



Chapter 7

Carbonatites in Western North America—Occurrences and Metallogeny

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Abstract

Carbonatites are relatively rare igneous rocks that are of considerable economic interest due to their common enrichment in certain elements, such as the rare earth elements (REEs), Nb, Ta, Th, and P. There are more than 37 known carbonatite occurrences in western North America, six of which have published resource estimates: these are the Aley and Upper Fir in British Columbia (for Nb, Ta, P), the Bear Lodge Mountains (for REEs), the Wet Mountains area in Colorado (for Th, Nb, U, and REEs), Iron Hill in Colorado (for REEs, Nb, and Th), and Mountain Pass in California (for REEs).

Based on their distribution in geologic space and time, the carbonatites in western North America can be divided into four distinct groups: group 1 (~1450–1375 Ma) is Mountain Pass; group 2 (~813–449 Ma) comprises several carbonatites in Canada and the United States; group 3 (~359–328 Ma) comprises most of the carbonatites in western Canada; and group 4 (~52–37 Ma) comprises carbonatites in the northwestern United States and northern Mexico. It is not possible to distinguish between economically more or less favorable carbonatites based on their intrusion ages and geologic settings alone because all of the above groups contain both potentially mineralized and barren carbonatites. Therefore, other factors, such as the source region of the parental magma, the depth and degree of melting of that region, and the evolution of the parental magma during ascent and emplacement, control whether or not a carbonatite reaches ore grade.

In terms of regional exploration, the vast majority of the carbonatites in western North America are situated parallel and in close proximity to the Cordilleran deformation front. These carbonatites are of Neoproterozoic to Paleozoic age, are related to rifting and/or extensional tectonic events, and are commonly hosted by miogeoclinal strata. Carbonatites that are distal to the Cordilleran deformation front are (1) the Eocene carbonatites in Montana and Wyoming, which follow a confined N40°W trend, presumably governed by the edge of the subducted Kula plate, and (2) the Mesoproterozoic Mountain Pass carbonatite, which is unique in terms of age and geologic setting.

The repetitive and localized nature of carbonatite and alkaline magmatism makes areas in proximity to known carbonatite occurrences prime exploration targets; furthermore, Th-REE-rich quartz dikes are possibly indicative of buried carbonatitic and alkaline intrusions, and the lack of REE carbonates in amphibolite facies metacarbonatites suggests that these phases are not stable at elevated metamorphic pressure and temperature conditions.

Introduction

CARBONATITES are relatively rare igneous rocks, composed of >50% primary carbonate minerals (Woolley and Kempe, 1989), that are predominantly (≥88%) located in cratons and related to extensional tectonic events (Woolley and Bailey, 2012). The petrogenesis of carbonatites requires metasomatism of their source region (Woolley and Bailey, 2012) and may involve the mixing of various mantle components (Bell and Tilton, 2001).

Carbonatites are of considerable economic and scientific interest; the economic interest is explained by their geochemical enrichment in a range of elements, such as the rare earth elements (REEs), Nb, Ba, Sr, Ta, Th, U, V, F, P, and Zr (e.g., Mariano, 1989; Pell, 1996; Rankin, 2005). This enrichment may reach ore grade for certain elements in some carbonatites, and carbonatite-associated deposits continue to be the major source for Nb and REEs (cf. Rankin, 2005). Examples of well-known deposits are Mountain Pass (United States, light rare earth elements [LREEs]), Oka and St. Honoré/Niobec (Canada, Nb), Jacupiranga (Brazil, P), Amba Dongar (India, CaF₂), and the multicommodity deposit of Phalaborwa (South Africa, P, Ti, Cu, Zr, etc.; Heinrich, 1966;

Mariano, 1989; Richardson and Birkett, 1996). The scientific interest, on the other hand, is driven by diverse peculiarities pertaining to carbonatites, such as their unusual geochemical features, petrogenesis, and associated silicate rocks. These peculiarities entail that the domain of carbonatite research encompasses and sheds light on adjunct areas, such as (intra) continental tectonics, the (deep) carbon cycle, trace element fractionation, mantle metasomatism, and the chemical evolution of the mantle over time (Heinrich, 1980; Bell et al., 1999; Bell, 2001; Bizzaro et al., 2002; Woodard, 2010).

The purpose of the present synthesis is to provide an update of the known carbonatite occurrences in western North America (Figs. 1, 2; Table 1) and to explore their metallogenic setting. Special emphasis will be put on the carbonatite occurrences with published resource estimates. The distribution and available geochronological data of the carbonatite occurrences and associated alkaline rock types are shown in Figure 1 and summarized in Table 1.

Carbonatite Occurrences in Western North America

Woolley and Kjarsgaard (2008) listed 112 carbonatite occurrences in North America (77 in Canada, 12 in Greenland, and 23 in the United States). However, the renewed interest

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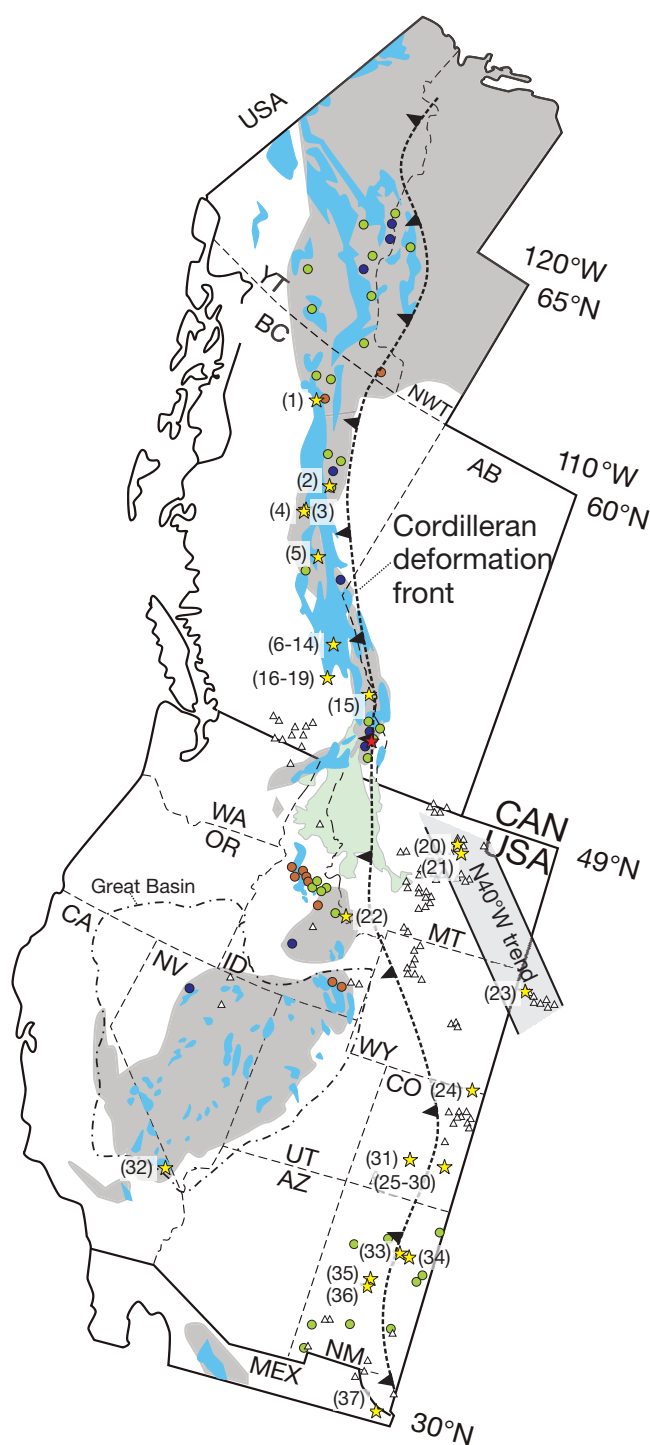


FIG. 1. Map of western North America showing the distribution of carbonatites in relation to the Cordilleran deformation front, miogeoclinal strata, and Neoproterozoic to Cenozoic igneous rocks. Carbonatite occurrences of potential economic importance, as discussed in the text, and intrusion ages obtained from carbonatites (Table 1) are in bold fonts. The red star marks the location of the "Rock Canyon Creek" occurrence, possibly a buried carbonatite, as indicated by REE and F mineralization of sedimentary strata. Data were compiled from Pell (1994), Mutschler et al. (1998), McLemore et al. (1999), Duke (2009), Woolley and Kjarsgaard (2008), Lund et al. (2010), and Millonig et al. (2012a, b). See Figure 3 for a complete list of occurrences in the Blue River area. Age references are given in Table 1.

Carbonatites in Western Canada:

- (1) Kechika area
- (2) Aley (~344 Ma) - Nb, P**
- (3) Vergil (~357 Ma)
- (4) Lonnie (?~357 Ma)
- (5) Wicheeda Lake

Blue River area*:

- (6) Howard Creek (~356 Ma)
- (7) Paradise Lake (~363-340 Ma)
- (8) Serpentine Creek (~341 Ma)
- (9) Little Chicago (~496 Ma)
- (10) Verity (~350 Ma)
- (11) Upper Fir (~332 Ma) - Ta, Nb, P**
- (12) Bone Creek
- (13) Felix (~498 Ma)
- (14) Mud Lake (~328 Ma)

- (15) Ice River (Complex) (~362-357 Ma)

Frenchman Cap dome area:

- (16) Mount Grace (~359 Ma)
- (17) REN/Ratchford Creek (~698 Ma)
- (18) Perry River (~813 Ma)
- (19) Three Valley Gap

Carbonatites in the Western United States and Mexico:

- (20) Rocky Boy Stock (~53-50 Ma)
- (21) Missouri Breaks Diatreme (~50-47 Ma)
- (22) Ravalli and Lemhi Counties (~1100-800, 530, and 370-315 Ma)
- (23) Bear Lodge Mountains (~51-49 Ma) - REE**
- (24) Sloan Pipe

Wet Mountains area - Th, Nb, REEs, U:

- (25) Amethyst and Gribble Mountain
- (26) McCoy Gulch
- (27) Goldie
- (28) McClure Mountain-Iron Mountain (~535-506 Ma)
- (29) Democrat Creek (~534-511 Ma)
- (30) Gem Park (~551 Ma)

- (31) Iron Hill (~561 Ma; ~579-567 Ma) - REEs, Nb, Th**
- (32) Mountain Pass (~1375 Ma; ~1450-1380 Ma) - REEs**

- (33) Monte Largo Hills
- (34) Lobo Hill (~518 Ma)
- (35) Lemitar Mountains (~449 Ma)
- (36) Chupadera Mountains (?~449 Ma)
- (37) Chihuahua carbonatite complex (≥37 Ma)

- Neoproterozoic (709-650 Ma) alkalic igneous rocks
- Cambrian-Ordovician alkalic igneous rocks
- Devonian-Mississippian igneous rocks
- △ Laramide (75-42 Ma) alkaline igneous centers
- Paleozoic miogeoclinal rocks
- Neoproterozoic miogeoclinal rocks
- Mesoproterozoic Belt-Purcell basin

in carbonatites as sources for "rare metals," such as Nb, Ta, and REEs, has led to the discovery of new occurrences in recent years (Table 1; Figs. 1, 3). This review focuses on

the carbonatites found in western North America, which we define as the area shown in Figure 1. This seemingly arbitrary definition is based on recognition that most of the carbonatites

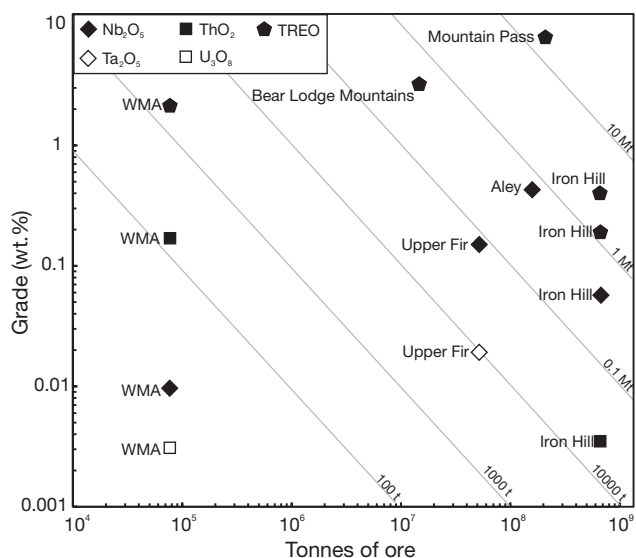


FIG. 2. Grade-tonnage relationships for carbonatite-hosted deposits discussed in the text. Data and references are given in Table 2. Note that not all of the listed carbonatite occurrences may prove to be economic. Two different estimates are shown for total rare earth oxides at Iron Hill; see Table 2 for details. WMA = Wet Mountains area.

contained in this region share related geodynamic histories, as discussed in the Metallogeny section. Note that we have not included the Shanks Bend diatreme and Rainy Creek occurrences in our discussion and these are not shown in Figure 1 or listed in Table 1 due to their dubious identification as carbonatites (Woolley and Kjarsgaard, 2008).

The area shown in Figure 1 hosts more than 37 carbonatite occurrences, at least six of which are considered to be of potential economic importance. For the purpose of this study, “potential economic carbonatites” are those occurrences that are in the advanced stages of exploration and have published resource estimates, or are past and possibly future producers, such as Mountain Pass (Fig. 2; Table 2; cf. Berger et al., 2009; Long et al., 2010; Simandl and Hancock, 2011; Simandl et al., 2011). Note that the various occurrences in the Wet Mountains area, Colorado, are treated as one entity and that not all approximately 28 occurrences from the Blue River area (Fig. 3), British Columbia, are counted separately, as discussed in the Occurrences section. In the following sections we will summarize the geology and mineralogy of carbonatites with published resource estimates according to their geographic positions from north to south. Resource estimates and grades of the respective carbonatite-hosted deposits are given in Table 2 and Figure 2, and commodities of economic interest include Nb, Ta, P, Th, U, and the REEs. Furthermore, alkaline rocks associated with the Iron Hill carbonatite contain substantial resources of Ti, Fe, U, and V (cf. Armbrustmacher, 1981; Van Gosen and Lowers, 2007).

Potentially economic carbonatites in British Columbia, Canada

The alkaline rock and carbonatite occurrences in the Cordillera of British Columbia were last reviewed by Woolley (1987) and Pell (1994). Notably, the prediction made by Woolley (1987, p. 5) that “it is likely that many future

TABLE 1. Intrusion Ages of the Carbonatites and Associated Alkaline Rocks in Western North America Shown in Figure 1

Ref. no.	Location name ¹	Country	Province/state	Inferred intrusion age	Dating method	Age reference	Associated igneous rock types
1	Kechika area	Canada	British Columbia	n.a.			Trachyte, sodalite-cancrinite syenite, tuffs, and a breccia and tuffite pipe
2	Aley	Canada	British Columbia	339 ± 12, 349 ± 12 Ma, 323 ± 10, 338 ± 3 Ma; 365.9 ± 2.1 Ma	K-Ar on mica from carbonatite; K-Ar and Rb-Sr on phlogopite from the allititic Ospika pipe; U-Pb on titanite from the Ospika pipe	LeConteur (1986, pers. com.), quoted in Mäder (1986); McLeish et al. (2011b)	Aegirine-magnesian arvedsonite rock; lamprophyre dikes
3	Vergil	Canada	British Columbia	340, 351–365 Ma; 357 ± 17 Ma	U-Pb and Pb-Pb on zircon from carbonatite; U-Pb on zircon from carbonatite	Pell (1994); Rukhlov and Bell (2010)	Syenite, fenite
4	Lonnie	Canada	British Columbia	Age inferred to be similar to that of the Vergil carbonatite (Pell, 1994)			Fenite
5	Wicheeda Lake	Canada	British Columbia	n.a.			Aegirine-, cancrinite-, and leucite-bearing syenites, dikes of feldspar and augite-feldspar porphyry and sodalite-albite rock
6	Blue River area ² Howard Creek	Canada	British Columbia	356 ± 2 Ma	U-Pb on zircon from lempriereite (apatite-titanite-amphibole rock, ± pyroxene, calcite, allanite)	Millonig et al. (unpub. data)	Amphibole melteigite, nepheline syenite

TABLE 1. (Cont.)

Ref. no.	Location name ¹	Country	Province/state	Inferred intrusion age	Dating method	Age reference	Associated igneous rock types
7	Paradise Lake	Canada	British Columbia	340, 351, 363 Ma	U-Pb and Pb-Pb on zircon from syenite	Pell (1994)	Nepheline and sodalite syenite gneisses
8	Serpentine Creek	Canada	British Columbia	341 ± 6 Ma	U-Pb on zircon from carbonatite	Millonig et al. (2012a)	n.a.
9	Little Chicago	Canada	British Columbia	496 ± 6 Ma	U-Pb on zircon from carbonatite	Millonig et al. (2012b)	n.a.
10	Verity	Canada	British Columbia	350 ± 13 Ma	U-Pb on zircon from carbonatite	Rukhlov and Bell (2010)	Carbonatite isolated, but sodalite syenite in the vicinity
11	Upper Fir	Canada	British Columbia	332 ± 5 Ma	U-Th-Pb on zircon from carbonatite?	Simonetti (2008) in Stone and Selway (2010)	n.a.
12	Bone Creek	Canada	British Columbia	n.a.			Nepheline syenite
13	Felix	Canada	British Columbia	498 ± 2 Ma	U-Pb on zircon from carbonatite	Millonig et al. (2012a)	n.a.
14	Mud Lake	Canada	British Columbia	328 ± 30 Ma	U-Pb on zircon from carbonatite?	Parrish (1985; pers. com.), quoted in Pell (1994)	Nepheline syenite
15	Ice River (Complex)	Canada	British Columbia	357 ± 1 Ma; 362 ± 1 Ma	U-Pb on perovskite from ijolite; U-Pb on perovskite from ijolite and melteigite	Heaman (2009); Tappe and Simonetti (2012)	Jacupirangite, ijolite-urtite, syenites
<u>Frenchman Cap dome area:</u>							
16	Mount Grace	Canada	British Columbia	359 ± 1 Ma	U-Pb on zircon from carbonatite	Millonig et al. (2012a)	Possibly syenitic gneisses
17	REN/Ratchford Creek	Canada	British Columbia	692 ± 21–704 ± 88 Ma	U-Pb on zircon from carbonatite	Millonig et al. (2012a)	Syenite and nepheline syenite gneisses, fenite
18	Perry River	Canada	British Columbia	813 ± 27 Ma	U-Pb on zircon from carbonatite	Millonig et al. (2012b)	Syenite (possibly leucocratic fenite) and mafic fenite, the latter with accessory nepheline
19	Three Valley Gap	Canada	British Columbia	n.a.			Syenite, mafic fenite
20	Rocky Boy stock	United States	Montana	52.9 ± 2.6; 50.0 ± 1.9, 50.5 ± 2.5 Ma	K-Ar on K-feldspar, and K-Ar on biotites from carbonatite	Marvin et al. (1980), quoted in Duke (2009)	Pyroxenite, syenite, monzonite, nepheline syenite, phonolite
21	Missouri Breaks diatremes	United States	Montana	~50–47 Ma	K-Ar (no details given)	Marvin et al. (1980), quoted in Duke (2009)	Kimberlite, mica peridotite, monticellite peridotite, alnöite (cf. Scambos, 1991)
22	Ravalli and Lemhi Counties	United States	Montana and Idaho	99–90 Ma; ~1055 Ma, 1100–800 (mnz cores) and 400–200 (mnz rims) Ma, 370–330 Ma (thorite); 529.1 ± 4.5 Ma; 534.4 ± 0.2 Ma, 317.9 to 315.1 Ma	Pb-alpha on monazite; Re-Os on molybdenite from ore of the Copper Queen mine; U-Th-Pb on monazite (cores and rims) and thorite from ore of the Lucky Horseshoe mine; U-Pb on zircon from syenite; U-Pb on zircon from pyroxene porphyry lamprophyre, and from REE-Th-qtz veins	Jaffe et al. (1959), see also Heinrich (1966); Gillerman et al. (2002); Gillerman et al. (2008); Gillerman et al. (2010)	Fenite; note that age relationships between carbonatite, syenite, lamprophyre, and REE-Th-qtz veins are ambiguous (see text for details)
23	Bear Lodge Mountains	United States	Wyoming	50.5 ± 0.8, 38.3 ± 0.6, 50.5 ± 1.2, and 48.8 ± 1.7 Ma; ~46 Ma	K-Ar on sanidine from two dikes, one trachyte and one phonolite porphyry; Ar-Ar on amphibole from trachyte	Staatz (1983); Duke et al. (2002)	Phonolite, trachyte, syenite, nepheline syenite, latite, pseudoleucite porphyry, lamprophyre
24	Sloan Pipe	United States	Colorado	n.a.			Kimberlite
<u>Wet Mountains area:</u>							
25	Amethyst and Gribble Mountain	United States	Colorado	n.a.			K fenite and veins bearing amethyst and smoky quartz
26	McCoy Gulch	United States	Colorado	n.a.			Lamprophyre, fenite
27	Goldie	United States	Colorado	n.a.			Carbonated lamprophyre, fenite

TABLE 1. (Cont.)

Ref. no.	Location name ¹	Country	Province/state	Inferred intrusion age	Dating method	Age reference	Associated igneous rock types
28	McClure Mountain-Iron Mountain	United States	Colorado	534 ± 4 Ma ; 535 ± 5 Ma; 520, 508, and 506 Ma; 523.2 ± 0.9 Ma; 523.98 ± 0.74, 523.26 ± 1.27, 523.51 ± 2.09 Ma	U-Pb on zircon from (?)-carbonate; Rb-Sr whole-rock isochron; average K-Ar age from amphibole and biotite, and fission track age from titanite; Ar-Ar on hornblende from syenite; U-Pb on zircon, titanite, and apatite from syenite	Bickford et al. (1989), quoted in McMillan and McLemore (2004); Arnbrustmacher and Hedge (1982); Olson et al. (1977); Spell and McDougall (2003); Schoene and Bowring (2006)	Pyroxenite, dunite, gabbro, ijolite, nepheline syenite, trachyte, phonolite, lamprophyre, fenite
29	Democrat Creek	United States	Colorado	519 ± 13, 534 ± 36 Ma; 511 ± 8 Ma	K-Ar on biotite and hornblende from quartz syenite; Rb-Sr whole-rock isochron	Olson et al. (1977); Arnbrustmacher and Hedge (1982)	Pyroxenite, gabbro, dolerite, quartz syenite, lamprophyre
30	Gem Park	United States	Colorado	551 ± 30 Ma	K-Ar on riebeckite from fenite	Olson et al. (1977)	Pyroxenite, gabbro, nepheline syenite, lamprophyre, fenite
31	Iron Hill	United States	Colorado	567 ± 10 Ma; 568 ± 9, 574 ± 9 Ma; 561 ± 10 Ma ; 579 ± 10 Ma; 762 ± 15 Ma	K-Ar on biotite from pyroxenite; K-Ar on biotite from pegmatite; K-Ar on muscovite from carbonatite; Rb-Sr whole-rock isochron; K-Ar on plagioclase from diabase dike (not discussed by Olson et al., 1977)	Olson et al. (1977)	Pyroxenite, mellitohite, ijolite, nepheline syenite, fenite
32	Mountain Pass	United States	California	1440 ± 35, 1385 ± 35 Ma; 1380 ± 50, 1450 ± 80 Ma; 1523 ± 40 Ma; 1410 ± 2 and 1400 ± 8, 1403 ± 7, and 1375 ± 7 Ma	K-Ar on biotite shonkinite; Rb-Sr (same samples); model Pb galena; U-Pb on apatite and Ar-Ar on phlogopite from shonkinite, Ar-Ar on arfvedsonite from syenite, and Th-Pb on monazite from carbonatite	Lamphere (1964); Mitchell (1973); DeWitt et al. (1987)	Potassic shonkinite, syenite, garnite, and fenite
33	Monte Largo Hills	United States	New Mexico	n.a.	Ar-Ar on biotite from monzonite	McLemore et al. (1999)	Syenite, monzonite
34	Lobo Hill	United States	New Mexico	518 ± 5.7 Ma	K-Ar on biotite from silicio-carbonatite dike	McLemore (1982)	Fenites
35	Lemitar Mountains	United States	New Mexico	449 ± 16 Ma			Quartz veins
36	Chupdera Mountains	United States	New Mexico	Likely similar to the Lemitar Mountains (McLemore, 1982)			
37	Chihuahua carbonatite complex	Mexico		≥37.00 ± 0.19 Ma	Ar-Ar on porphyritic latite	Nandigam et al. (2009)	Rhyolite, ignimbrite

Note: Carbonatite-hosted deposits discussed in the text and intrusion ages obtained from carbonatites are in bold

n.a. = not available

¹Following Pell (1994), McMillan and McLemore (2004), Woolley and Kjarsgaard (2008), Duke (2009), and Millonig et al. (2012a)

²See also Figure 3

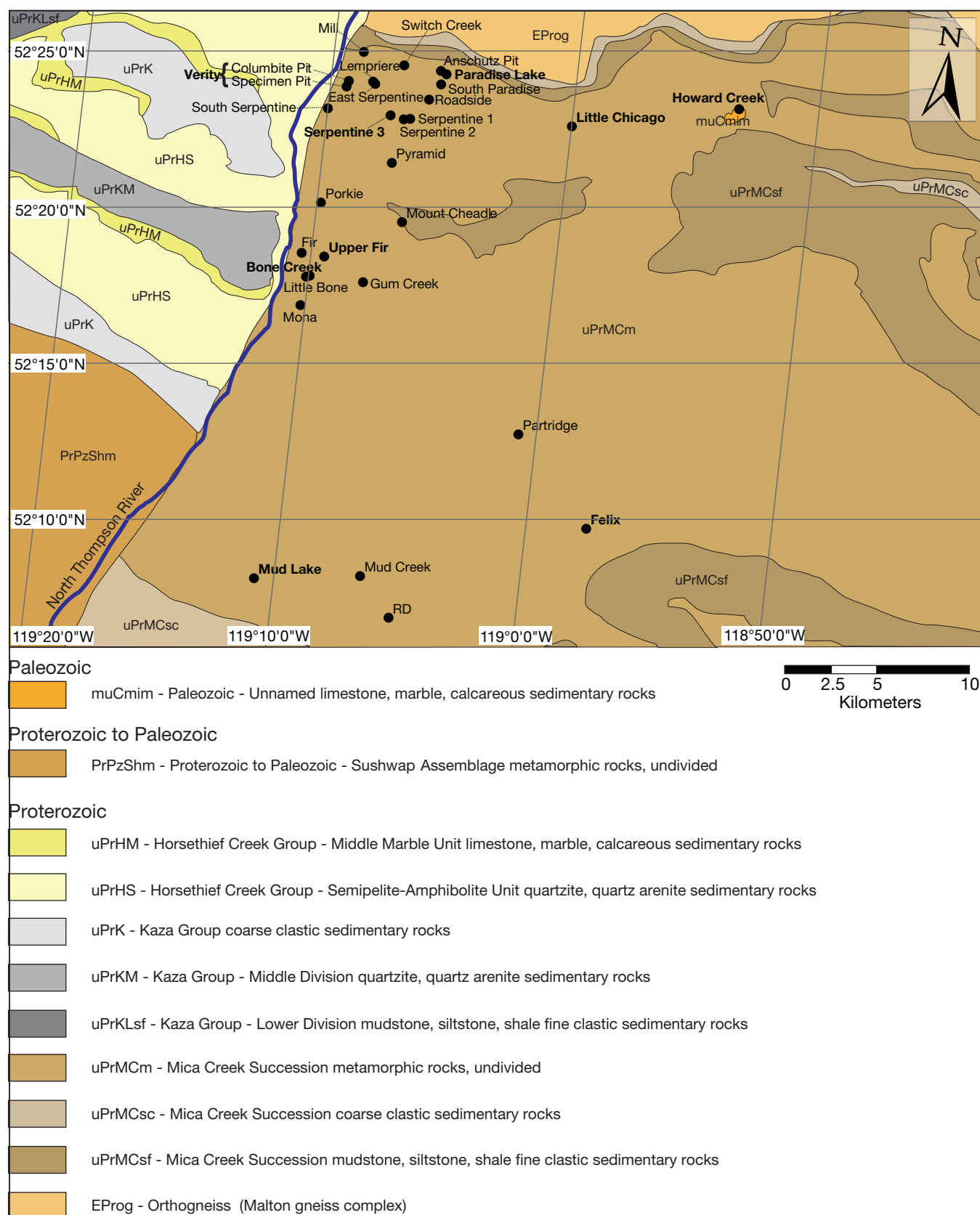


FIG. 3. Geologic map showing the various carbonatite occurrences in the Blue River area, British Columbia. Intrusion ages within this area range from Late Cambrian to early Carboniferous (Table 1), and the occurrences also shown in Figure 1 are in bold. Data provided by Commerce Resources Corp. (pers. com., 2012; cf. Chong et al., 2012).

TABLE 2. Grade-Tonnage Relationships for Carbonatite-Hosted Deposits Shown in Figures 1 and 2 and Discussed in the Text

Deposit name	Country	Deposit volume (metric tons)	Grade (wt %)	Commodity	Resource	Reference
Aley Upper Fir	Canada	158,892,000	0.43	Nb ₂ O ₅	Inferred resources	Simpson (2011)
	Canada	51,800,000	0.0192	Ta ₂ O ₅	Indicated resources	Chong et al. (2012)
			0.149	Nb ₂ O ₅		
		8,800,000	0.0186	Ta ₂ O ₅	Inferred resources	
Bear Lodge Mountains	United States	14,700,000	0.166	Nb ₂ O ₅		
			3.22	TREOs	Measured and indicated resources	Noble et al. (2013)
Wet Mountains area	United States	69,907	0.17	ThO ₂	Estimated resources	Armbrustmacher (1988)
			0.0097	Nb ₂ O ₅		
			0.0031	U ₃ O ₈		
			2.15	TREOs		
Iron Hill	United States	655,600,000	0.4	TREOs ¹	Estimated resources	Long et al. (2010)
			0.19	TREOs ²		
			0.0035	ThO ₂		
			0.057	Nb ₂ O ₅		
Mountain Pass	United States	209,273,183	7.98	TREOs	Estimated proven and probable reserves	SRK Industries (2012)

TREO = total rare earth oxide

¹Average grade from Staatz et al. (1979)²Average grade from Van Gosen (2008)

discoveries (of alkaline volcanic and intrusive rocks) will be concentrated in the latter area (BC)” was proven correct by the discovery of numerous carbonatites, especially in the Blue River area (Figs. 1, 3; Table 1; cf. Gorham et al., 2011a; Chong and Postolski, 2011). Compared to the compilation of Woolley and Kjarsgaard (2008), the number of carbonatite occurrences in that area has increased from five to approximately 28.

Carbonatites of potential economic importance in the advanced stages of exploration in BC are the Aley and the Upper Fir occurrences (Fig. 1; Simandl and Hancock, 2011). These carbonatites possibly contain substantial resources of Nb, Ta, and P (Table 1; Fig. 2).

Aley carbonatite

The Aley carbonatite, discovered in 1980, represents a potential resource of Nb and P (Pell, 1994; Richardson and Birkett, 1996) with inferred resources of 158,892,000 tonnes (t) grading 0.43% Nb₂O₅ (Fig. 2; Table 2; Simpson, 2011). Recent resource estimates, however, do not include phosphorous (Simpson, 2011). The principal ore phases for Nb are pyrochlore and its alteration products fersmite and columbite, and for P it is apatite (Pell, 1994; Richardson and Birkett, 1996; Simpson, 2011). The geology and mineralogy of the complex have been investigated and described by Pride (1983), Mäder (1986, 1987), and Pell (1986, 1994), and the following summary is based on these studies.

The Aley carbonatite complex is circular in outline, 3 to 3.5 km in diameter (Fig. 4), and intruded Cambrian miogeoclinal sediments between 349 ± 12 and 339 ± 12 Ma (K-Ar on mica from carbonatite; LeCouteur, 1986, pers. com., quoted in Mäder, 1986; Table 1). According to Mäder (1987) and Pell (1994), the emplacement predates a main Late Jurassic-Early Cretaceous orogenic event and subgreenschist facies metamorphism. In contrast, McLeish et al. (2011a) proposed a syndeformational emplacement at ~365 Ma, based on structural relationships and U-Pb dating

of lamprophyre dikes and the aillikitic Ospika pipe diatreme (Pell, 1994; Fig. 4), which are spatially associated with the carbonatite complex. The relationship between these alkaline rocks and the carbonatites is, however, ambiguous (Pell, 1994) and inferred emplacement ages (Table 1) for the Ospika pipe range from 323 ± 10 (K-Ar on phlogopite, LeCouteur, 1986, quoted in Mäder, 1986) to 365.9 ± 2.1 Ma (U-Pb on titanite, McLeish et al., 2011b).

The core of the carbonatite complex (Fig. 4) consists of a ~2-km-wide dolomite-carbonatite that also contains calcite-carbonatite and rare earth carbonate “sweats” (Pell, 1994). This inner zone is composed of dolomite (80–95%), apatite (5–15%), and minor amounts of phlogopite, pyrite, magnetite, monazite, strontianite, and zircon. The rare earth carbonate-rich sweats are composed of crystal aggregates of huanghoite and bastnäsite in a matrix of dolomite. Surrounding this core zone is a calcite-carbonatite (McLeish, 2011b) and a ~1-km-wide zone of “amphibolite” (amphibole-syenite of Mäder, 1986). The latter is interpreted to be a primary igneous phase, metasomatically altered to fenite (Mäder, 1986). The mineralogy of the calcite-carbonatites is variable and is dominated by calcite with or without dolomite, apatite, biotite, magnetite, richterite, pyrochlore, fersmite, and pyrite. Zircon, baddeleyite, and zirkelite have also been reported (Pell, 1994). The “amphibolite” (fenite?) consists of magnesioarfvedsonite, quartz, albite, and aegirine. Furthermore, rare earth carbonate-rich ferrocarnatite dikes preferentially occur in a ~500-m-wide contact aureole of recrystallized carbonate rocks, outward from the “amphibolite” zone. These dikes contain burbankite, cordylite, and huanghoite together with abundant barite and secondary quartz. In total, Mäder (1987) lists about 50 identified minerals from the Aley carbonatite complex. The tentatively suggested sequence of emplacement for the complex is (amphibole-)syenite, dolomite-carbonatite, calcite-carbonatite, and rare earth-carbonatite dikes (Mäder, 1986).

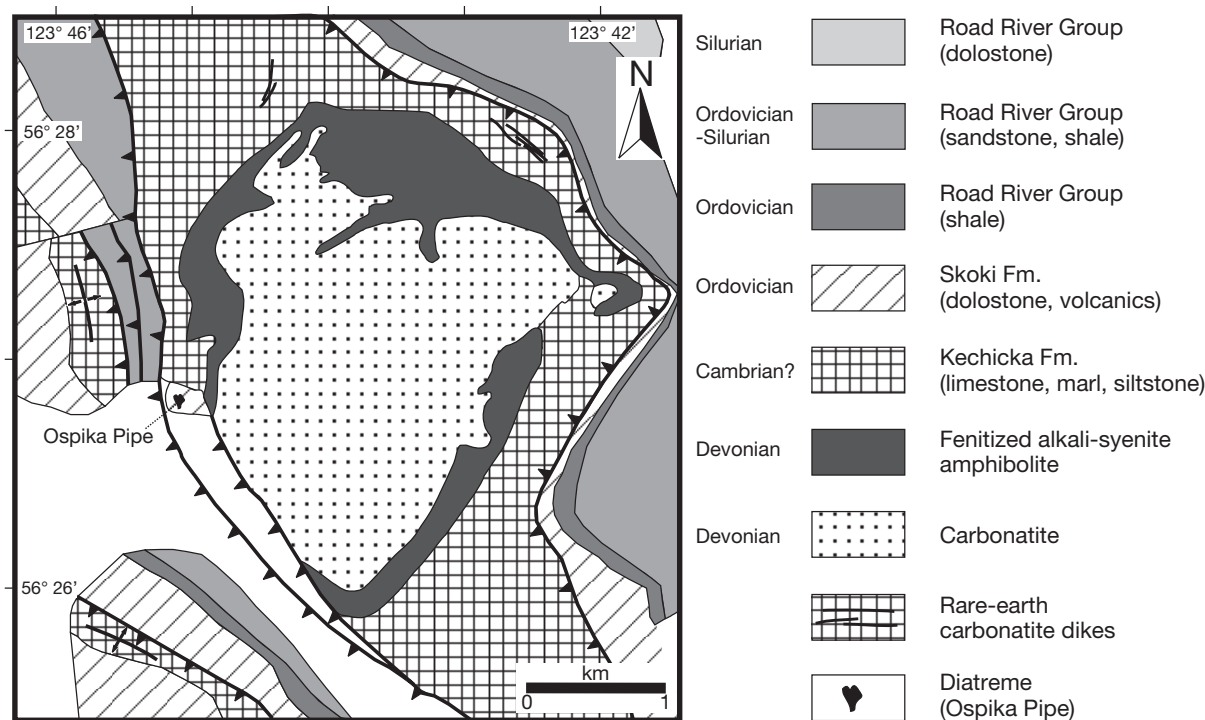


FIG. 4. Simplified geologic map of the Aley carbonatite, British Columbia, modified after Mäder (1986). The circular to round shape of the Aley carbonatite is regarded as typical for carbonatite intrusions in general.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7034 to 0.7036 suggest a genetic relationship between the (amphibole-) syenite and the carbonatite and are indicative of a mantle source for these rocks (Mäder, 1986). In addition, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotope values of unaltered calcite, dolomite, and ankerite from the calcite-carbonatite, dolomite-carbonatite, and rare earth-carbonatite dikes, respectively, are also consistent with a mantle origin (Mäder, 1987).

Blue River area

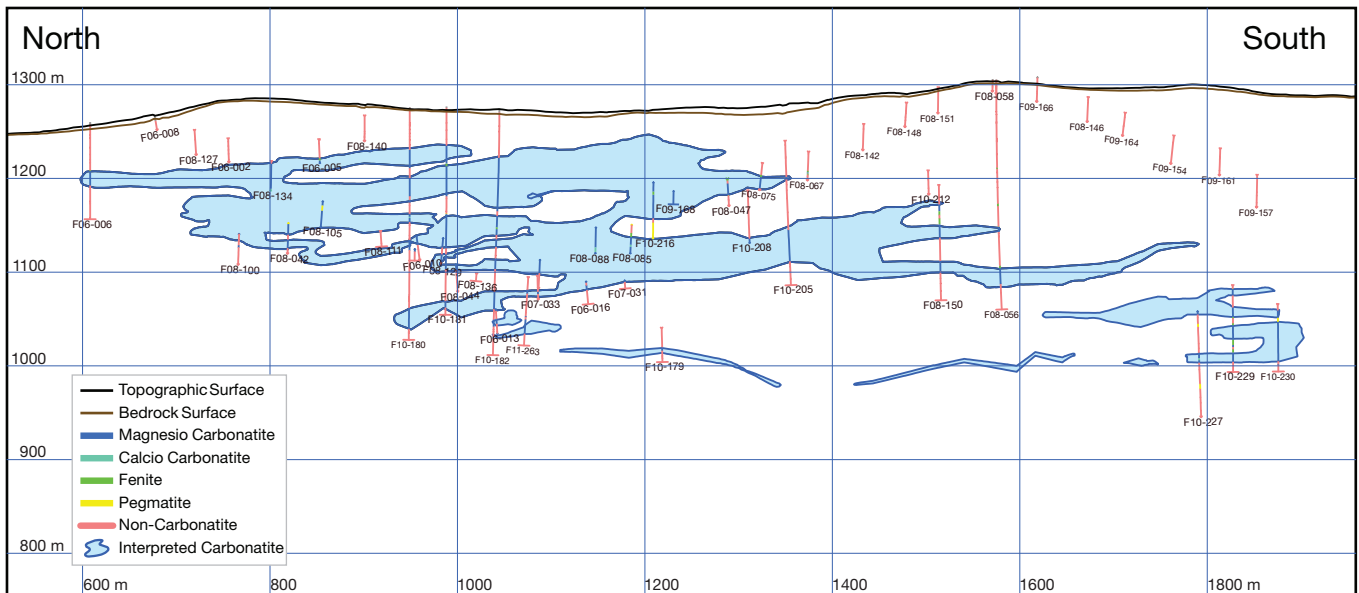
The Blue River area is host to ≥ 28 carbonatite occurrences (Figs. 1, 3; Table 1; Pell, 1994; Woolley and Kjarsgaard, 2008) and has been subject to intermittent exploration for vermiculite, P, REEs, U, Nb, and Ta since the 1950s (Pell, 1994; Gorham et al., 2011a). A comprehensive review of the exploration history and of literature on the local geology is presented in Gorham (2007) and Gorham et al. (2011a). Due to the recent nature of many of the discoveries, a complex deformational history, and commonly poor outcrop conditions, only limited information on the mineralogy and associated alkaline rock types is available for many carbonatite occurrences in the Blue River area. Furthermore, some of the occurrences shown in Figure 3 may be part of a single intrusion that was disrupted during subsequent deformation (cf. Fig. 5). Considering this, all occurrences known as of 2012 are shown and listed in Figure 3, but only carbonatites that have been studied in some detail are shown in Figure 1.

The best studied occurrence in the Blue River area is the "Upper Fir" carbonatite, with indicated resources of 51.8 Mt grading 192 ppm Ta_2O_5 and 0.15% Nb_2O_5 (Figs. 2, 5; Table 2; Chong et al., 2012). Principal ore phases in this carbonatite are pyrochlore and ferrocolumbite (Chong and Postolski,

2011). According to Mariano (1982), the pyrochlore from the Blue River carbonatites has Nb/Ta ratios of ~ 6 , unlike most carbonatite pyrochlores, which have Nb/Ta ratios averaging 200 to 500.

The carbonatites in the Blue River area occur as layers and lenses within miogeoclinal metasediments and amphibolites of the late Neoproterozoic Horsethief Creek Group (Fig. 3; Pell, 1994). These carbonatites and associated alkaline rocks, when present, were emplaced during the Late Cambrian (~ 500 Ma; U-Pb on zircon from carbonatite) and Late Devonian to early Carboniferous (~ 363 – 328 Ma; U-Pb on zircon from carbonatite; Table 1; Millonig et al., 2012a). The igneous rocks and enclosing strata were subsequently deformed during up to five events and metamorphosed to amphibolite facies grade (cf. Pell, 1994; Kraft, 2010, in Gorham et al., 2011b). This complex deformational and metamorphic history caused the partial remobilization of Ta and Nb by dissolution-precipitation processes, as inferred from the replacement of pyrochlore by ferrocolumbite, and led to the development of a variety of textures that are strongly dependent upon the mineralogy and rheology of the respective carbonatites and their structural position within the complex (Chudy and Groat, 2011a, b).

The two main carbonatite rock types in the Blue River area are dolomite- and calcite-carbonatite, both of which display considerable mineralogical variations. The dolomite-carbonatite is mainly composed of ferroan dolomite, amphibole (Na-Ca, Fe-Mg), and fluoroapatite, and may contain varying amounts of magnetite, phlogopite, ilmenite, pyrochlore, ferrocolumbite, fersmite, calcite, monazite, sulfides, and zircon (Pell, 1994; Chudy and Groat, 2010, 2011b). A subtype of the dolomite-carbonatite is composed of almost pure dolomite (Chudy and Groat, 2010, 2011b). In



contrast, the calcite-carbonatite is mainly composed of calcite, fluoroapatite, magnetite, and (Fe-Mg) amphibole with minor to trace amounts of zircon, olivine, pyroxene, phlogopite, dolomite, monazite, sulfides, pyrochlore, and ferrocolumbite (Pell, 1994; Chudy and Groat, 2010). Pell (1994) noted that a subtype of this lithology, associated with nepheline syenite, occurs at the Paradise Lake locality (Fig. 1) and is composed of calcite, biotite, apatite, and magnetite, with or without nepheline and sodalite and in places with abundant zircons.

Alkaline rock types that may be associated with the carbonatites of the Blue River area are (1) nepheline and sodalite syenites, typically composed of microcline, plagioclase, nepheline, and biotite, with accessory muscovite, sodalite, cancrinite, zircon, and perthite (Pell, 1994); and (2) mafic to ultramafic silicate rocks that are mainly composed of varying amounts of amphibole, pyroxene, and titanite, with or without accessory nepheline, plagioclase, pyrite, calcite, biotite, allanite, apatite, olivine(^P), magnetite, and spinel (Pell, 1994; Chudy and Groat, 2010). Furthermore, mafic biotite-vermiculite or amphibole fenites commonly separate carbonatites and host rocks (Pell, 1994; Chudy and Groat, 2010). Notably, no REE carbonates have been documented from carbonatites of the Blue River area.

Total trace element distributions of the Blue River carbonatites, associated alkaline rock types, and Sr isotope ratios support a mantle origin for these rocks (Mariano, 1982; A. Rich, pers. com., 1982, in Mariano, 1982).

(Potentially) economic carbonatites in the western United States of America

The area shown in Figure 1 comprises four carbonatite occurrences in the United States for which resource estimates for carbonatite-hosted deposits are available (Castor, 2008b; Berger et al., 2009; Long et al., 2010; Noble et al., 2013).

Commodities of economic interest are the REEs, Th, Nb, and U (Fig. 2).

Bear Lodge Mountains, Wyoming

The Bear Lodge Mountains are situated in northeastern Wyoming and form part of a series of Tertiary alkaline intrusions extending from the Black Hills uplift of western South Dakota to northeastern Wyoming (Luedke, 1994; Noble et al., 2013). The LREE mineralization is predominantly hydrothermal in origin (Mariano and Mariano, 2012) and hosted in carbonatite dikes that occur in the southern part of the mountains in the center of the Bear Lodge dome, which is principally composed of trachyte (~46 Ma; Ar-Ar on amphibole; Duke et al., 2002) and phonolite (Staat, 1983). According to Noble et al. (2013), the mineralized dikes contain measured plus indicated resources of 14.7 Mt grading 3.22% total rare earth oxide (TREO; Table 2; Fig. 2). The commonly oxidized REE-bearing dikes formed late in the magmatic sequence of the complex (<46 Ma), are up to 40 m wide, and range in composition from carbonatitic to silica-carbonatitic (Noble et al., 2013). The main ore phases in the unoxidized dikes are ancylite-(Ce) plus lesser carbocelestite (Mariano and Mariano, 2012). Furthermore, the REE minerals calcioancylite, bastnäsite, parisite, synchysisite, monazite, cheralite, burbankite, and cerianite occur in the oxidized and unoxidized carbonatites (Mariano and Mariano, 2012). Gangue minerals include calcite, biotite, K-feldspar, apatite, clinopyroxene, strontianite, dolomite, barite, celestite, sulfides, and Fe-Ti oxides (Staat, 1983; Noble et al., 2013). Isotopic values ($\epsilon_{\text{Nd}} \sim -1$; $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.70463$; Duke, 2009, and references therein) are interpreted to indicate a dominantly asthenospheric source for the carbonatite dikes.

Wet Mountains area, Colorado

The Wet Mountains area, Colorado, includes three central alkaline complexes—the McClure Mountain-Iron

Mountain, Gem Park, and Democrat Creek complexes—as well as associated carbonatite dike swarms (Table 1; Heinrich, 1966; Armbrustmacher, 1984; Woolley, 1987). The latter include carbonatite occurrences referred to as Amethyst and Gribble Mountain (Heinrich and Shappirio, 1966), Goldie (Heinrich, 1977; Bailey, 1980), and McCoy Gulch (Heinrich and Salotti, 1975; Armbrustmacher, 1988). It should be noted that no “Wet Mountains” carbonatite per se, as listed in Woolley and Kjarsgaard (2008), exists. The following summary of the geology of the Wet Mountains area is based on Armbrustmacher (1988), if not stated otherwise.

Three deposit types, discovered in the late 1940s, that potentially contain economic amounts of Th, together with REEs and Nb, can be distinguished in the Wet Mountains area: (1) quartz-barite-thorite veins and fracture zones, (2) carbonatite dikes, and (3) red syenite dikes. Type (1) contains the largest resources of Th, Nb, U, and REEs; all three deposit types are genetically and spatially related to the three aforementioned alkaline complexes.

The carbonatite dikes can be further subdivided into replacement carbonatites and primary magmatic carbonatites, of which the latter appear “to be the better source of potentially economic commodities” (Armbrustmacher, 1984, p. F1). The primary magmatic carbonatite dikes are a few cm to 3 m wide and up to ~350 m long, except for a plug-shaped, approximately 30 m wide carbonatite that occurs southeast of the Gem Park alkaline complex (Parker and Sharp, 1970). The seven largest carbonatite dikes contain, on average, 0.17% ThO₂, 0.0097% Nb₂O₅, 0.0031% U₃O₈, and 2.15% total rare earth oxides. The estimated resources for these dikes are 119 t ThO₂, 36 t NbO₂, 15 t U₃O₈, and 2,268 t TREOs, and probable potential resources are 683 t ThO₂, 207 t Nb₂O₅, 95 t U₃O₈, and 12,973 t TREOs (Armbrustmacher, 1988). The REEs are mainly contained in bastnäsite, synchysite, ancylite, and monazite.

The main carbonate phase in the dikes is either calcite (Armbrustmacher, 1988) or dolomite (Parker and Sharp, 1970); bastnäsite, synchysite, quartz, microcline, hematite, and barite are common constituents. In addition, ancylite, strontianite, ankerite, monazite, xenotime, and fluorapatite may occur in varying amounts, as well as the accessory minerals thorite, fluorite, pyrochlore, pyrite, sphalerite, and galena. For a more comprehensive list of minerals, see Heinrich (1966), table 3 of Parker and Sharp (1970), and table 1 of Armbrustmacher (1988).

The alkaline complexes and associated carbonatites, lamprophyres, red syenites, and quartz-barite-thorite veins were emplaced into Proterozoic metasediments, metavolcanic rocks, quartz diorites, granodiorites, and granites (Armbrustmacher, 1984) during the Cambrian to Early Ordovician (Table 1; Olson et al., 1977), presumably in an aulacogen setting (McMillan and McLemore, 2004). Fenites developed in the contact zone between the alkaline rocks and the host rocks (Armbrustmacher, 1988). The three aforementioned alkaline complexes may contain nepheline syenite, hornblende-biotite syenite, mafic nepheline-pyroxene rocks, and (layered) mafic-ultramafic cumulates, as well as quartz syenite (Democrat Creek only).

The inferred magmatic sequence for the McClure Mountain-Iron Mountain Complex, from oldest to youngest, is gabbro and peridotite with titanomagnetite lenses, syenite,

ijolite and nepheline syenite, alkalic dikes and lamprophyres, and carbonatites (Heinrich, 1966). However, Armbrustmacher (1988) points out that in some instances the carbonatites predate the lamprophyres. More elaborate descriptions of the three alkaline complexes and their rock types are given, e.g., in Parker and Sharp (1970), Armbrustmacher (1984), and Armbrustmacher (1988). The most robust age data stems from the McClure Mountain syenite, which contains the K-Ar, ⁴⁰Ar-³⁹Ar hornblende standard MMhb with an age of 523.26 ± 1.27 Ma (Table 1; cf. Spell and McDougall, 2003; Schoene and Bowring, 2006). Based on crosscutting relationship, the carbonatites postdate this syenite.

On the basis of differences in age, mineralogy, chemistry, and initial Sr isotope ratios, Armbrustmacher and Hedge (1982) concluded that fundamental genetic differences exist between rocks of the McClure Mountain Complex and Democrat Creek, and postulated that at least three distinct source materials and a variety of geologic processes, e.g., liquid immiscibility and crystal fractionation, were necessary to form the major alkaline rock types of the Wet Mountains area.

Iron Hill, Colorado

The Iron Hill alkaline complex, Powderhorn district, Colorado, is situated ~135 km west of the alkaline complexes of the Wet Mountains area (Fig. 1; Olson et al., 1977) and is considered “the best example of the carbonatite-alkalic rock association in the United States” by Olson and Hedlund (1981, p. 5). Owing to this, its early discovery in the 1870s, and its varied and substantial mineral resources (Olson et al., 1977; Van Gosen and Lowers, 2007; Long et al., 2010), a wealth of studies have been published about this complex. Aspects of the geology, geochemistry, mineralogy, and geochronology of this alkaline complex have been covered in considerable detail by, e.g., Larsen (1942), Olson and Wallace (1956), Temple and Grogan (1965), Nash (1972), Olson et al. (1977), and Olson and Hedlund (1981).

The economic potential of the complex has recently been reviewed by Van Gosen and Lowers (2007) and potential commodities include Ti, Fe, Nb, REEs, Th, U, V, and vermiculite (see also Staatz et al., 1979; Armbrustmacher, 1981; Olson and Hedlund, 1981). The carbonatite stock, with an estimated rock mass of 722.7 million short tons (655.6 million tonnes [Mt]; Table 2; Staatz et al., 1979; Van Gosen, 2009), as well as radial and concentric carbonatite dikes (Nash, 1972) are especially enriched in the REEs, Nb, and Th (cf. Van Gosen, 2008; Long et al., 2010). According to Long et al. (2010), the carbonatite stock contains estimated resources of 1.34 Mt of TREOs, 25,300 t of ThO₂, and 412,000 t of Nb₂O₅ (Fig. 2). These estimates are based on the median values of 0.19% TREO and 0.0035% ThO₂ (Van Gosen, 2008, in Long et al., 2010), and 0.057% Nb₂O₅ (Staatz et al., 1979). In contrast, applying median values of 0.4% TREO and 0.0043% ThO₂ (Staatz et al., 1979), the estimated resources are 2.865 Mt and 31,080 t, respectively (Castor, 2008b; Van Gosen, 2009; Long et al., 2010). Other rock types of potential economic importance include a perovskite-rich pyroxenite unit and Th-rich hydrothermal veins (Armbrustmacher, 1981; Van Gosen and Lowers, 2007). The former is likely the largest titanium resource in the United States (Long et al., 2010), with mineable proven, probable, and possible reserves of 41.8 Mt

grading 13.2% TiO₂ (Shaver and Lunceford, 1998, in Van Gosen, 2009). In contrast, Teck Cominco Limited reported an inferred resource of 1,031 Mt grading 10% TiO₂ for its White Earth property, located within the northeastern part of the pyroxenite unit (Van Gosen, 2009; Teck Cominco Limited, 2005). Perovskite is, however, currently not a competitive economic resource for titanium (Mariano, pers. com., 2013).

According to Nash (1972), the carbonatites at Iron Hill are composed dominantly of ankeritic dolomite, siderite, or calcite. The carbonatite stock, in particular, is composed chiefly of ankeritic dolomite and minor amounts of apatite, phlogopite, biotite, barite, pyrite, calcite, magnetite, ilmenite, pyrochlore, and sodic amphibole (Olson and Hedlund, 1981). Moreover, the carbonatite dikes consist of dolomite, calcite, siderite, biotite, phlogopite, pyrite, barite, apatite, orthoclase, pyrochlore, monazite, chalcopryrite, sphalerite, galena, fluorite, synchysite, and parasite, listed in decreasing abundance (Olson and Hedlund, 1981). Rare calcite-carbonatite at Iron Hill intrudes ijolite and contains euhedral aegirine-augite, biotite, titanite, apatite, magnetite and, frequently, melanite (Nash, 1972).

Rocks of the Iron Hill alkaline complex comprise, from oldest to youngest, pyroxenite, uncomphagrite, ijolite, diverse hybrid pyroxenite-syenite rocks, magnetite-ilmenite-perovskite bodies, nepheline syenite, and carbonatite (Hedlund and Olson, 1961; Olson et al., 1977). These rocks intruded at about 570 Ma (Olson et al., 1977; see Table 1 for details), presumably in an aulacogen setting (McMillan and McLemore, 2004), and are ~50 m.y. older than the alkaline complexes of the Wet Mountains area (~523 Ma). Olson et al. (1977, p. 686) suggest that the age relations between these two alkaline districts may be due to the “migration of sites of localized melting or volatile enrichment in the mantle, or westward movement of the continent above a single site.” Alternatively, given the proposed aulacogen setting (McMillan and McLemore, 2004), localized rifting or extensional tectonics may have triggered the alkaline magmatism.

Based on rock associations, textural evidence, and Sr isotope data, Nash (1972) proposed the following evolution for the Iron Hill alkaline complex: Crystal fractionation of a carbonated mafic nephelinitic magma produced the silicate rocks, such as pyroxenite, uncomphagrite, ijolite, and nepheline syenite. This fractionation process led to an enrichment of the remaining magma in CO₂ and H₂O until the separation of a discrete carbonate fluid took place, shortly followed by the crystallization of the calcite-carbonatite. The carbonate-rich fluid differentiated further to produce the (ankeritic) dolomite-carbonatites and, ultimately, siderite dikes. Further crystallization of this carbonate-rich fluid resulted in hydrothermal veins rich in thorium minerals, barite, fluorite, and quartz. Inferred emplacement temperatures for these successive carbonatite varieties decreased from 700° to 300°C (Nash, 1972).

Besides these Late Proterozoic alkaline rocks, another suite of intrusions, ranging in composition from leucosyenitic to shonkinitic (Olson and Wallace, 1956), was emplaced prior to and in close vicinity of the Iron Hill alkaline complex. Geochronological studies on these rocks by Fenton and Faure (1971) yielded Rb-Sr whole-rock ages of 1443 ± 77 and 1454 ± 88 Ma for the syenites (see discussion in Olson and Marvin,

1971). These results are within error of K-Ar biotite ages of 1380 ± 40 to 1390 ± 40 Ma obtained by Olson et al. (1977), also from the syenites. In addition, a K-Ar biotite age of 1330 ± 36 Ma obtained from a minette (calcite-biotite-microcline) dike is interpreted to possibly indicate that the dike is a late differentiate related to the earlier intrusions (Olson et al., 1977). The emplacement of these Mesoproterozoic alkaline rocks was coeval with similar rocks at Mountain Pass and their significance is further discussed in the Metallogeny section.

Mountain Pass, California

The carbonatite deposit at Mountain Pass, California (Figs. 1, 6), was discovered between 1949 and 1950 (Olson et al., 1954), and was the world's main source of REEs from 1965 to 1995 (Castor, 2008b). The Mountain Pass ore is especially enriched in the light REEs (Haxel, 2005) and Molycorp Inc. recently resumed production. The deposit is estimated to contain proven and probable mineral reserves of 18.4 million short tons (16.7 Mt) of rare earth ore at an ore grade of 7.98% REO (Table 2; SRK Industries, 2012). Bastnäsite, interpreted to be of primary magmatic origin (Mariano, 1989), is the principal ore phase at Mountain Pass (Olson et al., 1954; Castor, 2008a). Relatively little has been published on the Mountain Pass carbonatite after 1954, and the study of Olson et al. (1954) remains the most comprehensive report on its geology (cf. Castor, 2008b; Long et al., 2010).

The inferred sequence of emplacement for the alkaline rocks at Mountain Pass is shonkinites, syenites, granites, shonkinitic dikes, and magmatic and hydrothermal carbonatites (Olson et al., 1954). These rocks are part of a narrow, but at least 130-km-long, N-trending zone of ultrapotassic alkaline rocks of similar age (Castor and Nason, 2004), and are intruded into Precambrian metamorphic rocks at ~1410 to 1400 Ma (U-Pb on apatite and ⁴⁰Ar-³⁹Ar on phlogopite from shonkinites), 1403 ± 7 Ma (⁴⁰Ar-³⁹Ar on arfvedsonite from syenite), and 1375 ± 7 Ma (Th-Pb on monazite from carbonatite; Table 1; DeWitt et al., 1987; see also Lanphere, 1964). The granites are assumed to be similar to the syenites in age (Castor, 2008b).

The following description of the Mountain Pass carbonatites is based on Olson et al. (1954), if not stated otherwise. The main orebody, referred to as the Sulphide Queen carbonatite, is a massive carbonatite approximately 215 × 730 m in size. In addition, a total of ~200 carbonatite veins and mineralized shear zones, up to ~6 m wide and 185 m long, have been documented from the area. Calcite is the most abundant carbonate, followed by dolomite, ankerite, and siderite. These carbonates are mostly fine grained and account for up to 60% of the massive carbonatite and associated veins. Other constituents present in variable amounts include barite, bastnäsite, parisite, quartz, and minor amounts of magnesiocrocidolite, biotite, phlogopite, chlorite, muscovite, apatite, hematite, goethite, fluorite, monazite, galena, allanite, cerite, titanite, pyrite, chalcopryrite, tetrahedrite, malachite, azurite, strontianite, sahamalite (Jaffe et al., 1953), cerussite, wulfenite, aragonite, and thorite, as well as pyrochlore, vanadinite, strontio-barite, barite-celestine, and rutile (Mariano, 1976, 1980). Notably, the Mountain Pass carbonatites are characterized by overall unusually low contents of Nb-, Ti-, and Zr-bearing minerals, as well as low apatite and magnetite contents, compared to other carbonatites (Olson et al., 1954;

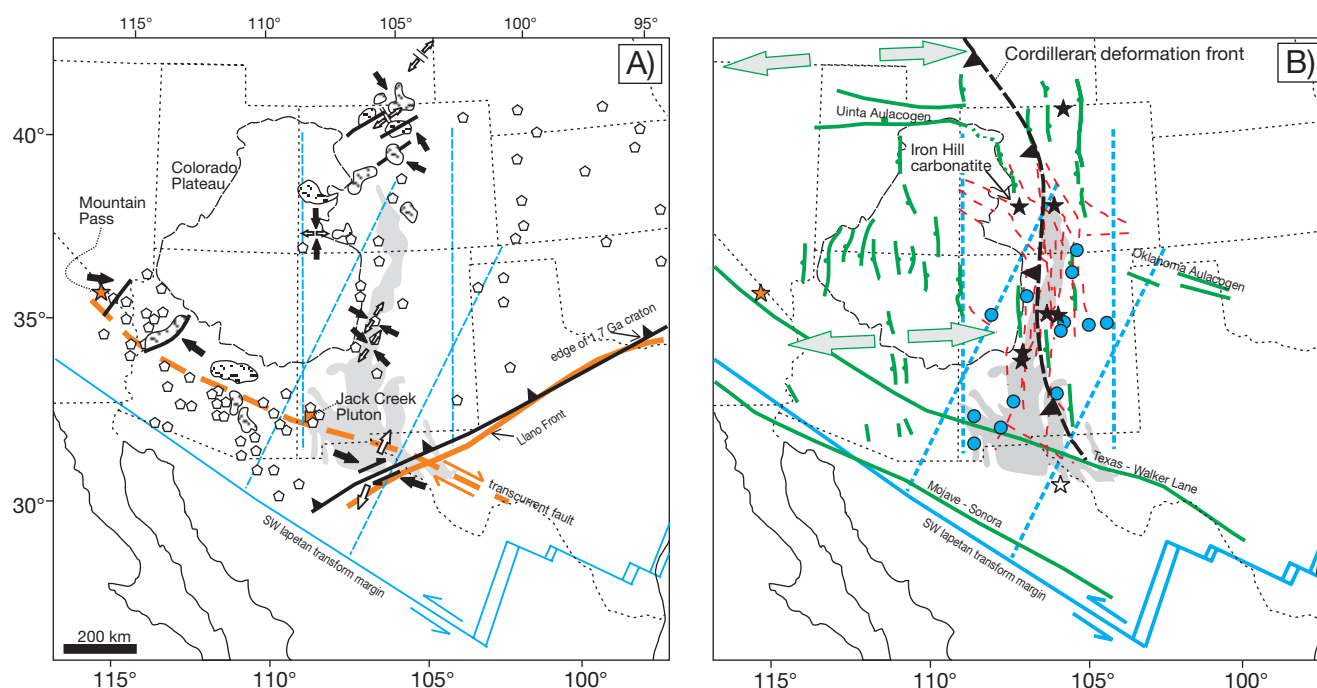


FIG. 6. Index maps of the southwestern United States showing selected structural features and igneous intrusions. Meso- and Neoproterozoic faults were intermittently reactivated and promoted Phanerozoic magmatism and deformation. The present-day Rio Grande rift is shown in gray. (A) Emplacement of Mesoproterozoic ~1.4 Ga anorogenic granitoids (polygons and patterned areas), as well as the Mountain Pass carbonatites and (ultra)potassic rocks and the Jack Creek pluton, was triggered by a transpressional stress regime. Compiled and modified from Karlstrom and Humphreys (1998; black and white symbols and lines) and Rämö et al. (2003; orange colors). (B) Neoproterozoic structures (green and red) were reactivated during the Phanerozoic and facilitated the emplacement of Cambrian-Ordovician carbonatites (black stars) and alkaline rocks (blue circles), presumably in an aulacogen setting (blue dashed lines). Note that some of the structures already developed during the Mesoproterozoic, as indicated by the accordance of the transcurrent fault shown in (A) and the Texas-Walker Lane in (B). The white star marks the location of the Chihuahua carbonatite complex in northern Mexico. Data were compiled from Timmons et al. (2001; green lines), McLemore et al. (1999; blue circles), McMillan and McLemore (2004; blue lines), Nandigam et al. (2009; white star), and Luther et al. (2012; red lines).

Heinrich, 1966; Mariano and Mariano, 2012; Mariano, pers. com., 2013).

The genesis of the carbonatites at Mountain Pass and their relationship to the (ultra)potassic rocks are ambiguous (cf. Mitchell, 2005; Castor, 2008b). On the basis of the sequence of emplacement and spatial association between the (ultra)potassic and “carbonate” rocks, Olson et al. (1954, p. 62) argued that the carbonate rocks formed from late fluids that developed “as end products of the differentiation of a potash-rich magma,” and that “at least some of the vein-like carbonate bodies were formed by deposition from hydrothermal solutions.” Similarly, Mitchell (2005, p. 2056) stated that the Mountain Pass carbonatites, considered to be of magmatic origin by Mariano (1989) and Jones and Wyllie (1983), may also be “carbothermal residua derived by the fractional crystallization of a potassic magma.” Moreover, Castor (2008b) argues that the carbonatites were derived by the separation of a “Mountain-Pass-type carbonatite related fluid” from a high-Ca, -Ba, -F, and -LREE magma that gave rise to the mafic alkaline rock types.

Possibly carbonatite related deposits of potential economic interest: Ravalli and Lemhi Counties, Montana and Idaho

More than 30 carbonatite dikes and veins occur in a rectangular area 30 by 40 km straddling the border between

Ravalli County, Montana, and Lemhi County, Idaho (Fig. 1; Heinrich, 1966; Woolley, 1987; Long et al., 2010). Resource estimates are based, however, on analysis from REE-Th-rich quartz veins that also occur in the area (Castor, 2008b; Long et al., 2010). A direct relationship between these veins and a local carbonatite is questioned by Gibson et al. (1997), based on differing REE patterns between these rock types at the Lemhi Pass locality. However, Heinrich (1966) suggested that the area may represent a major alkalic province in the uppermost stages of disinterment. Similarly, Gillerman (2011, p. 3) wrote that a “large ‘source’ for the Lemhi County rare earth mineralization, such as a carbonatite or alkali pluton, has yet to be found, though it certainly could be buried under gravels, or hidden by later structures.”

The main REE phases in the carbonatite dikes and veins are monazite, ancylite, bastnäsite, and allanite, and the main Nb phases are niobian rutile and columbite with intergrown fersmite (Heinrich, 1966, and references therein).

Previous studies of the mineralization at Lemhi Pass were interpreted to indicate a Late Cretaceous (90–99 Ma) or Eocene age, based on geochronological (Table 1; Pb-alpha on monazite; Jaffe et al., 1959) and other studies (uncited references in Gillerman et al., 2002), respectively. However, more recent studies (Table 1; Gillerman et al., 2002, 2008, 2010) delineate a more complex geologic history. An Re-Os

age of molybdenite (~1055 Ma) and Th-U-Pb ages of monazite (800–1100 Ma for monazite cores, 200–400 Ma for rims) and thorite (fracture infill in monazite; 330–370 Ma) led Gillerman et al. (2002) to propose a Precambrian age for regional mineralization and a Paleozoic hydrothermal event. Furthermore, geochronological studies (U-Pb on zircon) conducted on a syenite, a pyroxene porphyry lamprophyre, and REE-Th-quartz veins yielded ages of ~529, ~534, and ~315 Ma, respectively (Gillerman et al., 2008, 2010). The latter indicates a Carboniferous age for the REE-Th mineralization, and together these ages indicate recurrent magmatic and hydrothermal activity in the Lemhi Pass district (Gillerman et al., 2010).

Although the relationships of the various events in this area are not well understood, the geochronological data suggest that they may represent an important link between carbonatites in British Columbia and the southwestern United States, as discussed below.

Metallogeny

In this section we attempt to construct a coherent metallogenic model for the carbonatite occurrences in western North America by emphasizing their origin and distribution in geologic space and time (Fig. 1, Table 1). This section should be seen in the context of related publications, e.g., by Dawson et al. (1991), McMillan et al. (1991), Nelson and Colpron (2007), and Nelson et al. (2013), which discuss the general tectonic and metallogenic aspects of the Canadian and Alaskan Cordillera, and by Spencer and Titley (2008), who edited a compilation of articles titled *Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits*. The aforementioned studies, however, omitted ore deposits related to carbonatites and, to the best of our knowledge, the only synthesis of the tectonic and economic significance of carbonatites and associated alkaline rocks in western North America, with an emphasis on British Columbia, was presented by Pell (1994). In the light of new, mainly geochronological, results (e.g., Duke et al., 2002; Gillerman et al., 2010; Rukhlov and Bell, 2010; Millonig et al., 2012a, b; Tappe and Simonetti, 2012), a review of this subject is timely.

Discriminating the carbonatites shown in Figure 1 according to their origin and distribution in geologic space and time indicates that the majority of these carbonatites are situated parallel and in close proximity to the Cordilleran deformation front (Fig. 1; Pell, 1994) and are genetically related to intermittent Neoproterozoic to Early Paleozoic and mid-Paleozoic extensional events along the western continental margin or continental interior of ancestral North America (cf. McMillan and McLemore, 2004; Lund et al., 2010; Millonig et al., 2012a). Carbonatites that are located outside this general trend are either markedly younger (Tertiary), e.g., the Bear Lodge Mountains carbonatites, Wyoming, or considerably older (Mesoproterozoic), e.g., the Mountain Pass carbonatite, California (Fig. 1; Table 1). The Tertiary carbonatites in Wyoming and Montana follow a N40°W trend that is presumably dictated by the southwestern edge of the subducted Kula plate (Breitsprecher et al., 2003; Duke, 2009; see Group 4 section below). In contrast, intrusion of the Mountain Pass carbonatite was triggered and governed by

Mesoproterozoic transpressive intracratonic tectonism (Rämö et al., 2003).

Carbonatites shown in Figure 1 can be divided into four distinct metallogenic groups based on their geographic and geologic positions and intrusion ages. The carbonatites that are of unknown age but in proximity to carbonatites or associated alkaline rocks of known age are inferred to be of approximately the same respective age. Caution is advised in areas with a complex deformational history, such as the Blue River and Frenchman Cap dome areas, where carbonatites of widely differing intrusion ages occur in close proximity to each other (Figs. 1, 3; Table 1).

Group 1: ~1450 to 1375 Ma Mountain Pass (ultra)potassic rocks and carbonatite, California

The Mountain Pass carbonatite is by far the oldest carbonatite shown in Figure 1 and represents a significant LREE deposit (Fig. 2). Despite this fact, only very limited information is available with respect to its genesis.

Castor (2008a) suggested that emplacement of the Mountain Pass ultrapotassic rocks and the genetically related carbonatite may have been focused by “local deep-seated crustal rupturing” during a Middle Proterozoic thermal episode originating in the mantle. The reasons for this thermal event are not fully understood; underplating due to asthenospheric upwelling or a progressive buildup of radiogenic heat have been proposed (Karlstrom and Humphreys, 1998). Anorogenic K-rich granites of crustal origin also formed during this thermal event (Fig. 6a; Anderson and Bender, 1989; Karlstrom and Humphreys, 1998; Goodge and Vervoort, 2006), but differing REE patterns suggest a different genesis from that of the Mountain Pass ultrapotassic rocks (Castor, 2008a). On the basis of chemical similarities between the ~1460 Ma anorogenic high-K Jack Creek granite as well as associated minettes in New Mexico and the ~1410 Ma Mountain Pass shonkinite-syenites, Rämö et al. (2003) proposed that these rocks were formed during extensional or transensional tectonics in a continental rift zone by melting of a potassium-metasomatized mantle. According to Rämö et al. (2003), this interpretation is supported by the fact that both these high-K rock occurrences lie on a proposed transcurrent fault zone (Fig. 6a; Bickford et al., 2000). This interpretation is in line with the preferred model of Karlstrom and Humphreys (1998), who ascribe the widespread ~1.4 Ga magmatic event to underplating of mantle-derived basaltic magma, resulting in magmatism by partial melting of a heterogeneous lower crust and heterogeneous mixing of crustal and mantle-derived components in a wide transpressive intracratonic regime (Fig. 6a). In addition, the contemporaneity of extensional tectonics in and around the Belt-Purcell basin (Fig. 1), manifested by the intrusion of mafic sills and dikes between ca. 1468 and 1380 Ma (see discussion in Sears and Price, 2003), and the intrusion of the Mountain Pass ultrapotassic rocks has been emphasized by Castor (2008a).

We would like to stress the fact that Middle Proterozoic (~1390 Ma) leucosyenites, shonkinites, and minette dikes have also been documented from the area surrounding the ~570 Ma Iron Hill alkaline complex, ca. 900 km to the east (Figs. 1, 6; Table 1; Olson and Wallace, 1956; Olson et al.,

1977). The chemical similarities and overlapping intrusion ages between these rocks and the Mountain Pass syenites and shonkinites suggest some genetic commonality. We propose that Middle Proterozoic transpression triggered the emplacement of the Mountain Pass (ultra)potassic rocks and the Jack Creek granite and minettes (Fig. 6a; Rämö et al., 2003) along the WNW-trending transcurrent fault zone (Bickford et al., 2000), and simultaneously initiated intracratonic, mainly NE-directed extension (Karlstrom and Humphreys, 1998), resulting in the formation of similar rock types in the Iron Hill area (Fig. 6a, b). This model is supported by kinematic studies of 1.4 Ga granitoids in the southwestern United States (Fig. 6a), and the fact that the proposed transcurrent fault zone, which coincides with the Tertiary Texas-Walker line/lane (Marshak et al., 2000; Timmons et al., 2001), has the same orientation as and is in close proximity to the transform margin that presumably initiated the aulacogen, which also hosts the Cambrian to Ordovician alkaline and carbonatite igneous rocks (Fig. 6b; McMillan and McLemore, 2004). In addition, this aulacogen coincides with the present-day Rio Grande rift (Fig. 6; Kelley and Chamberlin, 2012), and it has been suggested that Phanerozoic structures in the Rocky Mountains of the western United States have a Proterozoic ancestry (Fig. 6b; Marshak et al., 2000; Luther et al., 2012, and references therein). It therefore seems likely that the reactivation of Proterozoic (≥ 1.4 Ga?) structures facilitated the Cambrian to Ordovician alkaline magmatism in New Mexico and Colorado (Fig. 6), as well as the rifting along the presently active Rio Grande rift.

Group 2: Late Proterozoic (813 Ma) to Late Ordovician (449 Ma) carbonatites

Carbonatites of this group include the Little Chicago, Felix, REN/Ratchford Creek, and Perry River occurrences in Canada, and the Wet Mountains area, Iron Hill, Lobo Hill, and Lemitar and Chupadera Mountains carbonatites in the United States (Fig. 1; Table 1). Of potential economic interest are the carbonatites in the Wet Mountains area (Th, REEs, Nb, U) and at Iron Hill (Th, REEs, Nb; Figs. 1, 2, 6).

The inferred intrusion ages for carbonatites and associated alkaline rocks (Table 1) of this group span an extensive time period from the Cryogenian to the Late Ordovician, and defining the limits and distinguishing additional age groups within group 2 are hampered by ambiguity related to the available geochronological data. As McMillan and McLemore (2004, p. 3) pointed out for the alkaline complexes in New Mexico and Colorado (Fig. 6), “it is not clear at this point whether the range of ages is an analytical artifact, a record of several unrelated igneous events, or a record of one prolonged event.” However, for the purpose of this study we justify this grouping based on the fact that all carbonatites within group 2 were emplaced during extensional episodes related to or coeval with either the breakup of Rodinia (Li et al., 2008; Lund et al., 2010) or the final separation of Laurentia and Siberia (Sears and Price, 2003). Possible exceptions are the Late Ordovician (~ 449 Ma, K-Ar on biotite, McLemore, 1982; Table 1) Lemitar and Chupadera Mountains carbonatites, which most likely postdate the continental separation (≤ 570 Ma, Colpron et al., 2002) but were emplaced in the same aulacogen as, e.g., the late Precambrian Iron Hill

carbonatites (~ 570 Ma). Competing theories regarding the initial breakup of Rodinia and the final continental separation are discussed by Whitmeyer and Karlstrom (2007) and Lund et al. (2010). Nevertheless, important differences in the geodynamic setting and history of individual carbonatites exist and are considered below.

The onset of (localized) extensional tectonics, heralding the initial breakup of Rodinia, is recorded by the intrusion of the Perry River carbonatite and associated syenites (~ 813 – 800 Ma; Millonig et al., 2012a) and the Gunbarrel dike swarm (780 Ma; cf. Harlan et al., 2003), followed by emplacement of the Mount Copeland syenite (~ 740 Ma; Parrish and Scammell, 1988) and the REN/Ratchford Creek carbonatite (~ 700 Ma; see discussion in Millonig et al., 2012a). Subsequent extensional events are indicated by alkalic magmatism, e.g., in central Idaho (665–650 Ma, 500–485 Ma, Lund et al., 2010; ~ 530 Ma, Gillerman et al., 2010), in Colorado at Iron Hill (~ 762 Ma?, 579–561 Ma) and the Wet Mountains (~ 551 – 506 Ma, cf. McMillan and McLemore, 2004), and in the Blue River area in British Columbia (~ 497 Ma, Felix and Little Chicago carbonatites, Millonig et al., 2012a). Synrift volcanic rocks of the Hamill Group in British Columbia are interpreted to indicate the final separation between Siberia and Laurentia at ~ 570 Ma (Colpron et al., 2002). If this is the case, the Little Chicago and Felix carbonatites may be late expressions of continuous localized extension along the continental margin. Alternatively, continental separation might not have occurred before the Cambrian-Ordovician in this part of Laurentia.

Unlike the carbonatites and alkaline rocks in Idaho and British Columbia, which formed during rifting events at what was to become the western continental margin of Laurentia, the alkaline complexes in the southwestern United States intruded in an aulacogen setting. According to McMillan and McLemore (2004), this aulacogen was active at least between 664 and 449 Ma, and possibly formed by the reactivation of Mesoproterozoic structures (Fig. 6; see Group 1 section). An additional K-Ar whole-rock age of ca. 427 Ma (Brock and Singewald, 1968, quoted in Olson et al., 1977), obtained from the Democrat Creek alkaline complex, Colorado, as cited in McMillan and McLemore (2004), is not in agreement with other geochronological data from that area and is probably incorrect, according to Olson et al. (1977).

Group 3: Late Devonian (359 Ma) to early Carboniferous (328 Ma) carbonatites

This group comprises most of the carbonatites in western Canada, such as the Aley, Vergil, Howard Creek (Blue River area), Paradise Lake (Blue River area), Serpentine Creek (Blue River area), Verity (Blue River area), Upper Fir (Blue River area), Mud Lake (Blue River area), Ice River, and Mount Grace carbonatites (Figs. 1, 3; Table 1). Resource estimates have been published for the Aley (Nb, P) and Upper Fir (Nb, Ta) carbonatites (Fig. 2; Occurrences section). All of these carbonatites and associated alkaline rocks are hosted by miogeoclinal strata (Fig. 1; Pell, 1994) and are interpreted to be related to extensional tectonics that affected the Canadian part of the western Laurentian margin in response to slab rollback during the Late Devonian to early Carboniferous (Nelson et al., 2002). This episode of extensional tectonics or pulses triggered the genesis of carbonatites and associated

alkaline rocks for at least 32 m.y. and is bracketed by intrusive and extrusive carbonatites in the Frenchman Cap dome area (~360 Ma, U-Pb on zircon; Parrish, 1995; Millonig et al., 2012a) and the intrusion of the Mud Lake carbonatite at ~328 Ma in the Blue River area (U-Pb on zircon; Table 1).

Group 4: Tertiary (~50–37 Ma) carbonatites

This group includes the Rocky Boy stock (~53–50 Ma) and Missouri Breaks (~50–47 Ma) carbonatites, Montana, the Bear Lodge Mountains carbonatites (~46 Ma; see discussion in Duke et al., 2002), Wyoming, and the Chihuahua carbonatite complex (≥ 37 Ma), Mexico. Of potential economic interest are the Bear Lodge Mountains carbonatites and, possibly, the Chihuahua carbonatite complex.

The Eocene carbonatites and associated alkaline rocks in Montana and Wyoming follow a N40°W trend in the Great Plains alkalic province (Duke, 2009). The Great Plains alkalic province belongs to the Kamloops-Challis-Absaroka volcanic belt and is part of the Laramide magmatic fields (~75–42 Ma; cf. Armstrong and Ward, 1991; Mutschler et al., 1998; Breitsprecher et al., 2003). Various tectonomagmatic models have been proposed to explain Eocene magmatism in the Great Plains alkalic province (see discussion in Duke, 2009) and recent models favor a slab window (Breitsprecher et al., 2003) or slab window edge scenario (Duke, 2009). In these models, subduction of the Kula-Farallon spreading ridge led to the formation of a slab window, and the alignment of ≤ 50 to 48 Ma alkaline rocks along the N40°W trend is presumably governed by the southwestern edge of the Kula plate (Duke, 2009). In addition, a change in lithospheric stress from compression to extension at ~53 to 49 Ma supposedly led to an increase in asthenospheric melts that penetrated the lithosphere in the area (Duke, 2009). Isotopic and trace element characteristics are in accordance with these models and suggest that several geochemically distinct mantle sources were involved in the generation of the alkaline rocks in the Great Plains alkalic province, including asthenospheric and enriched lithospheric mantle (Scambos and Farmer, 1988; O'Brien et al., 1991; Duke and Carol, 2004). A broadly similar conclusion has been drawn for the Chihuahua carbonatite complex (≥ 37 Ma) in northern Mexico, which is interpreted to result from localized post-Laramide extensional tectonics that created pathways for asthenospheric melts (Nandigam et al., 2009).

Group 5: Carbonatites of uncertain affinity (Ravalli and Lemhi Counties)

The geochronological data for alkaline and REE-Th-mineralized rocks from the Lemhi Pass district, and, by inference, the adjacent Ravalli County, are complex and indicate several mineralizing events and recurrent magmatic and hydrothermal activity from Proterozoic to Paleozoic times (see Occurrences section for details). Based on geochronological studies (Table 1), Gillerman et al. (2002) inferred a Precambrian mineralizing event (~1055 and/or 1000–800 Ma) and a Paleozoic (370–330 Ma) hydrothermal event for rocks from the Lemhi Pass area. Additional geochronological studies conducted on a syenite, a pyroxene porphyry lamprophyre, and REE-Th-quartz veins from Lemhi Pass yielded ages of ~529, ~534, and ~315 Ma, respectively

(Gillerman et al., 2008, 2010). The latter date indicates a Carboniferous age for the REE-Th mineralization; together, these ages indicate recurrent magmatic and hydrothermal activity in the Lemhi Pass district (Gillerman et al., 2010).

Owing to this diversity and ambiguity of intrusion ages and mineralizing events and the ambiguous relationship to the local carbonatite occurrences, we refrain from assigning the Lemhi and Ravalli County carbonatites to any of the general metallogenic groups defined above. However, the range of geochronological data from the Lemhi Pass district, which lies geographically between the carbonatites and associated alkaline rocks of Canada and the southwestern United States (Fig. 1), overlaps and coincides with periods of carbonatite and alkaline magmatism in those areas (groups 2 and 3 above; Table 1).

Metallogenic implications

Most carbonatites in western North America are concentrated along the Cordilleran deformation front (Fig. 1) and it is not possible to distinguish between economically more or less favorable carbonatites based on their intrusion ages alone, because all of the aforementioned metallogenic groups contain potentially mineralized as well as barren carbonatites. The Mountain Pass LREE deposit may be the exception, because it is the only carbonatite of Middle Proterozoic age in western North America. It is important to recognize, however, that carbonatites and/or associated alkaline rocks tend to cluster and occur repetitively in restricted areas (Figs. 1, 3; Table 1), as exemplified by carbonatites in the Blue River and Frenchman Cap dome areas, British Columbia, and carbonatites and alkaline rocks at Iron Hill and the Wet Mountains area, Colorado. The repetitive nature of carbonatite and alkaline magmatism within restricted areas and its relation to rift-related structures have long been recognized and pointed out (e.g., Heinrich, 1966; Bailey, 1977; Guilbert and Park, 1986, table 21-1 therein; Burke et al., 2003; Woolley and Bailey, 2012). Given that the intrusion age of a carbonatite in western North America is not a suitable criterion for supporting or negating its potential economic significance, other factors control whether or not a carbonatite reaches ore grade. Factors that most likely exert a major influence include chemical differences in the source region of the parental magma, the depth and degree of melting of that region, and the evolution of the parental magma during ascent and emplacement (cf. Bailey, 1993; Lee and Wyllie, 1998; Bell et al., 1999; Bell, 2001; Mitchell, 2005; Williams-Jones, 2010; Woolley and Bailey, 2012).

The accordance between the location of most carbonatite occurrences and the Cordilleran deformation front can be explained by their intrusion in rift- and continental breakup-related basins, followed by continental separation and subsequent deformation during accretionary processes along the western margin of ancestral North America (cf. Burke et al., 2003; Johnston, 2008). This scenario is applicable to the carbonatites of British Columbia, except that carbonatites of Late Devonian to early Carboniferous age were emplaced during extensional episodes due to slab rollback (Nelson et al., 2002) and postdate rifting and continental separation. In the southwestern United States, the coincidence between the occurrence of carbonatites and the Cordilleran deformation

front is less clear. As discussed, the intrusion of these Cambrian-Ordovician carbonatites in an aulacogen setting was presumably facilitated by the reactivation of Mesoproterozoic structures. The extensional/transpressive regime (Karlstrom and Humphreys, 1998) that gave rise to these structures possibly also triggered the intrusion of the carbonatites and ultrapotassic rocks at Mountain Pass (~1450–1375 Ma; Castor, 2008a), mafic sills in the Belt basin (~1469–1443 Ma, U-Pb on zircon; Sears et al., 1998; Evans et al., 2000; Fig. 1), and mafic dikes that cut Precambrian basement across a 600-km length from southwest Montana to western Wyoming (~1460 Ma; U-Pb age, details not given; Chamberlain et al., 2000, quoted in Sears and Price, 2002). The fact that the Belt-Purcell basin is in close proximity to the carbonatites in southern British Columbia may indicate that the Cordilleran deformation front reflects an extensive ancient (Meso- to Neoproterozoic?) zone of weakness, trending from the Yukon to the southwestern United States (Fig. 1), which intermittently promoted the intrusion of mafic and alkaline rocks. Spatially associated mafic dikes in southwest Montana with interpreted intrusion ages of ~1450 and 780 Ma (Harlan et al., 2005) are in support of this interpretation, but further geochronological data is needed to test this hypothesis.

In contrast, the emplacement of Tertiary carbonatites in Montana and Wyoming is unrelated to the tectonic events that gave rise to the carbonatites in proximity to the Cordilleran deformation front, and was presumably triggered by asthenospheric upwelling in a slab window between the subducted Farallon and Kula plates (Duke, 2009).

Exploration for carbonatite in western North America

Many carbonatites in western North America are located in proximity to the Cordilleran deformation front, and the repetitive intrusion of carbonatites in the area of the present-day Rio Grande rift (Figs. 1, 6) indicates that this area has been episodically fertile for carbonatite genesis. Another prospective area is defined by the N40°W trend in Montana and Wyoming (Fig. 1), which hosts Tertiary carbonatites.

Features that may guide exploration efforts toward carbonatitic or alkaline intrusion are REE-Th-quartz veins, as described from the Lemhi and Ravalli Counties (Gillerman, 2011) and documented for the Wet Mountains (Armbrustmacher, 1988) and Iron Hill areas. With regard to the exploration for REEs in carbonatites, it is noteworthy that no REE carbonates have been documented from amphibolite facies carbonatites in British Columbia. A comparison with other carbonatite occurrences in western North America suggests that these phases are not stable under high-grade metamorphic conditions.

In general, carbonatites are mostly volumetrically small intrusions that are often associated with larger alkaline complexes. The emplacement of these complexes is commonly facilitated by deep-seated faults in rift systems, which appear as large-scale lineaments on regional gravity anomaly maps (Richardson and Birkett, 1996). Intrusive or volcanic centers within these rifts will show as circular to elliptic bodies (cf. Fig. 4) on magnetic, gravimetric, and radiometric surveys (Hoover et al., 1992). In addition, alkaline and carbonatitic complexes can be easily recognized using geochemical data due to their enrichment in certain chemical elements, such as the REEs,

Zr, Ta, and Nb (Steenfelt, 1991). On a reconnaissance-scale study in Greenland, Nb in stream sediments was found to be the best indicator (Steenfelt, 1991). Moreover, Sadeghi and Steele (1989) investigated stream sediment samples from Arkansas and found that the enrichment index REEs + Ti + F is the best indicator for carbonatite intrusions, and that the finest grain size fraction ($<75 \times 10^{-3}$ mm) produces the most distinct anomalies. Furthermore, remote sensing techniques with high spatial resolution allow for the spectral identification of minerals rich in CO₃, REEs, and Fe²⁺, which, in combination, yield characteristics unique to carbonatites, if outcrop conditions are favorable (Rowan et al., 1986; Hoover et al., 1992; Rowan and Mars, 2003; Bedini and Tukiainen, 2008). Phosphate and potassium enrichment related to carbonatite-alkaline complexes can also be expressed in remote sensing images by enhanced vegetation (Hoover et al., 1992, and references therein).

On a local scale, detailed radiometric and geochemical surveys can be utilized to further identify carbonatitic bodies within larger alkaline complexes due to their elevated U, Th, and K contents, and many carbonatites have been discovered owing to their radioactivity (cf. Rowe, 1958). This is exemplified by the discovery of the Mountain Pass carbonatite. The deposit was initially discovered by prospectors looking for uranium using a Geiger counter (Hewett, 1954). These prospectors sent samples to the United States Geological Survey, where bastnäsite was identified. The USGS consequently undertook a detailed field survey of the immediate area (Olson and Pray, 1954), which led to the discovery of the weakly radioactive Sulphide Queen carbonatite (Olson et al., 1954).

Limitations and Perspectives

This article builds on and strongly depends on the availability and quality of petrological, mineralogical, geochronological, and geochemical data, and the classification of carbonatites and definitions of terms. The latter is reflected upon by Mitchell (2005).

In relation to the present study, the main obstacles that hinder a better understanding of the various carbonatites and associated alkaline rocks in western North America (Fig. 1, Table 1) and their relationship to each other are (1) insufficient or imprecise geochronological data, (2) the limited number of isotope and trace element studies, (3) ambiguities regarding their magmatic and possibly hydrothermal evolution and, consequently, their classification, and (4) ambiguities with respect to the evolution of the western margin of Laurentia (cf. Timmons et al., 2001; Lund et al., 2010).

Doubtless, some of these issues will be resolved with time and will lead to a better understanding of the genesis of the carbonatites and associated deposits in western North America.

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REFERENCES

- Anderson, J.L., and Bender, E.E., 1989, Nature and origin of Proterozoic A-type granitic magmatism in the southwestern United States of America: *Lithos*, v. 23, p. 19–52.
- Armbrustmacher, T.J., 1981, The complex of alkaline rocks at Iron Hill, Powderhorn district, Gunnison County, Colorado: New Mexico Geological Society Guidebook, 32nd Field Conference, Western Slope Colorado, p. 293–296.
- 1984, Alkaline rock complexes in the Wet Mountains area, Custer and Fremont Counties, Colorado: U.S. Geological Survey Professional Paper 1269, 38 p.
- 1988, Geology and resources of thorium and associated elements in the Wet Mountains area, Fremont and Custer Counties, Colorado: U.S. Geological Survey Professional Paper 1049-F, 42 p.
- Armbrustmacher, T.J., and Hedge, C.E., 1982, Genetic implications of minor-element and Sr-isotope geochemistry of alkaline rock complexes in the Wet Mountains area, Fremont and Custer Counties, Colorado: *Contributions to Mineralogy and Petrology*, v. 79, p. 424–435.
- Armstrong, R.L., and Ward, P., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera: The temporal and spatial association of magmatism and metamorphic core complexes: *Journal of Geophysical Research*, v. 96, p. 13,201–13,244.
- Bailey, D.K., 1977, Lithosphere control of continental rift magmatism: *Journal of the Geological Society*, v. 133, p. 103–106.
- 1993, Carbonate magmas: *Journal of the Geological Society*, v. 150, p. 637–651.
- Bailey, J.C., 1980, Formation of cryolite and other aluminofluorides: A petrologic review: *Bulletin of the Geological Society of Denmark*, v. 29, p. 1–45.
- Bedini, E., and Tukiainen, T., 2008, Using spectral mixture analysis of hyperspectral remote sensing data to map lithology of the Sarfartoq carbonatite complex, southern West Greenland: *Geological Survey of Denmark and Greenland Bulletin*, v. 17, p. 69–72.
- Bell, K., 2001, Foreword: *Journal of Asian Earth Sciences*, v. 19, p. 259–260.
- Bell, K., and Tilton, G.R., 2001, Nd, Pb and Sr isotopic compositions of East African carbonatites: Evidence for mantle mixing and plume inhomogeneity: *Journal of Petrology*, v. 42, p. 1927–1945.
- Bell, K., Kjarsgaard, B.A., and Simonetti, A., 1999, Carbonatites—into the twenty-first century: *Journal of Petrology*, v. 39, p. 11–12.
- Berger, V.I., Singer, D.A., and Orris, G.J., 2009, Carbonatites of the world, explored deposits of Nb and REE—database and grade and tonnage models: U.S. Geological Survey Open-File Report 2009-1139, 17 p., and database (<http://pubs.usgs.gov/of/2009/1139/>).
- Bickford, M.E., Soegaard, K., Nielsen, K.C., and McLelland, J.M., 2000, Geology and geochronology of Grenville-age rocks in the Van Horn and Franklin Mountains area, west Texas: Implications for the tectonic evolution of Laurentia during the Grenville: *Geological Society of America Bulletin*, v. 112, p. 1134–1148.
- Bizzarro, M., Simonetti, A., Stevenson, R.K., and David, J., 2002, Hf isotope evidence for a hidden mantle reservoir: *Geology*, v. 30, p. 771–774.
- Breitsprecher, K., Thorkelson, D.J., Groome, W.G., and Dostal, J., 2003, Geochemical confirmation of the Kula-Farallon slab window beneath the Pacific Northwest in Eocene time: *Geology*, v. 31, p. 351–354.
- Burke, K., Ashwal, L.D., and Webb, S.J., 2003, New way to map old sutures using deformed alkaline rocks and carbonatites: *Geology*, v. 31, p. 391–394.
- Castor, S.B., 2008a, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: *Canadian Mineralogist*, v. 46, p. 779–806.
- 2008b, Rare earth deposits of North America: *Resource Geology*, v. 58, p. 337–347.
- Castor, S.B., and Nason, G.W., 2004, Mountain Pass rare earth deposit, California: Reno, NV, Nevada Bureau of Mines and Geology Special Publication 33, p. 68–81.
- Chong, A., and Postolski, T., 2011, Blue River Ta-Nb project, Blue River, British Columbia: NI 43-101 Technical Report, p. 145.
- Chong, A., Postolski, T., Mendoza, R.R., Lipiec, T., and Omidvar, B., 2012, Commerce Resources Corp. Blue River tantalum-niobium project, British Columbia, Canada: NI 43-101 Technical Report on Mineral Resource Update, 250 p.
- Chudy, T.C., and Groat, L.A., 2010, The origin of the tantalum-bearing Upper Fir carbonatite (Monashee Mountains, east central British Columbia): Preliminary results: Association for Mineral Exploration in British Columbia (AME BC), AME BC Roundup Conference, Vancouver, Canada, 2010, Poster Presentation, 1 p.
- 2011a, The niobium-tantalum mineralization of the Upper Fir carbonatite, east-central British Columbia, Canada: Preliminary results: Geological Association of Canada, Mineralogical Association of Canada, GAC-MAC Annual Meeting, Ottawa, Canada, 2011, Program with abstracts.
- 2011b, Structures in metamorphic carbonatites: An example from the Upper Fir carbonatite, east-central British Columbia, Canada: Abstract Volume PERALK-CARB 2011, Workshop on peralkaline rocks and carbonatites, Tübingen, Germany, 2011, p. 20–21.
- Colpron, M., Logan, J.M., and Mortensen, J.K., 2002, U-Pb zircon age constraint for late Neoproterozoic rifting and initiation of the lower Paleozoic passive margin of western Laurentia: *Canadian Journal of Earth Sciences*, v. 39, p. 133–143.
- Dawson, K.M., Panteleyev, A., Sutherland Brown, A., and Woodsworth, G.J., 1991, Regional metallogeny, chapter 19, in Gabrielse, H., and Yorath, C.J., eds., *Geology of the Cordilleran orogen in Canada: Geology of Canada*, no. 4, also *The geology of North America*, v. G-2: Geological Survey of Canada, Geological Society of America, p. 707–768.
- DeWitt, E., Kwak, L.M., and Zartman, R.E., 1987, U-Th-Pb and ⁴⁰Ar/³⁹Ar dating of the Mountain Pass carbonatite and alkalic igneous rocks, S.E. California: Geological Society of America, Abstract Programs, v. 19(1), p. 642.
- Duke, G.I., 2009, Black Hills-Alberta carbonatite-kimberlite linear trend: Slab edge at depth?: *Tectonophysics*, v. 464, p. 186–194.
- Duke, G.I., and Carol, D., 2004, Carbonatite fingerprints on the Black Hills alkalic suite: Geological Society of America Abstracts with Programs, v. 36, p. 224.
- Duke, G.I., Singer, B.S., and DeWitt, E., 2002, ⁴⁰Ar/³⁹Ar laser incremental-heating ages of Devil's Tower and Paleocene-Eocene intrusions of the northern Black Hills, South Dakota and Wyoming: Geological Society of America Abstracts with Program, v. 34(6), p. 473.
- Evans, K.V., Aleinikoff, J.N., Obradovich, J.D., and Fanning, C.M., 2000, SHRIMP U-Pb geochronology of volcanic rocks, Belt Supergroup, western Montana: Evidence for rapid deposition of sedimentary strata: *Canadian Journal of Earth Science*, v. 37, p. 1287–1300.
- Fenton, M.D., and Faure, G., 1971, The age of the Iron Hill Complex of Colorado: Reply: *Mountain Geologist*, v. 8, p. 223.
- Gibson, P.E., Wood, S.A., and Lang, L., 1997, Geochemistry and mineralogy of the Lemhi Pass REE-Th deposits: An example of REE-Th mobility: Seventh Annual V.M. Goldschmidt Conference, Tuscon, Arizona, Program with abstracts, p. 2054.
- Gillerman, V.S., 2011, Rare earth elements and other critical metals in Idaho: Geological Survey of Idaho, GeoNote 44, 4 p.
- Gillerman, V.S., Jercinovic, M.J., and Stein, H.J., 2002, U-Pb and Re-Os geochronology suggest a multistage Precambrian-Mesozoic history for thorium and copper mineralization, Lemhi Pass, Idaho: Geological Society of America Abstracts with Programs, v. 34, p. 337.
- Gillerman, V.S., Fanning, C.M., Link, P.K., Layer, P., and Burmester, R.F., 2008, Newly discovered intrusives at the Lemhi Pass thorium-REE iron oxide district, Idaho: Cambrian syenite and mystery ultramafics—signatures of a buried alkaline complex or two systems?: Geological Society of America Abstracts with Programs, v. 40, p. 51.
- Gillerman, V.S., Schmitz, M.D., Jercinovic, M.J., and Reed, R., 2010, Cambrian and Mississippian magmatism associated with neodymium-enriched rare earth and thorium mineralization, Lemhi Pass district, Idaho: Geological Society of America Abstracts with Programs, v. 42, p. 334.
- Goodge, J.W., and Vervoort, J.D., 2006, Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence: *Earth and Planetary Science Letters*, v. 243, p. 711–731.
- Gorham, J., 2007, Technical report on the Upper Fir tantalum-niobium-bearing carbonatite: British Columbia, Kamloops Mining Division, 66 p.
- Gorham, J., Uly, B., and Carter, M., 2011a, 2009 Diamond drilling and exploration of the Blue River property: British Columbia Ministry of Forests, Mines and Lands, Assessment Report #31948, 1085 p.
- Gorham, J., Uly, B., and Brown, J., 2011b, 2010 diamond drilling and exploration at the Blue River property: British Columbia Ministry of Forests, Mines and Lands, Assessment Report #32424, 3261 p.

- Guilbert, J.M., and Park, C.F., 1986, *The geology of ore deposits*: New York, W.H. Freeman and Co., 985 p.
- Harlan, S.S., Heaman, L., LeCheminant, A.N., and Premo, W.R., 2003, Gunbarrel mafic magmatic event: A key 780 Ma time marker for Rodinia plate reconstructions: *Geology*, v. 31, p. 1053–1056.
- Harlan, S.S., Premo, W.R., Unruh, D., and Geissman, J.W., 2005, Isotopic dating of Meso- and Neoproterozoic mafic magmatism in the southern Tobacco Root Mountains, southwestern Montana: *Precambrian Research*, v. 136, p. 269–281.
- Haxel, G.B., 2005, Ultrapotassic mafic dikes and rare earth element- and barium-rich carbonatite at Mountain Pass, Mojave desert, southern California: Summary and field trip localities: U.S. Geological Survey, Open-File Report 2005-1219, 56 p.
- Heaman, L.M., 2009, The application of U-Pb geochronology to mafic, ultramafic and alkaline rocks: An evaluation of three mineral standards: *Chemical Geology*, v. 261, p. 43–52.
- Hedlund, D.C., and Olson, J.C., 1961, Four environments of thorium-, niobium-, and rare-earth-bearing minerals in the Powderhorn district of southwestern Colorado, Art. 121: U.S. Geological Survey Professional Paper 424-B, p. B283–286.
- Heinrich, E.W., 1966, *The geology of carbonatites*: Chicago, USA, Rand McNally and Co., p. 555.
- 1977, Aluminofluoride minerals of the Goldie carbonatite, Fremont County, Colorado: *Mountain Geologist*, v. 14, p. 33–46.
- 1980, *The geology of carbonatites*, reprint edition: Huntington, USA, Krieger Pub Co., p. 585.
- Heinrich, E.W., and Salotti, C.A., 1975, A colloform carbonatite, McCoy Gulch, Fremont County, Colorado: *Mountain Geologist*, v. 12, p. 103–111.
- Heinrich, E.W., and Shappiro, J.R., 1966, Alkaline rocks and carbonatites of the Arkansas River canyon, Fremont County, Colorado. 3. The Amethyst carbonatites: *American Mineralogist*, v. 51, p. 1088–1106.
- Hewett, D.F., 1954, Foreword: U.S. Geological Survey Professional Paper 261, 75 p.
- Hoover, D.B., Heran, W.D., and Hill, P.L., eds., 1992, *The geophysical expression of selected mineral deposit models*: U.S. Geological Survey Open File Report 92-557, 136 p.
- Jaffe, H.W., Meyrowitz, R., and Evans, Jr., H.T., 1953, Sahamalite, a new rare earth carbonate mineral: *American Mineralogist*, v. 38, p. 741–754.
- Jaffe, H.W., Gottfried, D., Waring, C.L., and Worthing, H.W., 1959, Lead-alpha age determinations of accessory minerals of igneous rocks: U.S. Geological Survey Bulletin 1097-B, 148 p.
- Johnston, S.T., 2008, The Cordilleran ribbon continent of North America: *Annual Review of Earth and Planetary Sciences*, v. 36, p. 495–530.
- Jones, A.P., and Wyllie, P.J., 1983, Low temperature glass quenched from a synthetic rare earth carbonatite: Implications for the origin of the Mountain Pass deposit, California: *Economic Geology*, v. 78, p. 1721–1723.
- Karlstrom, K.E., and Humphreys, E.D., 1998, Persistent influence of Proterozoic accretionary boundaries in the tectonic evolution of southwestern North America: Interaction of cratonic grain and mantle modification events: *Rocky Mountain Geology*, v. 33, p. 161–179.
- Kelley, S., and Chamberlin, R., 2012, Our growing understanding of the Rio Grande rift: *New Mexico Earth Matters*, v. 12, p. 1–4.
- Kraft, J.L., 2010, Geological report—structural geology of the Upper Fir carbonatite deposit, Blue River, British Columbia, appendix A14 and A15: British Columbia Ministry of Forests, Mines and Lands, Assessment Report 32424, p. 3224–3259.
- Lanphere, M.A., 1964, Geochronologic studies in the Eastern Mojave desert, California: *Journal of Geology*, v. 72, p. 381–399.
- Larsen, Jr., E.S., 1942, Alkaline rocks of Iron Hill, Gunnison County, Colorado: U.S. Geological Survey Professional Paper 197-A, 64 p.
- Lee, W.-J., and Wyllie, P.J., 1998, Petrogenesis of carbonatite magmas from mantle to crust, constrained by the system $\text{CaO}-(\text{MgO} + \text{FeO}^*)-(\text{Na}_2\text{O} + \text{K}_2\text{O})-(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2)-\text{CO}_2$: *Journal of Petrology*, v. 39, p. 495–517.
- Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008, Assembly, configuration, and break-up history of Rodinia: A synthesis: *Precambrian Research*, v. 160, p. 179–210.
- Long, K.R., Van Gosen, B.S., Foley, N.K., and Cordier, D., 2010, The principal rare earth elements deposits of the United States—a summary of domestic deposits and a global perspective: U.S. Geological Survey Scientific Investigations Report 2010-5220, 96 p.
- Luedke, R.G., 1994, Map showing distribution, composition, and age of early and middle Cenozoic volcanic centers in Idaho, Montana, west-central South Dakota, and Wyoming: U.S. Geological Survey Miscellaneous Investigations Series Map I-2291-B, scale 1:1,000,000, p. 16.
- Lund, K., Aleinikoff, J.N., Evans, K.V., duBray, E.A., Dewitt, E.H., and Unruh, D.M., 2010, SHRIMP U-Pb dating of recurrent Cryogenian and Late Cambrian-Early Ordovician alkaline magmatism in central Idaho: Implications for Rodinian rift tectonics: *Geological Society of America Bulletin*, v. 122, p. 430–453.
- Luther, A., Axen, G., and Cather, S., 2012, Deciphering the early history of a multiply reactivated fault using strain analysis in an adjacent fold: Evidence for early brittle-plastic slip on the Picuris-Pecos fault, New Mexico, USA: *Geosphere*, v. 8, p. 703–715.
- Mäder, U.K., 1986, *The Aley carbonatite complex*: Unpublished M.Sc. thesis, Vancouver, Canada, University of British Columbia, 176 p.
- 1987, *The Aley carbonatite complex, northern Rocky Mountains (94B/5)*, British Columbia: B.C. Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork 1986, Paper 1987-1, p. 283–289.
- Mariano, A.N., 1976, A study of the Mountain Pass carbonatite: Confidential report to Molycorp Inc., 208 p.
- 1980, A study of barite from the Mountain Pass carbonatite: Confidential report to Molycorp Inc., 33p.
- 1982, Petrology, mineralogy and geochemistry of the Blue River carbonatites: Confidential report to Anschutz (Canada) Mining Ltd., 130 p.
- 1989, Economic geology of rare earth elements: *Reviews in Mineralogy*, v. 21, p. 309–337.
- Mariano, A.N., and Mariano, A., 2012, Rare earth mining and exploration in North America: *Elements*, v. 8, p. 369–376.
- Marshak, S., Karlstrom, K., and Timmons, J.M., 2000, Inversion of Proterozoic extensional faults: An explanation for the pattern of Laramide and ancestral Rockies intracratonic deformation, United States: *Geology*, v. 28, p. 735–738.
- McLeish, D.F., Kressall, R., Chakhmouradian, A., Crozier, J., Johnston, S.T., and Mortensen, J.K., 2011a, The Aley carbonatite complex—part I, structural evolution of a Cordilleran niobium deposit: *British Columbia Geological Survey, Open File 2010-10*, p. 21.
- McLeish, D.F., Kressall, R., Johnston, S.T., Chakhmouradian, A., Crozier, J., and Mortensen, J.K., 2011b, The Aley carbonatite complex: Structural evolution, petrogenesis, and tectonic implications of a Cordilleran niobium deposit: Association for Mineral Exploration in British Columbia (AME BC), AME BC Roundup Conference, Vancouver, Canada, 2011, Poster Presentation.
- McLemore, V.T., 1982, Geology and geochemistry of Ordovician carbonatite dikes in the Lemitar Mountains, Socorro County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open File Report 158, 115 p.
- McLemore, V.T., McMillan, N.J., Heizler, M., and McKee, C., 1999, Cambrian alkaline rocks at Lobo Hill, Torrance County, New Mexico: More evidence for a Cambrian-Ordovician aulacogen: *New Mexico Geological Society Guidebook*, 50th Field Conference, p. 247–254.
- McMillan, N.J., and McLemore, V.T., 2004, Cambrian-Ordovician magmatism and extension in New Mexico and Colorado: *New Mexico Bureau of Geology & Mineral Resources, Bulletin* 160, p. 1–11.
- McMillan, W.J., Höy, T., MacIntyre, D.G., Nelson, J.L., Nixon, G.T., Hammack, J.L., Panteleyev, A., Ray, G.E., and Webster, I.C.L., 1991, Ore deposits, tectonics and metallogeny in the Canadian Cordillera: *British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper* 1991-4, 273 p.
- Millonig, L.J., Gerdes, A., and Groat, L.A., 2012a, U-Th-Pb geochronology of meta-carbonatites and meta-alkaline rocks in the southern Canadian Cordillera: A geodynamic perspective: *Lithos*, v. 152, p. 202–217.
- 2012b, The effect of amphibolite facies metamorphism on the U-Th-Pb geochronology of accessory minerals from meta-carbonatites and associated meta-alkaline rocks: *Chemical Geology*, in press.
- Mitchell, R.H., 1973, Isotopic composition of lead in galena from the Mountain Pass carbonatite, California: *Nature Physical Science*, v. 241, p. 17–18.
- 2005, Carbonatites and carbonatites and carbonatites: *Canadian Mineralogist*, v. 43, p. 2049–2068.
- Mutschler, F.E., Larson, E.E., and Gaskill, D.L., 1998, The fate of the Colorado Plateau—a view from the mantle: *U.S. Geological Survey Bulletin* 2158, p. 203–222.
- Nandigam, R., Clark, K.F., Anthony, E.Y., and Comaduran, O., 2009, Geological and geochemical characteristics of a Zn and LREE-enriched

- Tertiary Chihuahua carbonatite complex, northern Mexico, in Clark, K.F. and Salas Piza, G., eds., *Geología económica de México*, segunda edición del libro *geología económica de México: Asociación de Ingenieros de Minas, Metalurgistas y Geólogos de México*, A.C., Servicio Geológico Mexicano, p. 11.
- Nash, W.P., 1972, Mineralogy and petrology of the Iron Hill carbonatite complex, Colorado: *Geological Society of America Bulletin*, v. 83, p. 1361–1382.
- Nelson, J., and Colpron, M., 2007, Tectonics and metallogeny of the British Columbia, Yukon and Alaskan Cordillera, 1.8 Ga to the present: Geological Association of Canada, Mineral Deposits Division, Special Publication no. 5, p. 755–791.
- Nelson, J.L., Paradis, S., Christensen, J., and Gabites, J., 2002, Canadian Cordillera Mississippi Valley-type deposits: A case for Devonian–Mississippian back-arc hydrothermal origin: *Economic Geology*, v. 97, p. 1013–1036.
- Nelson, J.L., Colpron, M., and Israel, S., 2013, Tectonics and metallogeny: The Cordillera of British Columbia, Yukon and Alaska: Society of Economic Geologists, Special Publication 17, p. 53–109.
- Noble, A.C., Pickarts, J.T., and Larsen, R.K., 2013, Technical report on the mineral reserves and resources and development of the Bull Hill mine: Rare Element Resources Inc.-Bear Lodge Mountain project: Canadian National Instrument 43-101, 265 p.
- O'Brien, H.E., Irving, A.J., and McCallum, I.S., 1991, Eocene potassic magmatism in the Highwood Mountains, Montana: Petrology, geochemistry, and tectonic implications: *Journal of Geophysical Research*, v. 96, p. 13,237–13,260.
- Olsen, J.C., and Pray, L.C., 1954, The Mountain Pass rare earth deposits: California Bureau of Mines and Geology Bulletin 170, p. 23–29.
- Olson, J.C., and Hedlund, D.C., 1981, Alkaline rocks and resources of thorium and associated elements in the Powderhorn district, Gunnison County, Colorado: U.S. Geological Survey Professional Paper 1049-C, p. 40.
- Olson, J.C., and Marvin, R.F., 1971, Rb-Sr whole-rock age determinations of the Iron Hill and McClure Mountain carbonatite-alkalic complexes, Colorado: Discussion: *Mountain Geologist*, v. 8, p. 221.
- Olson, J.C., and Wallace, S.R., 1956, Thorium and rare earth minerals in the Powderhorn district, Gunnison County, Colorado: U.S. Geological Survey Bulletin 1027-0, p. O693–O723.
- Olson, J.C., Shawe, D.R., Pray, L.C., and Sharp, W.N., 1954, Rare-earth mineral deposits of the Mountain Pass district, San Bernardino County, California: U.S. Geological Survey Professional Paper 261, 75 p.
- Olson, J.C., Marvin, R.F., Parker, R.L., and Mehnert, H.H., 1977, Age and tectonic setting of lower Paleozoic alkaline and mafic rocks, carbonatites, and thorium veins in south-central Colorado: U.S. Geological Survey Journal of Research, v. 5, p. 673–687.
- Parker, R.L., and Sharp, W.N., 1970, Mafic-ultramafic rocks and associated carbonatites of the Gem Park Complex, Custer and Fremont Counties, Colorado: U.S. Geological Survey Professional Paper 649, p. 33.
- Parrish, R.R., 1995, Thermal evolution of the southeastern Canadian Cordillera: *Canadian Journal of Earth Sciences*, v. 32, p. 1618–1642.
- Parrish, R.R., and Scammell, R.J., 1988, The age of the Mount Copeland syenite gneiss and its metamorphic zircons, Monashee Complex, southeastern British Columbia: Radiogenic age and isotopic studies: Report 2: Geological Survey of Canada, Paper 88-2, p. 21–28.
- Pell, J., 1986, Carbonatites in British Columbia: The Aley property (94B/5): B.C. Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork 1985, Paper 1986-1, p. 275–278.
- 1994, Carbonatites, nepheline syenites, kimberlites and related rocks in British Columbia: B.C. Geological Survey Branch, Bulletin 88, 136 p.
- 1996, Mineral deposits associated with carbonatites and related alkaline igneous rocks: Mineralogical Association of Canada Short Course Series, v. 24, p. 271–310.
- Pride, K.R., 1983, Geological survey on the Aley claims, Omineca Mining Division, British Columbia: B.C. Ministry of Energy, Mines and Petroleum Resources, Assessment Report 12018, 9 p.
- Rämö, O.T., McLemore, V.T., Hamilton, M.A., Kosunen, P.J., Heizler, M., and Haapala, I., 2003, Intermittent 1630–1220 Ma magmatism in central Mazatzal province: New geochronologic piercing points and some tectonic implications: *Geology*, v. 31, p. 335–338.
- Rankin, A.H., 2005, Carbonatite-associated rare metal deposits: Composition and evolution of ore-forming fluids—the fluid inclusion evidence: Geological Association of Canada, GAC Short Course Notes 17, p. 299–314.
- Richardson, D.G., and Birkett, T.C., 1996, Carbonatite-associated deposits: Geological Survey of Canada, *Geology of Canada* no. 8, p. 541–558.
- Rowan, L.C., and Mars, J.C., 2003, Lithologic mapping in the Mountain Pass, California area using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data: *Remote Sensing of Environment*, v. 84, p. 350–366.
- Rowan, L.C., Kingston, M.J., and Crowley, J.K., 1986, Spectral reflectance of carbonatites and related alkaline igneous rocks: Selected samples from four North American localities: *Economic Geology*, v. 81, p. 857–871.
- Rowe, R.B., 1958, Niobium (Columbium) deposits of Canada: Geological Survey of Canada, *Economic Geology Series*, no. 18, 105 p.
- Rukhlov, A.S., and Bell, K., 2010, Geochronology of carbonatites from the Canadian and Baltic shields, and the Canadian Cordillera: Clues to mantle evolution: *Mineralogy and Petrology*, v. 98, p. 11–54.
- Sadeghi, A., and Steele, K.F., 1989, Use of stream sediment elemental enrichment factors in geochemical exploration for carbonatite and uranium, Arkansas, U.S.A.: *Journal of Geochemical Exploration*, v. 32, p. 279–286.
- Scambos, T.A., 1991, I. Geochemistry and source characteristics of alkaline igneous rocks of central Montana; II. The release factor for non-radiogenic volatiles on Mars; III. Detection of kimberlitic diatremes using Landsat: Unpublished Ph.D thesis, Boulder, University of Colorado, 246 p.
- Scambos, T.A., and Farmer, G.L., 1988, Multiple source components for alkaline igneous rocks in the Wyoming province: Isotopic and trace element evidence from central Montana: *EOS Transactions*, v. 69, p. 1510.
- Schoene, B., and Bowring, S.A., 2006, U-Pb systematics of the McClure Mountain syenite: Thermochronological constraints on the age of the $^{40}\text{Ar}/^{39}\text{Ar}$ standard MMhb: *Contributions to Mineralogy and Petrology*, v. 151, p. 615–630.
- Sears, J.W., and Price, R.A., 2002, The hypothetical Mesoproterozoic supercontinent Columbia: Implications of the Siberian-West Laurentian connection: *Gondwana Research*, v. 5, p. 35–39.
- 2003, Tightening the Siberian connection to western Laurentia: *Geological Society of America Bulletin*, v. 115, p. 943–953.
- Sears, J.W., Chamberlain, K.R., and Buckley, S.N., 1998, Structural and U-Pb geochronological evidence for 1.47 Ga rifting in the Belt basin, western Montana: *Canadian Journal of Earth Sciences*, v. 35, p. 467–475.
- Simandl, G., and Hancock, K., 2011, Rare metals in British Columbia: Geological Survey of British Columbia, Information Circular 2011-2, p. 2.
- Simandl, G.J., Prussin, E.A., and Brown N., 2011, Specialty metals in British Columbia, Canada: British Columbia Ministry of Energy and Mines, Geofile 2011-10, p. 1.
- Simpson, R.G., 2011, Technical report—Aley carbonatite niobium project: Vancouver, Report for Aley Corporation, 50 p.
- Spell, T.L., and McDougall, I., 2003, Characterization and calibration of $^{40}\text{Ar}/^{39}\text{Ar}$ dating standards: *Chemical Geology*, v. 198, p. 189–211.
- Spencer, J.E., and Titley, S.R., eds., 2008, Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: *Arizona Geological Society Digest* 22, 611 p.
- SRK Industries, 2012, Guide 7 report for MolyCorp Inc., April 2012: Information available online at <http://www.molycorp.com/molycorps-rare-earth-reserves-at-mountain-pass-increase-by-36>.
- Staat, M.H., 1983, Geology and description of thorium and rare-earth deposits in the southern Bear Lodge Mountains, northeastern Wyoming: Geology and resources of thorium in the United States: U.S. Geological Survey Professional Paper 1049-D, 58 p.
- Staat, M.H., Armbrustmacher, T.J., Olson, J.C., Brownfield, I.K., Brock, M.R., Lemons, J.F., Jr., Coppa, L.V., and Clingan, B.V., 1979, Principal thorium resources in the United States: U.S. Geological Survey Circular 805, 42 p.
- Steenfelt, A., 1991, High-technology metals in alkaline and carbonatitic rocks in Greenland: Recognition and exploration: *Journal of Geochemical Exploration*, v. 40, p. 263–279.
- Stone, M., and Selway, J., 2010, Independent technical report, Blue River property, Blue River, British Columbia, Canada: Report prepared by Caracle Creek International Consulting Inc. for Commerce Resources Corp., 118 p.
- Tappe, S., and Simonetti, A., 2012, Combined U-Pb geochronology and Sr-Nd isotope analysis of the Ice River perovskite standard, with implications for kimberlite and alkaline rock petrogenesis: *Chemical Geology*, v. 304–305, p. 10–17.
- Teck Cominco Limited, 2005, Annual Report 2005, 104 p., available online at <http://www.teck.com/DocumentViewer.aspx?elementId=103948&portalN>

- ame=tc&ei=3Dz1UY6aK6friQLQ5IGACQ&usg=AFQjCNGlXg7b972VKe
g00HjLoubQ10JdHQ&bvm=bv.49784469,d.cGE.
- Temple, A.K., and Grogan, R.M., 1965, Carbonatite and related alkalic rocks at Powderhorn, Colorado: *Economic Geology*, v. 60, p. 672–692.
- Timmons, J.M., Karlstrom, K.E., Dehler, C.M., Geissman, J.W., and Heizler, M.T., 2001, Proterozoic multistage (ca. 1.1 and 0.8 Ga) extension recorded in the Grand Canyon Supergroup and establishment of northwest- and north-trending tectonic grains in the southwestern United States: *Geological Society of America Bulletin*, v. 113, p. 163–181.
- Van Gosen, B.S., 2008, Geochemistry of rock samples collected from the Iron Hill carbonatite complex, Gunnison County, Colorado: U.S. Geological Survey Open-File Report 2008-1119, 27 p.
- , 2009, The Iron Hill (Powderhorn) carbonatite complex, Gunnison County, Colorado—a potential source for several uncommon mineral resources: U.S. Geological Survey Open-File Report 2009-1005, 31 p.
- Van Gosen, B.S., and Lowers, H.A., 2007, Iron Hill (Powderhorn) carbonatite complex, Gunnison County, CO—a potential source of several uncommon mineral resources: *Mining Engineering*, v. 59, p. 2–11.
- Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: *Geosphere*, v. 3, p. 220–259.
- Williams-Jones, A.E., 2010, The geology and geochemistry of REE deposits—a primer: British Columbia Geological Survey, Open File 2010-10, p. 35.
- Woodard, J., 2010, Genesis and emplacement of carbonatites and lamprophyres in the Svecofennian domain: Ph.D. thesis, Finland, University of Turku, 50 p.
- Woolley, A.R., 1987, Alkaline rocks and carbonatites of the world. Part 1: North and South America: Austin, Texas, University of Texas Press, 216 p.
- Woolley, A.R., and Bailey, D.K., 2012, The crucial role of lithospheric structure in the generation and release of carbonatites: Geological evidence: *Mineralogical Magazine*, v. 76, p. 259–270.
- Woolley, A.R., and Kjarsgaard, B.A., 2008, Carbonatite occurrences of the world: Map and database: Geological Survey of Canada, Open File 5796, 1 CD-ROM, 1 map, scale 1:20,000,000.