper mantle that was previously metasomatised during repeated Devonian to Triassic subduction events (Nelson and Bellefontaine, 1996). At the time that they were emplaced, the overriding plate(s) – the Quesnel and Stikine arcs – were in a state of compression (or sinistral transpression; P. Schiarizza, pers. comm., 2005). Evidence for crustal thickening includes Triassic-Jurassic folding and reverse-faulting, Triassic-Jurassic unconformities, a transition from predominantly marine conditions in the Triassic to widespread subaerial and shallow submarine volcanism in the Jurassic, and the continentward migration of the Quesnel arc axis. The porphyry deposits were accompanied by other epigenetic deposit types, including gold skarn at Hedley, gold-silver in structurally controlled carbonate replacements at Golden Bear, and transitional vein to stratabound ores that were mined at Big Missouri (Fig. 13; Appendix 1). The abundance of porphyry and other deposits marks Stikinia and Quesnellia as remarkably rich metallotects, comparable to modern arc settings like Papua New Guinea.

In contrast to the porphyry deposits that occur throughout Stikinia and Quesnellia, the now-closed Granduc mine in northwestern British Columbia exploited a series of stratiform Late Triassic, copper-rich VMS lenses. The sulphide lenses are associated with magnetite iron formation. They overlie a section of primitive tholeiitic basalts that have been dated as ca. 223 Ma by U-Pb methods (Childe, 1997). A primitive arc or back-arc setting is inferred for this unusual deposit. It is located along the Unuk River shear zone, which later became the setting of the Eskay and related mid-Jurassic VMS deposits (see below).

The Cache Creek terrane intervenes structurally between the nearly identical Stikine and Quesnel arc terranes. It is an accretionary assemblage that contains late Paleozoic to Lower Jurassic oceanic strata; the remnants of late Paleozoic oceanic plateaus; limestones with Permian Tethyan fusulinid faunas that most closely resemble those of China and Japan; melange belts; a peculiar, primitive Late Permian arc, the Kutcho arc; and Late Triassic and mid-Jurassic blueschists. It marked a major destructive plate boundary. Correlative assemblages that occur west of pericratonic arc terranes in Oregon and California are considered to mark the paleo-Pacific outer margin of North America and its marginal terranes in late Paleozoic to early Mesozoic time (Miller, 1988).

The role of the Cache Creek terrane in the Canadian Cordillera is more complex. Triassic fore-arc facies in central Quesnellia, including ultramafic-gabbro clast conglomerates, occur adjacent to the eastern Triassic blueschist belt of the Cache Creek terrane (Paterson, 1977; Struik et al., 2001): they are clear evidence that Cache Creek formed the fore-arc accretionary wedge for a west-facing Quesnel arc, analogous to arc terranes farther south (Miller, 1988). Conversely, Lower Jurassic clastic strata of probable fore-arc affinity occur in northeastern Stikinia and adjacent Cache Creek terrane (Mihalynuk, 1999), and the Late Triassic Granduc orebody may have formed in a back-arc environment in western Stikinia, evidence of an easterly facing arc. Apparently, opposing arcs in Quesnel and Stikine terranes faced the same, open, still-subducting ocean in early Mesozoic time (Mihalynuk et al., 1994a). In Figures 14 and 15, the Stikinia block is rotated clockwise to restore this scenario. Of the two alternate options shown in Nokleberg et al. (2000, p. 60), the enclosure model is preferred. The other option of restoring a hypothetical mid-Jurassic sinistral fault with more than 1000 km offset does not account for observed continuity in Jurassic and older units in the Yukon-Tanana terrane to the north or for the east-facing Early Jurassic Stikine arc, and it would juxtapose fundamentally disparate tectonic facies such as thick Triassic volcanic sequences with thin sedimentary intervals, and the Early

Jurassic Hazelton arc or arcs with coeval metamorphic belts and coarse clastic accumulations.

Phase 5: Final Accretion of the Intermontane Terranes and the Eskay Event (180 to 170 Ma)

In mid-Jurassic time, the Stikine crustal block collided with the already accreted Quesnel terrane and western North America, killing both the Quesnel and eastern Stikine (Hazelton) arcs and trapping the Cache Creek accretionary prism and remaining Cache Creek ocean floor between (Fig. 16). The timing for this event is well constrained by:

- Youngest oceanic strata - radiolarian cherts in the Cache Creek terrane: Pleinsbachian-Toarcian (Cordey et al., 1987)
- Youngest arc magmatism in Quesnellia: late Pleinsbachian-early Toarcian (186-183 Ma; Nelson and Bellefontaine, 1996)
- Pinning plutons across Quesnel/North America boundary: Toarcian (ca. 185-181 Ma; Murphy et al., 1995)
- Youngest arc magmatism in eastern Stikinia (186 Ma; Larry Diakow, pers. comm., 2006)
- Oldest detritus from collision zone in Bowser basin: Bajocian, with interpreted Aalenian foreland depression (Ricketts et al., 1992)
- Oldest post-kinematic intrusions: Fourth of July suite near Atlin, ca. 172 Ma (Mihalynuk et al., 1992); Nelson plutonic suite, ca. 175 Ma, and younger (Murphy et al., 1995).

As a result of the final stages of collision, the Cache Creek terrane was obducted onto northeastern Stikinia. One panel, the French Range, contains coherent blueschist sheets that have been precisely dated as 172 Ma both for peak metamorphism (U-Pb zircon) and cooling (^{40}Ar/^{39}Ar plateau ages; Mihalynuk et al., 2004). They model the final collision as a Halmahera-like arc-arc collision (Fig. 16B,C). Evenchick et al. (2006) suggest that North America – specifically the orogen in southern British Columbia – formed a tectonic hinterland during west-southwesterly thrusting and foreland basin sedimentation in the Bowser basin (Fig. 13 inset).

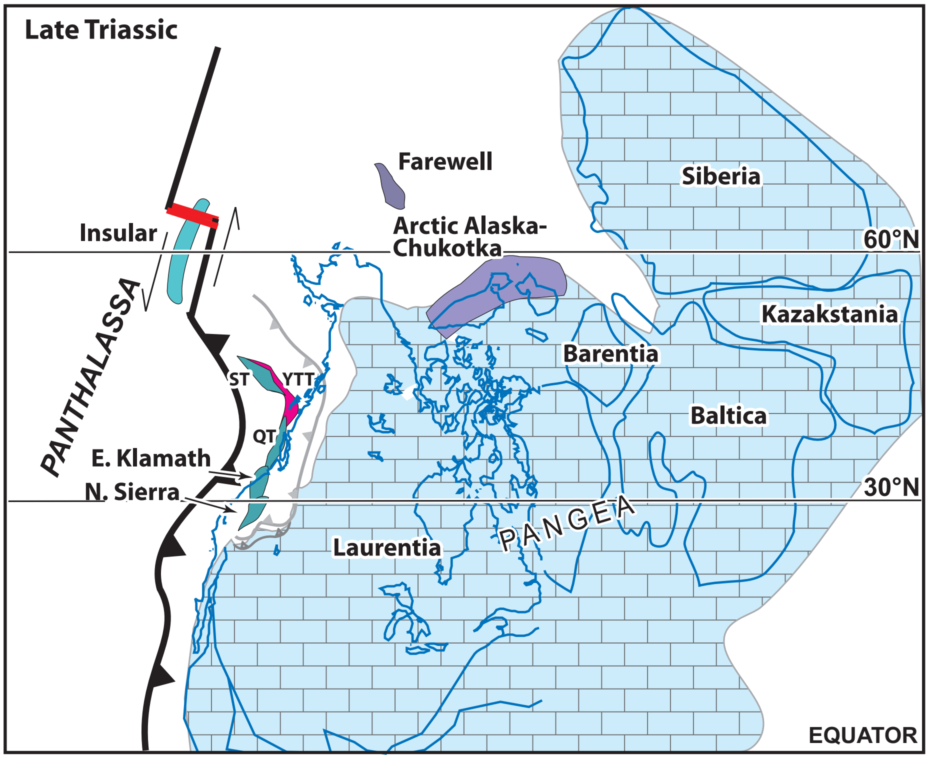

FIGURE 14. Late Triassic schematic reconstruction. Sources as in Figure 11. QT – Quesnel terrane; ST – Stikine terrane; YTT – Yukon-Tanana terrane.

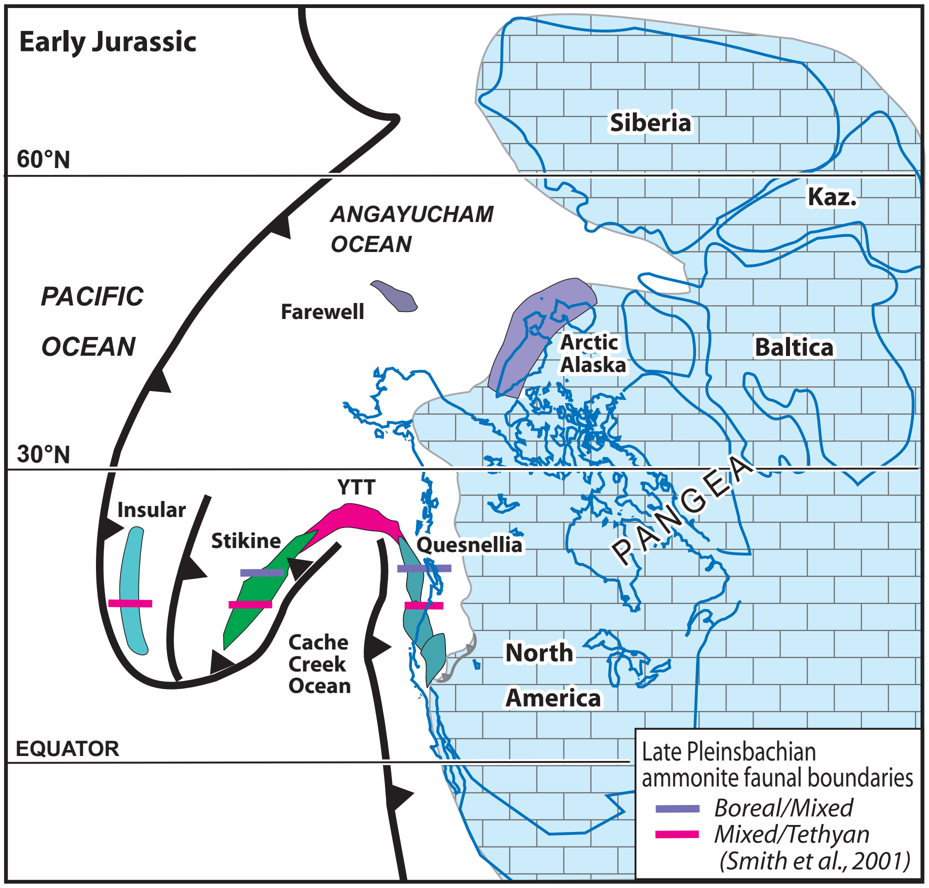

FIGURE 15. Early Jurassic schematic reconstruction. Fossil constraints from Smith et al. (2001). Continental reconstruction from Scotese (2002). YTT – Yukon-Tanana terrane.

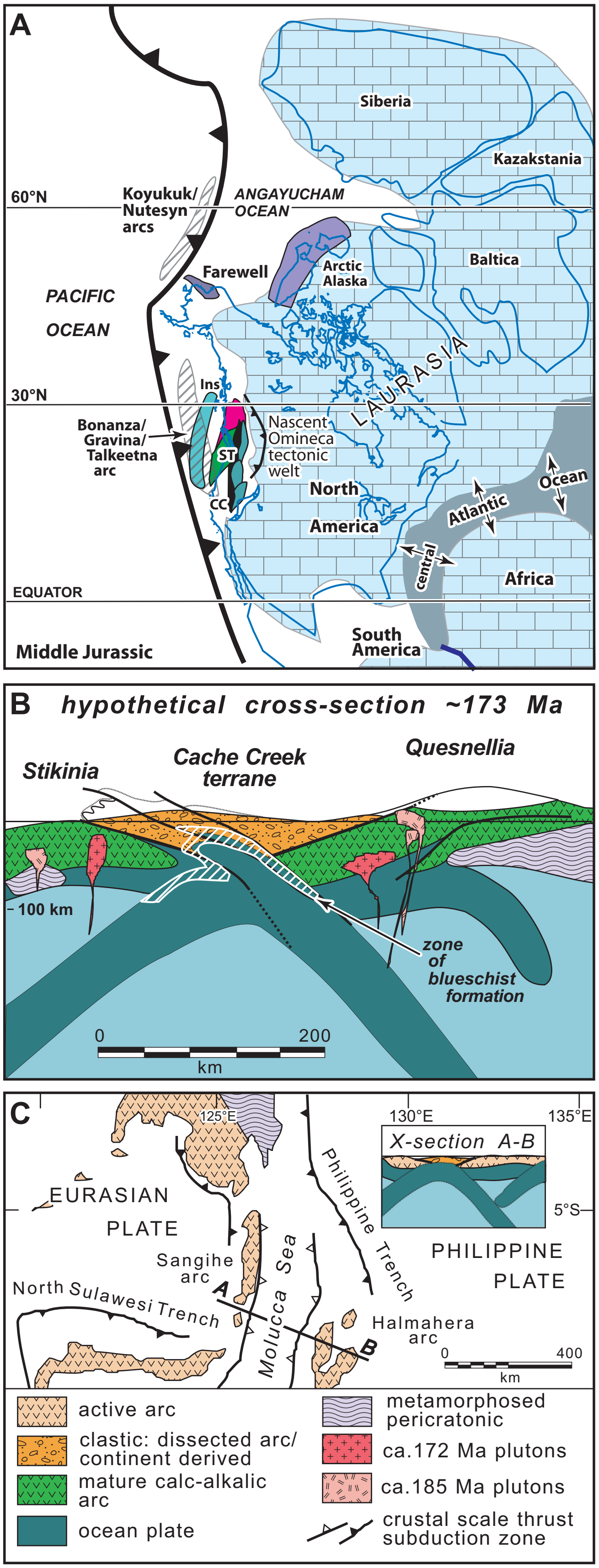

FIGURE 16. **A)** Middle Jurassic schematic reconstruction (after Mihalynuk et al., 1994a). Continental reconstruction from Scotese (2002). CC – Cache Creek terrane; Ins. – Insular terranes; ST – Stikinia. Nutesyn arc from Nokleberg et al. (2005). **B)** Middle Jurassic schematic cross-section across the Intermontane realm (after Mihalynuk et al., 2004). **C)** Tectonic map and cross-section of the modern Molucca Sea region.

Just prior to final tightening, the narrow, laterally continuous, north-trending Eskay rift zone cut across the Stikine crustal block, at a high angle to the incipient zone of collision as it is defined by the Nahlin and King Salmon faults (Fig. 13 inset). The rift filled with clastic sedimentary strata ranging from fanglomerate to conglomerate to sandstone/argillite (Alldrick et al., 2005), and a bimodal volcanic suite of locally thick pillow basalts and small rhyolite bodies that give ages of ca. 175 Ma (MacDonald et al., 1996). The Eskay Creek precious metal-rich massive sulphide deposit (Fig. 13; Appendix 1), which has been the highest grade VMS mine in the world since its opening in 1998, occurs in carbonaceous sedimentary strata above one of the rhyolites and below pillow basalts. Anyox, a Cu-rich, basalt-hosted VMS-style mined deposit, lies to the south along strike of the rift zone. It is considered to be coeval with Eskay, but of a more primitive character due to underlying crust, more advanced rifting, or both (Evenchick and McNicoll, 2002).

The Eskay rift zone is a back-arc rift in the sense that it lies north of a zone of subdued arc magmatic activity that succeeded the western mainstage Hazelton arc. However, it represents a complete departure from earlier tectonic/magmatic styles and trends. A sinistral shear sense is recorded on its bounding faults and in adjacent rocks (Alldrick et al., 2005). We speculate that it developed as a cross-fracture related to a shear couple across the Stikine block, in response to collisional stresses particularly on its northeastern margin (Fig. 13 inset). This would explain its anomalous northerly trend, its short-lived but intense development as a rift zone, and the lateral displacement across it.

One of the thrust sheets in the Cache Creek terrane comprises a Late Permian, primitive island arc assemblage, the Kutcho arc, along with its Triassic and Jurassic clastic cover (Childe et al., 1998). This arc is dissimilar to Stikinia and Quesnellia in its chemical composition, extremely primitive isotopic character, and age, and is regarded as a fragment of a nascent volcanic arc that formed within the paleo-Pacific ocean and was accreted along with the remainder of the Cache Creek terrane. The Kutcho Creek Cu-rich massive sulphide deposit (shown on Fig. 7; Appendix 1) is associated with felsic volcanic rocks in the northern part of the Kutcho arc. As this fragment is recognized along the length of the Cache Creek terrane (Childe et al., 1998), there is considerable strike potential for Kutcho equivalents.

The Arctic and Insular Terranes

We have followed the development of the Intermontane terranes, from the first separation of ensialic arc fragments from the continent in the Devonian, through their history in the peri-Laurentian realm, to the verge of re-accretion with North America. We now take up the story of the terranes of the Arctic realm, beginning with their conjectural time(s) and place(s) of origin, up to the arrival of the Insular terranes outboard of the peri-Laurentian realm, also in Jurassic time.

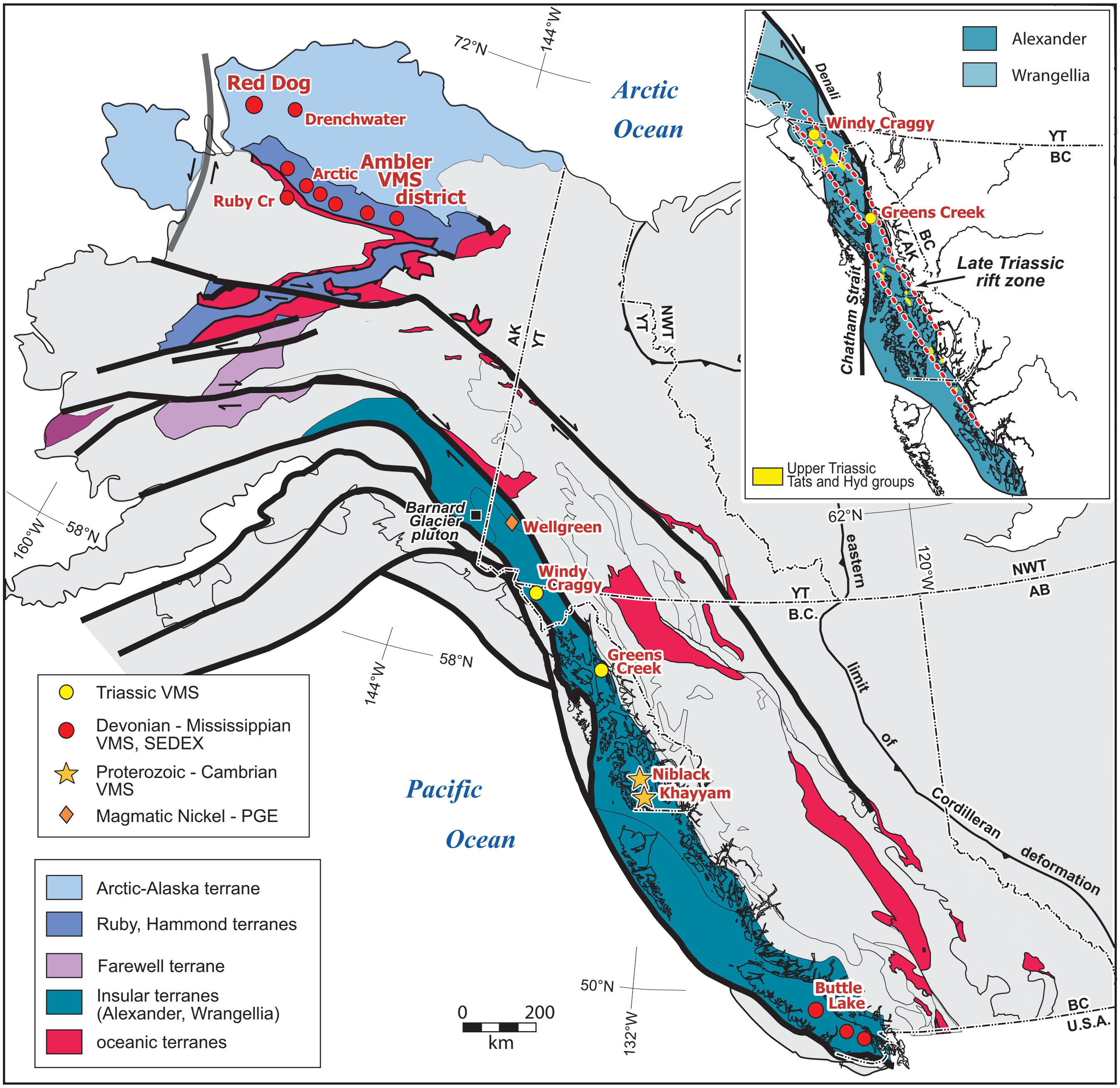

FIGURE 17. Mineral deposits and key tectonic features of the Arctic realm terranes. Deposit locations from Massey (2000a) and Nokleberg et al. (1994). Location of the Pennsylvanian Barnard Glacier pluton, that stitches Wrangellia and Alexander terrane, is from Gardner et al. (1988). Inset shows details of the Late Triassic rift zone in Alexander terrane and associated VMS deposits. Late Triassic outcrops compiled from Mihalynuk et al. (1993), Gehrels et al. (1987) and Silberling et al. (1994).

The Arctic realm comprises three major terrane affiliations (Figs. 1, 17):

- The Arctic Alaska terrane includes both Late Precambrian-Paleozoic continental shelf-slope strata of the northern Brooks Range, and Late Proterozoic and younger pericratonic rocks of the southern Brooks Range ("schist belt") and Seward Peninsula. The poorly studied Ruby terrane of central Alaska shows some affinities with the Brooks Range, but also some similarities with western Laurentia; it may be a structural composite of elements of both (Roeske et al., 2006).
- The Farewell terrane, formerly subdivided into the Nixon Fork, Dillinger, and parts of the Mystic terrane, comprises Proterozoic basement overlain by Paleozoic shelf and slope strata and Permian clastic wedge deposits (Bradley et al., 2003).
- The Insular terranes include the Alexander terrane and Wrangellia. The Alexander terrane is a crustal fragment with a regionally variable character. In southeastern Alaska, it consists of Late Precambrian to early Paleozoic volcanic arc rocks without obvious continental underpinnings, but with some continentally derived sedimentary strata that contain Precambrian detrital zircon populations (Gehrels et al., 1996). In far northwestern

British Columbia, southern Yukon, and far eastern Alaska, it comprises lower Paleozoic continental shelf-platform strata (Mihalynuk et al., 1993), overlain by late Paleozoic arc sequences that it shares with Wrangellia (Gardner et al., 1988). Wrangellia is a long-lived, multi-episodic, Devonian and younger arc terrane. Both Alexander and Wrangellia experienced non-arc mafic volcanism in Late Triassic time. In Wrangellia, this was expressed as the widespread Carnian-age Nikolai-Karmutsen basaltic event, which has been interpreted as the product of oceanic plateau volcanism (Lassiter et al., 1995). In the Alexander terrane, slightly younger, Norian basalts are confined to a single rift zone that hosts the giant Windy Craggy Besshi-type VMS deposit and the Greens Creek VMS mine (Fig. 17; Appendix 1).

Origins and Early Histories (Late Precambrian - Early Paleozoic)

Arctic Alaska terrane: In the northern Brooks Range, siliciclastic and carbonate strata are as old as late Neoproterozoic (Moore et al., 1994). Early Paleozoic deep-water, volcanic-rich and arc-related facies are also present, indicating the presence of offshore basinal and arc assemblages that were deformed and then truncated by pre-Middle Devonian and pre-Mississippian unconformities (Moore et al., 1994). Some Cambrian to Mississippian faunas are of Laurentian and some of Siberian affinities (Blodgett et al., 2002; Dumoulin et al., 2002; Dumoulin and Harris, 2006). In the southern Brooks Range, a single granitic orthogneiss body has been dated at ca. 970 Ma (McClelland et al., 2006). Orthogneiss and volcanic ages range from 750 to 540 Ma, both there and in the Seward Peninsula (Amato et al., 2006). On the Seward Peninsula, deformed igneous and related rocks are overlain by sandstone containing detrital zircons as young as ca. 540 Ma, which are overlain in turn by unmetamorphosed fossiliferous Early Ordovician carbonate. This Cambro-Ordovician deformational event may have been of significance throughout Arctic Alaska (Amato et al., 2006). Igneous ages of 750 to 540 Ma are rare in northern Laurentia, but compare to arcs and collisional orogens of northern Siberia, Barentia, and Baltica (Patrick and McClelland, 1995; Amato et al., 2006). Thus, Arctic Alaska and its western extension into Chukotka may be a crustal fragment that rifted from Siberia during the Neoproterozoic breakup of Rodinia (Dumoulin and Harris, 2006), but continued to interact with continental margins of the Arctic realm well into Paleozoic time. Detrital zircons from Triassic strata in Chukotka, Wrangel Island and westernmost Arctic Alaska (Lisburne Hills) share important Devonian-Carboniferous (380-320 Ma) and Permo-Triassic (ca. 250 Ma) components with the Verkhoyansk fold belt of eastern Siberia (Miller et al., 2004); Uralian granites and metamorphic rocks and silicic magmatism related to the Siberian traps are likely sources. Detrital grains with ages between 2030 to 890 Ma are reported from Seward Peninsula (Amato et al., 2004), a limited data set that nevertheless suggests parallels with the Farewell terrane (see below).

Farewell Terrane

The oldest crystalline rocks of the Farewell terrane include ca. 1200 Ma and 980 to 920 Ma rhyolites and ca. 980 to 850 Ma orthogneisses (Bradley et al., 2003, 2006; McClelland et al., 2006). The overlying carbonate and siliciclastic strata were deposited along a late Neoproterozoic continental margin; minor Silurian tuffs suggest arc activity (Bradley et al., 2006). Early Paleozoic faunas show the influence of both Siberian and Laurentian provinces (Blodgett et al., 2002; Bradley et al., 2006). Detrital zircon peaks of ca. 2050, 1375, and 950 Ma are unlike Laurentia (Bradley et al., 2006; compare with western Laurentian data of Gehrels et al., 1995 and Gehrels and Ross, 1998). The Early Permian (ca. 285 Ma) Browns Fork Orogeny is a distinctive event of deformation, metamorphism, and deposition of a clastic wedge; it has been linked to Uralian tectonism associated with collision between Baltica, Siberia, and Taimyr (Bradley et al., 2003). Like Arctic Alaska/Chukotka, the Farewell terrane seems to have been a player in the Arctic region during much of Paleozoic time.

The Kilbuck-Idono terranes are small pericratonic blocks located in southwestern Alaska. Kilbuck basement has been dated as ca. 2070 to 2040 Ma, an age range that may fit Siberia or other cratons more than western Laurentia (Box et al., 1990). Bradley et al. (2006) point out the similarity of ca. 2050 Ma detrital zircons in the Farewell terrane to the age of the Kilbuck terrane.

Alexander Terrane

The oldest known rocks in the southern Alexander terrane belong to the latest Proterozoic to Early Cambrian, arc-related Wales Group (U-Pb ages of ca. 595 and ca. 554 Ma; Gehrels et al., 1996). They host a number of VMS deposits, notably the Khayyam and Niblack on Prince of Wales Island in southeastern Alaska (Fig. 17; Appendix 1). These strata were deformed in the pre-Early Ordovician Wales Orogeny, coeval with deformation recorded in the Arctic Alaska terrane on the Seward Peninsula (Amato et al., 2006). In southern Alexander terrane, arc magmatism resumed in Early Ordovician-Early Silurian time, followed by clastic and carbonate sedimentation and pluton emplacement in the later Silurian. The Klakas Orogeny was marked by thrust imbrication, metamorphism, ductile deformation, and deposition of the Early Devonian Karheen Formation clastic wedge (Gehrels et al., 1996). Timing of Ordovician-Silurian arc building and Silurian-Devonian orogeny are similar to the Appalachian and Caledonian orogens (Bazard et al., 1995). By contrast, Paleozoic strata in the northern Alexander terrane are generally platformal, dominated by thick shallow-water carbonate sequences with lesser clastic strata and, particularly in the Cambrian section, basalt flows and sills (Mihalynuk et al., 1993).

Detrital zircon ages from the Karheen Formation show Precambrian peaks at 1.0 to 1.2 (dominant), 1.35 to 1.39, 1.48 to 1.53, 1.62 to 1.68, 1.73 to 1.77, 1.8 to 2.0, and 2.5 to 3.0 Ga, a pattern very unlike northwestern Laurentia, but showing strong Grenvillian influence and a possible connection with Baltica (Bazard et al., 1995; Gehrels et al., 1996; compare with dominant 1.8-2.0 Ga northwestern Laurentian peaks in Gehrels et al., 1995 and Gehrels and Ross, 1998). Silurian stromatolite faunas are very similar to those in the Ural Mountains, as well as those of the Farewell terrane (Soja and Antoshkina, 1997). This evidence, combined with paleomagnetic and detrital zircon constraints and northern

Alexander platformal stratigraphy, corroborates the Arctic, continent-proximal setting of the terrane in mid-Paleozoic time (Fig. 10).

For all their uniqueness, these three terranes share a number of themes that bear on their origins and early history. Detrital zircon signatures and, in the case of the Farewell terrane, ca. 1200 to 850 Ma basement ages, require a non-western Laurentian cratonal connection, with Baltica and Siberia as favoured alternates. Metarhyolites of 980 to 920 Ma are found in both Arctic Alaska and the Farewell terrane. Arctic Alaska shares a ca. 750 Ma plutonic event with Siberia and Barentia, and 565 to 544 Ma igneous activity with Baltica as well as the southern Alexander terrane. The sub-Early Ordovician unconformity is common to parts of Arctic Alaska, Chukotka, and the southern Alexander terrane. The stable platforms and basins of the northern Alexander terrane and the Farewell terrane were not affected by this event. Paleozoic faunas in all three terranes resemble each other (Soja and Antoshkina, 1997; Blodgett et al., 2002; Dumoulin et al., 2002; Dumoulin and Harris, 2006) and show mixed North American and Siberian affinities, with particularly strong Siberian/Baltic connections in Silurian time for Alexander and Nixon Fork, and Cambrian through Permian for the Farewell terrane. Figure 10 is a cartoon showing the proposed positions for the Farewell and Alexander terranes in mid-Paleozoic time.

Devonian-Mississippian Syngenetic Deposits

The Arctic Alaska terrane is host to two different types and ages of syngenetic sulphide deposits: the gigantic Red Dog SEDEX deposit, the largest Zn producer in the world (Fig. 17; Appendix 1) and other similar deposits in the western Brooks Range; and the Ambler district VMS deposits in the southern Brooks Range. Red Dog and its smaller equivalents are located within black shales of the Mississippian Kuna basin, and are related to extension and isolation of the basin by a seaward landmass (Young, 2004). The immense stratabound orebody has been dated at ca. 338 Ma by Re-Os methods on pyrite (Morelli et al., 2004), in accord with Osagean-Chesterian (mid- to Late Mississippian) radiolarian ages from the host Kuna Formation (Dumoulin et al., 2001).

The Ambler district lies within pericratonic rocks along the southern fringe of the Arctic Alaska terrane. The deposits are associated with metarhyolite bodies that have been dated at ca. 380 Ma by U-Pb methods (McClelland et al., 2006). Mineralization is hosted within a Middle Devonian ensialic arc sequence that reconstructs to the south (present coordinates) of the main Brooks Range. Unlike the Selwyn Basin-Yukon Tanana connection, there is no direct connection between the Ambler and Red Dog districts: they are separated in time by 40 m.y., in addition to their occurrence in separate allochthonous panels. However, their Pb-isotopic character is similar (Fig. 8), consistent with the involvement of similar crustal sources.

The oldest rocks in Wrangellia are exposed far to the south of its juncture with the Alexander terrane. They belong to the Devonian Sicker Group on Vancouver Island, which comprises island arc and related strata. The Myra Falls deposit (Fig. 17; Appendix 1), dated as ca. 370 Ma by U-Pb methods on associated rhyolites (Juras, 1987), consists of a series of lens-shaped massive sulphide bodies hosted by basaltic to rhyolitic flows and volcaniclastic rocks, lesser epiclastic rocks, argillites, and cherts of the Upper Devonian Myra Formation. The Myra Formation overlies feldspar-pyroxene porphyritic andesite flows, flow breccias, and minor pyroclastic deposits of the Price Formation. The Myra Falls (Buttle Lake) deposits are interpreted to lie within an arc-rift zone (Juras, 1987). Facies and thickness changes across later faults could be interpreted as a structurally inverted basin (Nelson, 1997; also see cross-sections of the Price zone in Juras, 1987). Lead isotopic data from Myra Falls form a distinct cluster that is significantly more radiogenic than the Ambler district and overlaps the least radiogenic end of the range (Stikinia) for western Cordilleran pericratonic Devonian-Mississippian deposits (Robinson et al., 1996; Fig. 8).

Pennsylvanian-Permian Insular Terrane Linkage and other Tectonic Events

Relationships between the Devonian Sicker Group and the Alexander terrane are undefined. In northern Wrangellia, the oldest exposed strata are of an arc-related succession of Pennsylvanian age, the Station Creek Formation. The Middle Pennsylvanian Barnard Glacier pluton (ca. 309 Ma) intrudes both the Station Creek Formation and nearby Paleozoic schists (the Kaskawulsh Group) that locally form the basement of the Alexander terrane (Gardner et al., 1988). It also seals the contact between them. Pennsylvanian-Permian arc deposits are widespread in Alaskan Wrangellia (Skolai arc; see Nokleberg et al., 1994), whereas in southern Wrangellia and in the Alexander terrane, Upper Mississippian to Permian strata are thin and non-volcanogenic (Mihalynuk et al., 1993; Massey, 1995; Gehrels et al., 1996). Given these relationships, the Barnard Glacier locality could be a point at which the Pennsylvanian-Early Permian Skolai arc was anchored on an older Insular crustal fragment, as the modern Aleutian arc is anchored to the Alaska Peninsula.

The Browns Fork Orogeny affected the Farewell terrane in Pennsylvanian-Early Permian time. This ca. 285 Ma metamorphic event is documented by ^{40}Ar/^{39}Ar muscovite plateau ages in the northern part of the terrane; thick Pennsylvanian-Permian coarse clastic deposits, interpreted as a foreland wedge, are widespread (Bradley et al., 2003). They speculate that the collision zone in the Urals and Taimyr could have been linked to a system of convergent plate boundaries such as that documented by the Skolai arc. A possibly correlative (or younger?) deformational event affects strata as young as Lower Permian but predates the deposition of Triassic rocks in Wrangellia of southwestern Yukon (Israel et al., 2006).

Statistical analysis of marine faunas – brachiopods, corals, and fusulinids – suggests that in Early Permian time, the Insular terranes lay north of the peri-Laurentian terranes (Quesnellia, Stikinia, and the Eastern Klamaths), and perhaps some few thousands of kilometres west of the northern Laurentian continental margin (Fig. 11; Belasky et al., 2002). This suggests that by late Paleozoic time, the Insular terranes had been transported out of the Arctic realm, and were already enroute to their more southerly Mesozoic location.

Late Triassic Rifting, Flood Basalts, and Associated Deposits

Through the end of Paleozoic time, the story of the Arctic and Insular terranes involved pericratonic crustal fragments and arcs developing near them, or even stepping onto them. In the Late Triassic, a new tectonic style affected the Insular terranes. During a very short time interval in the Carnian (ca. 230 Ma), flood basalts of non-arc, enriched, tholeiitic affinity inundated the older arc basement of Wrangellia (Lassiter et al., 1995). The short duration (approximately 5 m.y.) and high volume of this event, along with the chemical and isotopic signatures of the Karmutsen and Nikolai basalts, has led to its interpretation as a plume-related event, intermediate between true oceanic plateaus and continental flood basalts such as the ca. 250 Ma Siberian traps (Lassiter et al., 1995; see also Reichow and Saunders, 2005). Mafic-ultramafic sills and dykes intruding Paleozoic strata of Wrangellia in southwestern Yukon and adjacent Alaska are thought to be feeders to the Nikolai basalts (Hulbert, 1997); they host a number of Ni-Cu-PGE occurrences, including the Wellgreen deposit (Fig. 17; Appendix 1).

In Norian time, a rift zone developed in the northern and eastern part of the Alexander terrane. It is defined by a narrow, discontinuous belt of rift-fill clastic and volcanic strata of the Tats (Mihalynuk et al., 1993) and Hyd (Gehrels et al., 1987) groups. Volcanic rocks in the northern end of the rift zone are predominantly calc-alkaline basalts (Mihalynuk et al., 1993); farther south, intermediate and felsic units become important (Taylor et al., in press). The very large Windy Craggy Besshi-type Cu-Co-rich deposit (Peter et al., 1999; Fig. 17; Appendix 1) is hosted in interbedded argillite and basalt in the northern part of the rift. The Greens Creek mine (Fig. 17; Appendix 1), a long-producing VMS deposit with enhanced precious metal contents, is associated with rhyolite in the southern part of the rift. Taylor et al. (in press) infer a south to north transition from incipient rifting of thick, older crust, associated with low-volume mixed volcanic rocks and polymetallic VMS mineralization, to wider, more complete rifting, accompanied by basalt and Cu-enriched deposits.

These Triassic volcanic, tectonic, and metallogenetic events were unique to the Insular terranes. During that time, the Farewell and Arctic Alaska terranes were the sites of stable, clastic and carbonate sedimentation, and although there is evidence of rifting as old as 185 to 190 Ma in the northern Arctic Alaska terrane, an Early Cretaceous breakup unconformity is taken as the initial opening of the Canada Basin and beginning of significant rotation there (Moore et al., 1994). Ammonite species distribution suggests that, by ca. 186 Ma, Wrangellia had reached a position significantly south of its present location (Smith et al., 2001). It is tempting to relate the Triassic Wrangellian flood basalts and rifting within the Alexander terrane to their southward translation from the Arctic realm, perhaps crossing a plume track. It is also significant that during the Triassic there is no evidence of arc development in the Insular terranes, and thus no deep subduction zone root to stabilize their position. They could have been completely coupled to a fast-moving oceanic plate (Fig. 14).

Bringing the Realms Together: The Middle Jurassic

There is good evidence for the evolving relationship of the Insular terranes to the western North American pericratonic realm in Jurassic time. Variations in latitude of the present boundaries between late Pleinsbachian boreal amaltheid, mixed, and southern Tethyan ammonite taxa show that Quesnellia has been displaced about 500 km northward since that time (ca. 185 Ma), Stikinia and southern Wrangellia about twice that, and the Peninsular terrane in south-central Alaska has travelled north several thousand kilometres (Fig. 15; Smith et al., 2001). Distribution of high- vs. low-latitude Sinemurian and Pleinsbachian pectinoid bivalves shows similar patterns (Aberhan, 1999). By this time, the Insular terranes – once of high-Arctic provenance – were outboard of, and in part co-latitudinal with, Stikinia.

Their initial accretion to the pericratonic belt has been documented at several localities in the northern and central Coast Mountains. In southeastern Alaska, the Alexander terrane lies structurally beneath the Taku terrane (=Yukon-Tanana/Stikine terrane; see Gehrels, 2001, 2002) along a large-magnitude, low-angle ductile fault system that is crosscut by Late Jurassic (162-139 Ma) dykes (Saleeby, 2000). In this region, Middle Jurassic (ca. 177-168 Ma) volcanic rocks and Upper Jurassic-Lower Cretaceous strata of the Gravina belt overlie both terranes (Gehrels, 2001). Farther north, the inboard margin of the Alexander terrane is involved in a broad dextral shear zone of mid-Jurassic age (McClelland and Gehrels, 1990). In the central Coast Mountains, intrusion, ductile deformation, and metamorphism occurred ca. 160 to 155 Ma; this is interpreted to reflect collision between the Insular and Intermontane terranes (van der Heyden, 1992).

Similar timing for collision between the Insular terranes and the outer margin of the Intermontane terranes is seen in the 205 to 156 Ma Talkeetna arc in the Peninsular terrane of southwestern Alaska (Clift et al., 2005). It is modelled as south-facing and continuous with the Bonanza arc of southern Wrangellia. Uplift, cessation of magmatism, and deposition of conglomerates at about 160 Ma are taken to record its collision with the Intermontane terrane by north-dipping subduction. The absence of continental signatures in Talkeetna arc igneous rocks argues against the alternative of south-dipping polarity, which would have involved subduction of pericratonic material (Clift et al., 2005). The subduction zone under the western edge of Stikinia would correspond to the western Hazelton arc, which underwent profound changes in configuration at ca. 175 Ma (see above).

As outlined above, Stikinia, Quesnellia, and the North American margin were involved in west-vergent collision by ca. 175 Ma, probably centred on the latitude of southern British Columbia. The Insular terranes were beginning to impinge on the outer fringe of the Intermontane terranes at roughly the same time. Most likely, the two collisional events were related to each other. They also coincide with the initial opening of the Atlantic Ocean and the beginning of strong westward motion of the North American plate (May and Butler, 1987). Thus, accretion of the Insular and Intermontane terranes was not due to the serendipitous arrival of exotic crustal blocks, but rather to impingement of the western continent margin on its fringing elements.

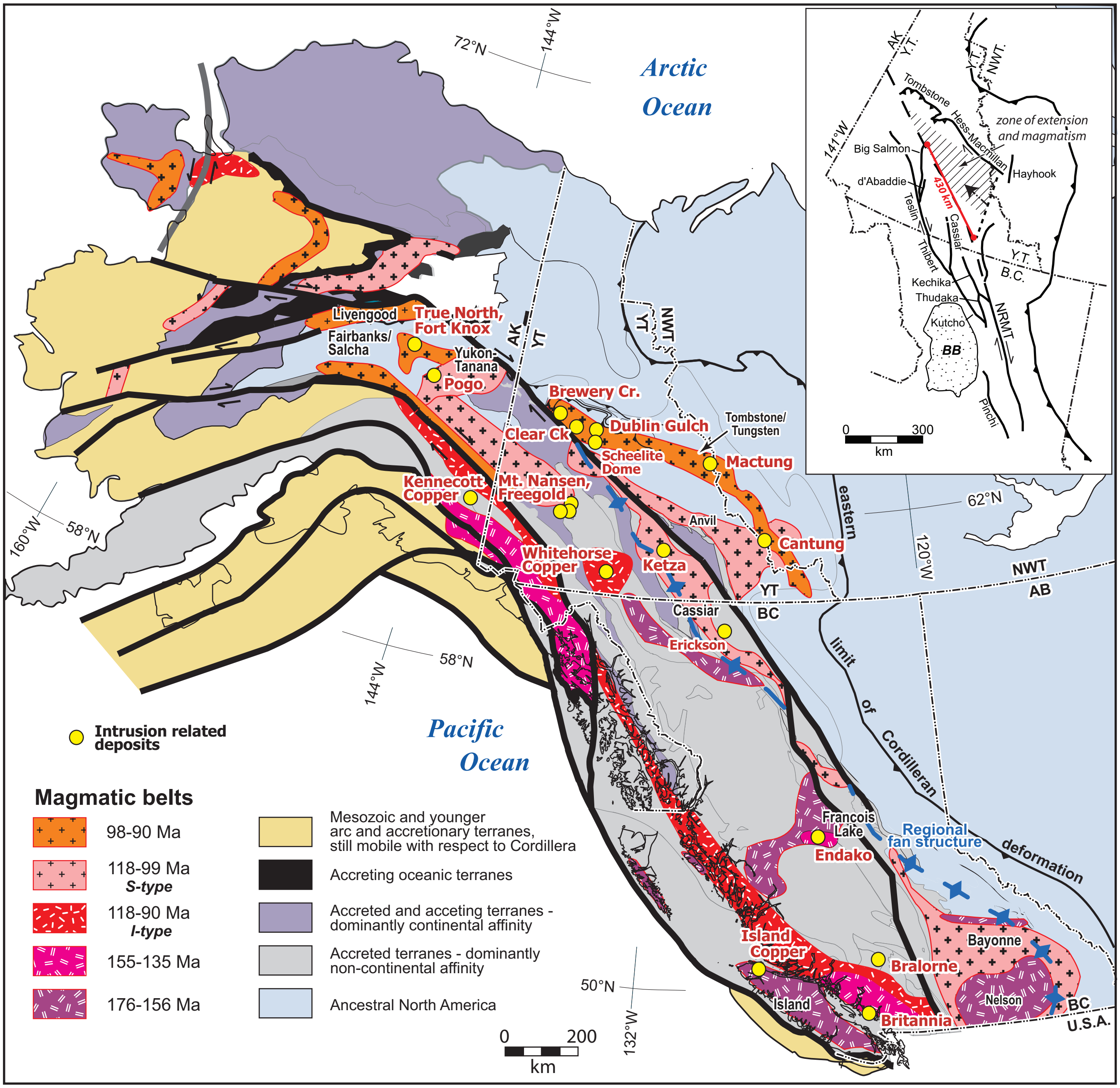

Figure 18. Middle Jurassic to mid-Cretaceous magmatism, tectonics and associated deposits. Deposit locations from Hart et al. (2002), Panteleyev (1991), Nokleberg et al. (1994), and BC MINFILE. Magmatic belts from Hart et al. (2004) and Massey et al. (2005). Inset shows relationship of Early Cretaceous transcurrent faults and inferred zone of extension and magmatism in northern B.C. and southern Yukon (after Gabrielse et al., 2006). Dextral strike-slip displacement along the Northern Rocky Mountain Trench (NRMT) and related faults is inferred to transfer into northwest-directed extension in southeast Yukon and compression along Tombstone thrust in western Yukon, when 430 km of displacement is restored along the Eocene Tintina fault (long dash). BB – Bowser basin.

Collision was accompanied by a strong incursion of magmatic activity across the newly accreted terranes and the continental margin. It is represented by the voluminous ca. 175 to 150 Ma Nelson plutonic suite in southern British Columbia. Intrusions of this suite were emplaced during and after development of west-vergent structures in the west flank of a regional fan structure (Murphy et al., 1995; Colpron et al., 1996; Gibson et al., 2005; Fig. 18), and show pronounced crustal influence in their isotopic character (Armstrong and Ghosh, 1990; Murphy et al., 1995). Mid-Jurassic plutonism is also prevalent in a belt that includes insular southeastern Alaska, Vancouver Island (Island plutonic suite, ca. 177-160 Ma; G. Nixon, pers. comm., 2006) and the Queen Charlotte Islands (Breitspreicher and Mortensen, 2004) of southern Wrangellia, and crosses the Insular/Intermontane suture into the central and southern Coast Plutonic Complex and the Skeena Arch of central Stikinia. This arc hosts the now-closed Island Copper mine near Port Hardy on Vancouver Island (Fig. 18; Appendix 1), a Cu-Mo porphyry deposit associated with a ca. 168 Ma body, one of the Island intrusions.

In a coeval but probably unrelated event, the Arctic Alaska and at least parts of the Ruby terrane subducted abortively under the Yukon-Koyukuk arc during Middle Jurassic to Early Cretaceous time. Earliest evidence is $^{40}Ar/^{39}Ar$ cooling ages of 169 to 163 Ma for granulites and peridotites structurally high within the oceanic Angayucham and Tozitna terranes (Wirth et al., 1993; Ghent et al., 2001), and north-vergent deformation in the Brooks Range accompanied by exhumation of blueschists in the hinterland at about 145 to 112 Ma (Moore et al., 2004). Rifting of roughly this age is shown by Jurassic failed-rift deposits overlain by an interpreted Early Cretaceous rift-drift unconformity in northern Arctic Alaska (Grantz et al., 1994). Detachment of Arctic Alaska/Chukotka from the Canadian Arctic Islands by initial opening of the Canada Basin has been linked to southward collision (Lane, 1992, 1997). It is proposed that these events were driven by slab-pull towards the Yukon-Koyukuk subduction zone and its continuation as the South Anyui suture in the Russian Far East (Lane, 1992). Toro et al. (2006) show that there was probably a change in subduction polarity, from southward along the Yukon-Koyukuk zone to northward, with a component of dextral transpression at the Chukotka/South Anyui boundary.

Post-Amalgamation, Cordilleran-Wide Tectonics, Arc Development, and Mineralization

The mid-Jurassic accretionary event fundamentally changed the nature of the emerging Canadian Cordillera from a set of loosely connected arc and pericratonic entities to a thickening transpressional/transtensional orogenic belt on which successor arcs would be built. The developing orogen would prove fertile ground for a variety of epigenetic deposits, with increasing influence of subjacent continental sources on contained metals (e.g. Mo, W), and increasing propensity for the concentration of precious metals. From Late Jurassic through Tertiary time, the combined allochthons impinged eastward as a tectonic wedge over the cratonal margin. Offscraped shelf and foreland sedimentary strata were incorporated into the wedge, while the denuded continental basement drove deep under the advancing allochthons, entering a zone in which widespread crustal melting could occur. Arc-axial igneous activity, as well as broader zones of crustal melting, contributed heat and fluids to the generation of ore deposits. Major types include Cu-Mo(-Au) and Mo porphyries, a variety of intrusion-related gold, silver-lead-zinc and tungsten deposits, and epithermal and mesothermal Au veins. There were four main metallogenetic events during this period: Late Jurassic-Early Cretaceous, mid-Cretaceous, Late Cretaceous, and Paleocene-Eocene (see Nokleberg et al., 2005). The unique character of each is probably related to changing subduction styles, rates, and geometries, as well as to temporal variations in stress regimes and heat transfer into the overlying plate.

Late Jurassic-Early Cretaceous (150-135 Ma)

This earliest post-accretionary magmatic episode represents a continuation of synaccretion (175-150 Ma) intrusion and volcanism, with which it is partly cospatial, although of more limited extent (Fig. 18). The notable deposit associated with this suite is the Endako molybdenite mine (Fig. 18, Appendix 1), for which ca. 144 Ma Re-Os dates on molybdenite coincide with U-Pb dates on the host Endako pluton, part of the Francois Lake suite (Selby and Creaser, 2001; see also Whalen et al., 2001). The orebody is a series of major east-striking veins oriented en echelon to form a zone of approximately 3360 m by 370 m, elongated in a northwesterly direction (British Columbia MINFILE). The veins contain molybdenite, pyrite, and magnetite, with minor chalcopyrite and traces of sphalerite, bornite, specularite, and scheelite. The mine has been in periodic production since 1965, producing over 43 million pounds of Mo concentrate from 309 million tons of ore milled.

Mid-Cretaceous (120 to 90 Ma)

The mid-Cretaceous saw very extensive plutonic activity in the Canadian Cordillera, with the beginning of development of the Coast Plutonic Complex as the prominent linear belt that it appears today, as well as more inboard intrusive belts and clusters, including the metallogenetically important Tombstone/Tungsten and Fairbanks suites (Fig. 18). This episode followed on a Cordilleran-wide magmatic hiatus (Armstong, 1988) that marked, among other changes, the extinction of magmatic activity in most of the Insular belt. With renewed igneous activity in the Coast Plutonic Complex, the region between it and the western plate margin became an essentially amagmatic arc-trench gap.

The mid-Cretaceous plutonic and volcanic rocks of the Coast Plutonic Complex and also the Kluane arc in Alaska (Nokleberg et al., 2005) are clearly the products of a magmatic arc, as shown by their unevolved isotopic character (Friedman and Armstrong, 1995) and linear distribution parallel to, and 100 to 150 km inboard of, the current plate margin. The more inboard plutonic belts were probably not directly related to slab melting. Many of the larger bodies are peraluminous to weakly metaluminous, ilmenite-series granitoids with evolved isotopic signatures; they are interpreted as melts that have interacted substantially with continental crust (Hart et al., 2004). They include the Cassiar suite, plutons in the Yukon-Tanana upland, the Ruby terrane, and an extensive set of plutons in southeastern British Columbia.

Clusters and belts of smaller and comparatively younger plutons tend to be of enhanced metallogenetic significance. The 94 to 90 Ma Fairbanks-Salcha plutonic suite is associated with a variety of intrusion-related Au deposits, including the 7 million ounce Fort Knox mine and the True North mine (Fig. 18; Appendix 1; Hart et al., 2004). Its eastern continuation across the Tintina fault, the 97 to 92 Ma Mayo-Tungsten suites, host Au mineralization at Dublin Gulch, Scheelite Dome, and Clear Creek, and world-class tungsten deposits, including Mactung (57 Mt of 0.95% WO_3) and Cantung (9 Mt of 1.4% WO_3). The ca. 92 Ma Livengood-Tombstone belt hosts the Brewery Creek gold deposit, as well as several Au skarns. These suites are of both ilmenite and magnetite series, and variably reduced.

Sumitomo and Teck Cominco‘s newly opened Pogo mine, which has reserves of 7.7 Mt at slightly less than 0.5 oz/ton Au (Szumigala and Hughes, 2005), is a 104 Ma mesothermal (orogenic-type) vein deposit that may or may not relate to the mid-Cretaceous plutonic event (Fig. 18; Appendix 1;

Hart et al., 2004). It is located near plutons of the Yukon-Tanana uplands suite, but a direct connection cannot be demonstrated. The mesothermal veins of the Erickson (Table Mountain) mine near Cassiar, British Columbia, have been related to fluid movement in the aureole of a buried mid-Cretaceous intrusive body (Nelson, 1990). Manto deposits in southern Yukon, such as Ketza River and Sa Dena Hes, are also distally related to subjacent Cretaceous intrusions.

The tectonic setting of the Canadian-Alaskan Cordillera during the mid-Cretaceous magmatic climax is complex, and shows a great degree of regional variability. In the southern Coast belt, a compressional, possibly sinistral transpressive event (Monger et al., 1994) closed the Bridge River Ocean and led to southwesterly vergent thrusting of the slightly older (ca. 114 Ma) Gambier arc and its contained Britannia VMS deposit (Lynch, 1991). The Bralorne mesothermal (orogenic-type) vein system developed at a late stage in this event, within a sinistral-reverse shear zone in the southeastern Coast Plutonic Complex (Leitch, 1990). In the Wrangell Mountains of southern Alaska, northeasterly vergent, compressional structures formed during a protracted event during and after accretion of the Peninsular terrane (150-100 Ma). The Kennecott copper deposits, the highest grade copper deposits ever mined, formed as stratabound bodies in the Triassic Chitistone limestone controlled by synorogenic structures (Price et al., 2006).

In the central Coast Plutonic Complex, thick-skinned, west-vergent deformation at ca. 90 to 85 Ma thickened the crust in a zone centred on the Insular/Intermontane tectonic contact (Stowell and Crawford, 2000). In the interior of northern British Columbia and southern Yukon, the ca. 110 Ma Cassiar batholith was emplaced along a synplutonic, northwesterly striking dextral fault. Across the Tintina fault, this motion transfers via a north-striking zone of extension and northwestwardly striking dextral strike-slip faults into the Tombstone strain zone and northwesterly vergent Tombstone and Robert Service thrusts (Murphy, 1997; Gabrielse et al., 2006; Fig. 18). In the Yukon-Tanana upland, in the presumed hinterland of these thrusts, the predominant mid-Cretaceous regime was of northwest-southeasterly extension in the previously-thickened orogen (Hansen and Dusel-Bacon, 1998). The somewhat younger Tombstone, Mayo, and Tungsten belt intrusions may have been lithospheric melts emplaced during a final stage of extension localized along basement structures (Mair et al., 2006).

Late Cretaceous (90 to 65 Ma)

Following the mid-Cretaceous, magmatic activity declined generally across the Cordillera, but with some important exceptions. Along the axis of the Coast Mountains, plutonism shifted northeasterly into the central gneiss belt (Fig. 19; Stowell and Crawford, 2000). In Alaska, Late Cretaceous volcanic-plutonic zones are located generally to the west of the mid-Cretaceous Fairbanks district. The ca. 75 to 67 Ma Kuskokwim district of southwestern Alaska is host to the Donlin Creek intrusion-related gold deposit, with its approximately 12 million ounce resource (Hart et al., 2002; Nokleberg et al., 2005). The gigantic (1 billion tonne plus) Pebble porphyry deposit is located farther southwest, on the Alaska Peninsula near Lake Iliamna (Fig. 19; Appendix 1). Mineralization there, which is hosted by a Late Cretaceous granodiorite body, has been dated at ca. 87 Ma (Schrader et al., 2001).

Elsewhere in the Cordillera, Late Cretaceous intrusions are sparser; although there are some significant deposits of this age. In southern Yukon, the Red Mountain (Boswell River) porphyry Mo deposit (Appendix 1) is contained within a Late Cretaceous quartz-monzonite stock associated with nearby 80 Ma volcanic rocks. The Casino porphyry Cu-Mo-Au deposit in the central Yukon is focused on a ca. 73 Ma complex of subvolcanic intrusions and intrusive breccias (Bower et al., 1995). The hypogene zone of this large but undeveloped deposit contains 445 Mt of 0.23% Cu, 0.024% Mo, and 0.27 g/t Au, and the supergene zone contains 86 Mt at 0.43% Cu, 0.031% Mo, and 0.41 g/t Au (Bower et al., 1995). The Adanac (Ruby Creek) near Atlin and Glacier Gulch near Smithers are both porphyry Mo deposits that focus on small ca. 70 Ma quartz-monzonite stocks, probably late-stage crustal melts. Current high Mo prices have created a new interest in these deposits, which are currently in mine permitting stage. In central British Columbia, the currently producing Huckleberry mine is associated with two small ca. 82 Ma porphyritic granodiorite stocks, part of the Bulkley intrusive suite (Fig. 19).

Paleocene-Eocene (65 to 37 Ma)

The Eocene was the last great metallogenetic epoch in the northern Cordillera. It was characterized by a sharp break from previous magmatic and tectonic patterns, although the influence of previous events can be identified. The most stable element remained the Coast Plutonic Complex. There, the axis of plutonism once again shifted east, but developed adjacent to the older Cretaceous belt of intrusions (Fig. 19). Vigorous volcanic and intrusive activity flared over a short time interval throughout southern British Columbia, from the Skeena arch south into eastern Washington and Idaho. In southern Stikinia, these rocks are termed the Ootsa Lake Group and in the southern Okanagan, the Kamloops and Princeton groups. Compositions are variable, with some tendency to mildly alkalic (shoshonitic); felsic units are abundant. Volcanism accompanied crustal extension and the exhumation of core complexes in the southern and central Omineca belt and southern Stikinia (Price and Carmichael, 1986; Struik, 1993). Sometime during this interval, the Tintina fault accommodated some 430 km of dextral motion, along with ca. 100 km of mostly Late Eocene motion on the Fraser fault. Dextral motion on the Denali fault also began. Overall, the tectonic framework for this interval is viewed as one of rapidly emerging, dextral transtension accompanied by extension and collapse of previously thickened crust, particularly in the southern Omineca belt. This tectonic and magmatic setting created a fertile environment for epithermal deposits, which concentrate within the volcanic fields and near transcurrent faults, and for porphyry Cu-Au-Mo and Mo deposits, which concentrate in the Skeena arch of central Stikinia.

The Skeena arch porphyry deposits are associated with small plutons of the Babine Igneous Suite that are very abundant in the area, in many cases localized along northwest- and northeast-striking faults (Carter et al., 1995; Wojdak and Stock, 1995). The belt contains two past producers, Bell and Granisle, with a total of 130 Mt milled (Carter et al., 1995),

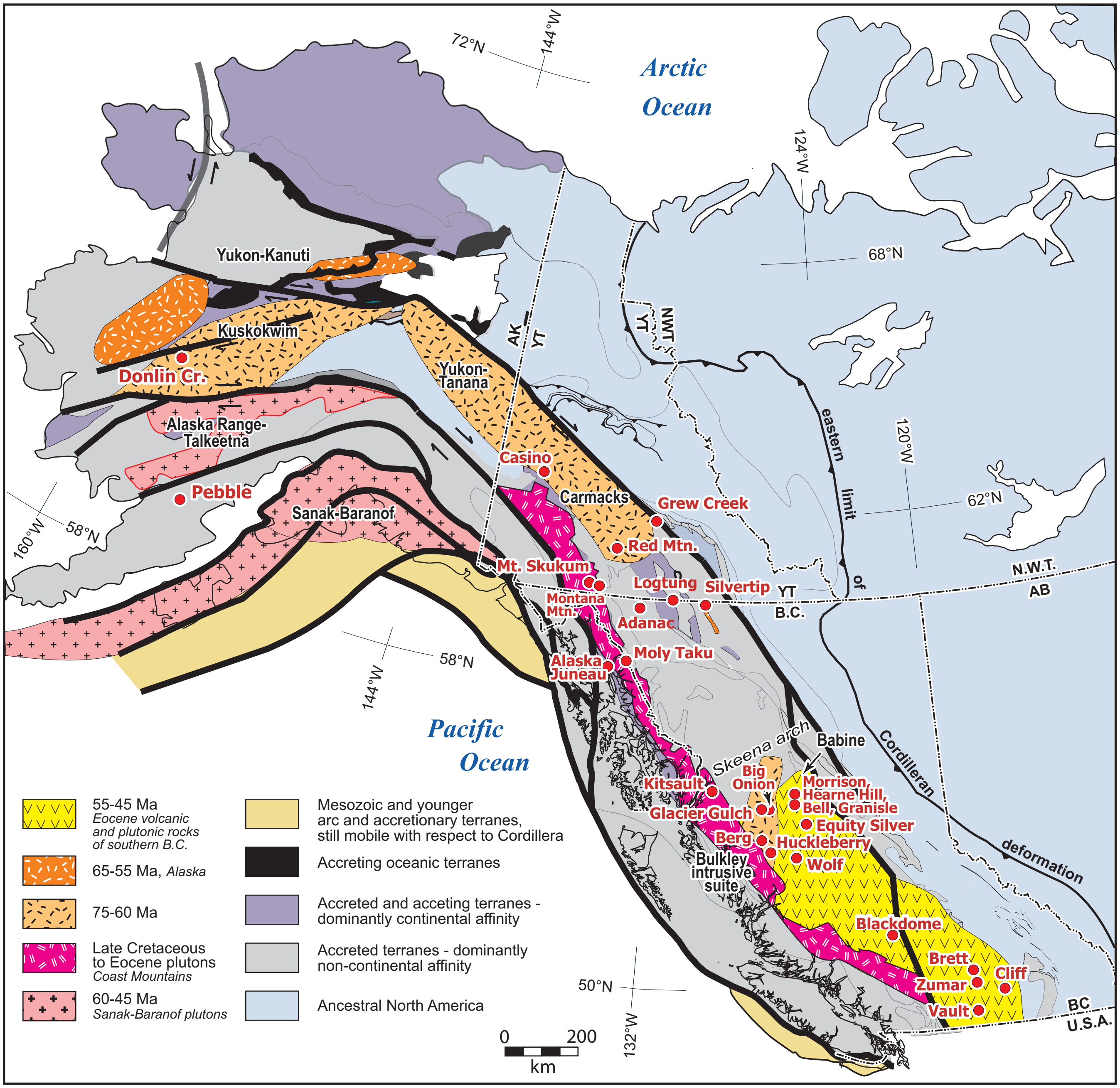

Figure 19. Late Cretaceous to Eocene magmatism, tectonics and associated deposits. Volcanic fields of Alaska from Moll-Stalcup (1994) and Hudson (1994). Volcanic fields in British Columbia from Massey et al. (2005). Deposit locations from Hart et al. (2002), Panteleyev (1991), Nokleberg et al. (1994), and BC MINFILE.

and significant resources at the Berg, Morrison/Hearne Hill, and Big Onion deposits (Fig. 19; Appendix 1). Late-stage basin-and-range-style block faulting is apparent in the Skeena arch, as shown by local, fault-controlled differences in erosion levels (Wojdak and Stock, 1995). These faults also controlled the emplacement of the porphyries, suggesting a genetic link. The Skeena arch marks an abrupt northern edge of the voluminous Eocene magmatic belt: it must have been a fundamental structural or thermal boundary in the upper mantle/lower crust.

The Kitsault porphyry molybdenite deposit, which was mined briefly in 1960 to 1972 and 1981 to 1983, is located farther north, on the eastern margin of the Coast Plutonic Complex. There are a few other molybdenite occurrences known in this eastern Eocene belt, such as Moly Taku in far northwestern British Columbia and showings in the Carpenter Creek pluton near Terrace. Given the large concentration of Eocene plutons in the eastern Coast Plutonic Complex, it is surprising that more substantial molybdenum resources have not been found. The Logtung porphyry/skarn W-Mo deposit, located on the British Columbia-Yukon border, has been dated at ca. 58 Ma by U-Pb methods on zircon considered to be of hydrothermal origin (Mihalynuk and Heaman, 2002).

Eocene Au-Ag epithermal deposits are distributed widely but sparsely in the volcanic-rich areas of the Okanagan and southern Stikinia. A few have been mined, such as Blackdome, which is associated with Eocene volcanic rocks near the Fraser fault, and the deposits of the Republic graben in Washington State south of the British Columbia border. Grew Creek, which lies adjacent to the Tintina fault in central Yukon, is a low-sulphidation vein system hosted by Eocene volcanic rocks. Mt. Skukum, a past producer, is a set of epithermal quartz veins in an isolated volcanic centre near the British Columbia-Yukon border. There are a number of developed prospects in the Okanagan, notably the Brett, Zumar, Cliff, and Vault. Exploration in the Nechako Plateau of southern Stikinia has borne less fruit so far. The Wolf property is a swarm of low-sulphidation veins with reported values in one trench of 8.49 g/t Au and 42.21 g/t Ag over 7.5 metres. The Trout comprises patches and veins of chalcedonic quartz with erratic Au and Ag values. In this area, extensive Miocene basalt flows and Quaternary deposits thwart prospecting and the quartz-vein targets do not have pronounced geophysical signatures. Airborne remote sensing and multi-element surveys may be of aid.

In southeastern Alaska, auriferous mesothermal veins of the Juneau gold belt were emplaced along and near reactivated older contractional structures, the Sumdum and Fanshaw faults, at ca. 57 to 53 Ma (Miller et al., 2000). This corresponds to a time of rapid exhumation in the Coast Plutonic Complex, and it is proposed that metamorphic fluids were channelled upwards along the faults (Miller et al., 2000). The Juneau gold belt extends over 300 km in strike length, and has produced over 200 million grams of gold (Nokleberg et al., 1995).

Late Eocene to Present (<37 Ma)

In the Canadian Cordillera, the broad, intense magmatic belts of the Eocene dwindled by 45 Ma and were extinct by 40 Ma. In particular, the Coast Plutonic Complex, which had been an axis of arc activity for over 60 m.y., abruptly shut off, probably because subduction ceased off the west coast of Canada. This part of the plate margin is now the locus of the dextral transcurrent Queen Charlotte fault (Fig. 20). Within the North American plate, the main locus of dextral motion shifted outboard from the Tintina to the Denali fault. The main volcanic arcs shifted to the Aleutian arc of western Alaska and adjoining islands, and south into the Cascades of Washington and Oregon (Fig. 20; see also Nokleberg et al., 2005). This overall pattern would endure throughout the Cenozoic, sustained by easterly subduction of the Juan de Fuca plate and northerly subduction of the Pacific plate. Catface on western Vancouver Island (Fig. 20; Appendix 1) is an anomalously young late Eocene Cu-Mo porphyry deposit, associated with one of a belt of small, ca. 37 Ma plutons (Madsen et al., 2003). Although the setting of Catface has been interpreted as a fore-arc, by the time of its emplacement the ca. 50 Ma arc to the east was extinguished. Alternatively, it could represent the northern tip of the newly established Cascade arc.

Quartz Hill, near Ketchikan in southeastern Alaska (Fig. 20; Appendix 1), is a low-fluorine-type porphyry Mo deposit with one of the world's largest reserves of molybdenum, 1.7 billion tonnes at 0.136% MoS_2 (Nokleberg et al., 1994, 2005). It is associated with a small, high-level, granite-latite-quartz-feldspar porphyry stock, ca. 27 Ma, emplaced into upper-amphibolite-grade metamorphic rocks. This late-stage, post-orogenic body seemingly reaped the rewards of a long process of prior crustal thickening and melting in the Coast Plutonic Complex. By contrast, the earlier voluminous Cretaceous intrusions of the Coast Plutonic Complex tend to be relatively barren, perhaps because they are too deeply eroded.

The Cinola (Spegogna) vein system on eastern Graham Island (Haida G'wai; Fig. 20; Appendix 1) is a large hot-spring-type, low-sulphidation epithermal deposit related to active Miocene displacement on the Sandspit fault. Mineable reserves estimated to June, 1997 are 33.5 Mt grading 2.11 g/t Au at a cutoff grade of 1.20 g/t Au (British Columbia MINFILE). It is the youngest known deposit with significant reserves in the Canadian Cordillera and, significantly, it formed in conjunction with the transcurrent, post-subduction fault regime that now prevails there. Yet more recent seafloor massive sulphide deposits can be found at hydrothermal vents located along the axis of the Juan de Fuca ridge offshore.

By contrast with the now metallogenetically sleepy south, the Cenozoic to Recent Aleutian arc is host to a variety of epithermal and polymetallic vein and porphyry Cu and Mo deposits over an 800 km long belt (Nokleberg et al., 1994, 2005), associated with Tertiary and Quaternary volcanic centres and their hypabyssal roots. A suite of large, low-grade porphyry Cu-Mo deposits occupies the transitional zone, where the young Aleutian arc onlaps from oceanic substrate to the older rocks of the Peninsular terrane (Nokleberg et al., 1994, 2005). The most significant of these is the Pyramid deposit, with 113 Mt of 0.4% Cu and 0.05% Mo (Fig. 20; Appendix 1). Their occurrence points to the importance of previously constructed and thickened arc crust to the genesis of deposits of this type, as was the case with the Triassic-Jurassic porphyries of the Canadian Cordillera.

Discussion: Mechanisms and Models

The history of mineralization in the Canadian-Alaskan Cordillera is very long, spanning over 1.6 billion years, from Mesoproterozoic to the present time. The earliest events – the deep-water, rift-related hydrothermal system that gave rise to Sullivan, and the enigmatic Wernecke breccias – took place in intracontinental settings at unspecified distances from their margins, at a time when plate tectonics in the current sense may not have operated (Stern, 2004). The main tectonic and metallogenetic development of the Cordillera dates from the breakup of the Rodinia supercontinent in late Neoproterozoic to Early Cambrian time. This is particularly true of the western continental margin and the peri-Laurentian terranes, but arc and rift development in the Arctic and Insular terranes also dates to this time. The Paleozoic might be called "the age of syngenetic sulphides", in the sense that VMS deposits associated with rifting arcs and SEDEX deposits associated with rifting continental margins, characterize this phase of tectonic history. In particular, both peri-Laurentian and exotic pericratonic terranes of the Cordillera contain deposits that are part of a worldwide peak in syngenetic sulphide formation and preservation during Devonian-Mississippian time, probably because of dual factors of rift-related tectonics and ocean anoxia (Goodfellow, 2007). Following a weak period (Pennsylvanian to mid-

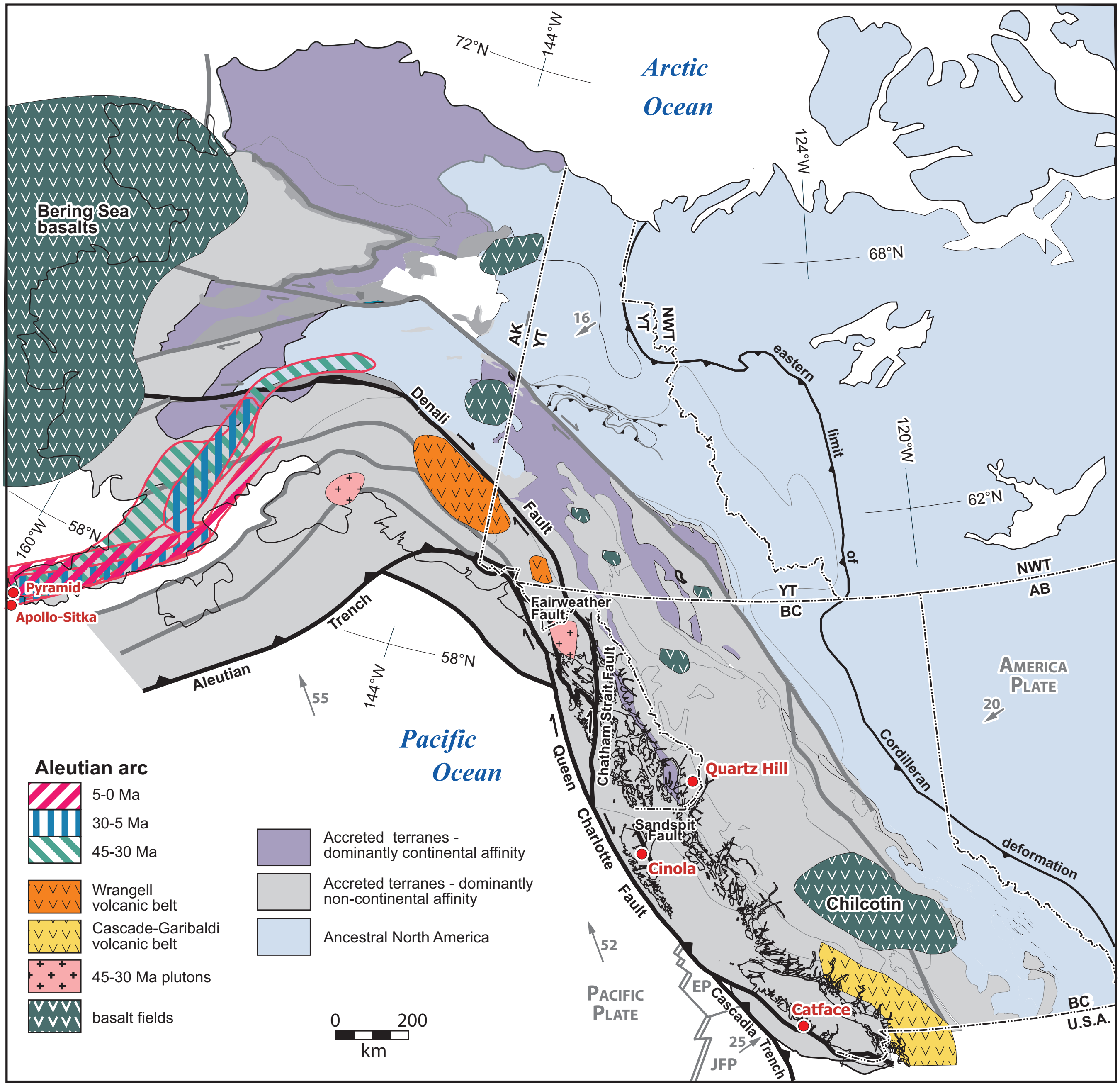

FIGURE 20. Oligocene to present tectonics and deposits. Volcanic fields of Alaska from Moll-Stalcup (1994). Modern plate configuration and relative motions (vs. fixed hotspot reference; in mm/a) from Riddihough and Hyndman (1991). EP – Explorer plate; JFP – Juan de Fuca plate.

Triassic) in the generation of syngenetic deposits, a new compressional and accretionary tectonic regime led to what could be called "the age of porphyries", which became the premier style of large Cordilleran deposit beginning in Late Triassic time in the pericratonic Intermontane arcs – a trend that would continue through the formation of the giant Pebble deposit within a successor arc during Late Cretaceous time, and only diminished as subduction faltered at the end of Eocene.

Overall, the history of the northern Cordillera depicts the dominance of extension-related tectonics throughout the Paleozoic, followed by increasingly compression-dominated tectonics from the Late Triassic through the Paleocene, with a brief episode of crustal transtension in the southern Canadian Cordillera in the Late Paleocene-Eocene. Monger and Price (2002) have related this fundamental evolution in tectonic style to a change from an offshore arc system dominated by slab rollback, to one in which the overriding North American plate advanced towards its subduction zone as the Atlantic Ocean opened. The initial propagation of magmatic arcs along the western margin of Laurentia (ca. 400-360 Ma) coincided with the final closing of Iapetus. Their rapid subsequent detachment (ca. 360-345 Ma) was probably due to slab rollback, in a process comparable to the Miocene to present opening of the Japan Sea, with concurrent formation of the Kuroko and younger VMS deposits in extending arc and back-arc settings. The Middle Jurassic and younger crustal thickening event that incorporated pericratonic blocks, arcs and accretionary prisms as well as the continental margin itself, was coeval with the opening of the Atlantic Ocean. Thus, a megacycle driven by major changes in continental plate motion can account for the broadest aspects of Cordilleran tectonic history.

Some phases are less clearly related to global-scale plate motions. The initial Permo-Triassic impingement of offshore arcs against North America – the margin-long Sonoman Orogeny – occurred some 70 m.y. before the initial opening of the Atlantic. Did Pangaea as a whole begin to track westwards prior to its breakup? Following this collisional event, new Late Triassic Intermontane arcs seem to have stepped seaward, perhaps due to renewal of slab rollback. At the same time, extension and widespread intraplate basaltic activity prevailed in the Insular terranes. Perhaps these crustal blocks then lay in a back-arc region, along with the Arctic terranes and the rest of the post-Sonoman continental margin. By Early Jurassic time, arcs were reestablished in the Insular terranes (Bonanza, Talkeetna), signifying that probably by then they were part of the circum-Pacific arc system, along with the Hazelton and Takla arcs.

Conclusions

There never was a truly "passive" western margin of Laurentia/North America. It was actively rifting and metallogenetically alive throughout early Paleozoic time. From Late Devonian through Early Jurassic, the seemingly passive miogeocline was protected from the effects of continent-ocean interactions by a moving wall of partly pericratonic island arcs. The large-scale cycle that we observe in the Cordillera, from Paleozoic extensional tectonics to Mesozoic-Paleogene accretion and compression, was largely caused by changes in relative motion of the North American plate with respect to its western subduction zone. The gross aspects of this cycle are clearly reflected in metallogenetic patterns, from the dominance of Paleozoic rift-related syngenetic sulphide deposits, through Cu-Au porphyries in early Mesozoic time, to porphyries and precious metal deposits with increasing continental influence as amalgamation and crustal thickening progressed in Cretaceous and later time. Overall, the duration and complexity of northern Cordilleran tectonics have led to a rich and varied endowment of metallic mineral deposits. Spectacular recent exploration successes such as Pogo (the Cordillera's newest mine at time of writing), Eskay Creek, and Pebble show that the mineral potential of this region is far from a closed book, and that the deposits we know now are also an intimation of future discoveries.

For More Information

Cordilleran study in Canada is vastly aided by excellent modern geological and tectonic assemblage compilations: Canadian Cordillera (Wheeler and McFeely, 1991); Yukon (Gordey and Makepeace, 2001); British Columbia (Massey et al., 2005); and a recent update for the pericratonic terranes of Yukon and northern British Columbia (Colpron, 2006). Large-scale geological and tectonic assemblage maps for Alaska include Silbering et al. (1994) and Nokleberg et al. (1997); a GIS compilation is available for northern Alaska and surrounding areas (Klemperer et al., 2002).

This short synthesis can serve as an introduction to more extensive and detailed metallogenetic/ tectonic syntheses such as that of the Canadian Cordillera by Dawson et al. (1991), and the Canadian-Alaskan Cordillera and Russian Far East of Nokleberg et al. (2005). The interested explorationist is also pointed to online databases in British Columbia and Yukon MINFILE, and the British Columbia mineral deposit profiles (Lefebure, 2005). MAPPLACE (www.em.gov.bc.ca/mining/Geolsurv/MapPlace/) and MapGallery (www.geology.gov.yk.ca/gallery/index.html) are integrated, online GIS-based map data systems for British Columbia and Yukon, respectively, that offer easy integration of spatial data sets, such as geological maps, geophysical and geochemical surveys, and mineral deposit information, in the MINFILE databases.

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