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ARTICLE

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Cripple Creek and other alkaline-related gold deposits in the southern Rocky Mountains, USA: influence of regional tectonics

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Abstract Alkaline-related epithermal vein, breccia, disseminated, skarn, and porphyry gold deposits form a belt in the southern Rocky Mountains along the eastern edge of the North American Cordillera. Alkaline igneous rocks and associated hydrothermal deposits formed at two times. The first was during the Laramide orogeny (about 70–40 Ma), with deposits restricted spatially to the Colorado mineral belt (CMB). Other alkaline igneous rocks and associated gold deposits formed later, during the transition from a compressional to an extensional regime (about 35–27 Ma). These younger rocks and associated deposits are more widespread, following the Rocky Mountain front southward, from Cripple Creek in Colorado through New Mexico. All of these deposits are on the eastern margin of the Cordillera, with voluminous calc-alkaline rocks to the west. The largest deposits in the belt include Cripple Creek and those in the CMB. The most important factor in the formation of all of the gold deposits was the near-surface emplacement of relatively oxidized volatile-rich alkaline magmas. Strontium and lead isotope compositions suggest that the source of the magmas was subduction-modified subcontinental lithosphere. However, Cripple Creek alkaline rocks and older Laramide alkaline rocks in the CMB that were emplaced through hydrously altered LREE-enriched rocks of the Colorado (Yavapai) province have $^{208}Pb/^{204}Pb$ ratios that suggest these magmas assimilated and mixed with significant amounts of lower crust. The anomalously hot, thick, and light crust beneath Colorado may have been a catalyst for large-scale transfer of volatiles and crustal melting. Increased dissolved H_2O (and CO_2, F, Cl) of these magmas may have resulted in more productive gold deposits due to more efficient magmatic-hydrothermal systems. High volatile contents may also have promoted Te and V enrichment, explaining the presence of fluorite, roscoelite (vanadium-rich mica) and tellurides in the CMB deposits and Cripple Creek as opposed to deposits to the south. Deep-seated structures of regional extent that formed during the Proterozoic allowed the magmas to rise to shallow crustal levels. Proterozoic sites of intrusions at 1.65, 1.4, and 1.1 Ga were also important precursors to alkaline-related gold deposits. Many of the larger gold deposits are located at sites of Proterozoic intrusions, and are localized at the intersection of northeast-trending ductile shear zones formed during Mesoproterozoic deformation, and an important north-trending fault formed during 1.1 Ga rifting.

Keywords Cripple Creek · Alkaline · Gold · Rocky Mountains

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Introduction

An important group of gold deposits that share a consistent spatial and temporal association with alkaline igneous rocks occur in a north-south belt that extends from Canada to eastern Mexico along the eastern edge of the North American Cordillera (Fig. 1). These deposits consist primarily of epithermal vein, breccia pipes, porphyry, and skarn deposits (Mutschler et al. 1985; Mutschler and Mooney 1993; McLemore 1996). Most of the gold deposits within the belt share similar characteristics and, by inference, similar geologic and geochemical controls on ore formation. Furthermore, the close spatial relationship of the deposits with alkaline igneous rocks suggests a genetic relationship between alkaline magmatism and gold mineralization (e.g., Jensen and Barton 2000). Geochronologic, geochemical, and isotopic data from some of these deposits provide direct evidence for this genetic relationship (Saunders 1991; Mutschler and Mooney 1993; McLemore 1996;

Kelley et al. 1998). Although the term alkaline refers to the general nature of the chemistry of the associated igneous rocks, not to the deposits themselves, in this paper we follow Jensen and Barton (2000) and call these deposits alkaline-related gold deposits.

Deposits in the North American Cordilleran belt have produced nearly 13% of the total lode gold production in the United States and Canada. The northern part of the belt includes deposits in the Black Hills, South Dakota (208 metric tons of Au production), and Galore Creek (Stikine Copper), British Columbia (54 metric tons of Au production) (Mutschler and Mooney 1993). To the south are districts such as Cripple Creek, the largest in the belt and one of the largest in the world (Fig. 2), having produced nearly 700 metric tons of gold (Table 1).

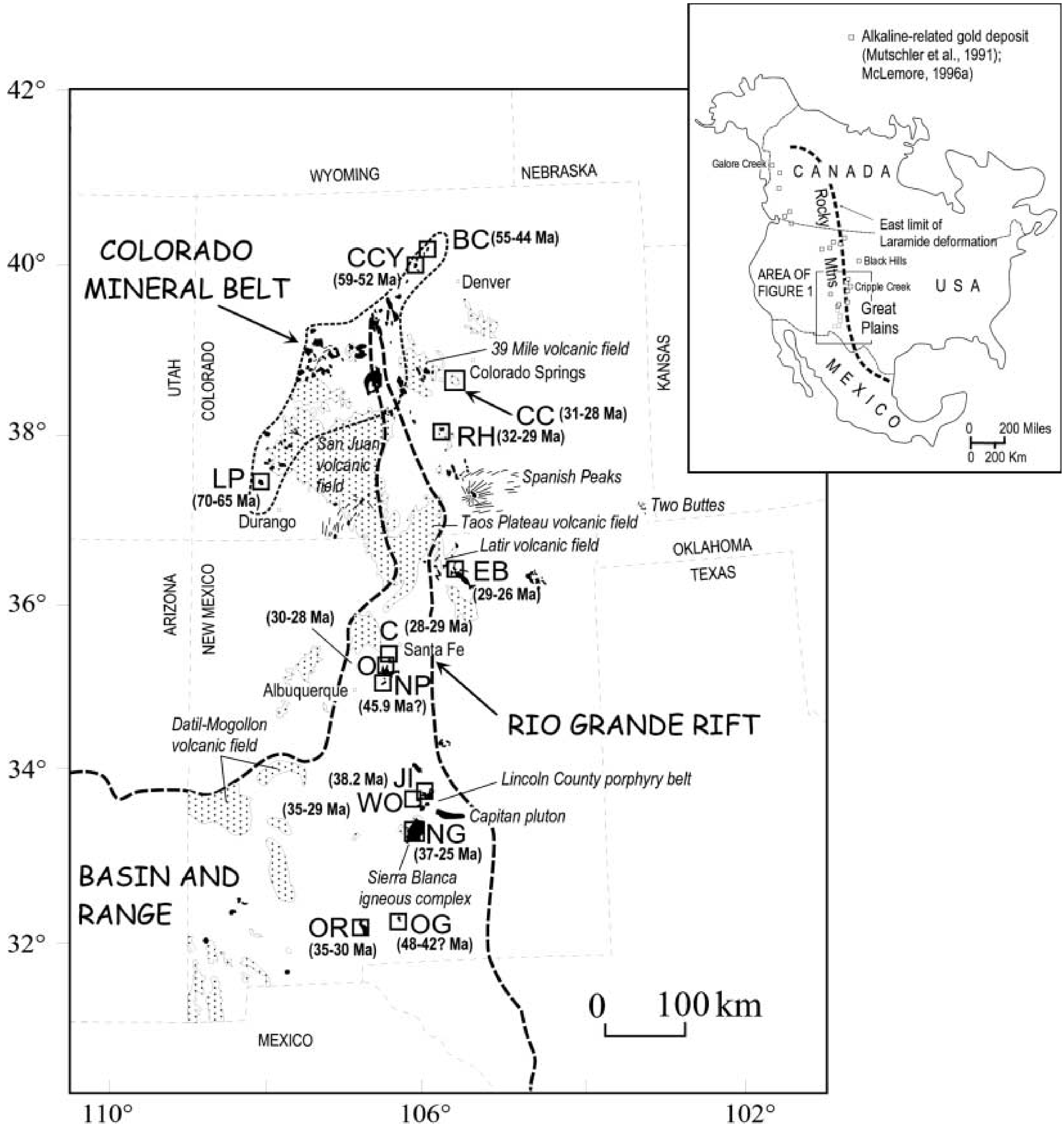
The Rocky Mountain region of the western United States has experienced a complex geologic history. It represents the juncture of two globally significant tectonic regimes. First, a 1500-km-wide juvenile Proterozoic orogenic belt records an episode of rapid accretion of continental material from mantle sources and the assembly of related terranes to southern Laurentia between 1.8 and 1.6 Ga (Karlstrom and Humphreys 1998). A long period of sedimentation during the Early Phanerozoic was followed by a second orogenic event (Laramide orogeny from 70 to about 35 Ma). This northeast-directed contractional orogenesis, accompanied by magmatism, affected a wide zone, with deformation and foreland uplift extending nearly to the middle of the continent (Fig. 1). Through most of the Cordilleran region, the main tectonic transition of post-Laramide time has been to an extensional regime, but that transition has occurred at different times and to different degrees in different parts of the region (Christiansen et al. 1992).

Gold deposits at Cripple Creek formed between 32 and 27 Ma (Kelley et al. 1998). This time period corresponds to the final stages of Laramide subduction-related magmatism in this region, and the inception of an extensional tectonic regime that has lasted until the present, and whose most prominent manifestation is the Rio Grande rift and Basin and Range province (Fig. 1). Most of the other alkaline-related gold deposits in this region of Colorado and New Mexico formed during this tectonic transition (Fig. 3). That this distinctive group of mineral deposits formed in a specific geographic area (along the eastern edge of the Cordillera), during a specific tectonic regime (end of subduction, beginning of extension), and in association with a specific magma chemistry (alkaline rocks), indicates a common origin. The genetic meaning of this singularity has been discussed extensively (Mutschler and Mooney 1993; McLemore 1996; Jensen and Barton 2000), and we offer no new resolution for the controversy regarding the primacy of depth of magma generation or mantle involvement in the genesis of these deposits. Our purpose is to discuss similarities and differences between Cripple Creek and other alkaline-related gold deposits in the southern part of the belt, and to examine how the tectonic history of the region, particularly the pre-Laramide history, has influenced their characteristics. This group of deposits is ideal for such study, because all the deposits are located in the area that has experienced the same general tectonic history. Therefore, we pay particular attention to how other factors such as magma source composition and evolution of the continental lithosphere may have influenced the location and nature of mineralization in the Cripple Creek district and other smaller deposits along the Rocky Mountain front.

Alkaline-related gold deposits of the southern Cordilleran belt

Although alkaline-related gold deposits occur along the eastern margin of the cordillera from Canada to Mexico (Fig. 1), our discussion will focus on the southern part of the belt. In Colorado, alkaline rocks and associated gold deposits occur within the Colorado mineral belt (La Plata, Central City, and Boulder County areas), and in isolated complexes such as Cripple Creek and the Rosita Hills (Fig. 1). In New Mexico, there are four important regions that contain alkaline-related gold deposits: (1) the northern part of the state (Elizabethtown-Baldy district), (2) the north-central part of the state that includes the Cerrillos, Old Placers, and New Placers districts, (3) the Lincoln County porphyry belt in the east-central part of the state (Jicarilla, White Oaks, and Nogal-Bonito-Schelerville districts), and (4) the Orogrande and Organ Mountains districts in the southern part of the state. The New Mexico deposits were described by McLemore (1996), who termed them Great Plains Margin gold deposits, and emphasized their relation to the boundary between thin crust under the southern Rocky Mountains and thick crust under the Great Plains.

Nearly all of the alkaline-related gold deposits have the following common characteristics: (1) they occur in areas of multiple episodes of intrusive activity, which in some cases was characterized by an early calc-alkaline stage followed by multiple episodes of alkaline intrusive activity; (2) they contain the products of magmatic-hydrothermal activity (e.g., breccia pipes, porphyry-type stockworks); (3) the hydrothermal system was generated late in the evolution of the igneous complex; (4) hydrothermal alteration assemblages include potassium-bearing silicate minerals (potassium feldspar, sericite, biotite); and (5) veins exhibit a consistent mineral paragenesis, with early base-metal sulfides followed by gold or gold-bearing telluride minerals. These characteristics are typical of economic alkaline-related deposits worldwide (Mutschler and Mooney 1993; Richards 1995; Jensen and Barton 2000). Differences between the deposits include the following: (1) the style of mineralization and the composition of alkaline host rocks differ between districts; and (2) not all vein deposits have



70 Ma to 5 Ma (Larmide and younger Tertiary) intrusive rocks

70 Ma TO 5 Ma (Laramide and younger Tertiary) volcanic rocks (Primarily calc-alkaline)

Boundary of the physiographic expression of the Rio Grande Rift and Basin and Range Province

Boundary of the Colorado Mineral Belt

Major alkalic gold deposit

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Fig. 1 Map showing locations of major alkalic gold deposits in Colorado and New Mexico, and their distribution to Laramide or Tertiary igneous rocks, the Colorado Mineral belt, and the Rio Grande rift. Inset shows the entire North American Cordilleran belt of alkalic gold deposits. *BC* Boulder County (includes Gold Hill, Sugarloaf, Jamestown, Magnolia, and Ward); *CCY* Central City; *CC* Cripple Creek; *RH* Rosita Hills; *LP* La Plata; *EB* Elizabethtown-Baldy; *C* Cerrillos; *O* Old Placers (includes Ortiz); *NP* New Placers; *JI* Jicarilla; *NG* Nogal-Bonito-Schelerville; *WO* White Oaks; *OG* Orogrande; *OR* Organ Mountains. The estimated ages of mineralization are listed for each district

similar ore and gangue minerals; for example, most deposits in Colorado contain roscoelite (vanadium-rich mica), fluorite, and telluride minerals, whereas many in New Mexico lack these minerals but instead contain tungsten-bearing minerals (primarily scheelite, particularly in the Old Placers and White Oaks districts).

Nearly all of the deposits in Colorado and New Mexico lie within or along the eastern margin of the Rio Grande rift (Fig. 1), and to the east of coeval or older and younger calc-alkaline rocks (Christiansen et al. 1992). Keith (1982) and Lipman (1987) proposed that alkaline magmas are the result of subduction-related processes, and that the K_2O content at a given SiO_2 content is a function of depth to the Benioff zone. However, alkaline rocks at Cripple Creek have geochemical and isotopic signatures that suggest primitive mantle sources rather than subduction-related magmas (i.e., low Sr_i ratios, and low La/Nb and Zr/Nb ratios; Kelley et al. 1998). In addition, ages indicate the alkaline magmas at Cripple Creek and at other coeval deposits formed at the end of subduction-related, calc-alkaline magmatism, and at the beginning of the bimodal magmatism that accompanied the development of the Rio Grande rift (Fig. 2). This petrotectonic setting has been recognized for many other alkaline-related gold deposits throughout the world (Richards 1995).

The following are brief descriptions of the major alkaline-related gold deposits in Colorado and New Mexico. Many of the similarities and differences mentioned above are evident in these summaries. For details about individual deposits, the reader is referred to specific references listed in Table 1 or included in each section below.

Colorado mineral belt (CMB)

Mines in the La Plata district at the southwestern end of the CMB (Fig. 1) have produced just under 8 metric tons of gold (Table 1). The district occupies the center of a structural dome formed by the intrusion of laccoliths into Permian to Jurassic metasedimentary rocks

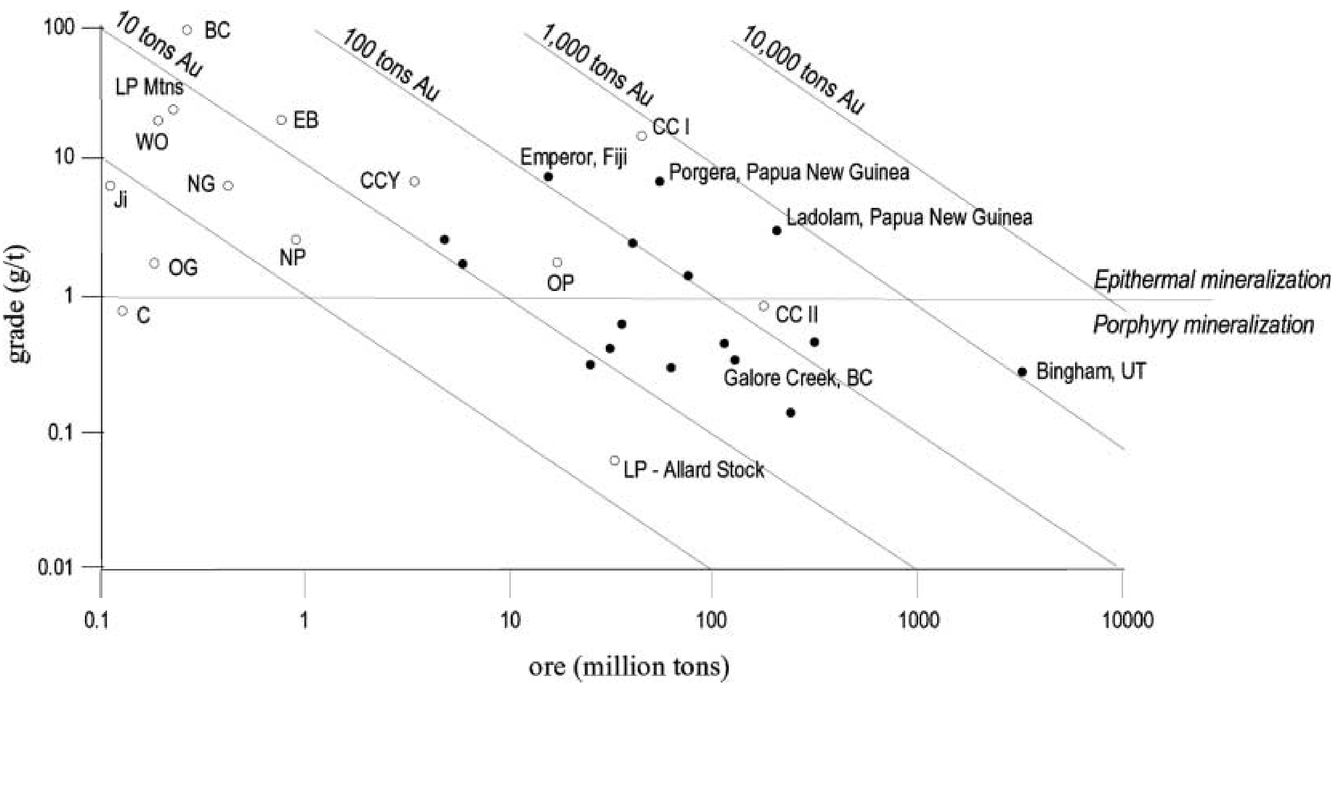


Fig. 2 Grade tonnage plot for alkaline-related gold deposits (modified from Jensen and Barton 2000) showing data for deposits or districts discussed in this paper for which data are available (shown as *open circles*; *abbreviations* for deposits/districts are as in Fig. 1 and Table 1). *Dashed contours* indicate total gold in deposit. Cripple Creek and the La Plata district have each been plotted as two points. The point labeled *LP Mtns* represents historic production from high-grade epithermal veins. The point labeled *LP – Allard Stock* represents the porphyry-style Cu–Au–PGE deposit. Cripple Creek is plotted as *CC I* and *CC II*, high grade vein systems and low-grade "disseminated" deposits, respectively (Jensen and Barton 2000). Reported grades for Boulder County deposits range from 17 to 350 g/t (Mutschler and Mooney 1993), so an average of about 100 g/t was used. Note that for most deposits and districts, it was not possible to distinguish the amount of gold that was produced from different deposit types; therefore, most districts include all gold produced, including that which is in vein, breccia, porphyry, skarn, or placer deposits. Because most of the deposits are incompletely explored, the data shown on this plot are not suitable for use as a predictive model

Table 1 Age and gold production data for major alkaline-related gold deposits in Colorado and New Mexico

Map symbol	Area	Deposits	Mineralization styles	Age (Ma)	Au production (metric tons)	Au resource remaining (metric tons)	References
LP	La Plata	Allard Stock, Bessie G	Au- and telluride-bearing, polymetallic veins, Au-bearing (?) porphyry Cu, Au placers	70–85	6	> 7	Long et al. (1998); Werle et al. (1984)
CCY	Central City	Many	Au- and telluride-bearing, polymetallic veins, Au placers	59–52	31	> 2	Long et al. (1998); Rice et al. (1985); Mutschler and Mooney (1993)
BC	Boulder County	Jamestown, Ward, Gold Hill-Sugarloaf, Magnolia	Au- and telluride-bearing polymetallic and epithermal veins, Au-bearing breccias	55–44	30	Unknown	Long et al. (1998); Lovering and Goddard (1950)
CC	Cripple Creek	Many	Au- and telluride-bearing epithermal veins, breccias	32–27	653	> 30	Long et al. (1998)
RH	Rosita Hills	Assick	Au-bearing breccias	32–26	3	Unknown	Sharp (1978); McEwan (1986)
EB	Elizabethtown-Baldy	Elizabethtown, Red River	Au-bearing polymetallic and epithermal veins, Au placers	29–19	15	Unknown	Long et al. (1998); McLemore (1996); Ludington et al. (1983)
C	Cerrillos	Cerrillos	Au-bearing polymetallic veins, Au-bearing (?) prophyry Cu, Au placers	48–28	0.1	Unknown	McLemore (1996)
OP	Old Placers	Ortiz (Cunningham Hill), Dolores, Lukas Canyon, Carache Canyon	Au-bearing breccias, Au-bearing skams, Au-bearing Cu skarns, Au-bearing polymetallic veins, Au placers	35–26	14	> 37	Long et al. (1998); McLemore (1996)
NP	New Placers	San Pedro	Au-bearing (?) Cu skarns, Au placers	46(?)	3.6	Unknown	McLemore (1996)
Ji	Jicarilla	Jicarilla	Au-bearing polymetallic veins, Au-bearing (?) Cu skarns, Au placers	38	0.5	Unknown	McLemore (1996)
WO	White Oaks	White Oaks	Au-bearing polymetallic veins, Au-bearing breccias, Au-bearing Fe skarns, Au placers	36–29	5.1	> 16	Long et al. (1998); McLemore (1996)
NG	Nogal-Bonito-Schelerville	Helen Rae, Mudpuppy-Waterdog, Vera Cruz	Au-bearing polymetallic veins, Au-bearing breccias, Au placers	38–26	0.7	> 9	Long et al. (1998); McLemore (1996)
OG	Orogrande	Orogrande	Au-bearing Cu skarns, Au-bearing (?) porphyry Cu, Au placer	48–42	0.5	Unknown	McLemore (1996)
OR	Organ Mountains	Sol, Torpedo	Au-bearing polymetallic veins, Au-bearing (?) porphyry Cu, skarns	33–30	0.4	Unknown	Ludington et al. (1988); McLemore (1996)

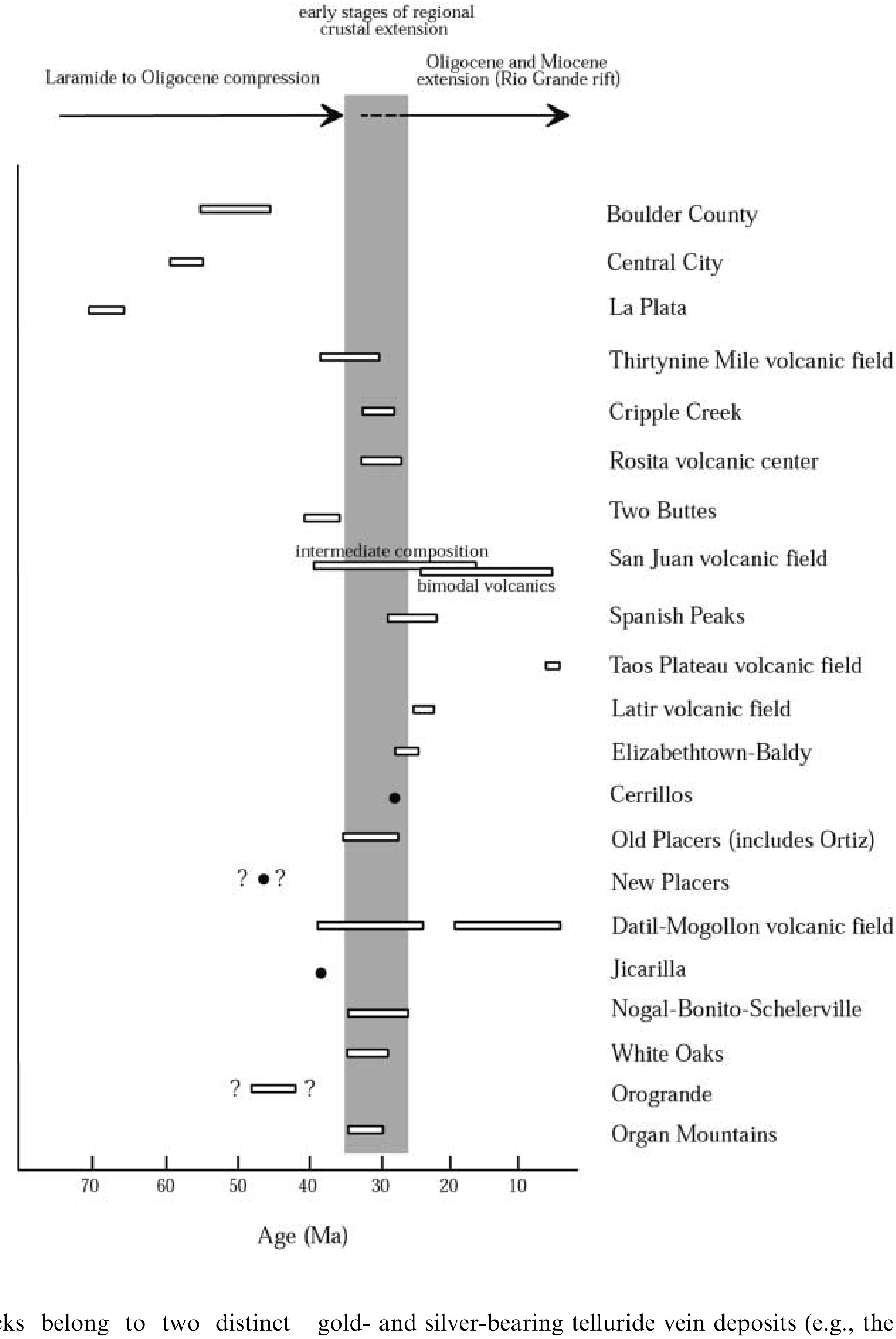


Fig. 3 Age comparison of igneous and volcanic complexes and related gold deposits in Colorado and New Mexico. Sources of data are as follows: Boulder County from Cunningham et al. (1994) and Geller (1994); Central City from Rice et al. (1985) and Wallace (1989); Thirtynine Mile volcanic field from Epis and Chapin (1974) and Mertzman et al. (1994); Cripple Creek from Kelley et al. (1998); Rosita volcanic center from Sharp (1978); San Juan volcanic field from Lipman et al. (1978); Two Buttes from Davis et al. (1996); Spanish Peaks from Penn (1994); Taos Plateau volcanic field from Dungan et al. (1986); Latir volcanic field from Lipman (1981); Datil-Mogollon volcanic field from Osburn and Chapin (1983); Elizabethtown-Baldy, Cerrillos, Old Placers, New Placers, Jicarilla, Nogal-Bonito-Schelerville, White Oaks, Orogrande, from references cited in McLemore 1996; see Table 1); Organ Mountains from McLemore (1996) and Verplanck et al. (1995)

(Eckel 1949). Igneous rocks belong to two distinct phases. The oldest are generally porphyritic and include hornblende monzodiorite, syenite, and lamprophyre. These intrusions occur as dikes, sills, and stocks primarily in the center of the dome. Younger igneous rocks consist of a suite of monzonite, syenite, and diorite that have been dated at 70–65 Ma (Werle et al. 1984). Mineralization was temporally associated with the younger phase of igneous rocks. Two distinct mineralization styles are present (Werle et al. 1984; Saunders 1991): (1) gold- and silver-bearing telluride vein deposits (e.g., the Bessie G deposit; Saunders and May 1986) and (2) porphyry-style Cu–Au (±PGE) stockworks and disseminations (e.g., the Allard stock; Eckel 1949; Werle et al. 1984). The grade tonnage plot from Jensen and Barton (2000) separates the two deposit types (Fig. 2); the point labeled "La Plata Mtns" represents historic production from high-grade epithermal veins, whereas the point labeled "Allard Stock" represents the porphyry-style Cu–Au–PGE deposits. Gangue minerals in the veins include quartz, barite, roscoelite, and carbonate minerals with minor fluorite (Saunders and May 1986). Ore mineral paragenesis is consistent with many other alkaline-related gold deposits that have early base-metal sulfides followed by telluride minerals and late native gold. For example, deposits in Boulder County (see discussion below), Cripple Creek (see below) and the Emperor deposit in Fiji (Ahmad et al. 1987; Setterfield et al. 1991) display a remarkable consistency with respect to the sequence of these minerals. The age of the alkaline igneous rocks suggests that the deposits formed shortly after the onset of the Laramide orogeny (Fig. 3) that was marked by regional northeast-directed compression.

The Central City district, located about 50 km west of Denver (Fig. 4), has produced more than 170 metric tons of gold since its discovery in 1859. Only about 31 metric tons of this total, however, are from deposits that have been linked to alkaline magmatism (Table 1). The region is characterized by a series of stocks, sills, and dikes of primarily leucocratic granodiorite, and monzonite and bostonite (potassium feldspar-rich rock with few or no mafic components) porphyry that intrude Precambrian rocks (Sims et al. 1963). Mineralization consists predominantly of sulfide- and/or telluride-bearing quartz veins. The telluride mineralization postdates the base-metal sulfide stage (Rice et al. 1985). Most of the mineralization developed at around 59–52 Ma at the end of igneous activity (Fig. 3); this age range is based on K–Ar dating of sericite in veins and biotite and whole rock ages of pre- and post-ore intrusions (Rice et al. 1982, 1985; Wallace 1989).

The gold-telluride deposits of Boulder County occur as a broad north-trending group at the northeastern end of the CMB. This area includes the mining districts of Jamestown, Gold Hill, Magnolia, Sugarloaf, and Ward (Fig. 4). Together, these districts produced about 30 metric tons of gold (Table 1) since 1872, primarily from gold-telluride veins. The district is also known for its tungsten ores, but these deposits are largely separate and distinct from the telluride belt, both spatially and genetically; the tungsten deposits form a northeast-trending belt that formed later than the telluride ores (Kelly and Goddard 1969). The region consists of 1.7 to 1.4 Ga Precambrian rocks that were intruded by early Tertiary monzonite and syenite stocks and dikes. Most of the ore occurs in northeast-trending veins that are offset by northwest-trending faults (Kelly and Goddard 1969). The age of mineralization is assumed to be 55–44 Ma based on the close spatial relationship between gold mineralization and a 44–45 Ma sodic granite stock in the Jamestown district (Cunningham et al. 1994), and a maximum $^{40}Ar/^{39}Ar$ age of 55 Ma for telluride-stage adularia from Gold Hill (Geller 1994). The age of the Boulder County deposits suggests they are the youngest gold-telluride deposits associated with the Laramide orogeny (Fig. 3; Saunders 1991).

Primary vein minerals in the Boulder County deposits include early quartz, adularia, roscoelite, fluorite, and

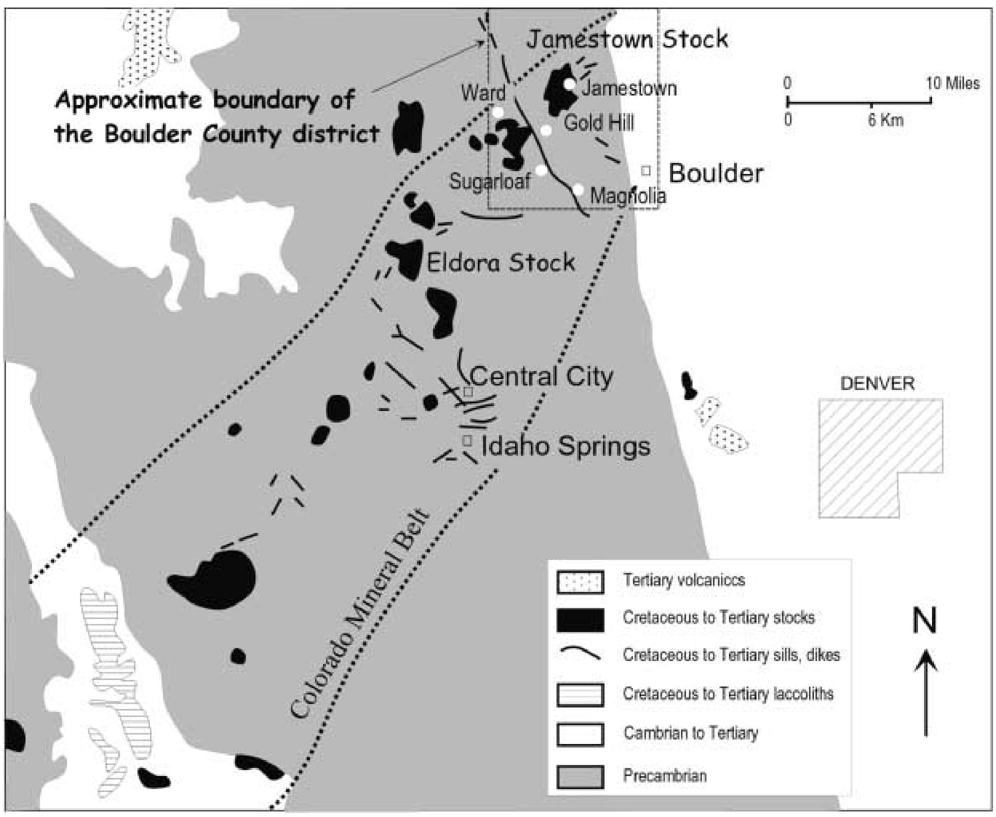


Fig. 4 Regional geology of the Central City and Boulder County areas, showing locations of major igneous stocks of Cretaceous to Tertiary age; primary deposits in the Boulder County area are also shown (modified from Tweto and Sims 1963; Rice et al. 1982)

barite that partly overlapped but largely preceded sulfide (galena and sphalerite) deposition. This was followed by deposition of gold-telluride minerals and native tellurium, native gold, and finally by deposition of carbonates (ankerite-dolomite and calcite) late in the sequence after the tellurides had formed (Kelly and Goddard 1969).

Cripple Creek

The Cripple Creek district is located about 30 km southwest of Colorado Springs (Fig. 1). Since its discovery in 1891, the district has produced nearly 700 metric tons of gold (Table 1). The deposits are localized within an Oligocene intrusive complex (Fig. 5a) that was emplaced into 1.7 to 1.0 Ga Proterozoic rocks (Lindgren and Ransome 1906; Thompson et al. 1985). There are two primary styles of mineralization: high-grade Au–Te veins that were the source of most of the historic gold production, and low-grade, disseminated gold deposits that are currently being mined (Jensen and Barton 1997; Kelley et al. 1998). The vein paragenesis includes quartz-K feldspar-fluorite-pyrite followed by base-metal sulfides and then telluride minerals (Lindgren and Ransome 1906). Roscoelite has been reported in association with some of the veins (Lindgren and Ransome 1906). Disseminated deposits consist of microcrystalline native gold with pyrite and are associated with zones of pervasive adularia (Jensen and Barton 1997). The deposits are spatially associated with alkaline igneous rocks such as phonolites and lamprophyres (Lindgren and Ransome 1906). All unaltered rocks are consistently rich in sodium, relative to potassium, but most within the district have been pervasively potassically altered (primarily potassium feldspar with some minor biotite- and sericite-bearing alteration zones) (Jensen and Barton 1997, 2000).

Interpretation of $^{40}Ar/^{39}Ar$ dates indicates a complex magmatic history. Eruption of phonolite and other relatively felsic rocks from 32.5 to 30.9 ± 0.1 Ma was followed by several stages of mafic and ultramafic intrusions, including one at about 28.7 Ma. Hydrothermal activity and gold mineralization coincided with magmatism, beginning at about 31–30 Ma and continuing, perhaps intermittently, for at least 2 million years (Kelley et al. 1998). Gold mineralization appears to be most closely associated temporally and genetically with the latest stage of alkaline magmatism (Kelley et al. 1998).

Evidence for a genetic link between the deposits and alkaline magmatism includes the following (Thompson et al. 1985; Kelley et al. 1998): (1) a close spatial association of the deposits with alkaline rocks; (2) similar ages of igneous rocks and associated deposits; (3) little or no geochemical zoning over the more than 1,000-m vertical extent of the vein systems; (4) similar lead isotope compositions of galenas from veins and feldspar from igneous rocks, (5) hypersaline fluid inclusions (250 °C) in quartz from early stages of vein formation, and (6) oxygen and hydrogen isotope data for quartz, biotite, and adularia from early veins that are consistent with a magmatic fluid origin.

Rosita

The Rosita Hills volcanic center is known primarily for its silver and base-metal production, but it also produced about 3 metric tons of gold from 1877–1885 (McEwan et al. 1996; McLemore 1996). The volcanic center is a mid-Tertiary alkali-calcic complex that overlies Precambrian metamorphic rocks (Sharp 1978). The center forms a conspicuous highland composed of lavas and breccias that were emplaced during two periods. The first cycle at 32–29 Ma (Sharp 1978) was an explosive event with deposition of rhyolites and volcaniclastic debris, followed by an extensive period of andesitic magmatic activity and forceful intrusion of rhyolitic magma along ring faults. This cycle ended with the collapse of the crater area and explosive activity, which formed two phreatic breccia pipes that contain most of the gold ($\pm$Ag and Te) mineralization in the area (Bassick orebody; McEwan 1986). The second cycle (27–26 Ma) consisted of trachyandesite and trachyte lava flows and latite stocks and dikes, followed by emplacement of lamprophyre dikes (Sharp 1978). Silver and base-metal mineralization with minor gold formed in veins after emplacement of the lamprophyre dikes (McEwan et al. 1996). Fluid inclusion and stable isotope studies, concentrated primarily on the second phase of vein mineralization, indicate that the ore fluids were magmatically derived (McEwan et al. 1996).

Elizabethtown-Baldy and Red River districts

The Elizabethtown-Baldy district in northern New Mexico is the largest gold producer in the state, and yielded more than 15 metric tons of gold from the time of discovery in 1867 until the end of mining in the 1940s (Table 1; Pearson 1961). The district is about 20 km east of the Questa stockwork molybdenite deposit and a deep tunnel beneath the district also encountered molybdenite mineralization (Pearson 1961). The entire district is on a private Mexican land grant, and has never been the subject of a formal geologic study. The deposits that were exploited appear to include gold-bearing polymetallic veins and gold-bearing copper skarns. There was also considerable production of placer gold. The deposits in the district are centered on a large quartz monzonite to monzonite stock, whose age is not well known, but is probably between 29 and 26 Ma (Kish et al. 1990). The vein style mineralization consists primarily of quartz and pyrite with chalcopyrite and galena. Gold is contained primarily in auriferous pyrite; telluride minerals have not been reported. Paragenetic relationships suggest the hydrothermal fluids were generated late in the evolution of the quartz monzonite pluton (Lindgren et al. 1910).

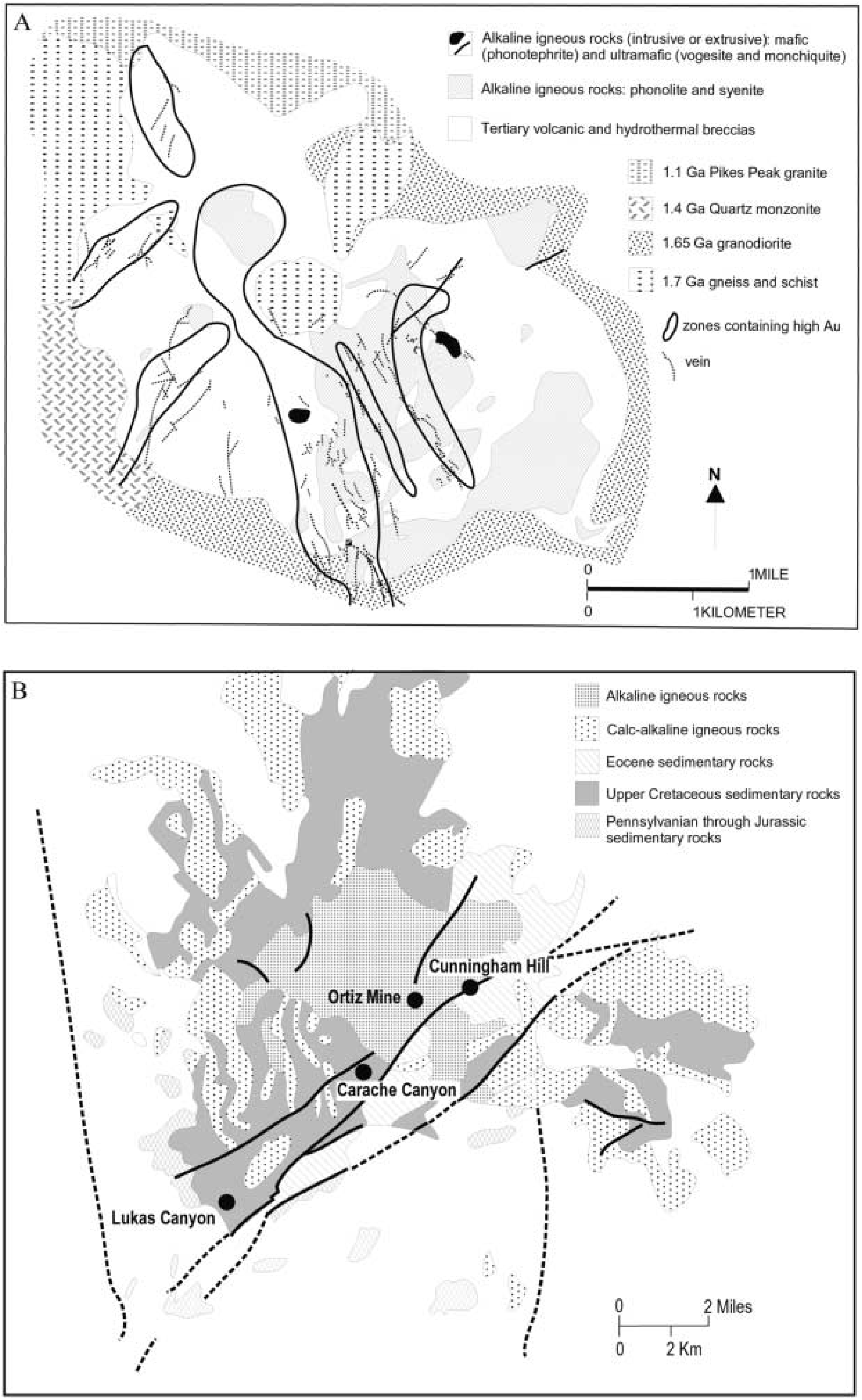


Fig. 5 Generalized geology of **A** the Cripple Creek district (modified from Kelley et al. 1998; zones containing high gold from Jensen and Barton 2000); and **B** the Ortiz Mountains region (Maynard 1995)

Cerrillos district

The Cerrillos mining district is located in southern Santa Fe County in the north-central part of New Mexico (Fig. 1). About 0.1 metric tons of gold have been produced from gold-bearing polymetallic veins, gold-bearing porphyry copper deposits and gold placer deposits (Table 1). The Cerrillos Hills are cored by multiple intrusive/extrusive centers with reported ages of 48–28 Ma (McLemore 1996; Fig. 3), although Giles (1991) indicated that most of the mineral deposits are associated with an intrusion dated at 28.9 Ma. The quartz-poor igneous rocks range from syenite to diorite, with monzonite (latite) predominant. They occur as plugs, stocks, dikes, laccoliths, flows, tuffs, and agglomerates (Giles 1991).

Gold is associated with chalcopyrite in Cu–Pb–Zn–Ag quartz–ankerite–pyrite veins and in porphyry copper occurrences. It also occurs in magnetite-quartz bodies in brecciated fault zones and small pipe-like features, and in narrow hornfels zones with copper- and iron-bearing oxide or sulfide minerals. Placer Au deposits are scattered throughout the district. The porphyry copper occurrences display most of the mineralization and alteration zoning patterns that are typical of many gold-rich porphyry systems (Sillitoe 1993), with a high chalcopyrite to pyrite ratio, very low molybdenite content, abundant magnetite, and significant gold. The auriferous polymetallic veins postdate the porphyry copper mineralization (Bauer et al. 1995). Giles (1991) suggested that mineral occurrences in the Cerrillos district are similar to those in the Ortiz Mountains (see below). The smaller size and lower grade of deposits discovered in the Cerrillos district to date (Fig. 2) are interpreted to reflect the deeper level of erosion in the Ortiz area. Alternatively, it may relate to the lack of a throughgoing fault zone, which is an important ore control at Ortiz, but is apparently lacking at Cerrillos.

Old Placers district

Since the 1820s, about 14 metric tons of gold have been recovered from the Old Placers district in the Ortiz Mountains (Table 1), located about 40 km south of Santa Fe, New Mexico (Fig. 1). Additional resources of more than 36 metric tons of gold in breccias at the Carache Canyon deposit and nearly 6 metric tons of gold at the Lukas Canyon gold-bearing skarn have recently been delineated (Maynard 1995; Schutz 1995). Tertiary igneous rocks in the region include an older calc-alkaline suite and a younger alkaline suite (Fig. 5B). Gold mineralization is associated with the latest stages of alkaline magmatism (Maynard 1995). Alkaline rocks emplaced during this stage include nepheline-bearing monzodiorite to monzonite stocks, phreatic breccia pipes, and trachyte dikes. Ages of these rocks range from about 30 to 28 Ma (Maynard 1995). Gold in the Ortiz Mountains occurs in five distinct deposit types: breccia pipes, skarns, veins, porphyry-related stockworks and placers. All of the gold deposits appear to be concentrated along strands of a major northeast-trending fault system (Fig. 5B; Maynard 1995; Schutz 1995). The mineralogy of the ores is variable between deposits, but typically includes adularia, quartz, scheelite, minor base-metal sulfides, and native gold; fluorite and telluride minerals are not present (Maynard et al. 1990; Maynard 1995; Schutz 1995). The results of fluid inclusion studies are consistent with the early ore fluids that deposited tungsten minerals and base-metal sulfides being of magmatic derivation. Deposition of native gold occurred from later, less saline, lower-temperature fluids that were magmatic and/or meteoric in origin (Schutz 1995).

New Placers district

The New Placers mining district in the San Pedro Mountains has a long history of production of gold and base metals. About 3.6 metric tons of gold were produced from gold-bearing copper skarns, gold-bearing epithermal veins, and placer deposits related to Tertiary quartz monzonite and diorite stocks (White 1991; McLemore 1996). A single K-Ar age on hornblende of 45.9 ± 3.9 Ma is reported by McLemore (1996) for the alkaline rocks. However, the temporal relationship between the dated stock and the mineral deposits is unclear, and McLemore (1996) suggests that the mineral deposits seem to be of approximately similar or younger age than the alkaline rocks.

Skarn mineralization consists primarily of chalcopyrite and auriferous pyrite with some native gold (White 1991). Adularia has also been reported in the skarn deposits (Atkinson 1961). Native gold occurs in veins within the stocks as well as in surrounding hornfels. Gold is associated with pyrite, calcite, quartz, and in rare cases barite (Atkinson 1961). Placer gold deposits occur in alluvium accumulated over portions of the alkaline stocks, as well as in pediment gravels adjacent to mineralized skarn and intrusive rocks (White 1991).

Lincoln County

The Lincoln County porphyry belt is located in south-central New Mexico and comprises several alkaline igneous centers, many of which host gold mineralization including in the Jicarilla district, in the White Oaks district, and in the Nogal-Bonito-Schelerville district in the Sierra Blanca igneous complex (Fig. 1). A total of about 6.3 metric tons of gold have been produced from the three districts (5.1 metric tons from White Oaks; 0.5 metric tons from Jicarilla; 0.7 metric tons from Nogal-Bonito-Schelerville) (Table 1), but important additional resources were discovered during the 1990s. The porphyry belt consists of alkaline and silica-oversaturated Tertiary intrusive and volcanic igneous rocks that were emplaced from about 38 to 26 Ma (Kelley and Thompson 1964). Igneous activity may have occurred in two pulses, although there are not enough geochronological data to determine this with certainty (McLemore et al. 1991). The current age constraints suggest an early (38.2–36.2 Ma) pulse that consisted of alkaline complexes emplaced along northeast-trending faults. The later pulse (30–26.5 Ma) consisted of multiple intrusions ranging from syenodiorite to alkali granite (Douglass and Campbell 1994).

Gold occurs in epithermal veins and hydrothermal breccias, and as placer deposits. Temporally related deposits include porphyry Mo–Cu systems and Ag–Pb–Zn veins. The gold deposits are often narrow vein systems emplaced along steeply dipping normal faults (Douglass and Campbell 1994; McLemore et al. 1991). Gold-bearing breccia pipes are particularly well developed in the Nogal-Bonito-Schelerville (Douglass and Campbell 1994) and White Oaks districts (Griswold 1959). The gold vein and breccia deposits have similar mineralogies and paragenesis. The most abundant minerals are early quartz, pyrite, and minor base-metal sulfide minerals, followed by gold-rich electrum and carbonate minerals (Campbell et al. 1991).

Orogrande district

The Orogrande district is located in the Jarilla Mountains in southern New Mexico (Fig. 1). Well-developed copper and more local lead-zinc skarns, both containing enrichments in gold and silver, occur in Ordovician to Mississippian limestones and dolomites (Strachan 1991). About 0.5 metric tons of gold were produced from the district (Table 1). Igneous rocks include early quartz latite and granodiorite that were emplaced at about 47 Ma, followed, after an unknown age interval, by the intrusion of monzonite- to quartz monzonite stocks. The ore deposits occur as late-stage epithermal veins and skarns associated with the later monzonitic complex (North 1992). The skarn deposits contain chalcopyrite as the main ore mineral; native gold is locally important. Potassium-silicate stockworks and porphyry copper occurrences have also been identified. Placer gold deposits, presumed to have eroded from the skarns, are found in many of the dry washes of the region (North 1992).

Organ Mountains

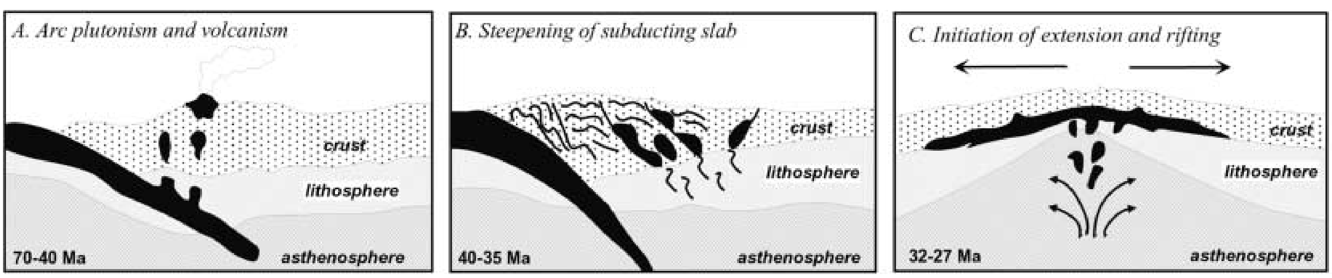
The Organ Mountains consist of a deeply eroded and extended Oligocene caldera complex, along with several subjacent plutons (Seager 1981). The area is relatively close to the axis of the Rio Grande rift, and strongly alkaline, silica-undersaturated rocks are sparse. Most of the plutons contain minor quartz and are dioritic to syenitic (Verplanck et al. 1995). Ages of plutonic rocks associated with mineralization range from 30 to 36 Ma (see references in McLemore 1996; Verplanck et al. 1995). At the northern margin of this igneous complex, the subeconomic Sol porphyry copper deposit is associated with mildly alkaline porphyritic latite, although the gold grades of this mineralized rock were either never determined, or are unrecorded (Newcomer and Giordana 1986). Other mineral deposits in the district are less clearly associated with the alkaline igneous rocks, and consist of silver-rich polymetallic skarn and replacement deposits, and minor polymetallic veins (Ludington et al. 1988).

Tectonic setting

Cretaceous to Tertiary tectonic history

The Laramide orogeny in western North America began during Late Cretaceous time at about 70 Ma (Fig. 6). Laramide subduction was characterized by northeast-directed regional compression, shortening, and uplift, and by emplacement of a varied suite of plutonic and volcanic rocks that were largely restricted to the CMB (Tweto and Sims 1963; Mutschler et al. 1988; Fig. 1). Magmatism was particularly active from 70 to about 55 Ma. Most of these rocks are calc-alkaline, but alkaline rocks were emplaced locally, particularly in the northeastern and southwestern ends of the CMB (Fig. 1). These alkaline rocks include those described above in the La Plata Mountains, at Central City, and in Boulder County. From about 55 to 40 Ma, magmatic activity waned, although it did not cease. This has been attributed to a speedup of subduction rate and temporary flattening of the subducting slab to a low angle (Dickinson and Snyder 1978; Lipman 1981). At about 40–35 Ma, a renewal of igneous activity culminated in a huge volume of volcanic rocks (e.g., Thirtynine Mile, San Juan, Latir, Datil-Mogollon,

Fig. 6 Schematic diagram illustrating the Cretaceous to Tertiary tectonic evolution of western North America. **A** At about 70 Ma, northeast-directed compression resulted in eruption and intrusion of calc-alkaline and alkaline igneous rocks. This changed dramatically at about 55 Ma when a temporary flattening of the subducted slab to such a low angle caused a dramatic decrease in igneous activity. **B** At 40–35 Ma, steepening dips of the subduction system resulted in renewal of igneous activity. **C** The tectonic regime changed from compression to extension, beginning at about 32 Ma in New Mexico and about 30–27 Ma in Colorado (modified from Lipman 1981)



and Trans Pecos volcanic field) that were nearly continuous from northern Colorado to Mexico. The voluminous magmatism is strong evidence for the removal of the subhorizontal slab, allowing the ascent of asthenosphere, an increase in heat, and the production of large quantities of melt (Humphreys 1995). Slab removal has been attributed to a rapidly steepening dip of the subduction system due to a decreased rate of plate convergence and subsequent rollback of the slab (Coney 1972; Christiansen et al. 1992) or slab removal by downward buckling of the slab beneath the western United States along an approximately east-northeast-trending axis (Humphreys 1995). This axis of slab buckling is proposed to have begun in the southernmost western United States and northern Mexico and propagated northward with time (Humphreys 1995). According to this model, the east–northeast–trending buckled slab would have passed beneath New Mexico and Colorado at approximately 43 to 27 Ma.

In summary, Laramide tectonism resulted in crustal thickening and significant magmatic modification of the lithosphere (Karlstrom and Humphreys 1998). For example, in the Datil-Mogollon volcanic field (Fig. 1), a batholith that accounts for about one-fifth of the crustal thickness has been detected in the upper crust, and a feature of similar dimensions exists in the San Juan region (Keller et al. 1998). As the tectonic regime changed toward the end of Laramide activity, upwelling of the asthenosphere and heating resulted in renewed igneous activity and a significant change in structural style at the Earth's surface.

The major post-Laramide structural manifestation was extension and formation of the Rio Grande rift and Basin and Range province (Fig. 1) that developed in the previously thickened crust. Physiographically, the rift is recognized as a series of grabens and half-grabens, which extend for more than 1,000 km from south-central Colorado to Mexico. Rift structures, however, are recognized as far north as the Colorado–Wyoming border (Steven 1960). The northern segment of the rift in Colorado began developing at about 30–27 Ma (Lipman et al. 1978; Lipman 1981), whereas to the south in New Mexico, extension began earlier, at 32–29 Ma (Chapin and Seager 1975). Most of the alkaline igneous rocks and associated gold deposits (from Cripple Creek south into Mexico) discussed in this paper formed precisely during this tectonic transition (Fig. 3), suggesting that the tectonic events in Late Cretaceous to Tertiary time were important for creating mantle and crustal conditions that were favorable for generating alkaline magmas and associated gold deposits. Post-subduction or back-arc settings is a feature that has been recognized for a number of other world-class alkaline-related gold deposits, such as the Porgera and Ladolam deposits in Papua New Guinea, and the Emperor deposit in Fiji (Richards 1995). The low degrees of melting of subduction-modified or metasomatized mantle in such settings typically results in the generation of small volumes of water-bearing, volatile-rich oxidized magmas that are important for generating gold-rich magmatic-hydrothermal fluids (Richards 1995).

Proterozoic tectonic history and evolution of the continental lithosphere

Alkaline magmas generated during the Tertiary would have remained trapped in the mantle or at lower crustal levels and be of no economic interest if not for the presence of deep-seated structures of regional extent that allowed the magmas to rise to shallow crustal levels. The Proterozoic tectonic evolution of southwestern North America strongly influenced successive tectonic and magmatic events (Karlstrom and Humphreys 1998) and we propose that regional basement features produced during the Proterozoic provided an important control on the location of Cripple Creek and other alkaline-related gold deposits. For example, the Cripple Creek intrusive complex is localized at the junction of Proterozoic (approximately 1.7 Ga) metamorphic rocks and three separate Proterozoic (1.65, 1.4, and 1.1 Ga) intrusive units (Fig. 5A). Clearly, this illustrates that prolonged and repeated magmatic activity was focused along the same zones of crustal weakness.

Terrane amalgamation of ancient North America during the Proterozoic (1.8–1.65 Ga) produced northeast-trending tectonic boundaries (Fig. 7A; Karlstrom and Humphreys 1998). Major blocks include the: (1) Archean craton, with protoliths and deformation dated between 2.5–3.5 Ga; (2) a 1.76–1.72-Ga juvenile arc terrane that constitutes the Yavapai Province (termed the Colorado Province in Colorado; Sims et al. 2001); and (3) Mazatzal province, 1.7–1.6-Ga supracrustal rocks on unknown basement (Karlstrom and Bowring 1988). No major shear zone that might represent a discrete suture between the Yavapai and Mazatzal provinces has been identified (Karlstrom and Humphreys 1998; Shaw and Karlstrom 1999). Instead, the boundary between the Yavapai and Mazatzal province is a wide zone, defined at its northern edge by the northern extent of 1.65-Ga deformation, and its southern edge by the southernmost extent of Yavapai (pre-1.7-Ga) crust (Karlstrom and Humphreys 1998).

Assembly of Proterozoic provinces took place by progressive shortening between 1.8 and 1.6 Ga. The arcs of the Yavapai (Colorado) province may have developed over a north-dipping subduction zone. The supracrustal rocks of the Mazatzal province were deposited on the south margin of the newly stabilized Yavapai province, then deformed during continued contraction at about 1.65 Ga. Late orogenic plutons (1.7–1.65 Ga) intruded older Proterozoic crust as far north as the Archean suture (Fig. 7A). These plutons were important precursors to Tertiary magmatism. For instance, deposits at Boulder County, Cripple Creek, and Elizabethtown-Baldy are located where 1.7–1.65 Ga plutons were intruded (Fig. 7A).

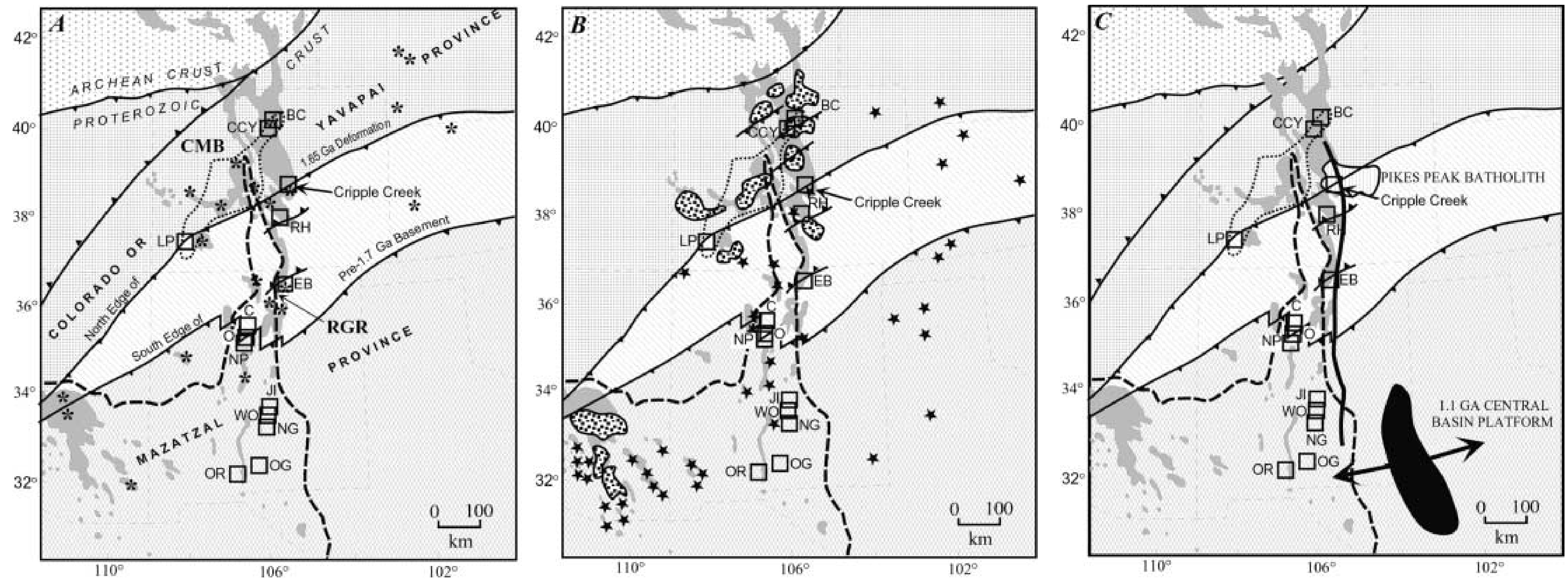


Fig. 7 **A**. Major northeast-striking tectonic boundaries produced during 1.8–1.65-Ga contractional amalgamation of lithosphere in the southwestern United States; The Yavapai–Mazatzal boundary marks the transition from 1.76–1.72-Ga juvenile arc terrane (Colorado Province in Colorado; Yavapai Province in New Mexico and Arizona) to 1.7–1.6-Ga supracrustal rocks on unknown basement (Mazatzal). This boundary (left diagonal lines) is a wide zone, defined at its northern edge by the northern extent of 1.65-Ga deformation, and its southern edge by the southernmost extent of Yavapai crust. *Asterisks* mark the location of late synorogenic (1.7–1.65 Ga) granitoids. **B** Map showing 1.4 Ga granitoids (*stars* for isolated intrusions; *heavy stipple* for large bodies) that were intruded into older crust within the Proterozoic orogenic belt. Plutons are most voluminous along northeast-striking crustal boundaries. **C** Map showing Pikes Peak granite (*vertical lines*) and mafic rocks (*black*) that were emplaced at 1.1 Ga. The major normal fault in New Mexico and Colorado produced at this time ignored earlier Proterozoic boundaries. *Shaded gray areas* are exposures of Precambrian rock outcrops. Major alkaline-related gold deposits are shown for reference, as are the boundaries of the Colorado Mineral Belt (*CMB*) and Rio Grande Rift (*RGR*). Note that the location of Cripple Creek is near major tectonic boundaries and it coincides with the location of 1.7, 1.4, and 1.1 Ga intrusive rocks (modified from Karlstrom and Humphreys 1998)

After 200 million years of stability, cratonic lithosphere was affected by a second major event that resulted in regional amphibolite-facies metamorphism, dominantly granitic magmatism (mainly 1.45–1.35 Ga), and tectonism (Fig. 7B). This event involved mantle and crustal melting (Anderson 1989), with magmatism concentrated and guided by older northeast-striking boundaries. Within the Proterozoic belts, isolated Mesoproterozoic plutons are widely distributed (stars on Fig. 7B), but larger bodies are localized along northeast-striking province boundaries and shear zones. Most of the magmatism was concentrated in what is now the Colorado mineral belt (Fig. 1), with a large body at the northeastern end (location of present-day Boulder County and Central City gold deposits), as well as isolated plutons at Cripple Creek and near Rosita Hills (Fig. 7B).

Deformation during the Mesoproterozoic was of regional extent and expressed by superposed folds and abundant northeast-trending ductile shear zones (Hildenbrand et al. 2000; Sims et al. 2001). The northwest and southeast margins of the CMB are marked by major Mesoproterozoic structures (shear zones), and in southern Colorado, the southwestward projection of the Arkansas shear zone marks the southwestern limit of the CMB (Sims et al. 2001). In addition to known prominent shear zones in Colorado, the interpretation of magnetic data implies the presence of abundant northeast-trending shear zones throughout the entire southern Rocky Mountain region (Carol Finn, personal communication, 2001). These shear zones were reactivated repeatedly in the Phanerozoic, as shown by mylonitic shear fabrics, late faulting and brittle fracturing, and by alignment of younger intrusions and structural and topographic features (Sims et al. 2001). In addition to having been a major factor in localizing the CMB, several specific features can be shown to be aligned along major Mesoproterozoic shears. The Cripple Creek district is located on or near the projection of the Arkansas shear zone, and near the major northeastern boundary (marked by the northernmost edge of 1.65 Ga deformation) separating the Colorado and Mazatzal provinces (Fig. 7A). Many of the other alkaline-related gold deposits (e.g., Rosita, Elizabethtown-Baldy, Old Placers, and New Placers districts) also fall along northeast-trending tectonic boundaries (Fig. 7B).

North American lithosphere underwent a major period of incipient rifting and accompanying bimodal magmatism at about 1.1 Ga (Fig. 7C). Tectonism involved tholeiitic basaltic magmatism and east-west extension, temporally coincident with 1.1–1.07 Ga granitic magmatism (Walker 1992). The largest granitic body is the 1.1-Ga Pikes Peak batholith. The Central Basin Platform (Fig. 7C; Karlstrom and Humphreys 1998), underlain by a 3–10-km-thick, 1.16–1.07-Ga layered mafic and ultramafic intrusion that trends toward, and may be related to, a major north-south fault (Fig. 7C) shows little relation to the earlier northeast-trending Proterozoic boundaries. Cripple Creek is situated along this Proterozoic rift trend, coincident with the location of the Pikes Peak batholith. Other deposits such as Elizabethtown-Baldy, Rosita Hills, and the Lincoln County deposits in southern New Mexico also occur parallel to and adjacent to this structure. The projection of this structure northward 20 km intersects the Boulder County and Central City deposits (Fig. 7C).

Proterozoic structural features have influenced the location of tectonic and magmatic events for almost 2 billion years. Many of the Tertiary alkaline-related gold deposits occur at the intersection of 1.8–1.65 or 1.4 Ga northeast-trending and 1.1 Ga north-trending structures, and/or in areas of previous Proterozoic intrusive events (Fig. 7). This suggests that the Proterozoic structures were important conduits through which Tertiary alkaline magmas and associated hydrothermal fluids ascended to the surface.

Compositional variation of alkaline rocks

In addition to providing the structures necessary for the localization of Tertiary magmatism, it is likely that compositional variation in the Proterozoic terranes of southwestern North America influenced the composition of Tertiary magmas. To better evaluate this, a compilation was made of available Sr and Pb isotope data for selected Tertiary alkaline igneous rocks from southern Colorado and New Mexico (Figs. 8 and 9). The compilation primarily includes alkaline rocks that have associated gold mineralization (described in this paper); however, some unmineralized magmatic provinces of similar age were also included for comparison. Unfortunately, data (especially lead isotope data) are not yet available for many of the alkaline-related gold deposits.

Comparison of strontium isotope compositions

Initial $^{87}Sr/^{86}Sr$ ratios for many of the alkaline rocks in Colorado and New Mexico are shown in Fig. 8. The initial $^{87}Sr/^{86}Sr$ ratios for some nonmineralized volcanic provinces are shown for comparison with ratios for gold-related alkaline rocks. Compositions vary from approximately 0.7048 to 0.7075 for the San Juan volcanic rocks (Lipman et al. 1978), 0.7041 to 0.7073 for the Spanish Peaks (Penn 1994), and 0.7050 to 0.7080 for the Latir volcanic field (Johnson et al. 1990). Strontium data from the CMB exhibit a wide range of values, and they show important isotopic differences between and within geographic provinces (Simmons and Hedge 1978; Stein 1985). Monzonitic intrusions related to mineralization at Central City and Boulder County have the lowest initial $^{87}Sr/^{86}Sr$ ratios in the CMB (Fig. 8). Data for igneous rocks related to mineralization at La Plata are not available.

Strontium isotope compositions for mafic to intermediate igneous rocks associated with gold deposits

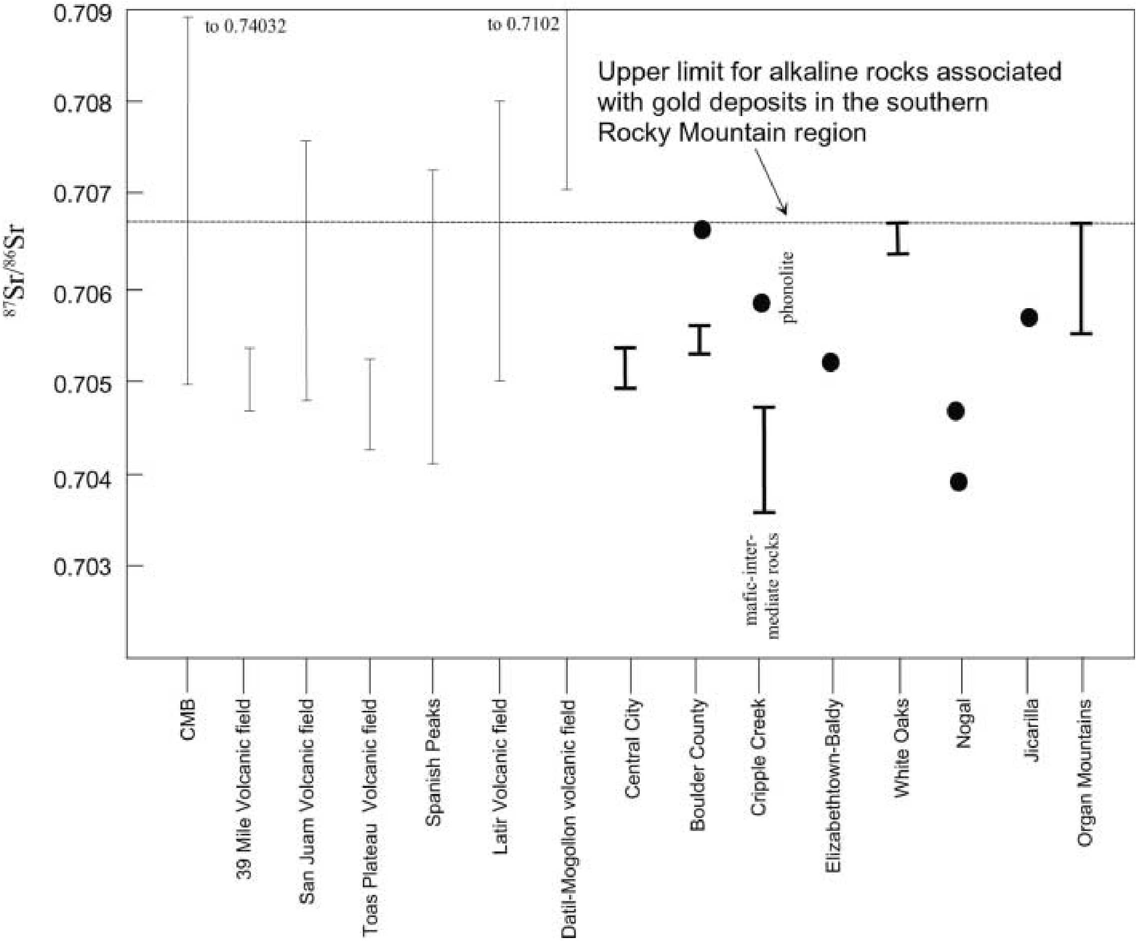


Fig. 8 Strontium isotope compositions of alkaline rocks from the southern Rocky Mountains. Alkaline rocks associated with gold mineralization are shown as *thick lines* for ranges of values, and *dots* for single analyses. Data for some alkaline rocks in the region that are not associated with gold deposits are shown for comparison (*thin lines*). Sources of data are as follows: Colorado Mineral belt (*CMB*) from Stein (1985); Central City (includes the Eldora-Bryan Mt., Caribou, and Apex stocks) from Simmons and Hedge (1978); Boulder County (includes the Gold Hill stock) from Simmons and Hedge (1978), and the Jamestown porphyry from Stein (1985); Cripple Creek (Birmingham 1987); San Juan volcanic field (Lipman et al. 1978); Thirtynine Mile volcanic field (Goldman 1989); Taos Plateau volcanic field (Dungan et al. 1986); Spanish Peaks (Penn 1994); Latir volcanic field (Johnson et al. 1990); Elizabethtown-Baldy (Kish et al. 1990); Datil-Mogollon volcanic field (Bove et al. 1995); White Oaks, Nogal, and Jicarilla (Allen and Foord 1991); Organ Mountains (Verplanck et al. 1995). *Dashed line* at 0.7067 marks the uppermost initial $^{87}Sr/^{86}Sr$ ratio of alkaline igneous rocks associated with gold deposits in the southern Rocky Mountain region

at Cripple Creek cluster from 0.70391 to 0.70474 (Birmingham 1987), although more felsic rocks contain higher values (e.g., 0.7060 for phonolite within the mineralized complex). The Cripple Creek rocks have the least radiogenic strontium compositions of any of the gold-associated alkaline rocks for which data are available, although all rocks associated with alkaline-related gold deposits contain values less than 0.7067 (Fig. 8). These data are consistent with a source for gold-related igneous rocks in the upper mantle or lower crust (Kelley et al. 1998; Allen and Foord 1991; McLemore 1996). A large lower crustal component is preferred over direct involvement of mantle-related magmas in the production of most calc-alkaline to alkaline intrusions in the CMB and at Cripple Creek based on additional information provided by lead isotopic compositions (see below).

Comparison of lead isotope compositions

The lead isotopic compositions of igneous rocks from Cripple Creek and other magmatic provinces in Colorado and New Mexico are shown on Figure 9. Unfortunately, Pb isotope data do not exist for most of the mineralized alkaline rocks in New Mexico, so inclusion of these is not possible. There is a wide range in $^{206}Pb/^{204}Pb$ for nearly all of the magmatic provinces (especially intrusions within the CMB, the San Juan volcanic field, and the Spanish Peaks), suggesting heterogeneous sources. With respect to $^{206}Pb/^{204}Pb$, the data from Cripple Creek show a small compositional range (Kelley and Stein 1994; Kelley et al. 1998). Interestingly, the lead isotopic composition of a 59–60 Ma alkaline monzonite suite near Central City (the Eldora stock) that is associated with gold-telluride mineraliza-

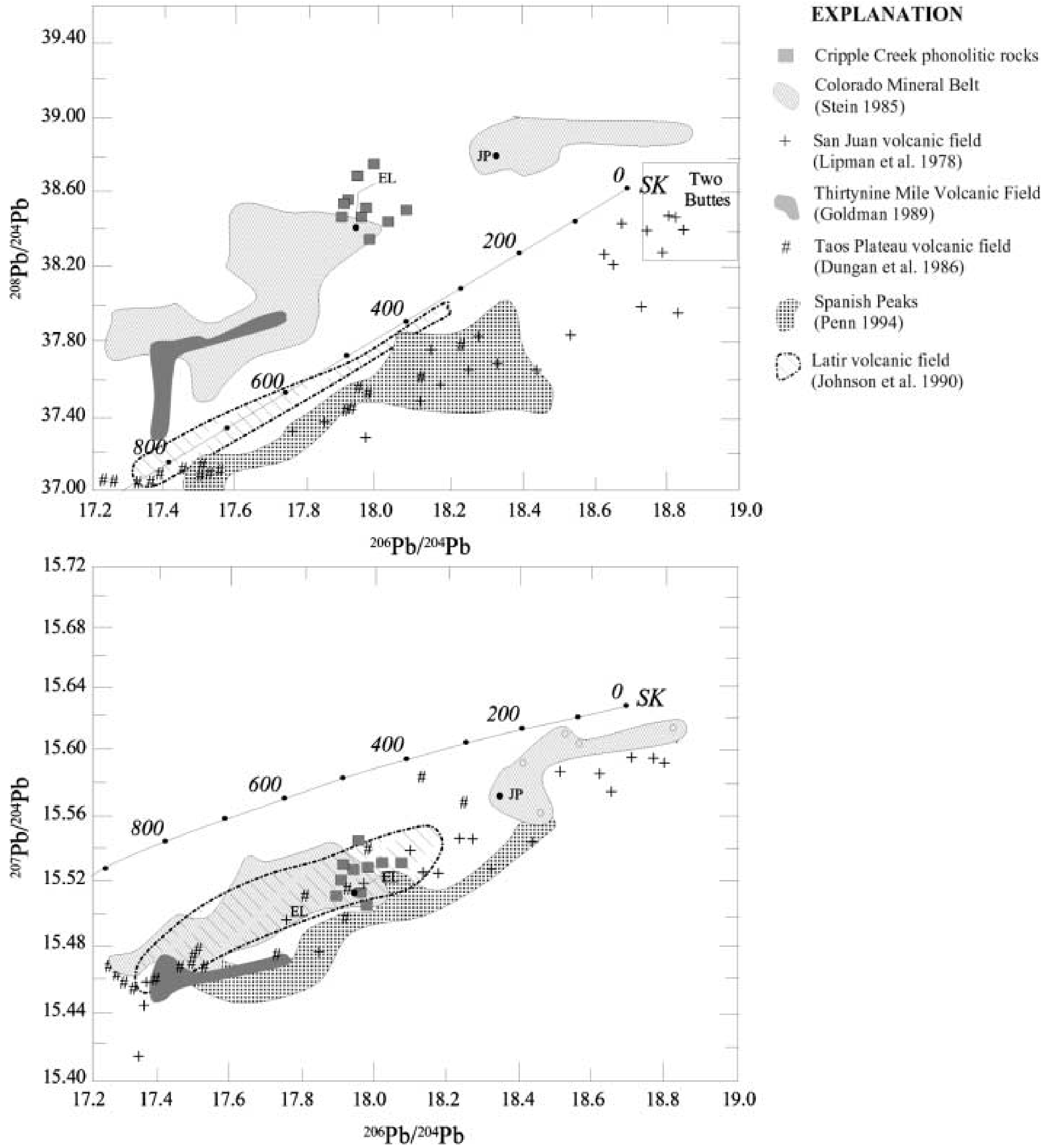


Fig. 9 Lead isotope compositions of Cripple Creek phonolitic rocks compared with other magmatic provinces. *Closed circles* from the CMB are intrusions spatially associated with Au–Te mineralization in the Central City (*El* Eldora Stock) and Boulder County district (*JP* Jamestown Porphyry). There are no data available for igneous rocks associated with mineralization at La Plata or Rosita. Sources of data are indicated in explanation. The Stacey and Kramers (1975) growth curve with *tick marks* showing time in 100-million year intervals is given for reference

tion (Lovering and Goddard 1950; Rice et al. 1982) coincides with the Cripple Creek data. The Jamestown Porphyry (44–45 Ma; Cunningham et al. 1994), associated with gold-telluride mineralization in the Boulder County district, lies on the same trend but is slightly more radiogenic than the Cripple Creek rocks (Fig. 9). The similarity in chemical and isotopic composition between some of the CMB alkalic stocks and Cripple Creek phonolitic rocks suggests a similar source and/or process for alkaline magmatism over a wide region of Colorado (Kelley and Stein 1994).

Although there is considerable overlap in $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ compositions between all of the alkalic igneous rocks, there are some distinct variations in $^{208}Pb/^{204}Pb$ compositions. In particular, there are systematic geographic variations between $^{208}Pb/^{204}Pb$ ratios of rocks in northern regions and those to the south. Rocks from Cripple Creek, the CMB, and the Thirtynine Mile volcanic field have a higher $^{208}Pb/^{204}Pb$ ratio for a given value of $^{206}Pb/^{204}Pb$ than rocks from further south (Fig. 9). The $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ compositions of all of the alkaline rocks are consistent with a mantle source (Zartman and Haines 1988). However, the

$^{208}Pb/^{204}Pb$ data for rocks in northern regions argue for significant involvement of lower crust in their evolution (Stein 1985; Kelley et al. 1998). This would suggest that, at least in northern regions, alkaline magmas that were generated by post-subduction melting of the asthenosphere and subcontinental lithospheric mantle assimilated and mixed with significant amounts of lower crust.

It is interesting to note that the lead isotopic compositions of Precambrian rocks from the Rocky Mountain region show a decrease in $^{208}Pb/^{204}Pb$ from north to south (Aleinikoff et al. 1993) that is similar to that shown by the Tertiary magmas. The CMB, Cripple Creek, and the Thirtynine Mile volcanic field overlie rocks of the Proterozoic Colorado Province (Fig. 7A), whereas all other rocks for which lead isotope data are available overlie the transition zone between the Colorado (Yavapai) and Mazatzal Province. This suggests that the differences in isotopic compositions of Tertiary alkaline rocks shown in Fig. 9 may be attributed to the chemical composition of Proterozoic crust underlying these two broad regions. The affects of compositional variations of underlying Proterozoic crust on alkaline magmas that generated gold-rich hydrothermal fluids are discussed in more detail below.

Discussion and conclusions

Alkaline igneous rocks and associated hydrothermal gold deposits formed at two times in the southern Rocky Mountains. The first episode was during Laramide time, and was confined spatially to the CMB, when the Boulder County deposits, Central City, and the deposits in the La Plata Mountains formed (Fig. 3). The second episode was early in the development of the Rio Grande Rift system, during the transition from a compressional to an extensional tectonic regime (about 35–27 Ma). The belt of rocks and deposits formed during this second episode follows the Rocky Mountain front southward, from Cripple Creek through New Mexico and Mexico. This alkaline suite is distinctive in that it contains the oldest rift-related rocks; the alkaline-related gold deposits and their accompanying rocks appear to be no younger than about 25 Ma, whereas other rocks of the bimodal suite, particularly alkaline basalts and high-silica rhyolites, are common well into Miocene time, and a few basalts have erupted in the last million years. In addition, the gold deposits and alkaline rocks (except the young basalts) are all on the eastern margin of the province, with voluminous calc-alkaline rocks to the west (San Juan and Mogollon-Datil volcanic fields).

It is likely that specific interrelated factors were responsible for generating and focusing the gold-rich hydrothermal systems. Some of these factors are listed below. We discuss how they possibly controlled the compositional differences of the alkaline rocks and ore deposits within the belt, how they may have influenced the mineralogy and style of mineralization, and how they may have contributed to the greater size and grade of Colorado deposits as opposed to others in the southern Rocky Mountains.

The generation of alkaline magmas

The most important factor in the formation of economically significant gold deposits in the southern Rocky Mountains was the near-surface emplacement of water-bearing, relatively oxidized, halogen-rich alkaline magmas. Alkaline magmas commonly show a positive correlation between high oxygen fugacities and dissolved water. The presence of hydrous phases (e.g., hornblende, biotite) as phenocrysts in alkaline igneous rocks is evidence for high dissolved water contents, and Fe^{3+}-bearing phases, such as magnetite and aegerine that are so common in alkaline rocks, are suggestive of high oxidation states (Jensen and Barton 2000). Oxidized magmas favor precipitation of large quantities of gold (Sillitoe 1979) because sulfide saturation is suppressed, and therefore sulfur is mostly present in the melt as sulfate, not sulfide, and the loss of precious metals into sulfide phases is minimized (Richards 1995). Another effective variable for increasing mineralization potential of a magma may be halogen contents (Müller et al. 2001). Both F and Cl are enriched in alkaline magmas, particularly potassic ones (Müller et al. 2001). The increased chloride solubility results in an increase in ore metals that are complexed with chloride. During magmatic devolatilization, gold (and copper) are partitioned into the volatile phase as a chloride complex (Seward 1984).

As discussed by Müller et al. (2001), lithosphere above subduction zones is commonly assumed to be more oxidized than other mantle regimes because of its infiltration by slab-derived fluids generated from dehydration and decarbonation reactions. Assuming this is true, lithosphere above the subducted slab in the Rocky Mountain region during the Laramide orogeny was probably oxidized and enriched in volatiles and halogens. The subsequent removal of the slab between about 35 and 27 Ma initiated small degrees of melting to produce the alkali- and volatile-rich oxidized magmas that were important for generating gold deposits.

Crustal characteristics

Cripple Creek is a true giant deposit, containing more than 20 times as much gold as deposits in the CMB and 100 times as much gold as those in New Mexico (Fig. 2; Table 1). Since all of the gold-associated alkaline melts were generated in the same tectonic environment, and at approximately the same time, additional factors must have been responsible for the large size of deposits at Cripple Creek and the CMB relative to those further south. Of course, many of the deposits, both in Colorado and New Mexico, are incompletely explored, and the knowledge of their true sizes could alter these inferences. It is now generally accepted that the metal budgets in alkaline-related deposits cannot simply be related to enriched source regions, but in addition are the products of efficient hydrothermal systems (Jensen and Barton 2000). This is the most likely explanation for the metal enrichment of Colorado deposits. In the discussion below, we point out some interesting observations that may have indirectly contributed to the efficiency of the Colorado systems.

The crust beneath Colorado is anomalous with respect to thickness (Fig. 10). Present-day crust underneath the CMB is at least 45 to 50 km thick (it may be greater than 50 km in the northeastern part of the belt) and it is about 50 km underneath Cripple Creek (Fig. 10). The thickness of the crust in these areas prior to Miocene extension was even greater (Karlstrom and Humphreys 1998). The crustal thicknesses in this region are largely the result of convergence and shortening during the Laramide orogeny. The crust beneath Colorado is also anomalous with respect to temperature and density. Lerner-Lam et al. (1998) show that the Colorado Rocky Mountains are underlain by low-velocity upper mantle, in contrast to the high-velocity mantle beneath the Great Plains to the east. The depression in velocity is suggestive of partial melt, and implies a higher temperature. The abnormally low density of the crust is illustrated by a large negative Bouguer gravity anomaly centered on the mountainous area of central and west-central Colorado (Wallace 1995). Assuming that these conditions were present at 30 Ma, perhaps the anomalous geothermal gradient promoted large-scale transfer of volatiles that were focused in this region, and melting of the thick but light crust occurred more readily.

Radiogenic isotopic evidence suggests that the composition of the Proterozoic crust and/or the greater degree of assimilation of crust by the Tertiary magmas may have contributed to the observed compositional differences between alkaline rocks at Cripple Creek and the CMB, and those to the south. Cripple Creek alkaline rocks show many isotopic similarities to the older Laramide rocks in the CMB, all of which were emplaced through crust of the Colorado province. Alkaline igneous rocks further south were emplaced into Mazatzal province rocks, and their isotopic compositions are significantly different (Fig. 9). Shaw and Karlstrom (1999) demonstrated a similar influence of the Yavapai-Mazatzal boundary on the isotopic composition of young igneous rocks in Arizona.

What role, if any, did crustal composition have on the genesis of the gold deposits in Colorado and New Mexico? Fluorite, roscoelite, and telluride minerals are common at both Cripple Creek and the CMB deposits, but are not prominent in the deposits further south. Could this suggest that the lithosphere beneath Colorado was compositionally different than that further south, or could volatiles and elements such as fluorine, tellurium, and vanadium (to make roscoelite) have been

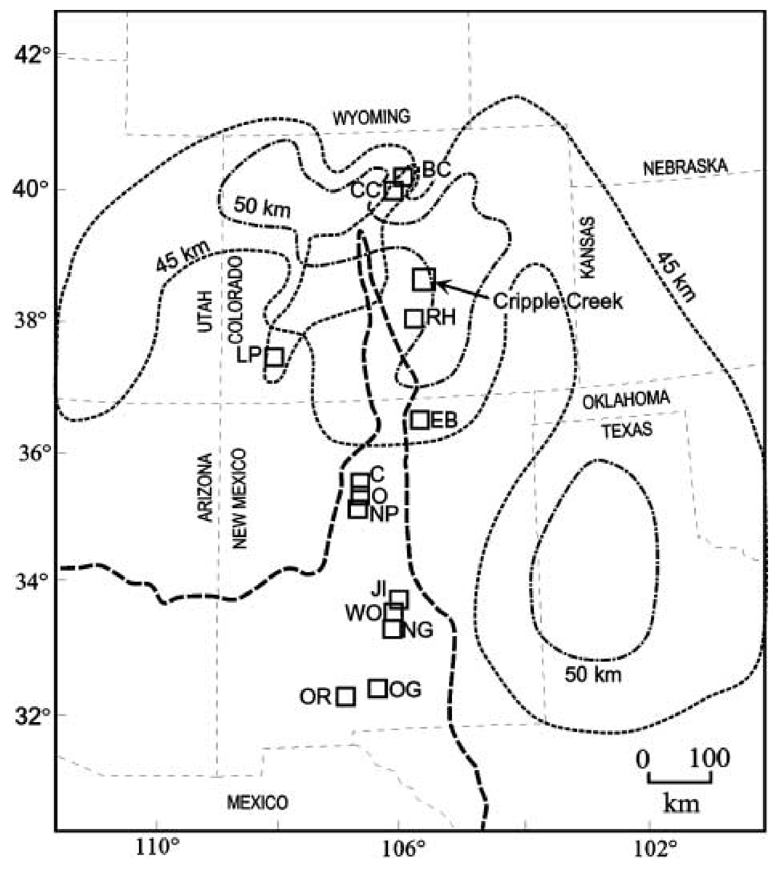


Fig. 10 Map showing present-day crustal thicknesses that were likely produced during Laramide shortening of the craton. Thickest areas are in Colorado and northern Texas (Karlstrom and Humphreys 1998)

inherited from the rocks of the Colorado province? If so, what are the implications for gold mineralization?

Selverstone et al. (2000) present xenolith, seismic, and heat-flow data from the Four Corners region of Colorado that straddles the proposed northeast-trending lithospheric boundary between the Yavapai (Colorado) and Mazatzal provinces. These data indicate that xenoliths from the northwest side of the province boundary (i.e., overlying the Colorado province) include LREE-enriched rocks with hydrous alteration whereas those southeast of the boundary (Mazatzal province) show no evidence of enriched sources and lack alteration. The metasedimentary biotite gneisses and schists (Idaho Springs type) and fluorine-rich anorogenic granites that underlie the Front Range in Colorado from Cripple Creek to the north (Reed et al. 1993) are likely candidates for providing fluorine to magmas that passed through them. We propose that the hydrously altered, LREE- and fluorine-enriched rocks that constitute the Colorado Province may also have contributed volatiles (H_2O, CO_2, and F) to the alkaline magmas through assimilation. The increased contents of volatiles may in turn have indirectly caused enrichments in tellurium and vanadium.

It has been proposed that the association of tellurides and alkaline magmatism may reflect enrichment of tellurium in the lithospheric mantle source, perhaps by sediment recycling (Jensen and Barton 2000). Tellurium is associated with organic materials (Cohen 1984), so subduction of organic tellurium-rich sediments could produce anomalous tellurium enrichments in the mantle, and melting of such enriched mantle would lead to tellurium-enriched magmas (Jensen and Barton 2000). In addition to a source enriched in tellurium, recent numerical modeling by Cooke and McPhail (2001) illustrates that the critical issue for tellurium enrichment is the generation of magmatic gases, because tellurium is likely transported in the gas phase (Cooke and McPhail 2001). Tellurium enrichment in hydrothermal fluids may therefore be somewhat dependant on high H_2O and CO_2 contents in the magma, so that transport of tellurium is ultimately enhanced.

Vanadium enrichment in alkaline-related gold deposits is expressed as the presence of roscoelite. Roscoelite is common in the Boulder County deposits (Kelly and Goddard 1969) and in the La Plata district (Saunders and May 1986) and it occurs at Cripple Creek (Lindgren and Ransome 1906), but it is not reported in deposits to the south (Rosita and deposits in New Mexico). Jensen and Barton (2001) suggest that in alkaline-related gold deposits, roscoelite correlates primarily with the proportion of mafic and felsic rocks because mafic rocks have much higher concentrations of vanadium than felsic rocks. However, mafic rocks do not predominate over felsic rocks in the CMB or Cripple Creek. Loucks (1990) showed that silica-undersaturated and water-rich melts indirectly affect the fractionation trend of vanadium. In melts with more than about 5 wt% H_2O, hornblende and aluminous augite crystallize. Because hornblende can accommodate appreciable Fe^{3+} and Ti, the modal proportion of Fe–Ti oxides decreases as the proportion of hornblende increases in the crystallizing assemblage. Magnetite is most efficient in depleting the melt in vanadium when the modal proportion of magnetite is maximized, but that occurs when magnetite crystallizes without hornblende, from melts that are dry as well as oxidized (Loucks 1990). Thus, in more hydrous magmas that crystallize hornblende and magnetite, vanadium is depleted from the melt relatively slowly.

The amount of dissolved H_2O may also affect mineralization potential of a magma. Hydrothermal fluids probably evolve from such systems in a manner analogous to porphyry systems (Richards 1995). During and/or after emplacement of the magmas, differentiation proceeds and H_2O and other volatiles are concentrated in the upper parts of the magma body. Thus, a dry magma will not evolve a magmatic-hydrothermal fluid. The gold segregates into a chloride-rich volatile phase, along with copper and other base metals. Breaching of this carapace by fractures results in formation of breccia dikes and pipes above and outward from the magma body. If gold remains in solution during the magmatic-hydrothermal stage, these residual auriferous fluids will mix with the circulating groundwater system. Economic concentrations of gold results from the rapid and perhaps explosive ascent of fluids from depth (Richards 1995). This rapid ascent and precipitation of gold requires deep-seated structural pathways.

Structural controls

Proterozoic structures played an important role in localizing alkaline-related gold deposits. Deformation during the Mesoproterozoic was of regional extent and expressed by abundant northeast-trending ductile shear zones (Sims et al. 2001). In addition to having been a major factor in localizing the CMB, the Cripple Creek district is located on or near the projection of the Arkansas shear zone, and near the major northeastern boundary (marked by the northernmost edge of 1.65-Ga deformation) separating the Yavapai and Mazatzal provinces (Fig. 7A). Many of the other alkaline-related gold deposits (e.g., Rosita, Elizabethtown-Baldy, Old Placers, and New Placers districts) also fall along northeast-trending tectonic boundaries (Fig. 7B).

Cripple Creek is also located on an important north-trending fault formed during 1.1-Ga rifting, and subsequently reactivated in Late Paleozoic and Tertiary time. Other deposits possibly related to this fault include Elizabethtown-Baldy, Rosita, Central City, and Boulder County. The sites of Proterozoic intrusions may also be important precursors to Tertiary alkaline magmatism. For example, Cripple Creek was emplaced in an area that was intruded three times in the Proterozoic – at 1.65, 1.4, and 1.1 Ga.

Differences in mineralization styles

With respect to mineralization style, we believe that depth of erosion is the most important factor. The semicontinuous zones of stockwork mineralization and the high-temperature mineral assemblages of the porphyry environment contrast with the dispersed nature of epithermal veins formed at relatively low temperatures. Gold-enriched porphyry, skarn, breccia, epithermal vein, and disseminated ores are all mineral deposit types likely to form at various pressures and temperatures surrounding the alkaline magmas. Even though documentation of the transition between environments remains elusive because of the huge size of composite systems, some recent discoveries (Arribas et al. 1995) lend credence to the idea that porphyry and epithermal deposits may be separate aspects of the same mineralizing event, although they may often be separated vertically by kilometers.

The breccia bodies at Cripple Creek, Rosita, Ortiz and Lukas Canyon, White Oaks, and Vera Cruz must have formed near the surface. Porphyry-style mineralization at the Allard Stock, at Jamestown in Boulder County, in the Cerrillos Hills and Organ Mountains, and the skarns at San Pedro (New Placers district), Jicarilla, and Orogrande must have formed in a somewhat deeper environment. The fact that Cripple Creek displays persistent veins and a remarkable lack of mineral zonation over more than a kilometer of vertical extent shows how large the mineralization interval can be.

Comparison to other alkaline-related deposits worldwide

Cripple Creek is the largest alkaline-related gold deposit in the Rocky Mountain belt (Fig. 2). Outside of this belt is the giant Bingham copper–gold porphyry deposit in Utah (Babcock et al. 1995) that contains about 1,256 tons of gold (Sillitoe 2000). The Bingham deposit is linked to late-stage mafic alkaline magmas that may have supplied a substantial portion of sulfur, copper, and gold to the system. Much like Cripple Creek, Bingham was generated during extension immediately following prolonged compressive tectonism, at about 37–38 Ma (Presnell 1997; Sillitoe 2000).

Other large alkaline deposits worldwide formed during arc magmatism. Although alkaline magmas are sometimes erupted in the initial stages of arc formation (Müller and Groves 1997), they more commonly erupt late in the evolution of the arc. Examples of alkaline-related gold (copper) deposits with a clear relationship to arc magmatism include Ladolam and Porgera in Papua New Guinea, and the Emperor deposit in Fiji (Fig. 2). At Porgera, the alkaline intrusive complex was emplaced in a fold thrust belt shortly after continent–island arc collision that took place following a period of subduction and modification of the upper mantle (Richards 1992). The Ladolam deposit also formed following cessation of subduction in a back-arc environment during incipient rifting (Moyle et al. 1990; Müller et al. 2001). Alkalic trachybasaltic-trachyandesitic volcanism at the Emperor deposit in Fiji occurred during the waning stages of subduction before failure of the subduction zone. Mineralization is related to intrusions that were emplaced into the volcanic pile at the margin of a caldera (Kwak 1990; Setterfield et al. 1991).

Although alkaline magmas show a general relationship with extensional tectonics, their tectonic settings are diverse (Richards 1995; Jensen and Barton 2000). However, a common theme for most alkaline-related gold deposits is a post-subduction or back-arc setting. In this setting, the driving force for voluminous arc magmatism is not present or has ceased, and melting that does occur in the mantle is usually small in extent and volume (Richards 1995). The exact mechanism and trigger for mantle melting in such settings are poorly understood.

Summary

One or more of the following factors were important in the genesis of alkaline-related gold deposits in the southern Rocky Mountains. We suggest that the combination of all factors may have been a key in forming the giant Cripple Creek deposit.

1. Subduction along western North America that modified the crust and lithosphere.
2. Removal of the subducting slab, and post-subduction melting of modified lithospheric mantle to produce oxidized, volatile- and halogen-rich alkaline magmas. The anomalous geothermal gradient, thickness and density of crust underlying Colorado shortly after the subducting slab was removed may have been a catalyst for large-scale transfer of volatiles. Assimilation of or contamination by hydrously altered, LREE-enriched rocks of the Colorado Province may have been important for enhancing volatile contents of the magmas.
3. Rapid emplacement of the magmas to shallow crustal levels along regional Proterozoic structures in areas of previous Proterozoic intrusive events.
4. Evolution of magmatic-hydrothermal fluids by a process analogous to porphyry-type systems; auriferous fluids mix with near-surface reduced waters and rapid precipitation follows.

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