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Metallogenic provinces of North America in a superplume-supercontinent framework

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ABSTRACT

Metallogenic provinces are the product of the interplay of plume and plate tectonics within the larger framework of the supercontinent cycle, and preservation potential. Prior to assembly of the first supercontinent Kenorland at ~2.7 Ga, via accretionary orogens, a Cu-Zn-Pb VMS province, including the Kidd Creek deposit, formed in the Abitibi intraoceanic back-arc. During accretion, a cumulative 5000 tonnes Au were deposited along and adjacent to the terrane-bounding fault zones. Preservation of these North American Late Archean deposits stems from the ~250-km-thick refractory continental mantle lithosphere (CLM). A second supercontinent, Columbia, was amalgamated at ~1.8 Ga by continent-continent collision. The Athabascan region is a foreland basin to one such orogen, the Trans-Hudson, where unconformity uranium deposits developed proximal to unconformities. Major plume events at ~1.9 Ga and 1.1 Ga induced norite melts in the CLM, which host magmatic Ni-Cu deposits such as Sudbury, Muskox, and Duluth. During rifting of Columbia in the Mesoproterozoic, IOCG±REE deposits were associated with A-type granites and the Sullivan Pb-Zn deposit was associated with a sill-sediment complex.

Amalgamation of Pangea included middle to late Paleozoic formation of MVT deposits in extensional domains of the North American mid-continent orogenic foreland basin and small orogenic gold deposits along accretionary terrane boundaries to the east of the craton margin. Late Paleozoic to Middle Jurassic Pacific margin SEDEX, VMS, and pre-accretionary porphyry deposits formed in the platform/shelf environment of the passive margin or in oceanic arcs and continental fragments in the Pacific basin. Jurassic onset of Cordilleran orogenesis, a function of North America-Pacific/Farallon/Kula plate interaction, led to a period between 185-50 Ma of widespread orogenic gold

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and porphyry formation within the active continental margin. Laramide subduction of the Juan de Fuca plate beneath western North American continental crust generated magmatism and formation of porphyry deposits and related epithermal systems. Eocene continental back-arc extension reopened favorably oriented older structures that facilitated formation of Carlin-type gold deposits and youngest epithermal deposits.

INTRODUCTION AND SCOPE

The secular distribution of metallogenic provinces can be understood in the framework of interactions of the supercontinent cycle, superplume time series, and evolving continental lithospheric mantle (CLM). There have been four supercontinents in Earth history (Table 1), and probably six to eight superplume events (Islay and Abbott, 1999; Condie et al., 2001; Rogers and Santosh, 2004; Bleeker and Ernst, 2006). The CLM has decreased in thickness from ~250 km under Archean crust to ~150 km under Phanerozoic crust, and concurrently became progressively more dense, but less refractory. Accordingly, Archean cratons are well-preserved given thick, buoyant, refractory CLM (Artemieva and Mooney, 2001).

Relevant also is the type of orogenic belt. Orogens have been classified into accretionary and continent-continent collision types. For example, the former are highly prospective for orogenic gold, whereas foreland basins of the latter are prospective for unconformity uranium, and Mississippi Valley-type Pb-Zn deposits are located in foreland basins of both types of orogen. Accretionary orogens, such as the North American Cordillera, involve amalgamation of numerous allochthonous terranes across multiple sutures to an older continental margin, general migration of the magmatic arc oceanward through the subduction-accretion process, and closure of any trapped ocean basins. Continent-continent orogens, exemplified by the Alpine-Himalayan belt, involve collision of two or more continents across a single suture, relatively minor arc magmatism, involvement of passive margin sedimentary rocks in the foreland, and closure of an internal ocean, such as the Tethys or the Mediterranean (Tables 1, 2; Barley and Groves, 1992; Sengor and Natal'in, 1996; Kerrich et al., 2000, 2005; Goldfarb et al., 2001; Groves et al., 2005). There is a broad consensus that plate tectonics was operating by 2.7 Ga (Kerrich and Polat, 2006), and perhaps even much earlier (e.g., O'Neil et al., 2008).

In this review, we synthesize major metallogenic provinces of North America relative to a geodynamic - heat flow - lithosphere framework. We do not attempt a comprehensive coverage of all major deposits in North America, but attempt to show how major metallic mineral deposit types relate to overall geodynamic evolution. In doing such, we also sometimes include select complementary examples from other continents.

LATE ARCHEAN KENORLAND

The first supercontinent, Kenorland (e.g., Rogers and Santosh, 2004), was assembled at ~2.7 Ga from diverse terranes aged ~4.0 to 2.7 Ga. Assembly was preceded by the 2.7 Ga superplume, represented by komatiite-basalt ocean-plateau sequences on all cratons, and dispersal 300 m.y. later was coeval with the subsequent 2.4 Ga Matachewan-Fortesque superplume. Assembly was by a series of transpressional accretionary orogens as evidenced by multiple sutures within the 3 million km^2 Superior Province of central Canada, as well as by accretionary suture counterparts in the Dharwar, Baltic, Kaapvaal, and Yilgarn cratons (Kerrich et al., 2005; Naqvi, 2005; Percival et al., 2006).

2.7 Ga plume - continental lithosphere interaction

In areas where komatiites from the 2.7 Ga superplume erupted through continental lithosphere, sulfur-saturation was induced by assimilation of high-silica crust and/or sulfur-rich sedimentary rocks. Sulfide minerals equilibrated with multiple

Table 1. Synthesis of accretionary and continent-continent orogenic belts

Accretionary Orogens:			***Continent-Continent Orogens:***		
Orogen	Location	Age	Orogen	Location	Age
Isua greenstone belt	W. Greenland	3.8 Ga			
Kenoran	Superior Province	2.7 Ga	Trans-Hudson	S. Dakota, Saskatchewan	1.7 Ga
Yilgarn	W. Australia	2.7 Ga	Barramundi	N Australia	1.9 Ga
Altaids	C. Asia	700-500 Ma	Grenville	E. Canada Fennoscandia	~1.2 Ga
Tasman	E. Australia	<500 Ma	Appalachian-Caledonian	N. America-Scandinavia	<500 Ma
Nipponides Cordillera	E. Asia N. America	<240 Ma <200 Ma	Alpine-Himalayan	Europe-Asia	<200 Ma

Sources: Sengör and Natal'in (1996, 2004)

Table 2. Comparison of the accretionary Altaid-Cordilleran and collisional Alpine-Himalayan type orogens*

Altaid-Cordilleran orogeny	***Alpine-Himalayan orogeny***
Accretion of allochthonous juvenile oceanic island arcs, fore-arcs, and continental blocks	Continent-continent collision, presence of giant ophiolite nappes between two continents
Closure of external ocean	Closure of internal ocean, such as Tethys
Multiple sutures, ophiolites (e.g., ensimatic arc basement, fore-arc), numerous ophiolitic fragments (ophifrags) in the accretionary prism	Long, narrow single suture zone with more or less complete ophiolite nappe emplaced onto passive continental margins (e.g., Oman, Kizildag)
Subduction-accretion complex	Deformed passive margin sedimentary rocks
Multiple deformation of subduction-accretion complex, large degree of structural shuffling by thrusting and strike-slip faulting	Reworking of pre-existing crust
Magmatic arc migrates through subduction-accretion complex	Subdued magmatism
Heat advected by magmas	Internal radiogenic heat production
Subduction-erosion of lithospheric mantle	Delamination of thickened lithospheric mantle
Highly prospective for orogenic gold	Low prospectivity for orogenic gold, prospective for MVT
Prospective for porphyry Cu-Mo and magmatic Sn-W	Prospective for porphyry Cu-Mo and magmatic Sn-W

*Data sources are from Sengör & Natal'in (1996, 2004).

pulses of magma in lava channels, where Ni, Cu, and minor PGE partitioned into sulfide phases in an open system. Examples include the Dundonald deposit at Timmins (Superior Province) and deposits at Kambalda (Yilgarn craton). There are also smaller, plume-related, mafic intrusion-hosted deposits in central Canada and elsewhere (Table 3; Naldrett, 1989; Lesher and Keays, 2002; Arndt et al., 2005).

2.7 Ga oceanic arc to back-arc settings

Volcanism in the Superior Province occurred from 3.1 to 2.7 Ga, yet volcanic-rock-hosted base metal (Cu-Zn-Pb) VMS deposits are restricted to the period 2720-2700 Ma. Major VMS provinces are present at Kidd Creek, Noranda, and Mattagami (Table 3; Franklin et al., 2005). It is likely that the 2.7 Ga superplume rearranged plate geometry, perhaps inducing oceanic back-arc rifting, which is intrinsically favorable for VMS deposit generation and ocean-crust obduction, as was the case for the better documented Cretaceous superplume event (Larson, 1991; Barley et al., 1998; Wyman et al., 1999a). The giant Kidd Creek deposit is the best-preserved Archean example of a VMS deposit in a magmatic-arc sequence with coeval eruption of plume lavas (Wyman et al., 1999b). In contrast to these North American examples, the greenstone terranes of this age on the Yilgarn and Dharwar cratons do not have VMS deposits, possibly because they erupted mostly through continental lithosphere (Table 3).

Relatively thin banded-iron formations (BIFs), the so-called Algoman-type BIFs, are prominent in greenstone belts that host VMS deposits, possibly because those also include plume lavas (Kerrich et al., 2005). The BIFs were precipitated during periods of volcanic quiescence and from warm seawater discharge. Carbonaceous horizons are present in units containing both VMS and Algoman BIFs.

2.7 Ga accretionary orogens

Orogenic gold deposits are located in sutures of ~2.7 Ga accretionary orogens associated with the assembly of the North American part of Kenorland. The largest are in the Superior Province, including the gold provinces of Red Lake, Timmins, Kirkland Lake, and Val d'Or, with a cumulative production >5000 tonnes Au. The deposits formed from metamorphic-hydrothermal fluids that were generated as subcreted, hydrated juvenile crust was heated during terminal transpressive accretion (McCuaig and Kerrich, 1998). Global counterparts in sutures of other accretionary orogens of the same age with significant gold provinces are those of the Fennoscandian, Dharwar, Kaapvaal, and Yilgarn cratons (Table 3; Goldfarb et al., 2001, 2005). The distribution of globally contemporaneous orogenic gold provinces favors a Kenorland supercontinent configuration, rather than the distinct Sclavia and Vaalbara cratonic reconstructions (Table 3; Bleeker, 2003).

2.4 Ga plume-Kenorland dispersal

Numerous BIFs were located on the passive margins of Kenorland during supercontinent break-up. The conjunction of factors leading to their generation was the presence of the first extensive belt of passive margins, which were stabilized by Archean CLM; the 2.4 Ga superplume that generated continental flood basalts, such as those of the Fortesque Group; and likely volcanic plateaus in ocean basins (Table 3). Reduced ocean bottom waters cooled the submarine lava fields, dissolving Fe^{2+} and Si, which were precipitated in oxygenated waters of continental shelves.

Well-preserved 2.4-2.2 Ga passive-margin sequences are present in the Huronian Supergroup of the southern Superior Province, which was formerly contiguous over >2000

Table 3. Synthesis of key geodynamic and superplume (LIP) events with suggested linkages to large metallogenic provinces

SUPER-CONTINENT	Craton or Block	Assembly	Ores Associated with LIP/Superplumes	Oceanic arc/backarc ores (distal to orogen core)	Orogen	Ores of Accretionary Orogen	Foreland Basin and Ores	Intracont. Rift-related Ores	Passive Margin Ores	Dispersal
KENORLAND	Superior Province	~2.7 Ga	Dundonald Ni (Timmins)	Kidd Creek VMS Noranda VMS Algoman BIFs	Kenoran	Timmins Au Kirkland Lake Au Val d'Or Au Red Lake Au		Cobalt Ag-Co-Ni (Huronian)	BIFs	~2.4 Ga
	Yilgarn	~2.7 Ga	Kambalda Ni			Kalgoorlie Au, Boddington Au porphyry				
	Kaapvaal	3.7-2.7 Ga				Witwatersrand Au source?	Witwatersrand paleoplacer Au		BIFs	~2.4 Ga
	Dharwar	~2.7 Ga				Kolar Au Porphyry Cu-Mo				
COLUMBIA	Laurentia	~2.0-1.8 Ga	Sudbury Ni-Cu Anorogenic Fe-Ti-V-P	Flin Flon VMS Jerome VMS	Trans Hudson CC	Homestake Au Flin Flon Au	Athabasca unconformity U	Sullivan SEDEX Missouri IOCG	Lake Superior and Labrador BIFs Minnesota phosphorites	~1.4 Ga
	Baltica - Siberia	~2.0-1.8 Ga	Anorogenic Fe-Ti-V-P	Boliden VMS					Krivoy Rog BIF	
	W Africa - Sao Francisco	2.1 Ga			Birimian	Ashanti Au	Eburnean			
	Australia	~2 Ga ~1.8 Ga			Barramundi		McArthur River unconformity U	Olympic Dam IOCG Mt Isa SEDEX Broken Hill-type		~1.6 Ga
RODINIA	E. Laurentia	~1.3-1.1 Ga	Voisy Bay Ni-Cu-Co Muskox Ni-Cu Duluth Ni-Cu		Grenville			Rapitran-type BIFs		~700 Ma
PANGEA	Laurasia	500-250 Ma	Norilsk Ni Diamond	Bathurst VMS Bay of Islands VMS Norwegian VMS West Shasta VMS Central Asia Cu-Au porphyries	Alleghenian, Ouachita, Marathon, Acadian, Caledonian, Hercynian, Altaids	Central Asia Au East Tennessee East Kemptville & Grey	Mid-Continent MVT Pb-Zn Appalachian MVT Pb-Zn		NW Laurentia SEDEX (Selwyn Basin, W. Brooks Range) & VMS (Ambler, Finlayson Lake, Tulsequah Chief) NW USA phosphorites	250 Ma-present
NEW	Gondwana	700-250 Ma			Terra Australis, Pan African	Victoria Au				
		200 Ma to ???	Diamonds (~120 Ma superplume)	Windy Craggy VMS Greens Creek VMS B.C pophyry Cu-Mo-Au Eskay Creek epithermal Carlin Au Nevada epithermal Au Bingham porphyry Cripple Creek epithermal Mexico epithermal Ag	Cordilleran, Laramide, Andean, Eastern Russia, Yanshanian, Alpine, Himalayan	Arizona Porphyr Cu Pine Point MVT & Kennecott Cu-Ag Pebble Cu-Au Fairbanks gold Mother Lode Au Coeur d'Alene Veins				

km with the Snowy Pass Supergroup of the Wyoming craton. Preserved units include continental siliciclastic sedimentary rocks, glacial diamictite, BIF, phosphorites, and carbonaceous shales (Table 3; Bekker et al., 2003; Long, 2004).

PALEOPROTEROZOIC COLUMBIA

About 500 m.y. after the breakup of Kenorland, a superplume at ~2.0-1.9 Ga preceded assembly of the second supercontinent, Columbia, at ~1.8 Ga (Condie et al., 2001). Columbia was assembled first by closure of internal oceans, expressed as oceanic arc complexes, and then stitched by continent-continent type orogens (Table 1; Fig. 1). The Archean-Proterozoic transition was diachronous and marked by: (1) preservation of 2.4 Ga passive margin sequences of Kenorland; (2) decreased thermal gradients at convergent margins recorded in a transition from slab melting tonalite-trondhjenite-granodiorite (TTG) to continental margin arc slab dehydration-wedge melting basalt-andesite-dacite-rhyolite (BADR) magma series; and (3) decreased Mg# of mantle plume basalts and, therefore, thinner, less refractory CLM that was more prone to reactivation (Taylor and McLennan, 1995; Drummond et al., 1996; Richards and Kerrich, 2007). Dispersal of Columbia at ~1.6-1.3 Ga was likely diachronous, the younger age corresponding to a superplume (Zhao et al., 2004; Vigneresse, 2005), and break-up likely overlapping with formation of Rodinia, the next supercontinent.

1.9 Ga superplume: BIF, phosphorites, hydrocarbons, and magmatic Ni

Several types of ore deposits are associated with this mantle plume-lithosphere interaction. On the circum-Superior Province cratonic passive margin, extensive BIFs were formed, notably in the Lake Superior region and Labrador trough. These were coeval with those on the Siberian craton passive margin that include the Krivoy Rog BIF. Phosphorite deposits, with significant amounts of uranium, are present in the 1.95-1.85 Marquette Range Supergroup, Minnesota, a passive margin sequence of the ~2.0 Ga Penokean orogen (Windley, 1995).

The oldest preserved oilfield occurs in a thick succession of 2.0 Ga siliciclastic and volcanic rocks along a rifted passive margin of Kenorland in northwestern Russia. The estimated carbon reserve is 25 x 10^{10} tonnes, which is present as shungite and carbonaceous shales (Melezhik et al., 2004). In North America, a metamorphosed oilfield is also present in a 2.2-1.9 Ga sedimentary rock sequence on the Superior craton passive margin (Mancuso et al., 1989). Most large mantle plume events have associated BIF and hydrocarbon deposits stemming from the biosphere sequestering greenhouse gases degassed from the plume (cf. Larson, 1991).

Ultramafic and mafic rock-hosted nickel deposits are also located on the craton margins, including those of the Thompson belt and the 1.8 Ga Sudbury deposits, central Canada. Host rocks to Sudbury include extensive norites that are not primary plume melts; rather, the Sudbury Intrusive Complex may be the net result of melting of metasomatized peridotite of the CLM by some combination of impact and associated asthenospheric decompressional melting. Mantle plumes cannot melt in the asthenosphere at pressures corresponding to CLM depths of 250 km. It seems plumes are "steered" to thinner CLM at craton margins at depths that record onset of melting, and nickel deposits form by crustal contamination of ultramafic-mafic melts or mixtures of melts having differing silica activities, accounting for the circum-Superior distribution of magmatic nickel deposits (Table 3; Lesher and Keays, 2002.).

~1.7 Ga oceanic arc to back-arc settings

Arc, or back-arc, sequences, reflecting assembly of Columbia, include significant base metal-rich VMS provinces. The largest and best preserved in North America are Jerome in the 1.8-1.69 Ga Yavapai Province of Arizona and Flin Flon in the Amisk Group of Manitoba. Globally correlative examples include Boliden of the Skellefte district in central Sweden, and Otukampu, Finland (Windley, 1995, Table 16.1).

Paleoproterozoic orogens and ~1.8-1.7 Ga foreland basins

Paleoproterozoic orogens that stitched Columbia together were dominantly of the continent-continent type. However, sectors of those orogens had subduction-accretion characteristics and these contain orogenic gold deposits. The largest deposits are the 1.7 Ga Homestake gold deposit (1,100 tonnes Au) in the South Dakota sector of the Trans-Hudson orogen, deposits of the 2.1 Ga Birimian orogen of West Africa, and equivalent orogenic gold deposits in the Sao Francisco craton of Brazil (Goldfarb et al., 2001).

Foreland basins developed inboard of the continent-continent orogens that stitched Columbia together (Table 3). Unconformity-type uranium deposits developed in siliciclastic sequences, proximal to unconformities of the Athabasca Supergroup, a foreland basin to the Trans-Hudson orogen. Equivalent basins are McArthur River in the foreland of the Barrimundi orogen in Australia's Northern Territory, and those of the foreland basin of the Eburnean orogen in western Africa. Foreland basins evolved into intracontinental basins (Fig. 1; Table 3). The critical conjunction of geological processes is: (1) transition from TTG (high Th/U) to BADR (lower Th/U) magma series; (2) foreland basins on unconformities above basement that included Fe^{2+} facies; (3) high preservation potential on or peripheral to Archean CLM; and (4) mixing of meteoric water aquifers in the basement and sedimentary rocks proximal to the unconformities (Table 3; Fig. 1; Kerrich et al., 2005).

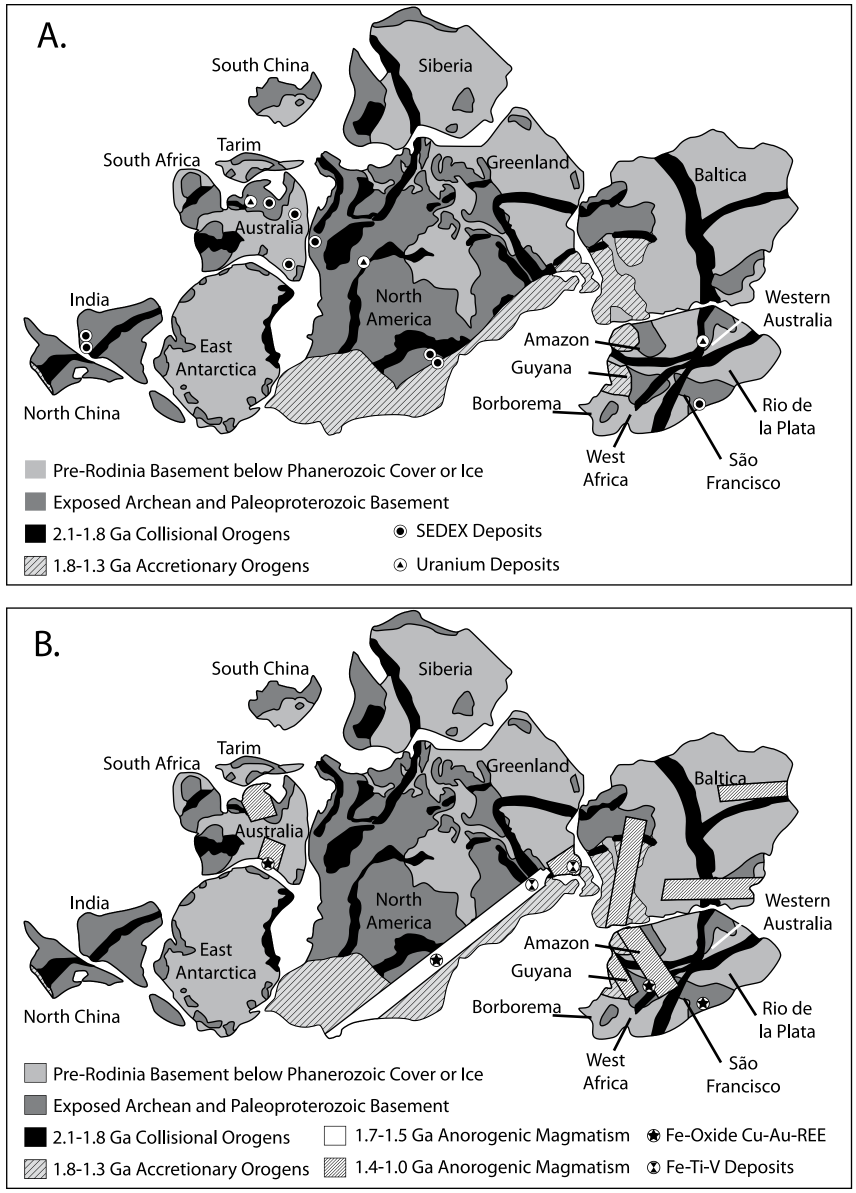


Figure 1. (A) Configuration of the Paleoproterozoic supercontinent Columbia of Zhao et al. (2004), illustrating the distribution of SEDEX deposits proximal to Archean cratonic margins which were the sites of subsequent rifting, and unconformity U deposits (Recast from Lydon, 2000). (B) Distribution of belts of 1.8-1.5 Ga and 1.5-1.4 Ga anorogenic magmatism, with IOCG and Fe-Ti-V deposits from Haapla and Ramo (1999).

1.7-1.5 Ga anorogenic magmatism

Abundant gabbro-anorthosite complexes and Rapakivi granites occur in a 5,000-km-long and ~1000-km-wide belt, extending from southern California, through Missouri and Labrador, and to Fennoscandia. Windley (1995) termed these anorogenic magmas, but a more recent interpretation is that this belt represents a long-lived active margin on the eastern side of Laurentia-Baltica (Rivers and Corrigan, 2000). Magmatic deposits of Fe-Ti-V-P are associated with gabbro-anorthosite complexes of this age, and include the Mealy Mountains (New York), Kiglapait (Canada), and Smaalands-Taberg (Sweden) deposits. Magmatic deposits of Sn-Be-W-Zn-Cu are present in 1.7-1.5 Ga Rapakivi granites of Missouri, Fennoscandia, and Brazil (Haapla and Ramo, 1999; Vigneresse, 2005).

~1.8-1.4 Ga intracontinental rift basins

Intracontinental basins developed on several cratons during disaggregation of Columbia. The Olympic Dam Fe-oxide-Cu-Au-REE (IOCG) deposit is associated with 1.6 Ga A-type granites in the Adelaide intracontinental rift of South Australia. In North America, younger Mesoproterozoic counterparts are present in A-type granites in Missouri. Magmatism carries signatures of depleted mantle, the low velocity zone at the base of the CLM, and lower crust. Whereas A-type granites are widespread in many Mesoproterozoic terranes, the specific conjunction of geological processes responsible for IOCG deposits in association with just a few terranes remains unconstrained.

Giant siliciclastic rock-hosted Pb-Zn deposits occur in intracontinental rifts that pre-dated the break-up of Columbia. The giant Sullivan deposit, British Columbia, formed in a 1.4 Ga mafic sill-sediment complex of the Belt-Purcell Supergroup. The Belt-Purcell basin subsequently evolved into the Meso-Neoproterozoic passive margin of Laurentia as rifting progressed to open new oceans. In reconstructions of Columbia, eastern Australia is interpreted to be adjacent to western Laurentia, and the Mt. Isa Pb-Zn deposit of Queensland may be correlative with deposits of the Laurentian passive margin (Kerrich et al., 2005). For the Belt-Purcell Supergroup, intracontinental extension involved thinning lithosphere, upwelling asthenosphere, and intraplate mafic magmas driving hydrothermal systems. For the 1.8 Ga McArthur River SEDEX in Australia, back-arc extension above a subduction zone is inferred (Fig. 20 in Leach et al., 2005a).

NEOPROTEROZOIC RODINIA

Rodinia was assembled by closure of external oceans in Grenville continent-continent orogens at ~1.1 Ga. This supercontinent was stable for ~400 m.y. and until the onset of rifting at ~700 Ma (Li et al., 2008). Few ore deposits are preserved from Grenville age orogens, or from Rodinia in general, possibly because those orogens involved delamination of CLM leading to crustal uplift and erosion to relatively deep crustal levels that were below depths at which most mineral deposits are formed (Houseman and Molnar, 1997; Kerrich et al., 2005).

Mantle plumes and LIPs

Two large mantle plume events are recorded in the Laurentian sector of Rodinia (Condie, 2001). At 1.3 Ga, troctolite magmas of the Nain intrusive complex were emplaced along the suture between the Archean Nain and Paleoproterozoic Churchill provinces; troctolites host the Voisey's Bay Ni-Cu-Co deposit in Labrador. For the 1.1 Ga plume event, all three components of large igneous provinces (LIPs) are preserved: mafic-ultramafic intrusions, giant dike swarms, and continental flood basalts. Magmatic Ni-Cu sulfide deposits are hosted in the Duluth complex of the mid-continent rift associated with the Keweenawan flood basalts, and the Muskox deposits of the Coppermine LIP, Northwest Territories.

700 Ma volcanic rifts

Rifting of Rodinia initiated at ~700 Ma. Associated with those rifts and asthenospheric magmatism are the Rapitan-type BIFs of Canada, Urucum (Brazil), and the Danmara Supergroup (Namibia; Windley, 1995).

PANGEA: APPALACHIAN OROGEN

Break-up of Rodinia in the Neoproterozoic was along intracontinental rifts that evolved into passive margins. Gondwana was then assembled from fragments of Rodinia, partly by Pan African orogens from 600-500 Ma. Laurasia has a different geological history than Gondwana, so an early Paleozoic supercontinent is unlikely (Rogers and Santosh, 2004). Pangea, however, was assembled by the 260 Ma Gondwana-Laurasia amalgamation. For eastern Laurentia, western mainland Europe, and western Scandinavia, the Appalachian-Caledonian orogenic system, which closed the 5,000-km-wide Iapetus Ocean, was a significant tectonic event in terms of metallogeny. Ophiolites span the period of 500-460 Ma and this orogenic system was terminated by 350 Ma; distinct stages of the larger Appalachian system in eastern North America, such as the Middle Ordovician-Silurian Taconic orogen, the Devonian-Early Carboniferous Acadian orogen, and the Late Carboniferous-Permian Alleghanian orogen represent the collision of successive arcs or terranes with the eastern margin of Laurentia. The Late Carboniferous-Permian Ouachita-Marathon-Sonora orogen is a 3,000-km-long belt of deformed Paleozoic rocks representing the closure of the Rhric Ocean along the southern margin of Laurentia that was being subducted beneath a Gondwanan continental-margin arc (Poole et al., 2005). The Ouachita-Marathon-Sonora orogenic event produced widespread hydrothermal alteration and mineralization for thousands of kilometers inboard of the orogenic belt within Laurentia (Leach et al., 2001).

Neoproterozoic rifts

Most sedimentary phosphate deposits accumulate on passive margins within 45° of the paleoequator, from high bioproductivity in upwelling ocean gyres (Trappe, 1998). The largest deposits are in the Permian Phosphoria Formation, Montana and Idaho, deposited on the western passive margin of Pangea in an epicontinental sea. Phosphorites are coeval with high sea-level stands reflecting some combination of enhanced plume and/or ridge activity.

Intraoceanic ophiolites

Polymetallic and Cu-Zn VMS deposits formed in arcs of the Iapetus Ocean and then were incorporated into the Appalachian-Caledonian orogenic system as parts of suprasubduction zone ophiolites (e.g., Galley and Koski, 1999). Examples include the VMS deposits of the Bay of Islands and Dunnage terranes, Newfoundland, and in the Norwegian Caledonidian sector. Chrysotile asbestos deposits are located in serpentinized sectors of oceanic mantle lithosphere peridotite, as in the Ordovician ophiolites of Quebec.

Continental margin arcs

The polymetallic (Cu-Zn-Pb) VMS deposits of the Bathurst-Newcastle district, New Brunswick, represent the largest concentration of base metal mineralization in the Appalachian-Caledonian orogenic system. Similar base metal deposits are in the Carolina slate belt, the Mineral district of Virginia, and at Buchans, Newfoundland. The Caradoc Avoca deposit in Ireland is a correlative deposit (Windley, 1995).

Post-orogenic granites

The East Kemptville and Grey River magmatic Sn-W deposits, Nova Scotia, are in post-tectonic, I-type granites of the Appalachian orogenic system, and were emplaced following crustal thickening. A critical feature in the formation of these deposits was melting of sedimentary rocks deposited below the chemocline as a control on redox state.

Foreland basin

The final amalgamation of Pangea was the most important time for formation of MVT lead-zinc deposits in Earth history (Leach et al., 2001, 2005a). Recent studies have shown that most MVT ores were deposited by sedimentary brines in active extensional domains within collisional orogenic forelands (Bradley and Leach, 2003; Leach et al, 2001). The largest MVT metallogenic province on Earth is located in the Ouachita foreland in the USA mid-continent, which includes the Southeast Missouri (Old Lead Belt and Viburnum Trend), Northern Arkansas, Tri-State, and Central Missouri districts. The MVT deposits in the Appalachian orogenic system include the Daniel's Harbour, East Tennessee, Friendenville, and Central Tennessee districts that are related to the Devonian-Early Carboniferous Acadian and the Late Carboniferous-Permian Alleghenian collisional orogenies. The MVT mineralization was mainly focused along forebulges (long-wavelength, 100-200 km, orogenic swells formed by vertical loading of the foreland plate) and along syn-collisional, flexure-induced normal and strike-slip faults. In many districts, the reactivation of pre-existing basement faults profoundly affected the ore-controlling structures in the districts (Bradley and Leach, 2003). Furthermore, the reactivation of deep-seated Proterozoic structures in the Reelfoot rift during the Ouachita orogenic events resulted in the intrusion of calc-alkaline bodies and the formation of the world's largest fluorite resource of the MVT Southern Illinois Fluorite District (Fig. 2).

Mantle plumes - diamonds

Globally, three of seven major kimberlite events are associated with mantle superplumes: (1) ~480 Ma in Canada, Russia, China, South Africa, and Zimbabwe; (2) ~280 Ma in Laurentia-Baltica; and (3) ~120-80 Ma (i.e., the well-documented Cretaceous superplume) in North America, India, Siberia, Brazil, and Africa. In Laurentia, these were responsible for four belts of diamond-bearing kimberlites: (1) a northeastern Cambrian province, (2) an eastern Jurassic province, (3) a central Cretaceous province, and (4) a western province of mixed Cambrian-Eocene age (Heaman et al., 2003).

PRE-CORDILLERAN PANGEA RIFTING

During the final stages of the amalgamation of Pangea, active rifts dominated the northwestern part of North America. This tectonism during the final 100 m.y. of supercontinent growth was responsible for development of a large base metal endowment along this edge of Pangea. Resulting deposits included the large shale-hosted Zn-Pb-Ag deposits of the western Brooks Range and Selwyn basin, as well as adjacent, commonly precious metal-enriched VMS ores. The world's largest sedimentary rock-hosted zinc deposits of the Red Dog district formed during a period of rapid transtensional rifting of the passive margin in the Mississippian. The ores were deposited within an organic-rich sub-basin flanked by a carbonate platform with evaporative environments (Leach et al., 2005b).

Some of the base metal deposits in southernmost SE Alaska formed far from the North American continent (Newberry et al., 1997; Goldfarb et al., 1999), perhaps during rifting along a margin of Baltica in the latest Neoproterozoic or early Paleozoic. These gold- and silver-bearing Cu-Zn VMS deposits (e.g., Niblack, Khayyam, Trocadero Bay) are associated with bimodal volcanism within the Wrangellia superterrane. Additional rifting within Wrangellia at ca. 220-195 Ma,

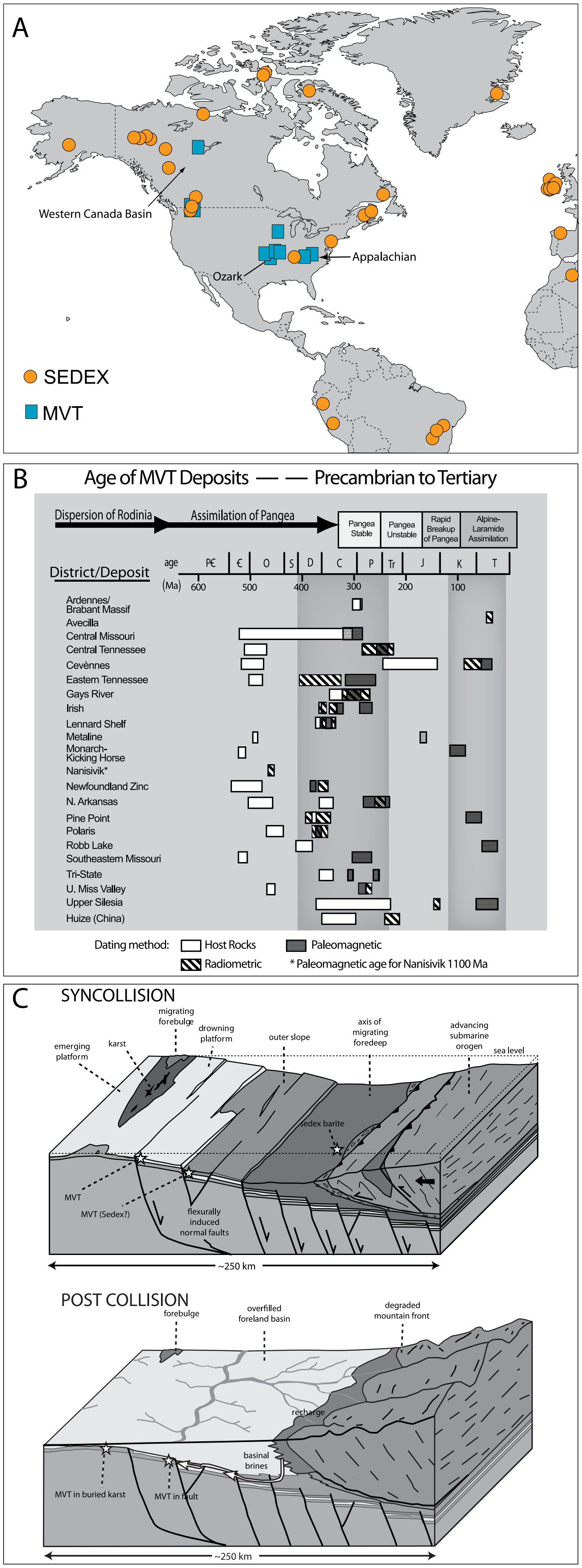


Figure 2. (A) Distribution of MVT and SEDEX (sedimentary exhalative) deposits. (B) Age span of host rocks and ages of MVT deposits, in the context of the Rodinia and Pangea supercontinents. (C) Model for deposition of MVT deposits in a foreland basin. From Leach et al. (2005a).

leading to development of a belt of Cu±Co, Au (i.e., Windy Craggy, Hidden Creek) and Ag-Pb-Zn±Au (e.g., Greens Creek) Besshi-type VMS deposits, took place as the oceanic block approached North America. During Late Jurassic accretionary collision of Wrangellia with western North America, these pre-Cordilleran deposits were added into the growing Cordilleran orogen.

Other important Paleozoic VMS deposits are presently located inland of the Wrangellia deposits within the Stikinia, Arctic Alaska, and Yukon-Tanana terranes that are major components of the northernmost sectors of the Cordilleran orogen (Newberry et al., 1997; Nelson et al., 2006). These ca. 375-330 Ma Cu-Pb-Zn-Ag-Au ores associated with bimodal volcanism, generally overlapping in age with the above-described shale-hosted deposits of the western Brooks Range and Selwyn basin, include those at Finlayson Lake, Tulsequah Chief, Ecstall, Bonnifield, Delta, and Ambler. They are products of back-arc spreading and associated volcanism along the Paleozoic margin of the growing supercontinent. The near-margin extension is suggested as having been driven by Devonian-Mississippian subduction rollback and slab sinking (Nelson et al., 2006). These mainly pericratonic blocks and their VMS ores were attached to the craton during the early stages (Jurassic) of the subsequent Cordilleran orogeny.

Pre-Jurassic, accreted VMS ores recognized further to the south on the Pangean margin are generally smaller and not as abundant as those of the northern Cordillera. This reflects, to some degree, the fewer allochthonous blocks along the western margin of the conterminous USA and the greater degree of Cenozoic volcanic and alluvial cover of many of the accreted blocks. A few relatively small VMS deposits are exposed throughout Paleozoic rock sequences of Washington, Oregon, and California, with the Cu-Zn-Au-Ag ores of the Devonian West Shasta arc in northern California being the most significant (Hutchinson and Albers, 1992). Thrusting during the Sonoma orogeny led to these ores becoming a part of the continental margin by Triassic times.

JURASSIC-CENOZOIC CORDILLERAN OROGEN OF NORTH AMERICA: PART OF A NEW SUPER-CONTINENT?

Breakup of Pangea, initiated in the latest Triassic to Early Jurassic, has continued to the present time. However, new tectonic events may be signaling the growth of a future supercontinent (Condie, 1998). These include important episodes of terrane accretion along western North America that define the Cordilleran orogen, including closure of the Pacific external ocean, as well as collision of Africa-Europe and India-Asia in continent-continent orogens by closure of internal oceans, and Australia is likely to accrete to Southern Asia. Such a broadly defined transition from one supercontinent to the next may be the norm, rather than an anomaly; the Columbia to Rodinia transition may record a similar history of coeval breakup and growth.

Accretionary tectonics: Cordilleran fore-arc to continental arc

Late Triassic-Middle Jurassic. The early stages of Cordilleran orogenesis, particularly in westernmost Canada, are associated with the evolution of important porphyry Cu-Au and Cu-Mo deposits (McMillan, 1998). These ca. 210-185 Ma deposits formed in some of the youngest rimming oceanic arcs, as well as the oldest continental arcs associated with the orogen. Country rocks were mainly pericratonic fragments of ancestral North America that had rifted during the Paleozoic and were being accreted back to the margin in the latest Triassic and earliest Jurrassic (Colpron et al., 2007). Much of the subduction-related arc development likely occurred within the Stikinia terrane (e.g., Schaft Creek, Galore Creek, Kemess, Kerr deposits) just prior to its accretion and within the Quesnellia terrane (e.g., Mount Milligan, Mount Polley, Copper Mountain, Highland Valley deposits) just subsequent to its accretion; the two blocks were then amalgamated on the edge of the continent by ca. 180-170 Ma (Nelson and Colpron, 2007). Most of the magmatism is calc-alkaline, although some of the younger and more gold-rich porphyries in the 25-m.y.-long period may be alkalic (e.g., Mount Milligan, Copper Mt., Galore Creek).

The oceanic and continental magmatic arc systems associated with the Triassic-Jurassic Canadian porphyry deposits are also responsible for commonly surrounding skarn (Ray and Webster, 1997) and low sulfidation epithermal (Panteleyev, 1991) deposits. These skarns in Stikinia (e.g., Galore Creek Cu) and Quesnellia (e.g., Hedley-Mascot Au, Craigmont Cu) generally pre-date spatially related porphyry mineralization, can be associated with either Cu-Au or Cu-Mo porphyry systems, and are dominated by Cu or Au. Important Early Jurassic epithermal ores in the Stikinia arc include those of the Stewart-Iskut region (e.g., Silbak-Premier, Sulphurets) and in the Quesnellia arc include those of the Todoggone district. The slightly younger (ca. 175 Ma) Eskay Creek deposit in the former region shows features of both epithermal ores and Au-rich VMS deposits, reflecting near sea-floor volcanic activity in the oceanic arc (Dubé et al., 2007).

The southern part of the North American Cordillera was dominated by development of an Aleutian-like oceanic to continental margin arc regime, with a significant transtensional component, subsequent to Pangea break-up (e.g., Busby, 2004) during the so-called "Nevadan orogeny". Although much of the arc is under cover or eroded, some economically important Middle Jurassic (i.e., Yerington, Nevada; Bisbee, Arizona; El Arco, Baja California) porphyry copper systems are preserved in probable near-margin, continental arcs from the pre-Laramide tectonism in this part of the Cordillera. Magmatism was driven by subduction of the Mezcalera and then Farallon plates (Dickinson, 2006).

Small Jurassic Kuroko-type polymetallic ores were formed during arc volcanism west of the conterminous USA. These were subsequently emplaced onto the continental margin during Jurassic convergence in southern Oregon, the California Coast Ranges, and the Sierra foothills (Hutchinson and Albers, 1992).

In Yukon and British Columbia, the oldest Cordilleran orogenic gold deposits formed ca. 180 Ma in metamorphic belts adjacent to the arcs and probably no more than 10-15 m.y. after the host rocks were added to this northern part of the orogen (Goldfarb et al., 1998; Berman et al., 2007). These deposits include those of the Atlin area, within Permo-Triassic rocks of the Cache Creek Ocean that closed between Quesnellia and Stikinia, and the Golden Bear deposit in Stikinia. In addition, new data from the Klondike goldfields now suggests that the source lodes for these world-class placer fields in the Yukon-Tanana terrane were also deposited at this time (Fig. 3; J. Mortensen, oral commun., 2006).

Late Jurassic-middle Cretaceous. Late Jurassic through middle Cretaceous subduction-related magmatism within the accreted margin led to formation of additional large porphyry deposits in the evolving subduction-related arc of the northern Cordillera. Calc-alkaline plutonic suites with late-stage, molybdenum-bearing porphyry bodies were emplaced along the eastern side of Stikinia in central British Columbia ca. 140-135 Ma (e.g., Endako, Mac; McMillan, 1998). An extensive belt of porphyry copper deposits, part of the 800-km-long Nutzotin-Kluane arc of I-type intrusions, was emplaced into Triassic rocks of the Wrangellia terrane and the overlapping Jura-Cretaceous Gravina flysch belt ca. 115-105 Ma in east-central Alaska during Farallon plate subduction (e.g., Bond Creek, Orange Hill, Baultoff; Hart et al., 2004). These copper deposits in the Wrangell Mountains formed about 20-30 m.y. after the host rocks were added to the continental margin. Post-collision circulation of surface waters through the Nikolai basalts of the Wrangellia terrane led to formation of the Kennecott high-grade Cu-Ag orebodies in faults in the overlying limestone; most likely this occurred during the Early Cretaceous (MacKevett et al., 1997). Westerly migration of the ca. 110 Ma event into southwestern Alaska included the 90 Ma emplacement of igneous rocks that are host to the giant Pebble Cu-Au-Mo deposit within the flysch belt. Also, at about 95-90 Ma, more landward migration of arc magmatism into eastern Alaska and central Yukon, adjacent to the craton margin, included intrusion of more reduced plutons into Neoproterozoic-Paleozoic rocks of the Yukon-Tanana terrane and Selwyn basin. These bodies of the Tombstone-Tungsten magmatic belt (Hart et al., 2004) included the causative plutons for formation of intrusion-related gold deposits (e.g., Fort Knox, Scheelite Dome) and large tungsten skarns (e.g., Cantung, Mactung).

Extensive subduction-related metamorphism led to Early Cretaceous orogenic gold formation along the entire length of the orogen. In the Sierra foothills of central California, extensive ca. 125 Ma goldfields formed along terrane-bounding faults of the Mother Lode belt (Marsh et al., 2008). The lodes and associated placers defined the largest gold resource of the Cordilleran orogen and are located within the forearc to the immense Sierra batholith. This massive hydrothermal event in the southern part to the orogen was likely a consequence of major plate reorganizations in the Pacific basin and subsequent changing kinematics along the major fault zones of the Sierra foothills (Goldfarb et al., 2008). Smaller gold systems in the Klamath Mountains of northern California and southern Oregon, as well as the giant Grass Valley orebodies in the Sierra foothills, may be part of earlier tectonism associated with 200 km of Late Jurassic offset of these two regions (Marsh et al., 2008). In the Alaskan part to the orogen, ca. 110-95 Ma hydrothermal events were widespread in the east-central to northwestern part of the state (Goldfarb et al., 1998, 1999). Slab rollback and extensional tectonism at 110 Ma led to the development of small lode systems, which eroded throughout the Seward Peninsula fore-arc region to form world-class beach placers at Nome. A very complex tectonic environment in east-central Alaska, associated with subduction, extension, and widespread magmatism (Goldfarb, 1997) was associated with generation of important orogenic gold lodes in the Goodpastor (e.g., Pogo) and Fairbanks (e.g., Ryan Lode, Hi-Yu, Cleary Summit) districts at 105 and 95 Ma, respectively (Fig.3).

Late Cretaceous – Eocene. A variety of young VMS deposits were formed offshore of the southern Alaskan continental margin during Cordilleran orogenesis and were then added into the forearc region of the evolving orogen within a few tens of million years of their formation. Both Besshi- (Beatson, Ellamar) and Cyprus-type (Knight Island) Fe-Cu-Zn ores are associated with a 15- to 30-m.y.-long period of seafloor spreading along the Kula ridge. These ores were obducted onto the continental margin, within the Chugach and Prince William terranes of the southern Alaskan accretionary prism, at ca. 65-60 Ma (Goldfarb 1997; Goldfarb et al., 1999).

Late Cretaceous plate subduction beneath the continental margin led to formation of ca. 70-60 Ma copper (e.g. Taurus, Casino, Fairplay) and molybdenum (Pluto, Red Mountain) porphyry systems mainly within rocks of Yukon-Tanana in the northern Cordillera. Migration of arc magmatism to the southeast in the early Tertiary included formation of larger copper (Morrison, Berg, Poison Mountain) and molybdenum (Adanac, Kitsault, Glacier Creek) deposits mainly in Stikinia. Goldfarb et al. (1999) suggested that these latter metalliferous events in the northern Cordillera might relate to the oblique subduction of the Kula plate as the Kula-Farallon-North American plate triple junction approached the continental margin. Simultaneously, in southern USA, Laramide age subduction was responsible for a remarkable concentration of porphyry copper deposits in southern Arizona (e.g., Morenci-Metcalf, Safford, Cananea, Santa Rita, Ray, Miami-Inspiration, Casa Grande, San Manuel-Kalamazoo), as well as adjacent New Mexico and northern Mexico, at ca. 72-45 Ma and approximately 350-400 km inland of the continental margin (Damon et al., 1983; Titley, 1993; Barra et al., 2005). Unlike in the northern Cordillera, these porphyry systems formed within or above the Proterozoic cratonic basement during the low-angle subduction of the Farallon plate, except for a few in southern Mexico.

Accretionary tectonics continued to lead to the formation of orogenic gold deposits within metamorphic rocks during the latest Cretaceous and early Tertiary within the northern parts of the orogen. Large gold deposits generated during this period included the ca. 66 Ma deposits of the Bridge River (back-arc of British Columbia) and Willow Creek (margin of the magmatic arc of south-central Alaska) districts, and the ca. 55 Ma deposits of the Juneau gold belt (fore-arc of southeastern Alaska). These lode systems were generated during the onset of transpressional events along terrane-bounding fault systems (Goldfarb et al., 2008). Progressive ridge subduction beneath the 2000-km-long accretionary prism of southern Alaska was responsible for the 60-50 Ma evolution of small orogenic gold deposits throughout the prism (Haeussler et al., 1995). Cordilleran mercury deposits, some within shallower crustal levels of orogenic gold districts (e.g., Silverquick, Bridge River district), may define upper levels to hydrothermal systems responsible for orogenic gold deposits (e.g., Nesbitt, 1988). In relatively unmetamorphosed rocks of the Kuskokwim basin of southwestern Alaska, the 70 Ma Donlin Creek deposit represents an epizonal orogenic gold system within a regional Hg-Sb metallogenic province (Goldfarb et al., 2004).

To the south, a complex migratory pattern of ca. 80-50 Ma arc magmatism was associated with a major metallogenic event in the Montana/Idaho region (Lund et al., 2002). This included the 70-64 Ma formation of the Butte Cu-Mo porphyry and base metal veins, as well as the alkalic magmatism-related epithermal gold ores (e.g., Zortman-Landusky). Some remobilization and concentration of Proterozoic metals in the Ag-rich polymetallic veins of the Coeur d'Alene province, Belt-Purcell basin, may have also occurred at this time, but evidence remains uncertain (i.e., Leach et al., 1998). Deformation adjacent to and coeval with emplacement of the Idaho batholith was associated with orogenic lode gold formation in districts such as Elk City (Lund et al., 1986).

Late Cenozoic. Extension within the Cordilleran forearc of southeastern Alaska facilitated formation of other significant ores during the final stages of Cordilleran orogeny. The development of a transtensional region within the continental margin terranes of southeastern Alaska led to formation of the giant Oligocene Quartz Hill porphyry molybdenum deposit and the 40-30 Ma emplacement of the gabbro and norite bodies of the Crillon-La Perouse plutonic complex with its large Brady Glacier nickel resource (Goldfarb, 1997). Also, during the last 30-40 m.y., development of the Aleutian oceanic-continental

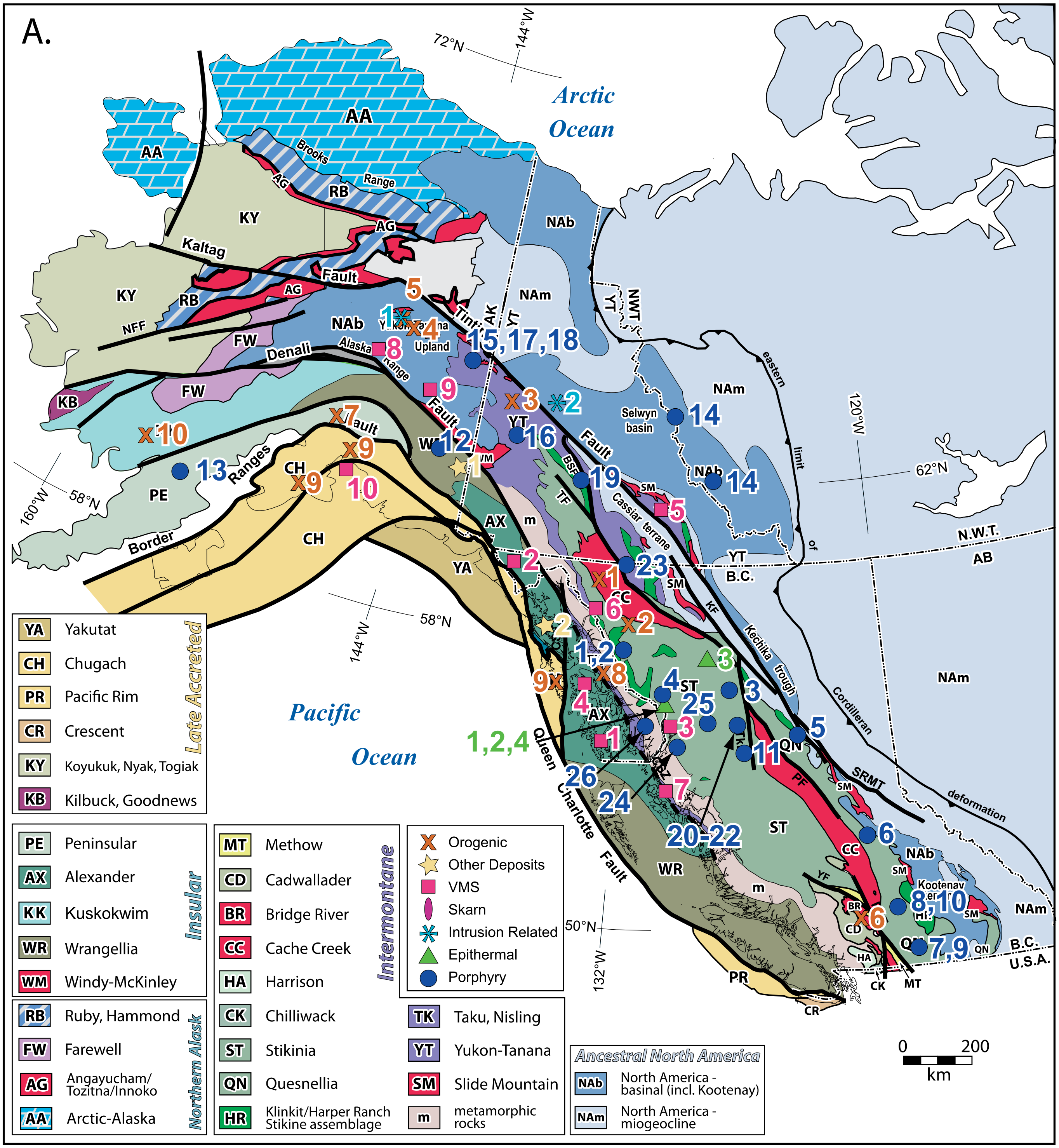


Figure 3a. Major mineral deposits and districts of the northern half of the Cordilleran orogen (Alaska, Yukon, and British Columbia). Terrane map after Colpron et al. (2007). Deposits shown include: VMS (1-Niblack/Khayyam,/Trocadero Bay, 2-Windy Craggy, 3-Hidden Creek, 4-Greens Creek, 5-Finlayson Lake, 6-Tulsequah, 7-Ecstall, 8-Bonnifield, 9-Delta, 10-Beatson/Ellamar/Knight Island), porphyry Cu or Mo/skarn (1-Schaft Creek, 2-Galore Creek, 3-Kemess, 4-Kerr, 5-Mount Milligan, 6-Mount Polley, 7-Copper Mountain, 8-Highland Valley, 9-Hedley/Mascot, 10-Craigmont, 11-Endako, 12-Bond Creek/Orange Hill/Baultoff, 13-Pebble, 14-Cantung/Mactung, 15-Taurus, 16-Casino, 17-Fairplay, 18-Pluto, 19-Red Mountain, 20-Morrison, 21-Berg, 22-Bell, 23-Adanac, 24-Kitsault, 25-Glacier Gulch, 26-Quartz Hill), epithermal gold (1-Silbak/Premier, 2-Sulphuret, 3-Toodoggone, 4-Eskay Creek), intrusion-related gold (1-Fort Knox, 2-Scheelite Dome), orogenic gold (1-Atlin, 2-Golden Bear, 3-Klondike, 4-Pogo, 5-Fairbanks, 6-Bridge River, 7-Willow Creek, 8-Juneau gold belt, 9-S. Alaska accretionary prism, 10-Donlin Creek), and other (1-Kennecott Cu, 2-Brady Glacier Ni).

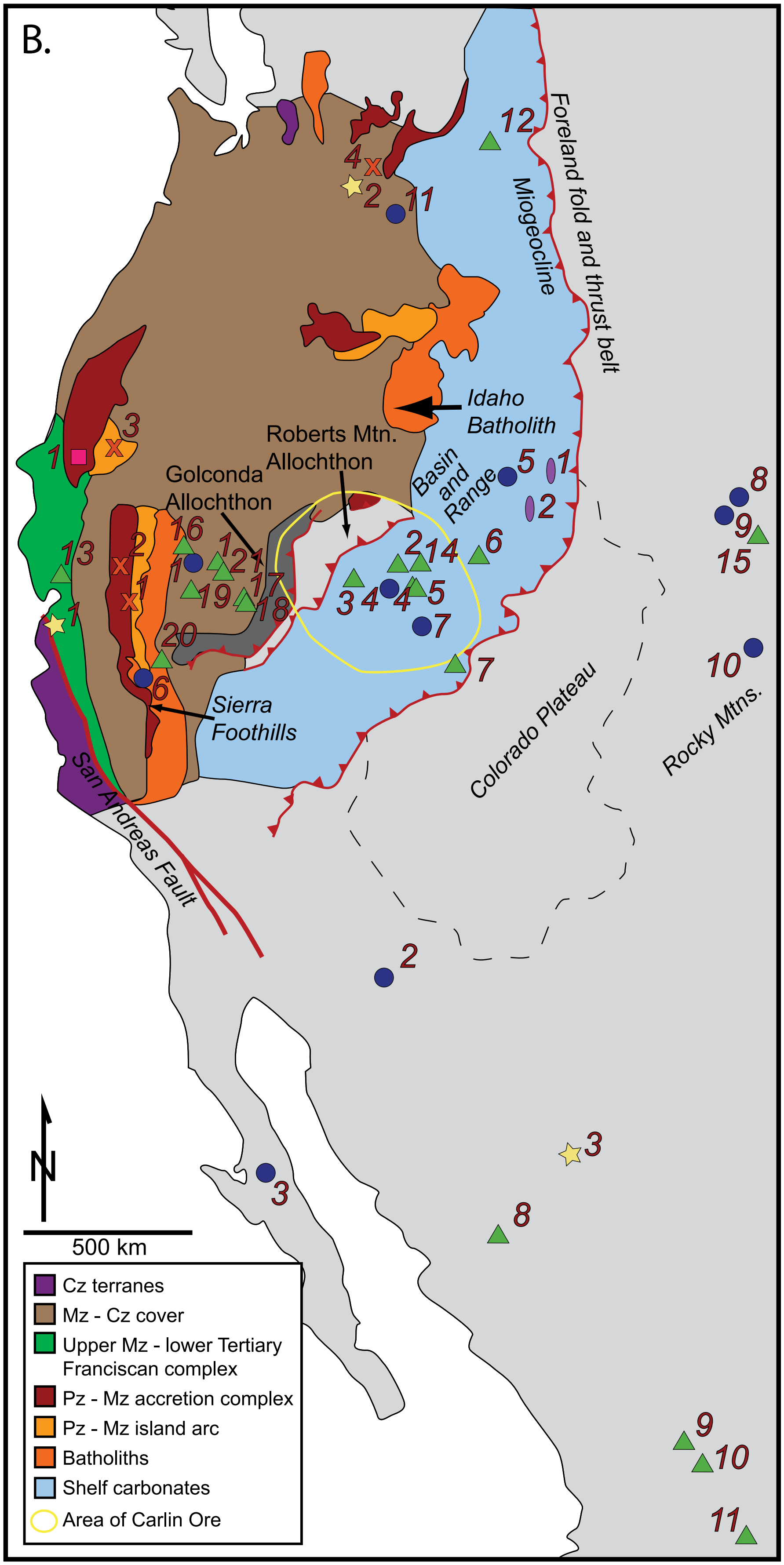


Figure 3b. Major mineral deposits and districts of the southern half of the Cordilleran orogen (conterminous USA and Mexico). In contrast to the northern half of the orogen (figure 4a), extensive Cenozoic alluvial and volcanic cover have hindered comprehensive terrane correlation along the length of the southern half of the orogen. Deposits shown include: **VMS** (1-West Shasta); **porphyry Cu or Mo** (1-Yerington, 2-Bisbee, 3-El Arco, 4-Copper Canyon, 5-Bingham, 6-Pine Grove, 7-Mt. Hope, 8-Urad-Henderson, 9-Climax, 10-Questa, 11-Butte); **skarn** (1-Park City, 2-Tintic); **epithermal gold** (1-Rawhide, 2-Midas, 3-Sleeper, 4-Mule Canyon, 5-Buckhorn, 6-National, 7-Ivanhoe, 8-Batopilas, 9-Fresnillo, 10-Zacatecas, 11-Guanajuato, 12-Zortman, 13-McLaughlin, 14-Tuscarora, 15-Cripple Creek, 16-Comstock, 17-Tonopah, 18-Goldfield, 19-Aurora, 20-Bodie, 21-Paradise Peak); **orogenic gold** (1-Mother Lode, 2-Grass Valley, 3-Klamath Mountains, 4-Elk City); and **other** (1-New Almanden, 2-Coeur d'Alene Ag-Pb-Zn). Deposit symbols are the same as shown in figure 3a legend.

arc has included formation of many porphyry Cu and Mo and epithermal gold deposits (e.g., Apollo) and prospects in southwestern Alaska (Goldfarb, 1997; Goldfarb et al., 1999).

Initiation of the San Andreas dextral strike-slip regime along coastal California, about 15-20 m.y. ago, is associated with the still-active hydrothermal events responsible for formation of the California mercury belt within the Late Jurassic to Late Cretaceous mélange of the Franciscan assemblage (Studmeister, 1984). Hot springs along the fault continue to deposit cinnabar and are anomalous in gold. The New Almaden deposit, located near San Jose, was the largest historic mercury producer in the USA and likely formed within a few million years of the 15.6 Ma volcanic rocks at the deposit (McLaughlin et al., 1996). A northwardly opening slab window behind the southern edge of the subducting Gorda plate has helped supply much of the shallow heat along the transform fault system. Pickthorn (1993) suggested that hot-springs epithermal gold deposits (e.g., McLaughlin) in the California Coast Ranges metallogenic province could be remobilized ores from underlying epizonal orogenic gold deposits being formed at depth along the San Andreas fault system (Fig.3).

Cordilleran back-arc: Metallogeny dominated by Basin and Range extension

During development of the subduction-related Cordilleran arc along the western margin of the conterminous USA, episodic back-arc magmatism characterized large areas of Nevada and adjacent states. Oldest episodes of magmatism were concentrated at ca. 170-150 Ma and ca. 115-70 Ma, reflecting Jurassic Mezcalera plate slab breakoff and Cretaceous Farallon plate shallow subduction, respectively (du Bray, 2007). Associated base metal-rich metallogeny includes the Jurassic skarns of the Battle Mountain district and the Cretaceous porphyry-skarn ores of the Robinson district. However, the most widely extensive and economically significant base and precious metal mineralization in the back-arc to the southern part of the North American Cordillera is associated with Cenozoic Basin and Range extension.

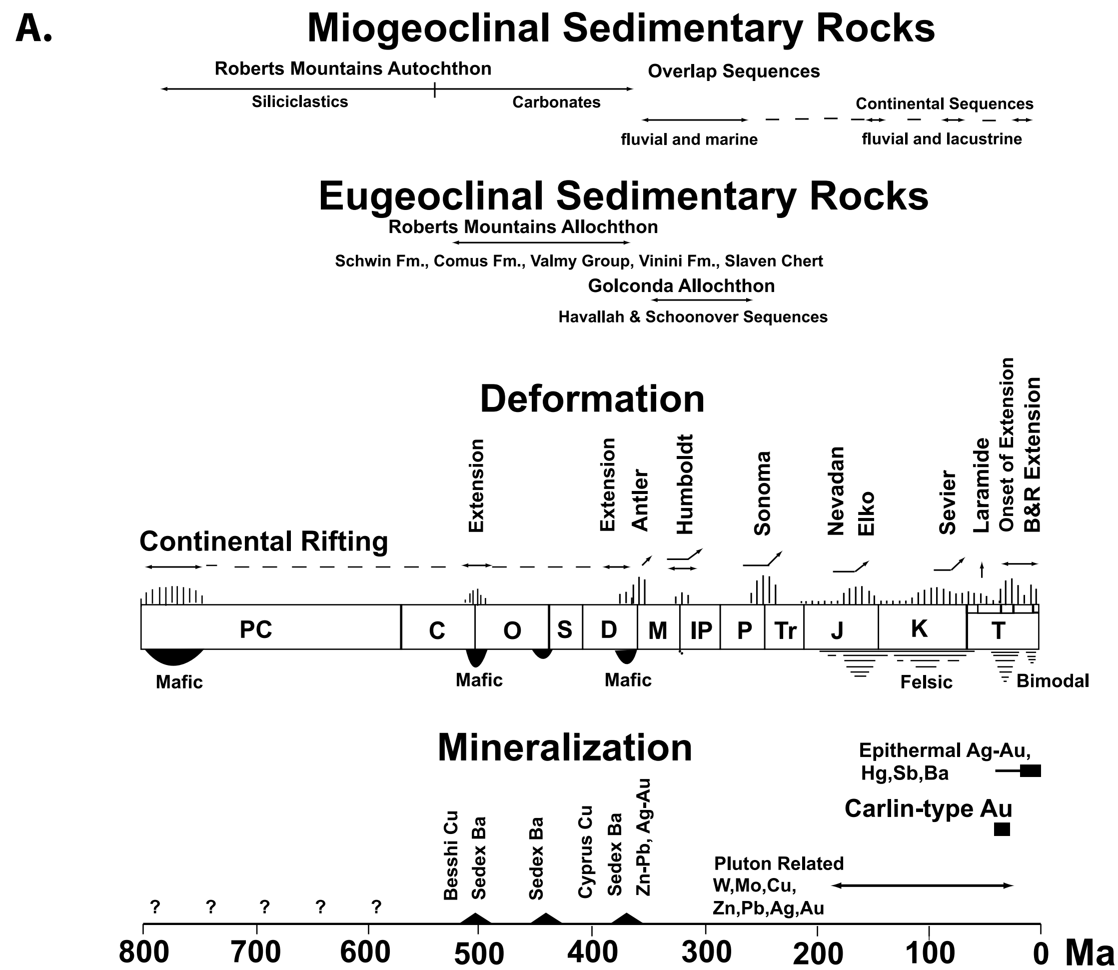
Compression related to subduction of the Farallon and Kula plates dominated the Basin and Range until the mid Eocene. At approximately 42 Ma, the subhorizontal Farallon plate (Dickinson and Snyder, 1978; Christiansen and Yeats, 1992) began to detach from the base of the lithosphere in response to either gravity-driven collapse of the thickened Sevier hinterland (Jones et al., 1998; Liu and Shen, 1998; Rahl et al., 2002) or transient shear stresses at the base of the brittle crust as lower crustal flow was reestablished (Westaway, 1999). Lower and mid-crustal flow was accompanied by extensional faulting in the upper crust over much of the western Cordillera. In northern Nevada, extension and contact of hot asthenosphere with the base of the lithosphere (Humphreys et al., 2003) was responsible for a lengthy period of calc-alkaline magmatism (Armstrong and Ward, 1991; Henry and Boden, 1998). This magmatism generated several important ore deposits that formed under the mid-Eocene near-neutral arc stress state (Tosdal and Richards, 2001) that existed during the transition from compression to tension and during subsequent incipient tension. Gold-rich porphyry copper, skarn, replacement, and distal-disseminated Au-Ag deposits formed ca. 39 Ma at Copper Canyon in the Battle Mountain mining district (Doebrich and Theodore, 1996; Theodore, 1998a, b). When the dip of the Farallon plate steepened, causing southwestward retreat of the subduction plate hinge line (Hildenbrand et al., 2000), the giant Bingham porphyry copper deposit formed at 38 Ma (Hildenbrand et al., 2000; Parry et al., 2001). The oldest Tertiary epithermal precious-metal mineralization in Nevada formed at Tuscarora during volcanism at about the same time (Henry and Boden, 1998).

The supergiant gold endowment of the ~42-36 Ma Carlin-type deposits of Nevada also formed at this time, following a protracted geodynamic evolution. Rifting of Columbia at ~1.4 Ga had originally generated intracontinental basins (e.g., hosts for the Sullivan and Mt. Isa SEDEX deposits), some of which remained as a part of long-lived passive margin on the western boundary of Laurentia, that were deposited on Precambrian lithosphere with a northwest-trending structural grain. The passive margin was preserved through growth and break-up of Rodinia, and subsequently deformed during the Antler, Humboldt, Sonoma, Sevier, and Laramide phases of the Cordilleran orogen. As mentioned above, back-arc extension to the continental-margin magmatic arc commenced ~40 Ma in the Basin and Range Province, with thinned lithosphere advecting heat from upwelling asthenosphere (Fig. 4). The protracted geodynamic evolution took advantage of a conjunction of factors favorable for formation of the Carlin gold province: (1) reactive pyritic and (or) carbonate-bearing sedimentary rock sequences of earlier passive margin or later foreland sequences; (2) a structural architecture of reactivated rift-related Precambrian steep structures with shallow Cordilleran thrusts; (3) high heat flow from advected asthenosphere generating, in turn, a variety of mantle and crustal sourced magmas; and (4) Eocene extension of continental lithosphere (Cline et al., 2005).

Continued extension and associated calc-alkaline magmatism during the Oligocene led to formation of the Park City (36-33 Ma; Barnes and Simos, 1968) and Tintic (~33 Ma; Keith et al., 1991; Stavast et al., 2006) Pb-Zn-(Ag-Au-Cu) skarns. The giant Climax and Urad-Henderson molybdenum porphyry deposits formed ca. 33-24 Ma due to northernmost Rio Grande rifting (Wallace, 1995). Other molybdenum porphyry deposits similarly formed under Basin and Range- (Mt. Hope, Nevada, 38-36 Ma; Pine Grove, Utah, 23-22 Ma) or Rio Grande Rift- (Questa, New Mexico, 25-24 Ma, Rowe et al., 2003) related extension (Wallace, 1995). Oligocene alkaline magmas associated with Rio Grande rifting produced major low sulfidation epithermal gold-telluride veins at Cripple Creek (Jenson and Barton, 2000) ca. 29 Ma.

Continued extension during the Miocene in Nevada produced one of the world's great concentrations of epithermal

Fig. 4


A.
Miogeoclinal Sedimentary Rocks
Roberts Mountains Autochthon
Siliciclastics
Carbonates
Overlap Sequences
Continental Sequences
fluvial and marine
fluvial and lacustrine
Eugeoclinal Sedimentary Rocks
Roberts Mountains Allochthon
Schwin Fm., Comus Fm., Valmy Group, Vinini Fm., Slaven Chert
Golconda Allochthon
Havallah & Schoonover Sequences
Deformation
Continental Rifting
Extension
Extension
Antler
Humboldt
Sonoma
Nevadan
Elko
Sevier
Laramide
Onset of Extension
B&R Extension
PC
C
O
S
D
M
IP
P
Tr
J
K
T
Mafic
Mafic
Mafic
Felsic
Bimodal
Mineralization
Epithermal Ag-Au, Hg,Sb,Ba
Carlin-type Au
Besshi Cu
Sedex Ba
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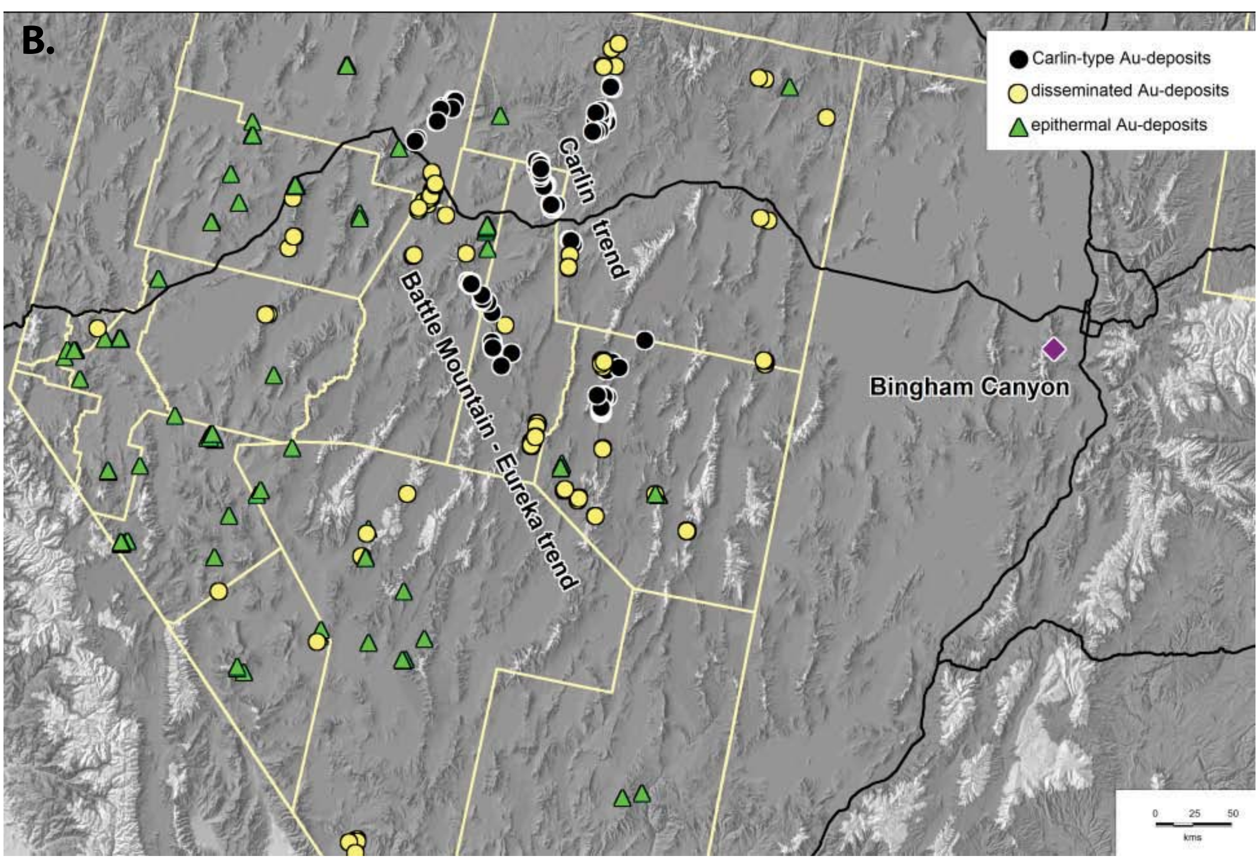
B.
Carlin-type Au-deposits
disseminated Au-deposits
epithermal Au-deposits
Carlin trend
Battle Mountain - Eureka trend
Bingham Canyon
0 25 50
kms

precious metal deposits, which are associated with two differing styles of volcanism. Arc-related, high-K calc-alkaline andesitic magmas and associated mineralization, ranging in age from 22 to 4 Ma, occur along the narrow Walker Lane belt of transtensional and strike-slip faulting in western Nevada. Deposits include both high and low sulfidation gold-silver systems: the Comstock Lode, Tonopah, Goldfield, Aurora, Bodie, Paradise Peak, and Rawhide (John, 2001; Simmons et al., 2005). Bimodal basaltic to andesitic and rhyolite volcanism during Basin and Range extension from 17 Ma to Holocene produced low sulfidation epithermal deposits including Midas, Sleeper, Mule Canyon, Buckhorn, National, and Ivanhoe; high sulfidation deposits are absent. These deposits are associated with tholeiitic magmas derived from lithospheric mantle during continental rifting (John, 2001; Simmons et al., 2005).

An additional large silver-gold epithermal district in Mexico is associated with the Eocene-Miocene component of the Sierra Madre Occidental (Clark et al., 1982), a large silicic igneous province formed during and immediately following the final stages of the subduction of the Farallon plate (Ferrari and Orozco-Esquivel, 2006). A belt of Ag-Pb-Zn deposits along the eastern flank of the Sierra Madre Occidental formed from 49 to 28 Ma during latest eastward progression and initial westward regression of the andesitic subduction-related arc. A subparallel belt of Pb-Zn-Ag-(Cu) manto deposits (Naica) formed further to the east, closer to intrusive centers from ca. 46 to 27 Ma. As convergence rates decreased and the arc regressed to the west (ca. 42 to 18 Ma), rhyolitic magmas generated a parallel belt of Ag-Au epithermal deposits (Batopilas, Fresnilo, Zacatecos, Guanajuato) along the western margin of the Sierra Madre Occidental (Clark et al., 1982).

CONCLUSIONS

The characteristics of orogenic gold deposits has changed little from the 3.4 Ga and 2.7 Ga provinces of Barberton and the Abitibi Terrane to those of the Cordillera, so the characteristics of accretionary orogens have secular consistency. Host rocks are the exception, which reflects decreasing mantle plume activity in ocean basins and therefore lowered sea levels; Archean deposits are dominantly hosted by submarine mafic volcanic sequences, whereas Phanerozoic counterparts have a significant component of siliciclastic sedimentary rocks. Similarly, base metal VMS deposits, formed in intraoceanic arcs, have changed little through earth history, although those like Bathurst and the Iberian Pyrite Belt, formed in continental backarcs, are a Phanerozoic phenomenon. The frequency and size of BIF reflects decreasing plume activity, which also explains the prevalence of large magmatic-hosted Ni-Cu-PGE deposits in the Precambrian, and lowered sea level accounts for the preservation of passive-margin sediments after 2.4 Ga.

Porphyry Cu and epithermal Au-Ag deposits form in topographically elevated convergent margins and therefore have low preservation potential, yet some are present in Archean greenstone terranes associated with rare calc-alkaline magmas, so their secular distribution is also a function of the transition from dominant TTG with rare calc-alkaline magma series in the Archean to BARD magma series in Phanerozoic convergent margins. Similarly, Carlin type deposits are unlikely to survive back-arc extension. Sparsity of most mineral deposits in Rodinia may stem from Grenville-type orogens with concomitant deep erosional levels. Carbonate-hosted Pb-Zn deposits, similar to MVT, are documented in Precambrian terranes, but their genetic status and geodynamic settings are unconstrained (Leach et al., 2005a). It remains unclear why unconformity U deposits are restricted to Paleoproterozoic forelands.

Figure 4 (facing page). (A) Synthesis of geochronological relationships for sedimentation, deformation, magmatism, and mineralization in the great Basin (from Hofstra and Cline, 2000, and Cline et al., 2005). (B) Distribution of different classes of gold deposits in Nevada (after Davis et al., 2006).

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