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GEOLOGICAL, GEOCHEMICAL AND ISOTOPIC CHARACTERISTICS OF THE LINCOLN COUNTY PORPHYRY BELT, NEW MEXICO: IMPLICATIONS FOR REGIONAL TECTONICS AND MINERAL DEPOSITS

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Abstract—The Lincoln County porphyry belt (LCPB) is composed of alkalic and silica-oversaturated Tertiary intrusive and volcanic igneous centers in east-central New Mexico. The LCPB alkalic rocks belong to the Rocky Mountain alkalic province (RMAP), which comprises magmas generated during post-Laramide time along the Rocky Mountain front from Canada into Mexico, to the east of a more voluminous continental calc-alkalic magmatic arc. Igneous activity in the LCPB occurred in two pulses. An early (38.2–36.5 Ma) pulse, coinciding with waning subduction, was concentrated along the north-trending Pedernal arch and consisted of alkalic complexes emplaced along northeast-trending faults. The later (30–26.5 Ma) pulse, coinciding with early rifting, consisted of bimodal, mafic, alkalic dikes and granite plutons intruded along the east-trending Capitan lineament, and granitic plugs intruded into the older Sierra Blanca alkalic complex. Geochemical data indicate that the mafic alkalic magmas were derived from metasomatized mantle, whereas the granitic magmas of the younger pulse were derived from the lower crust. Fractional crystallization of mafic alkalic magma and crustal contamination produced the compositional variation present in some LCPB complexes. Certain mineral deposit types are related to igneous rocks belonging to either magma suite. Gold deposits are hosted by LCPB alkalic complexes, and are similar to deposits elsewhere in the RMAP (e.g., Cripple Creek, Colorado; Ortiz, New Mexico). Molybdenum porphyry deposits and thorium vein deposits are hosted by evolved granites. Iron skarn deposits and REE deposits are associated with rocks of both magma types.

INTRODUCTION

The Lincoln County porphyry belt (LCPB) is a group of Tertiary igneous rocks exposed in east-central New Mexico (Kelley and Thompson, 1964). These igneous centers are included in the Rocky Mountain alkalic province (RMAP; Carmichael et al., 1974), which includes post-Laramide alkalic centers distributed along the Rocky Mountain front from Canada into Mexico (see Allen and McLemore, 1991, this volume, fig. 1). The rocks of the LCPB are characteristically porphyritic and occur in shallow stocks, laccoliths, dikes, sills and two volcanic/plutonic complexes.

Early studies of the igneous rocks of the Ruidoso region largely focused on mapping and field description of the centers. In many instances, the rocks of the LCPB were considered to be cogenetic and, within an individual complex, comagmatic. Although alkalic and silica-oversaturated rocks were sometimes recognized, few chemical data were available, and the alkalic nature of many of the rocks was overlooked. Where alkalic and oversaturated rocks were recognized, they were interpreted to be related through differentiation.

Acquisition of a broad spectrum of geochemical and isotopic data, and additional radiometric age determinations, has allowed us to constrain more accurately the magmatic types and sources, ages and differentiation processes. Results presented here further our understanding of the petrogenesis of these and related rocks, and the occurrence of mineral deposits related to these igneous rocks.

REGIONAL AND TECTONIC SETTING

Although the majority of alkalic igneous rocks worldwide are associated with arched structures and rifts in stable continental crust (Oftedal, 1978; Bailey, 1974; Williams, 1982), small volumes of alkalic magmatism may accompany voluminous calc-alkalic activity along convergent plate boundaries. Whereas the calc-alkalic magmas are generated at relatively shallow levels below a magmatic arc with a mobile belt, coeval alkalic magmas are generated deep below passive foreland regions (Sorensen, 1974) and are considered deep-level products of subduction (Fyfe and McBirney, 1975; Gupta and Yagi, 1980; Wyllie, 1981; Peccerillo, 1985; Boullier et al., 1986). In both the rift and magmatic arc setting, alkalic rocks are often concentrated along linear trends or faults (Bailey, 1974; Barker, 1974; Perfit, 1987). Structural flaws in thick crust seem to be necessary to tap the deep-generated alkalic magmas (Lameyre, 1987).

The southern Rocky Mountain region from the early to middle Tertiary contained a subduction-related continental magmatic arc (Lipman, 1980; Allen and McLemore, 1991, this volume, fig. 1). In the north, igneous activity of post-Laramide age (50 Ma) includes the Challis and Absoroka volcanic fields (Dickinson and Snyder, 1978). Within Colorado and New Mexico, the calc-alkalic San Juan and Datil-Mogollon igneous activity occurred at 37–30 Ma, just after the Laramide deformation and prior to the inception of rifting along the Rio Grande (Chapin and Seager, 1975; Chapin, 1979; Lipman, 1980, 1981; Morgan et al., 1986). Coeval alkalic igneous activity of the RMAP occurred consistently east of the more voluminous calc-alkalic igneous activity. Igneous activity in the RMAP occurred along the boundary between the stable craton and the Laramide deformation front as defined by Dickinson (1981). In southern New Mexico, Texas and Mexico, middle Tertiary subduction-related igneous activity is also represented by the calc-alkalic Sierra Madre Occidental volcanic field and the alkalic intrusive/volcanic rocks of the Trans-Pecos magmatic province (Henry et al., 1982). Beginning at about 29 Ma, extension and bimodal volcanism was initiated in New Mexico, focused particularly along the Rio Grande rift (Chapin and Seager, 1975; Chamberlin, 1978).

The igneous activity of the LCPB occurred near the margin of the stable craton in New Mexico, which is manifested by the relatively undeformed Paleozoic and Mesozoic rocks of the Pecos slope (Allen and McLemore, 1991, this volume, fig. 2). Little evidence for Laramide deformation is found east of Carrizozo (Kelley and Thompson, 1964; Moore et al., 1988a, b). Weber (1964) suggested that the volcanic-derived sediments of the early Tertiary Cub Mountain Formation were deposited in a Laramide foreland basin. The more recent uplift and block faulting associated with rifting along the Rio Grande has its limit in this region also, as Basin-and-Range structure and physiography are prominent west of the gently east-dipping Pecos slope. Thus, the igneous rocks of the LCPB occur in a setting that includes features related to convergent tectonics as well as younger rifting.

LOCAL SETTING AND STRUCTURE

The igneous rocks of the LCPB are concentrated along and at the intersection of two major structures (Fig. 1), the north-south-trending Pedernal arch and the east-west-trending Capitan lineament (Kelley and Thompson, 1964). No evidence for the existence of the Mesozoic Mescalero arch of Kelley and Thompson (1964) has been found by the

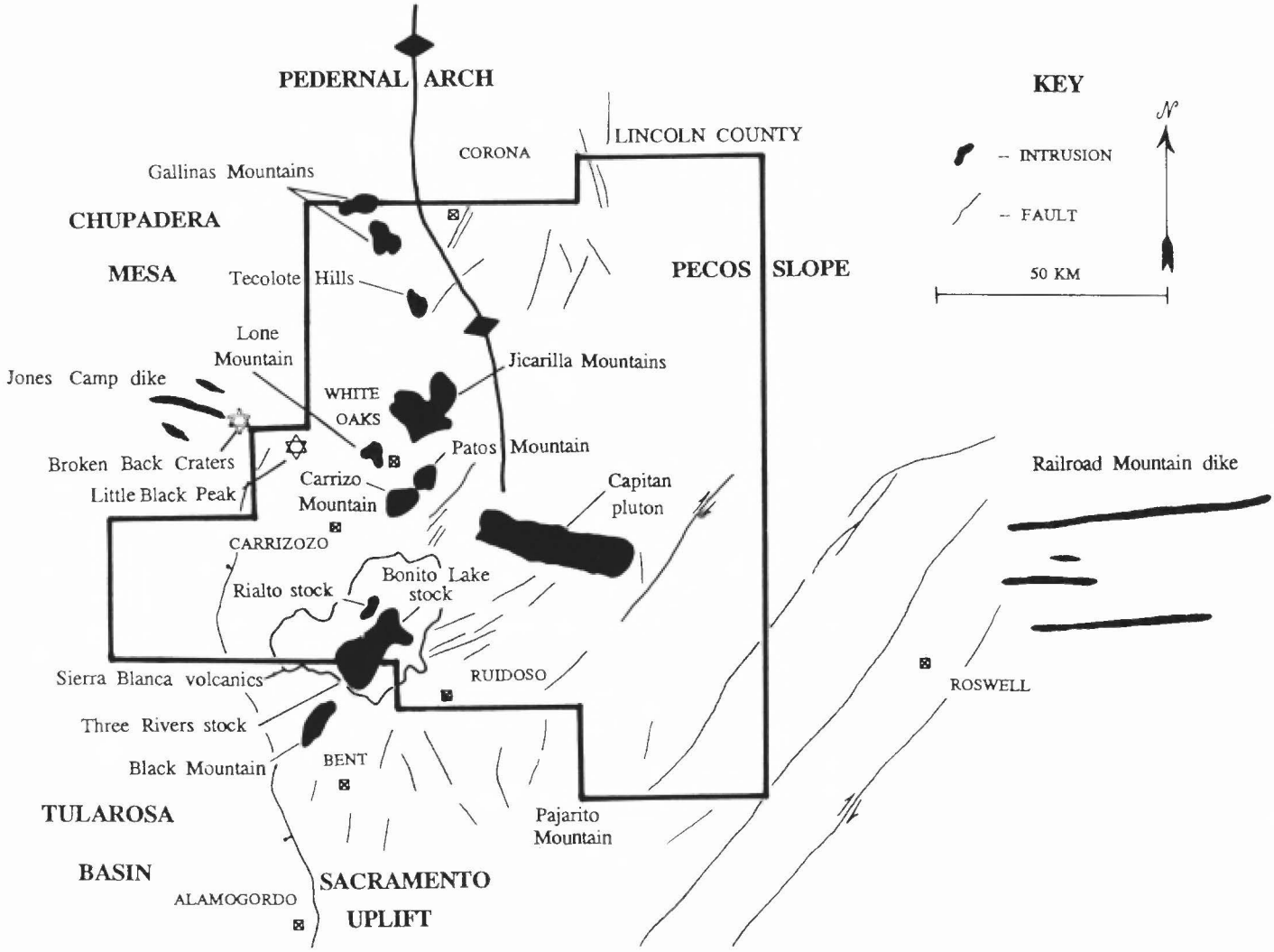


FIGURE 1. Map of the Lincoln County porphyry belt, New Mexico. Modified from New Mexico Geological Society (1982). (Stars are eruptive centers for the Quaternary Carrizozo basalt flows.)

detailed mapping of Moore et al. (1988a, b) on the Mescalero Apache Reservation south of Ruidoso. These structures controlled the spatial and temporal distribution of the magmas. The Pedernal arch is the remnant of a Pennsylvanian uplift that was eroded and submerged in Permian time (Weber, 1964; Kelley and Thompson, 1964; Kelley, 1971). This structure roughly controls the location of igneous centers of the LCPB, including the major complexes of Sierra Blanca, and the Jicarilla and Gallinas Mountains.

The Capitan lineament, as originally described by Kelley and Thompson (1964), is an alignment of structural and igneous features which includes the Matador arch of west Texas, the diabase dikes near Roswell, the Capitan pluton, the northern truncation of the Carrizozo anticline, the vents of the Quaternary Carrizozo basalt flows, and the composite Jones Camp dike (Fig. 1). Chapin et al. (1978) showed the Capitan lineament to deflect northward at the Rio Grande depression and persist westward to intersect the southwest-trending Jemez lineament in the vicinity of the Springerville volcanic field of eastern Arizona. They did not identify which features define the Capitan lineament west of the Rio Grande depression, however. We propose that the lineament includes the Anchor Canyon/Nitt igneous complex (Weber and Bassett, 1963; Park, 1971) and mafic alkalic dikes near Pie Town (Aldrich et al., 1986), based on the similarity of their ages (approximately 28 Ma) and compositions to rocks along the lineament east of the Rio Grande depression. The compositional similarity and proximity of the granite plutons of Patos Mountain, Carrizo Mountain and Lone Mountains, to the 26.5 Ma Capitan pluton suggests they may also belong to the lineament. The ages of these plutons are not known, however.

Thus, the Capitan lineament is a transverse fracture zone of the Rio Grande rift, which leaked basaltic and granitic magmas during early stages of rifting, and basalts recently. Differences in stratigraphy and structure north and south of the lineament, however, indicate a long-lived history prior to the Tertiary. The lineament served as a hinge line which controlled sedimentary depositional styles north and south of it in Paleozoic and Mesozoic times (Kelley and Thompson, 1964). Offset of structural contours on top of Permian strata north and south of the lineament near the Capitan pluton indicate between 15 to 30 km of left lateral motion, or 300 to 490 m of down-to-the-north motion before the Tertiary (Kelley and Thompson, 1964).

Geochronology data for igneous rocks of the Ruidoso region have been compiled in an effort to constrain more precisely the age of individual igneous bodies and the histories within the igneous complexes (Table 1). These data show that certain methods of age determination, particularly K-Ar on feldspar, and fission track on apatite, are of limited value in constraining ages where complex igneous, hydrothermal or structural histories are indicated, such as for the Sierra Blanca complex. Therefore, the ages of many units of the LCPB remain uncertain.

TABLE 1. Age determinations of igneous rocks from the Ruidoso region, Lincoln County, New Mexico. (Arrow indicates best estimate of age.)

Intrusive/Complex	Rock type	Mineral	Method	Age (Ma)	Source	Comment	Sample #	Latitude	Longitude
Carrizozo volcanic rocks									
Little Black Peak	basalt		geomorph.	<.0015 <--	1	estimated from weathering			
Broken Back Craters	basalt		LANDSAT	>.76 <--	here, 5	Comp. to Jornada del Muerto flows			
Capitan pluton	granite	biotite	K-Ar	26.5 <--	10	sample from porphyry core zone	CPT35	33 34 54	105 12 10
Patos Mountain pluton				?					
Carrizo Mountain pluton				?					
Lone Mountain pluton				?					
Jones Camp dike	syenodiorite	?	K-Ar	27.9 <--	9		312	33 57	106 12
Railroad Mountain dike	alkali gabbro	w.r.	K-Ar	27.9 <--	9		301	33 40	104 02
Sierra Blanca complex									
Three Rivers stock	alkali granite	w.r.	Rb-Sr	26.7 <--	8	NP3031, NP4037, NP4043, NP4074	33 22	105 48	
"	quartz syenite	biotite	K-Ar	28.1	8		SB2131	33 22 07	105 48 57
"	quartz syenite	feldspar	K-Ar	29.3 <--	8	anorthoclase	SB2131	33 22 07	105 48 57
"	syenite porphyry	feldspar	K-Ar	25.8	2	anorthoclase (>90% pure)	TT	?	?
"	syenite	feldspar	K-Ar	28.5	8	anorthoclase	SB4088	33 22 25	105 48 30
"	syenite	amphibole	K-Ar	29.9 <--	8	hornblende	SB4088	33 22 25	105 48 30
Older intrusions	essexite	feldspar	K-Ar	32.8	8	plagioclase and biotite altered	NP2164	33 22 37	105 45 25
"	nepheline syenite dike	biotite	K-Ar	36.6 <--	8	cuts essexite & neph. sy. (37 Ma)	SB2172	33 21 02	105 45 52
"	essexite		inferred	36.6-37.0		intrudes nepheline syenite (37 Ma)			
"	nepheline syenite	biotite	K-Ar	37.0 <--	8	cuts S.B. volcs., cut by essexite	SB4089	33 19 48	105 47 00
Bonito Lake stock	syenite	biotite	K-Ar	26.6	3	K-spar and amph. severely altered	L1051	?	?
Rialto stock				?					
Willow Hill sill	augite syenite	biotite	K-Ar	34.4	3	extensively deuterically altered	GB1241	33 33 49	105 52 16
Cub Mountain dike	essexite	w.r.	K-Ar	36.5 <--	9		407	33 34	105 54
Volcanic rocks	trachyphonolite	apatite	fission tr.	28.2	7	near syenite plug, age reset?	SB1081	33 21 55	105 49 47
"	trachyphonolite	feldspar	K-Ar	29.3	8	plagioclase (altered)	SB1081	33 21 55	105 49 47
"	trachyphonolite		inferred	37.0-37.3		cut by nepheline syenite (37 Ma)			
"	trachybasalt		inferred	37.0-37.3		cut by neph. sy. (37 Ma), basal volc.			
Godfrey Hills	trachyte	feldspar	K-Ar	26.1	2	sanidine (>95% purity) from flow	D-G	?	?
Church Mountain	phonolite	w.r.	K-Ar	31.8	3	"latite", glass with crystals	GR1242	33 33 27	105 46 08
Black Mountain stock	alkali gabbro	apatite	fission tr.	17.5	7	biotite chloritized	GD2218	33 15 36	105 54 06
"	alkali gabbro	biotite	K-Ar	36.0	8	biotite chloritized	GD2218	33 15 36	105 54 06
"	alkali gabbro	biotite	40/39 Ar	37.8 <--	11	biotite chloritized	GD2218	33 15 36	105 54 06
"	hornblende syenite porph.	apatite	fission tr.	22.6	7	plagioclase altered	GD2216	33 15 41	105 54 08
"	hornblende syenite porph.	plagioclase	K-Ar	32.6	8	plagioclase altered	GD2216	33 15 41	105 54 08
"	hornblende syenite porph.	plagioclase	40/39 Ar	34.6	11	plagioclase altered	GD2216	33 15 41	105 54 08
"	hornblende syenite porph.	zircon	fission tr.	36.3 <--	7	plagioclase altered	GD2216	33 15 41	105 54 08
"	hornblende syenite dike	hornblende	40/39 Ar	37.3 <--	11	xenocrystic amphibole	GD1079	33 15 35	105 54 46
"	hornblende syenite dike	hornblende	K-Ar	47.7	8	xenocrystic amphibole, excess Ar	GD1079	33 15 35	105 54 46
Gallinas Mountains				?					
Tecolote Hills				?					
Jicarilla Mountains	syenogabbro	biotite	K-Ar	38.2 37.3	6, 4	"monzonite"; recalculated from 37.2 Ma	JIC50	33 55	105 38

1 - Weber (1964)
2 - Thompson (1972)
3 - Weber (1971)
4 - Segerstrom and Ryberg (1974)
5 - Bachman and Mehnert (1978)
6 - Isochron West (1979)
7 - C.W. Naeser, U.S.G.S., written comm., 1984
8 - R.F. Marvin, U.S.G.S., written comm., 1983-84
9 - Aldrich et al. (1986)
10 - Allen (1988)
11 - L.W. Snee, U.S.G.S., written comm., 1989

Cenozoic igneous activity in the Ruidoso region spans the middle Tertiary to Recent, but can be divided into three pulses. The earliest pulse, from about 38.2 to 36.5 Ma, includes the Jicarilla intrusives and the undersaturated volcanic flows and intrusions of the Sierra Blanca and Black Mountain complexes (Table 1). The compositional similarities of undersaturated intrusions of the Tecolote Hills and Gallinas Mountains along the northern end of the Pedernal arch to these rocks suggest they also belong to this early event. A second pulse of igneous activity occurred near the onset of rifting at 30–26 Ma, and includes the late syenite-to-alkali-feldspar granite of Sierra Blanca and several igneous bodies along the Capitan lineament. The Capitan pluton was emplaced at 26.5 ± 1.2 Ma (Allen, 1988), slightly after the mafic dikes of the lineament (Railroad Mountain, Jones Camp, Pie Town dikes at 28 Ma; Aldrich et al., 1986). The proximity, and textural and compositional similarities of the granitic plutons of Carrizo Mountain, Lone Mountain and Patos Mountain to the Capitan pluton suggest they also belong to this pulse. The third pulse of activity in the Ruidoso region consists of the Quaternary eruptions of basalt flows near Carrizozo (the Malpais) from vents along the Capitan lineament. These eruptions are among the youngest in New Mexico (Renault, 1970).

DESCRIPTION OF FORM, PETROLOGY AND MINERALIZATION

"Younger" Tertiary granitic plutons

The fine-grained to aplitic rocks of the Capitan, Carrizo Mountain, Patos Mountain and Lone Mountain plutons share textural and compositional similarity. The quartz syenite and alkali feldspar granite units of the Three Rivers stock are compositionally similar to these rocks but will be described later with the Sierra Blanca complex. Considerable discrepancies are present in the literature that describes the form and composition of these plutons. Since these rocks are typically fine grained and porphyritic, and possess intergrowth textures, classifications based on modal analyses are subject to wide variation. Though age determinations are presently not available for all of these plutons, their similarity and proximity suggest that they are comagmatic.

Capitan pluton

Until recently the Capitan pluton was little studied. Early studies noted its remarkably uniform fine-grained texture and granite composition (Sidwell, 1946; Patton, 1951; Butler, 1964; Kelley and Thomp-

son, 1964; Kelley, 1971). Recent study has shown this elongate pluton (35 × 8 km) to be a single phase, texturally and compositionally zoned, aplitic to porphyritic alkali feldspar granite batholith, which was intruded at 26.5 Ma (Allen, 1988). Its shallow level of intrusion and release of volatiles caused rapid crystallization and formation of a granophyric cap. The core of the pluton is a fine-grained granite porphyry. Fractional crystallization appears to be responsible for its compositional zoning and evolution of an aqueous phase. However, in situ fractionation is implausible, due to its rapid crystallization. Allen and McLemore (1991, this volume) propose a model of flow differentiation to account for its zoning.

Iron skarn deposits associated with the pluton have been studied by Sheridan (1947), Kelley, (1949, 1952), Griswold (1959, 1964), Harrer and Kelley (1963) and Tuftin (1984). A roof pendant of Permian limestone hosts the largest iron skarn deposit in Lincoln County. The pluton itself hosts Th- and REE-bearing quartz veins (McLemore, 1983; McLemore et al., 1988; Willis et al., 1989; Phillips, 1990). These veins formed from a magmatic fluid derived from differentiation of the Capitan granite (Willis et al., 1989; Phillips, 1990).

Carrizo Mountain pluton

The Carrizo Mountain intrusion was described by Allen and Jones (1951), Patton (1951), Butler (1964), Kelley and Thompson (1964), Haines (1968), Kelley (1971) and Pertl (1984). Butler's (1964) limited sampling revealed the pluton to be a granitic stock similar in appearance to the Capitan and Lone Mountain plutons. He noted its trachytic texture and a concentric zonation. Pertl (1984) mapped a coarser-grained, porphyritic, quartz-monzonite core and a finer-grained rhyolite margin and cap. Our observations support the zoned nature of the stock, but compositions vary from quartz syenite to alkali-feldspar granite (quartz is dominantly interstitial and easily underestimated). Samples from both zones mapped by Pertl have trachytic texture, and contain domains of granophyre (Pertl's "glomeropheric groups"), similar to textures seen in the roof-zone of the Capitan pluton. Zoning in the pluton is gradational but appears to be less regular than mapped by Pertl. The pluton intrudes sandstone beds of the Mesaverde Formation and contains no known mineral deposits.

Lone Mountain pluton

Early studies of the Lone Mountain area include those of Sheridan (1947), Kelley (1949), Walker and Osterwald (1956) and Griswold (1959). The geology of Lone Mountain was first mapped by Smith and Budding (1959) and described by Smith (1964). Butler (1964) described the circular-outlined pluton as a "kalialaskite porphyry" stock, which forcefully intruded Permian and Mesozoic sedimentary rocks. His petrographic analyses indicate a peripheral felsic zone enclosing a more mafic core. Schnake (1977) substantiated this zoning and provided additional petrographic and chemical data. However, Schnake classified the pluton as granodiorite to quartz monzonite, based on normative data. Our observations support the existence of zoning but compositions range from quartz syenite (core) to alkali-feldspar granite (margin). Samples from the periphery of the stock have domains of micrographic texture interstitial to phenocrysts of alkali feldspar.

Iron skarn deposits occur in limestone roof pendants and in contact zones where the pluton intrudes limestones of the San Andres Formation (Griswold, 1964). Calc-silicate mineral assemblages are developed within veins cutting the intrusion, which can be traced into replacement deposits in limestone. Schnake believed these deposits were formed by metasomatic replacement of limestone via heat-driven hydrothermal cells of meteoric water.

Patos Mountain pluton

The Patos Mountain intrusion has been described by Allen and Jones (1951), Kelley and Thompson (1964), Haines (1968), Kelley (1971) and Pertl (1984). All but the earliest study refer to it as a laccolith. Its composition has been reported as syenite (Patton, 1951), monzonite (Kelley and Thompson, 1964) and rhyolite (Haines, 1968). Haines noted that the intrusion was compositionally and texturally zoned, with a more mafic and porphyritic core and a siliceous fine-grained margin. He also noted "vermicular-like" intergrowths of quartz and feldspar in margin samples and perthitic feldspar in interior samples. Pertl suggested that the feeder for the Patos Mountain laccolith was the Carrizo Mountain center, based on composition and proximity. No mineral deposits are known to be associated with the Patos intrusion.

"Younger" Tertiary dikes

Although numerous dikes occur in the Ruidoso region, two are of sufficient size and importance to be discussed here in relation to the LCPB: the Railroad Mountain dike and the Jones Camp dike. The Capitan dike swarm, comprising a variety of alkalic and oversaturated rocks with complex interrelationships, is not treated here (see Elston, 1991, this volume).

Railroad Mountain dike

Until recently, little was known about the dikes that occur east of Roswell, the Railroad Mountain dike being the longest (50 km). The dikes appear on several geologic maps (Dane and Bachman, 1965; Kelley, 1971; Allen and Kottlowski, 1981), and limited descriptions were given by Semmes (1920) and Kelley (1971). Aldrich et al. (1986) presented a chemical analysis of the Railroad Mountain dike and gave its age as 27.9 Ma. Our observations of the Railroad Mountain and Camino del Diablo dikes indicate that they are single-phase intrusions of different composition. The Railroad Mountain dike has passively intruded undeformed Triassic sedimentary rocks, resulting in a chilled margin and a thin baked zone adjacent to the dike. The dike is up to 45 m wide, unaltered and forms a resistant ridge. It is a fine-grained, equigranular, olivine syenogabbro which contains subhedral olivine (10%), anhedral augite (15%), anhedral plagioclase (An_{53}) laths (50%), interstitial anorthoclase (10%), euhedral titanomagnetite (10%), euhedral fluor-apatite (4%) and sparse blebs of chalcopyrite. Plagioclase and pyroxene display trachytic alignment in thin section. The Camino del Diablo dike is poorly exposed due to intense alteration and weathering. Where exposed, it is 3 to 5 m wide, aphanitic, melanocratic and locally amygdaloidal. It consists of fragmented alkali feldspar and sparse amphibole in a matrix of chlorite, sericite, clay and iron oxides.

Jones Camp dike

The Jones Camp dike is the largest of several dikes that cut the Paleozoic sedimentary rocks exposed on Chupadera Mesa. The dike is a multiphase body that has forcefully intruded Permian clastic and carbonate rocks along the Capitan lineament. It was intruded at the same time as the dikes east of Roswell, at 27.9 Ma (Aldrich et al., 1986). The composition of the dike has been variably referred to as syenodiorite, diorite and monzodiorite, but we have found the main phase of the dike to be hornblende syenite to quartz syenite. Younger subordinate dikes, lenses and sills along the margins of the dike are substantially more mafic in composition and are intensely altered. Noguiera (1971), Gibbons (1981) and Jenkins (1985) suggested that the multiphase dike formed through in-situ differentiation of a single magma. The rapid cooling, relative age relationships of mafic and felsic units, and geochemical constraints make this interpretation implausible.

The occurrence of iron skarn deposits along this dike where it has intruded Permian limestones has attracted much study (Keyes, 1904; Emmons, 1906; Schrader, 1910; Lindgren et al., 1910; Granthum and Soule, 1947; Kelley, 1949; Griswold, 1959; Noguiera, 1971; Bickford, 1980; Gibbons, 1981; Jenkins, 1985; Jochems, 1987). Jenkins (1985) believed that these deposits formed by leaching of the dike by convective hydrothermal ground water, and deposition of iron in replacement bodies in chemically reactive carbonate lithologies.

"Older" Tertiary alkalic complexes

Black Mountain complex

The Black Mountain complex is within the Mescalero Apache Indian Reservation and has been studied little. Moore et al. (1985, 1988a) mapped, obtained age determinations and described a variety of igneous

rocks present in this complex. The complex consists of two major intrusive bodies and a swarm of northeasterly trending dikes. The major intrusions consist of an older, biotite, clinopyroxene, amphibole, alkali-gabbro plug and a younger, arfvedsonite, augite syenite porphyry plug. These plugs have been intruded by dikes ranging in composition from monzogabbro to sodalite syenite. We sampled these units and collected xenoliths of foliated cumulus amphibole gabbro and amphibolite from some syenogabbro dikes. These xenoliths contain abundant microphenocrysts of apatite and titanite, and intrasilicate blebs of Fe, Cu and Ni sulfides suggesting the presence of an immiscible sulfide liquid during early crystallization. Igneous activity at Black Mountain occurred from 37.5 to 36.3 Ma (Table 1). The volcanic rocks of the Sierra Blanca complex rest unconformably on dikes of Black Mountain complex. No mineral deposits are known to be associated with the Black Mountain complex.

Sierra Blanca complex

The Sierra Blanca complex is the largest of the igneous complexes in the LCPB, and is one of only two volcanic centers in the LCPB, the Baxter Mountain center being the other. Previous investigations of the geology of the complex include Darton (1922), Knapp (1933), Kelley and Thompson (1964), Richmond (1964), Thompson (1964), Weber (1964), Thompson (1972) and Moore et al. (1985, 1988a). Studies of the mineral occurrences within the complex include those of Griswold and Missaghi (1964), Thompson (1968), Giles and Thompson (1972), Thompson (1973), Segerstrom et al. (1979) and Segerstrom and Stotelmeyer (1984).

The Sierra Blanca volcanic rocks comprise well over half of the areal extent of the complex, which presently covers about 600 km^2. The volcanic rocks are estimated to have been at least 1000 m thick and have been divided into four named formations that contain multiple units (Thompson, 1972). The oldest Walker "Andesite" Breccia and the youngest Nogal Peak "Trachyte" formations comprised the bulk of the volcanic rocks in the complex. Data in Table 1 indicate that volcanic activity at Sierra Blanca most likely occurred in two pulses. The early Walker "Andesite" pulse is constrained by lowermost trachybasalt flows that rest on dikes (37.3 Ma) of the Black Mountain complex, and by uppermost trachyphonolite flows that are cut by a nepheline syenite dike (37.0 Ma) near Sierra Blanca peak. The second pulse (approximately 30–26.5 Ma) of trachyte, quartz trachyte and rhyodacite of the Godfrey Hills and Nogal Peak, is more poorly constrained. These rocks unconformably overlie the Walker "Andesite" formation, possess the youngest date for any volcanic rock of the complex, and are compositionally similar to syenite and granite intrusions of the Three Rivers stock. Detailed descriptions of the Sierra Blanca volcanic rocks are presented by Moore et al. (1988a, 1991, this volume).

Numerous plugs and dikes of widely varying composition intrude the volcanic rocks of Sierra Blanca. Thompson (1972) mapped largely north of Sierra Blanca Peak and described primarily the granitic rocks of the multiphase Three Rivers, Bonito Lake and Rialto stocks of the complex. Moore et al. (1985, 1988a) mapped largely on the Mescalero Apache Indian Reservation south of the peak and described alkalic and granitic intrusions. Data in Table 1 indicate that the intrusive rocks of the Sierra Blanca complex were formed during two pulses, coeval with the volcanic pulses. Small biotite, augite, essexite to nepheline syenite plugs and dikes were intruded into the alkalic volcanic pile between 37 Ma and 36.6 Ma. The larger syenite and alkali feldspar granite plugs of the Three Rivers stock were intruded from 29.9 Ma to 26.6 Ma. A portion of the Bonito Lake stock may have been emplaced during this time, but ages for this stock and the Rialto stock are poorly constrained, and their chemical compositions indicate that some portions of them belong to the older alkalic pulse.

Giles and Thompson (1972) described three phases of the Three Rivers stock, whereas Moore et al. (1985, 1988a) described four phases, which include an arfvedsonite-aegirine syenite (29.9 Ma), a younger porphyritic syenite of similar composition, a quartz syenite (29.3 Ma), and an alkali feldspar granite (26.7 Ma) that bears minor biotite and arfvedsonite. The late quartz syenite and alkali feldspar granite display micrographic texture similar to the other LCPB granite plutons (e.g., Capitan). Giles and Thompson (1972) described a molybdenum porphyry deposit hosted by the latest phase of the Three Rivers stock.

The Bonito Lake stock was described by Thompson (1972) as hornblende biotite syenite. Our observations indicate that the pluton ranges from syenite to quartz syenite, but is intruded by dikes ranging from syenodiorite to syenite. Chloritic alteration of mafic minerals is common throughout the stock, and fresh samples are difficult to obtain. Although Thompson (1972) gave the age of the pluton as 26.6 Ma, the complexity of intrusive relationships and alteration of the stock suggests that this is a minimum, and further age determinations are required to constrain the stock's history. The center of the pluton has undergone intense potassic alteration in which hornblende (which replaces pyroxene) has been replaced by biotite. Along the northern contact of the pluton, zones of intense argillic and silicic alteration contain molybdenite and chalcopyrite-bearing quartz veins.

Thompson (1972) described the Rialto stock as a hornblende-biotite monzonite. We observed the stock to range from syenodiorite to syenite. However, alteration of the stock is extensive; biotite and hornblende are chloritized, and plagioclase is sericitized in even the freshest samples. Accessory minerals include apatite, titanite, magnetite and rutile. The age of the stock is unknown. Zoned alteration in which propylitic and argillic shells encompass silicic and sericitic zones related to breccia pipes that contain molybdenum and copper mineralization was described by Thompson (1973).

Baxter Mountain complex/White Oaks district

The Baxter Mountain intrusive/volcanic complex contains a variety of alkalic igneous rocks. The gold deposits of the White Oaks mining district are associated with this complex. The area has been studied by Griswold (1959), Haines (1968) and Grainger (1974). A detailed map and description of the igneous rocks of this complex and their relationship to structures and mineralization was compiled by R. H. Jahns (Carl Dotson, unpubl.) Intrusive rocks occur in irregular bodies, dikes and breccia pipes, and were emplaced in north- to northeast-trending faults. Compositions range from syenogabbro to syenite, with unusual lamprophyres ("mica trap" of Griswold) which contrain phenocrysts (>4 cm) of phlogopite and amphibole. Mafic units contain microphenocrysts of apatite, titanite and disseminated iron-sulfide blebs. Intrusive breccias consist of igneous and sedimentary rock fragments in a matrix of altered feldspar with disseminated pyrite. The age of this complex is unknown.

Mineralized veins and breccias in the White Oaks district are vertically persistent (>300 m) and display little change in ore grade over their extent. Ore mineralogy consists of free gold, auriferous pyrite, huebnerite and minor base-metal sulfides including chalcopyrite, galena and sphalerite. Gangue minerals include quartz, fluorite and selenite. Alteration adjacent to the veins is intense but limited to relatively thin selvages. The district has produced more than 150,000 oz of gold and more than 90,000 lbs of tungsten concentrate (Griswold, 1959).

Tecolote Hills complex

Several resistant intrusive beds underlie the Tecolote Hills. Rawson (1957) described dikes, sills and laccoliths composed of diorite, monzonite and miarolitic syenite which were intruded along north- to northeast-trending structures. Our sampling and analyses reveal compositions ranging from syenogabbro to syenite. The diorite of Rawson is an unusual biotite-hornblende-augite pyroxenite. Accessory minerals in the syenogabbro include magnetite, apatite and pyrite. Intrusion of mafic units preceded intrusion of felsic units, but absolute ages are unknown. Small iron-skarn deposits occur where igneous rocks have intruded carbonate units of the Permian Yeso Formation.

Jicarilla Mountains complex

The Jicarilla Mountains consist of north- to northeast-trending ridges and isolated hills that are underlain by intrusive igneous rocks of diverse composition. The geology and igneous rocks of this area were described by Budding (1964), Butler (1964), Kelley (1964), Ryberg (1968) and

Segerstrom and Ryberg (1974). Budding described monzonite in sills, dikes, plugs and laccoliths, whereas Butler referred to the main lithology as hornblende syenite. Segerstrom and Ryberg described units which varied from quartz diorite, granodiorite, monzonite and syenite. Our sampling and analyses indicate that the complex consists of a sequence of alkalic rocks, including biotite syenogabbro to syenite, and intermediate, calc-alkalic, hornblende, quartz monzonite and hornblende tonolite. The calc-alkalic rocks contain xenoliths of foliated garnet-bearing amphibolite, which may indicate assimilation of crustal rocks. No Precambrian rocks are exposed in the area. The syenogabbro of this complex contains microphenocrysts of apatite, titanite and magnetite, which are characteristic of LCPB mafic alkalic rocks. Igneous activity in the LCPB appears to have started in this complex; the syenogabbro has yielded an age of 38.2 Ma (Table 1).

The mineral deposits of the Jicarilla Mountains were described by Jones (1904), Lindgren et al. (1910), Darton (1928), Lasky and Wooton (1933), Kelley (1949), Griswold (1959), Butler (1964) and Segerstrom and Ryberg (1974). Several small iron-skarn deposits occur where igneous rocks intrude carbonate units of the host sedimentary formations. Gold has been produced from placer (6300 oz) and minor vein deposits. Gold occurs with pyrite, arsenopyrite, chalcopyrite and minor sphalerite and galena in thin quartz veins, and as disseminations in altered syenite and syenodiorite porphyry.

Gallinas Mountains complex

The Gallinas Mountains complex is the northernmost major center of the LCPB. Geologic studies and mapping of the Gallinas Mountains have been undertaken by Kelley (1946) and Perhac (1960, 1964, 1970). Perhac (1970) described andesite, latite, trachyte, hornblende microsyenite and rhyolite, which occur in three major laccoliths, dikes and a small plug. We have classified these units as syenogabbro, quartz syenite, syenodiorite and alkali rhyolite porphyry, respectively, based on chemical data and more appropriate plutonic equivalents. The age of the complex is unknown, and the relative age relationships of some units are indeterminable. However, intrusion of the syenodiorite preceded the quartz syenite (trachyte), which in turn preceded the rhyolite porphyry. All units contain aegirine and aegirine-augite and the accessory minerals magnetite, apatite, titanite and zircon. When present, plagioclase phenocrysts are typically sodic and rimmed by anorthoclase. Quartz occurs interstitially in felsic units. Alteration of these rocks ranges from intense to minor, with slight chloritization of mafic minerals and sericitization of plagioclase. Foliated Precambrian granite is exposed within the Gallinas Mountains, one of few exposures of the basement in the Ruidoso region.

The Gallinas Mountains also contain iron-skarn deposits in contact zones of intrusions with Permian limestones (Kelley, 1949; Griswold, 1959; Perhac, 1970). Veins and breccia pipes bearing fluorite, copper minerals, bastnaesite (REE-bearing carbonate), and minor amounts of gold, silver and lead occur in the Red Cloud mining district in the eastern Gallinas Mountains. Minor production of copper, fluorite and bastnaesite has occurred from the district (Griswold, 1959). These fluorite-rich deposits are intimately associated with the quartz syenite (trachyte) phase of the complex, but in places veins cut sedimentary rock above intrusions. Perhac (1970) concluded that the REE deposits in the Gallinas Mountains are of magmatic origin, noting the close association of the fluorite-bastnaesite deposits to the trachyte unit of the complex, and citing world occurrences of bastnaesite in alkalic igneous complexes (e.g., Mountain Pass carbonatite, California). Additionally, in thin section, mineralized quartz syenite breccia from the Red Cloud district has a matrix that consists of a pilotaxitic intergrowth of fluorite and unaltered feldspar, which supports a high-temperature origin.

ANALYTICAL METHODS

Over 210 samples have been collected by us throughout the LCPB for geochemical analyses, which were done by USGS laboratories in Denver and Menlo Park. Major element oxides were determined using energy-dispersive XRF methods (Johnson and King, 1988). Trace elements and REE were determined using wavelength-dispersive XRF methods (Taggart et al., 1988), and instrumental neutron activation analysis (Baedecker and McKown, 1988). Ferrous iron, CO_2, H_2O^+, H_2O^- and F were determined using wet chemical and gravimetric methods (Jackson et al., 1988). A report containing the geochemical data for these samples is in preparation. Strontium and neodymium isotope analyses were obtained through the University of Colorado, using methods described by Farmer et al. (1991).

GEOCHEMISTRY

Major element trends

The rocks of the LCPB display trends on an AFM diagram most closely resembling differentiation trends of Aleutian arc-type calc-alkalic magmas (Fig. 2). However, the trend for LCPB rocks is fortuitous and does not represent differentiation. Harker variation diagrams of the LCPB complexes also show regular patterns typical of differentiation. However, examination of plots for the Sierra Blanca complex reveals two trends of fractionation for the compatible oxides of Mg (Fig. 3A), Ti (Fig. 3B), Fe and P (not shown). The older alkalic volcanic and intrusive rocks follow coherent trends from alkali basalt to trachyphonolite, and plutonic equivalents. The younger, saturated to oversaturated syenites and alkali granite follow separate paths of differentiation. Two magmatic episodes with distinct chemical evolution are indicated by these data.

These two magma suites are also indicated on the Irvine and Baragar (1971) and the De la Roche et al. (1980) discrimination diagrams (Figs. 4A, 5A). The silica-saturation lines in these diagrams represent petrologic boundaries that limit the ability of an alkalic parent magma to differentiate via closed-system fractionation into silica-oversaturated magmas. The older Sierra Blanca alkalic suite, whether volcanic or intrusive, displays evolution toward more felsic rocks, but maintains silica undersaturation. For comparison, similar trends are displayed by the alkalic Cripple Creek complex of Colorado (Figs. 4C, 5C). The younger Sierra Blanca syenitic-to-granitic suite ranges from a slightly undersaturated composition to highly oversaturated (Figs. 4A, 5A). Samples from the Bonito Lake and Rialto stocks plot between mafic alkalic and felsic-oversaturated samples of the Sierra Blanca complex, indicating a complex parentage (Figs. 4A, 5A).

Recognition of two distinct magma suites in the Sierra Blanca complex provides insight into the petrogenesis of the other igneous rocks of the Ruidoso region. For the older-pulse Tertiary alkalic complexes

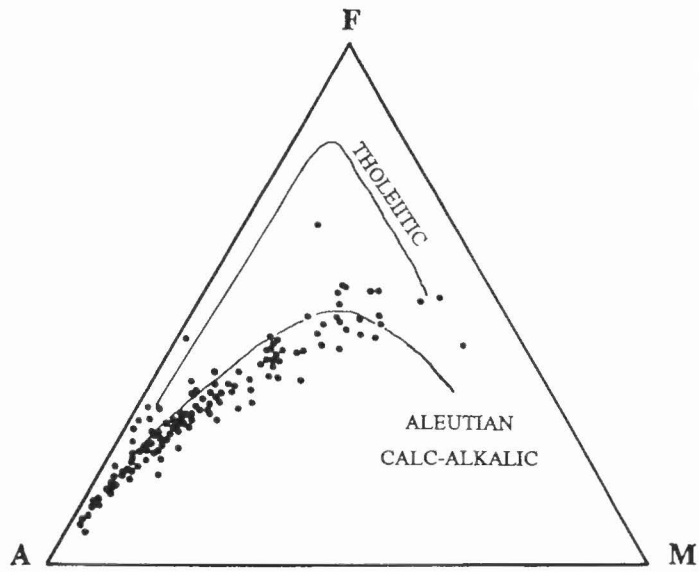


FIGURE 2. Ternary alkali-iron-magnesium (AFM) diagram for samples of igneous rocks of the Ruidoso region. $A = (Na_2O + K_2O)$; $F = (FeO + .8999 \times Fe_2O_3)$; $M = MgO$ (in weight percent). Trend lines from Irvine and Baragar (1971).

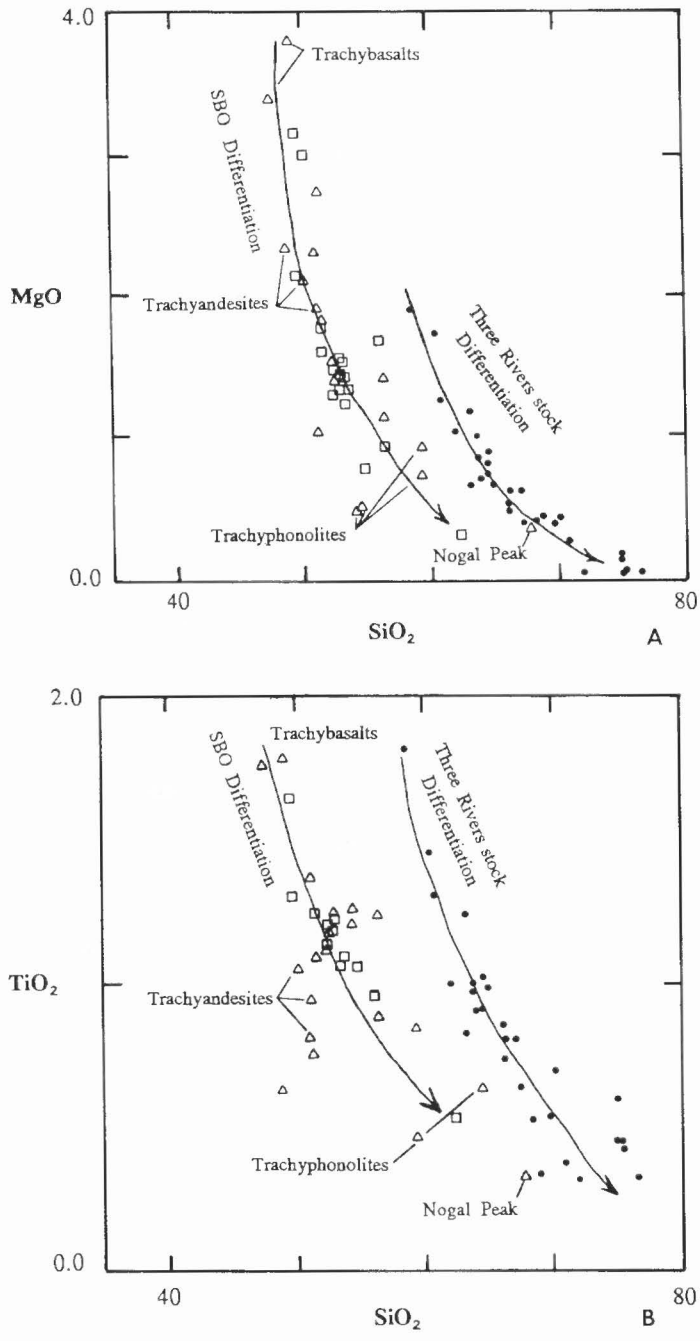


FIGURE 3. Harker variation diagrams for A, MgO and B, TiO_2 versus silica (in weight percent) for samples from the Sierra Blanca igneous complex, New Mexico. (Triangles—volcanic rocks; squares—older intrusions; dots—Three Rivers stock; SBO—Sierra Blanca "older suite.")

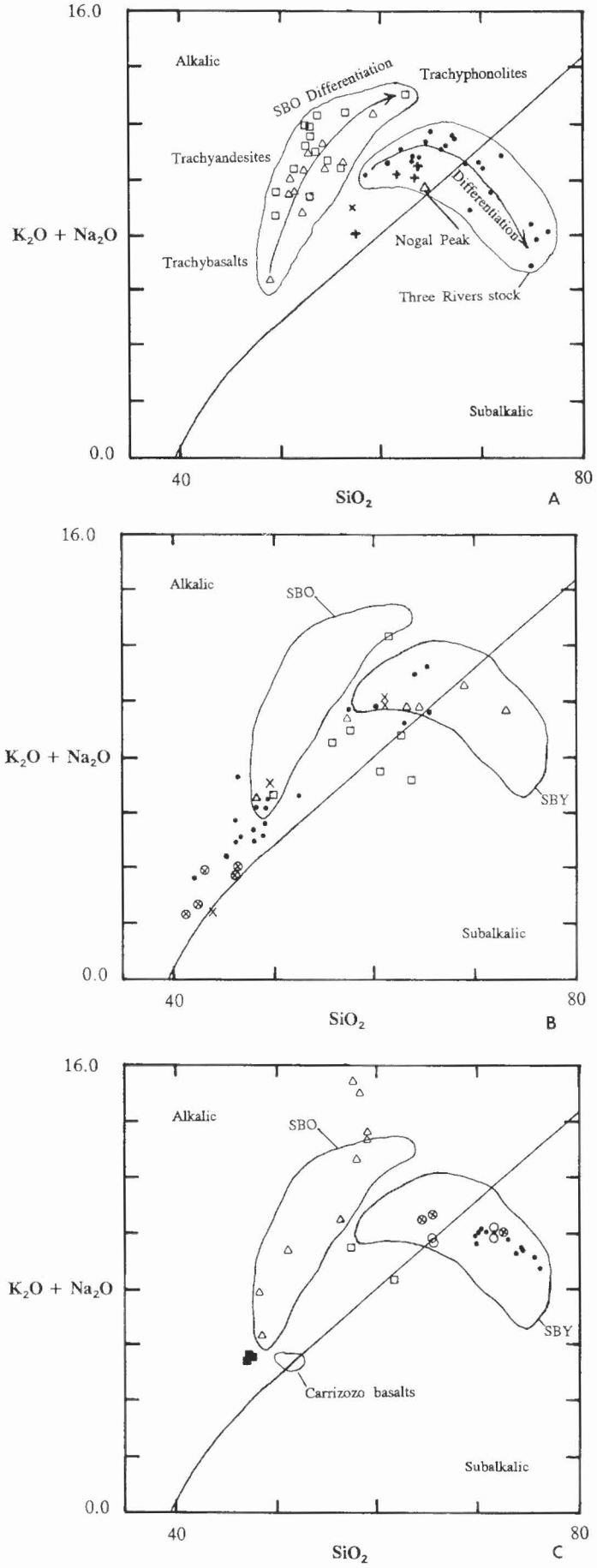
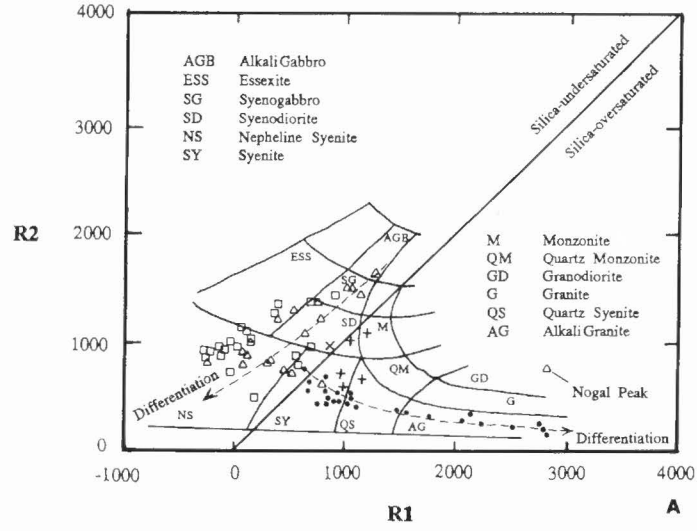
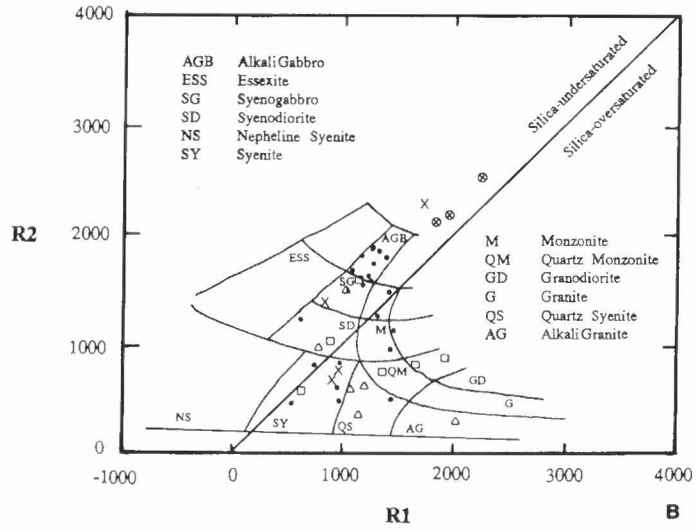


FIGURE 4. Plots of $Na_2O + K_2O$ versus silica (in weight percent). Boundary line from Irvine and Baragar (1971). A, Sierra Blanca complex (Symbols as in Fig. 3; pluses—Bonito Lake stock; cross—Rialto stock). B, Pedernal trend alkalic complexes (triangles—Gallinas Mountains; squares—Jicarilla Mountains; crosses—Tecolote Hills; dots—Black Mountain; circled crosses—Black Mountain xenoliths). C, Younger LCPB rocks and Cripple Creek, Colorado (dots—Capitan pluton; circles—Carrizo Mountain; circled crosses—Lone Mountain; open squares—Jones Camp dike; filled squares—Railroad Mountain dike; triangles—Cripple Creek, data from Eriksson [1987]; SBY—Sierra Blanca "younger suite").





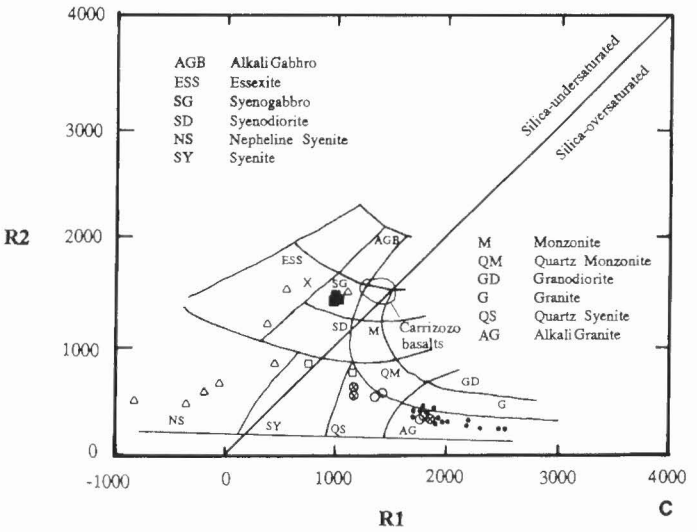


FIGURE 5. Chemical discrimination diagram of De la Roche et al. (1980), showing samples from igneous rocks from the Ruidoso region, New Mexico, and the Cripple Creek complex, Colorado. $R_1 = 4Si - 11(Na + K) - 2(Fe + Ti)$; $R_2 = 6Ca + 2Mg + Al$, in millication proportions. A, Sierra Blanca complex. B, Pedernal trend alkalic complexes. C, Younger LCPB rocks and Cripple Creek, Colorado. (Symbols as in Fig. 4.)

of the region, such as at Black Mountain, the Tecolote Hills, the Jicarilla Mountains and the Gallinas Mountains, mafic alkalic parent magma appears to have evolved to less alkalic to silica-oversaturated felsic magmas (Figs. 4B, 5B). Contamination of a mafic alkalic parent by oversaturated material (crust) is indicated. The younger-pulse Tertiary magmas along the Capitan lineament reflect end members of the two magma suites—the alkali gabbro of the Railroad Mountain dike, and the syenite to alkali granite of the Capitan, Patos Mountain, Carrizo Mountain and Lone Mountain plutons (Figs. 4C, 5C). The Jones Camp dike contains both alkali and silica-oversaturated rocks. By comparison, the Quaternary Carrizozo basalts are only slightly alkalic, and are less alkalic than any of the Tertiary mafic rocks of the LCPB (Fig. 4C).

REE patterns and trace-element data

Rare-earth-element (REE) patterns provide information concerning the processes of evolution of magmas, and help constrain the characteristics of the source of melting. REE patterns of both volcanic and plutonic rocks from the Sierra Blanca complex show evidence for the existence of two magma suites. Evolution from trachybasalts to trachyphonolites corresponds with enrichments of LREE and HREE, depletion of the MREE, and development of a small, negative Eu anomaly (Fig. 6). These patterns are consistent with the fractionation of clinopyroxene, hornblende, plagioclase and possibly apatite. Depletion of Eu by plagioclase is possibly offset by amphibole and apatite. The REE patterns from Cripple Creek alkalic complex are shown for comparison (Fig. 7). Samples from the Cripple Creek complex are also LREE enriched, but higher degrees of LREE and HREE enrichment, and MREE depletion accompany evolution. Using major- and trace-element data, Eriksson (1987) and Birmingham (1987) interpreted that evolution from trachybasalt to trachyphonolite at Cripple Creek occurred via extreme (70–90%) fractionation of olivine, pyroxene, amphibole, feldspar, magnetite and apatite. The REE patterns presented in Fig. 7 are consistent with this fractionation.

The Nogal Peak Trachyte (rhyodacite) has a REE pattern subparallel to the older volcanic rocks, but is substantially more REE-enriched and has a pronounced negative Eu anomaly (Fig. 6). This pattern cannot be derived by the same fractionation process operative in deriving the older felsic alkalic volcanic rocks, since continued fractionation of any of these minerals would preserve a concave-upward pattern. A distinct magma type is reflected by this pattern. REE patterns for intrusive phases of the Sierra Blanca complex are similar to those for the volcanic phases, displaying evidence for two magma suites. The older-pulse, essexite-to-nepheline syenite intrusions have REE abundances similar to the older trachybasalts to trachyphonolites (Fig. 8). The younger-

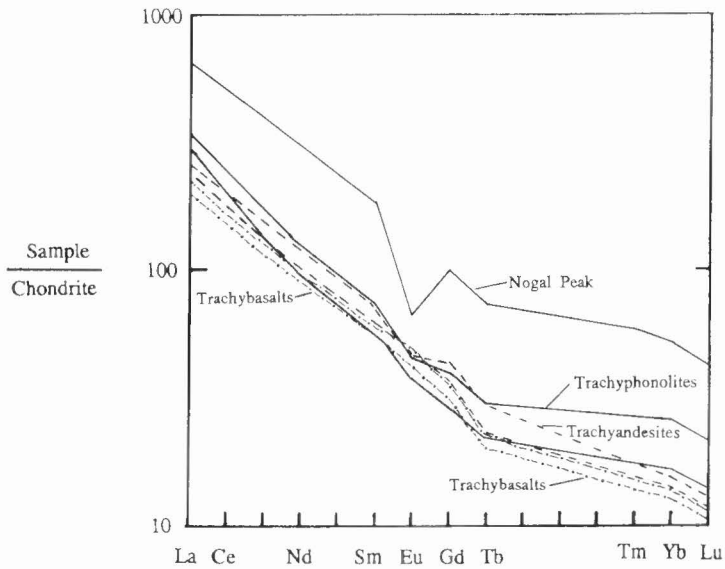


FIGURE 6. Rare-earth-element patterns for Sierra Blanca volcanic rocks.

pulse, syenite-to-alkali granite intrusions of the Three Rivers stock, however, have more REE-enriched patterns, similar to the upper-sequence volcanic rocks of Nogal Peak. Evolution from syenite to the alkali feldspar granite was probably accomplished through crystallization of K-feldspar, indicated by development of a large negative Eu anomaly and relative enrichment of the HREE.

Variations of incompatible elements (elements enriched in liquids undergoing fractional crystallization) in rocks of the Sierra Blanca complex support the conclusion that two magma suites are represented. Separate evolution paths for the older alkalic and younger silica-saturated magmas at Sierra Blanca are illustrated in Fig. 9, which shows distinct trends of variation for the incompatible elements La and Nb.

The REE patterns of the Bonito Lake and Rialto stock are similar to those of the older-pulse alkalic intrusive rocks of Sierra Blanca complex, which suggests that some parts of these stocks may belong to the older pulse. Additional age determinations are necessary to determine the timing of these intrusions.

The other alkalic complexes of the LCPB display REE patterns grossly similar to those of the older-pulse Sierra Blanca complex, being LREE enriched, and showing depletion of MREE with differentiation. The patterns are generally consistent with the fractionation of hornblende, clinopyroxene, plagioclase and apatite. These crystal fractionation (accumulation) products were preserved and incorporated as xenoliths into the magmas of the Black Mountain complex. Mafic and ultramafic gabbroic xenoliths have convex-upward REE patterns, opposite to those of the Black Mountain "liquids," which supports the interpretation from petrography that the xenoliths are cumulates from early Black Mountains magmas (Fig. 10). However, the REE patterns for the Gallinas Mountains, Jicarilla Mountains and Tecolote Hills complexes, in which mafic alkalic magmas appear to have evolved to silica-oversaturated magmas (Figs. 4B, 5B), are complicated and often display irregular crossing lines, suggestive of hybridization of magma types. Presentation and discussion of these complex patterns cannot be made here.

The younger Tertiary rocks of the Capitan lineament display REE patterns indicative of two magma suites (Fig. 11; Allen and McLemore, 1991, this volume, fig. 19). Samples from the Carrizo Mountain, Lone

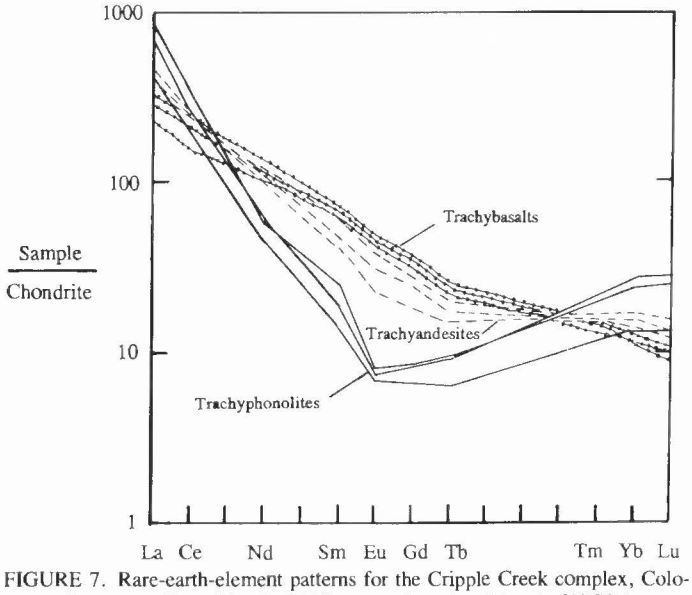


FIGURE 7. Rare-earth-element patterns for the Cripple Creek complex, Colorado. (Samples collected by Carl Eriksson and analyzed by the USGS.)

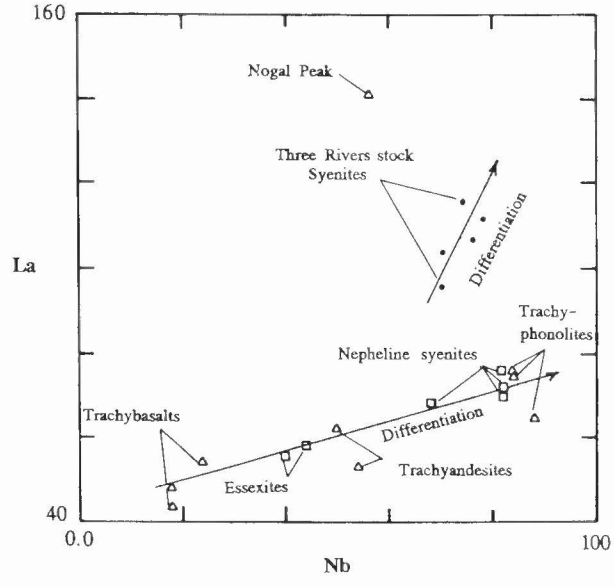


FIGURE 9. Plot of lanthanum versus niobium (in parts per million) for the Sierra Blanca complex. (Symbols as in Fig. 3.)

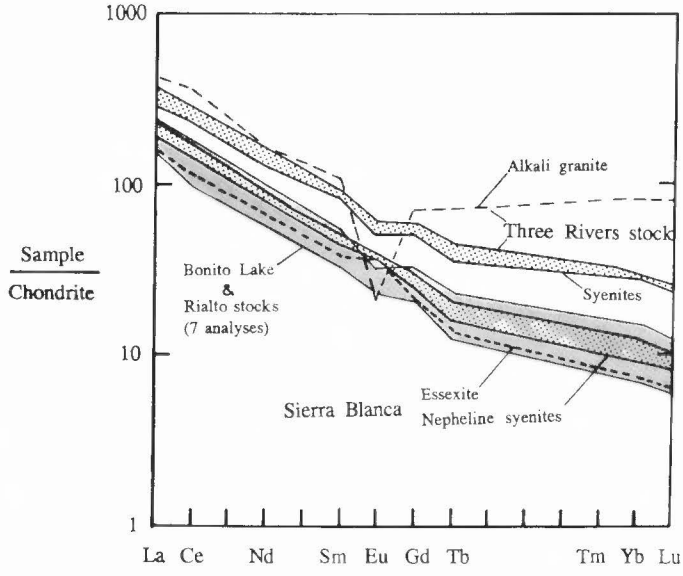


FIGURE 8. Rare-earth-element patterns for intrusive rocks of the Sierra Blanca complex.

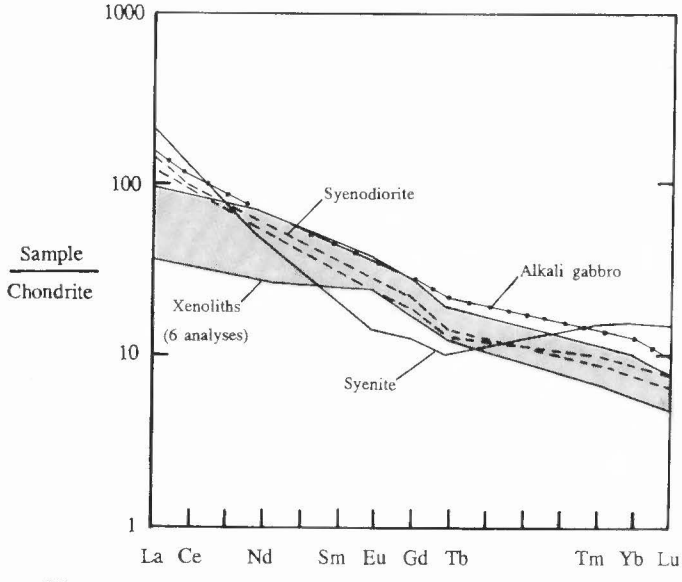


FIGURE 10. Rare-earth-element patterns for the Black Mountain complex.

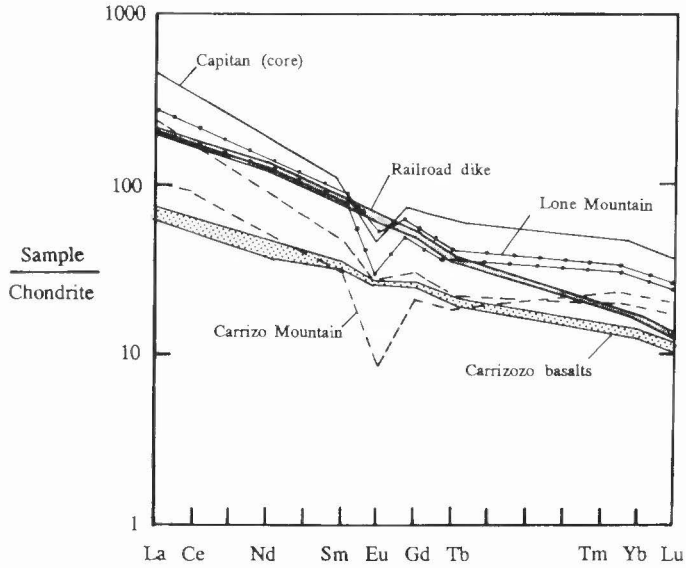


FIGURE 11. Rare-earth-element patterns for igneous rocks of the Capitan lineament east of the Rio Grande rift.

Mountain and Capitan plutons all exhibit LREE-enriched patterns with negative Eu anomalies, comparable to those for the granitic rocks of the Sierra Blanca complex. Within these plutons, silica enrichment of roof and margin zones is accompanied by more negative Eu anomalies, and overall depletion of the REE. The variation in REE in these plutons is controlled dominantly by the fractionation of feldspar and REE-rich minerals, such as apatite, titanite and zircon. Although the pronounced depletion of Eu in the most evolved granitic plutons (e.g., Capitan and Three Rivers plutons) is primarily due to feldspar fractionation, negative Eu anomalies displayed by the least-differentated granitic plutons may have resulted from partial melting of a plagioclase-bearing source. Allen and McLemore (1991, this volume) discuss more thoroughly the origin and differentiation of the Capitan pluton.

The syenogabbro of the Railroad Mountain dike has a LREE-enriched pattern, similar to the mafic alkalic rocks in the older Tertiary complexes distributed along the Pedernal trend. Its REE pattern is also similar to those of the granitic rocks of the Capitan lineament, but lacks a Eu anomaly (Fig. 11). However, the Quaternary basalts of the Carrizozo flows, which also vented along the Capitan lineament, are chemically distinct from this older syenogabbro. These flows are the least LREE-enriched mafic rocks of the Ruidoso region (Fig. 11). Additionally, the Tertiary mafic alkalic dikes of the Capitan lineament are Ti- and P-rich, whereas the Carrizozo flows are more closely related to the low-Ti and -P basalts of the central Rio Grande rift and Datil-Mogollon volcanic field (Fig. 12).

Isotopes

Since the radiogenic and stable isotopes of heavy elements remain unfractionated through differentiation, and their compositions are characteristic of certain magma source regions, Sr and Nd isotope compositions were determined for igneous rocks of the Ruidoso region to assess their interrelationships and to constrain their sources (Table 2). It is evident that two distinct magma sources are represented. The mafic alkalic rocks have generally unradiogenic initial $^{87/86}Sr$ values and $^{143/144}Nd$ values near "bulk earth," whereas younger silica-saturated rocks (i.e., Three Rivers, Capitan, Lone Mountain, Carrizo Mountain) have more radiogenic initial Sr isotopic values and more negative epsilon Nd values (Fig. 13). The latter isotope systematics are consistent with derivation from a lower-crustal source (elevated Rb/Sr and Nd/Sm ratios). The geochemical data of Allen and McLemore (1991, this volume), and the oxygen isotopic data of Phillips (1990) from the Capitan pluton support its derivation from a metaigneous (I-type) crustal source (White and Chappel, 1977; O'Neil et al., 1977).

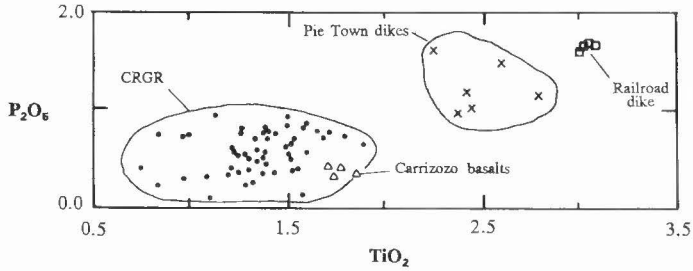


FIGURE 12. Plot of TiO_2 versus P_2O_5 (in weight percent) of samples of mafic rocks from the eastern portion of the Capitan lineament, shown in relation to the data fields of Laughlin et al. (1983) for mafic dikes (crosses) near Pie Town, New Mexico, and of Bornhorst (1980) and Baldridge (1979) for basaltic andesites (dots) of the central Rio Grande rift.

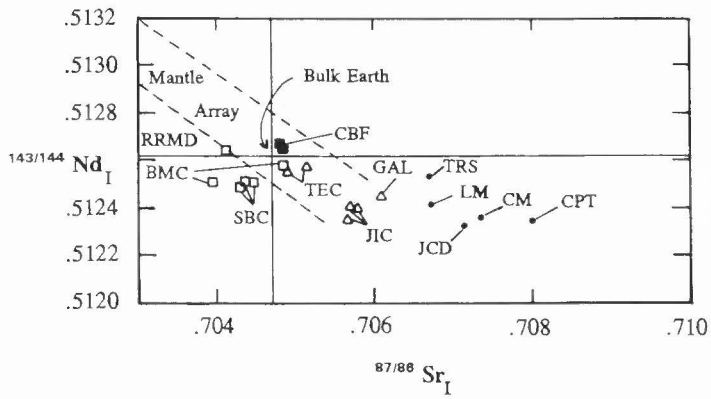


FIGURE 13. Plot of initial $^{143/144}Nd$ versus initial $^{87/86}Sr$ isotope data for Cenozoic igneous rocks of the Ruidoso region, New Mexico. (Dots—syenites to granite of the Capitan pluton [CPT], Carrizo Mountain [CM], Lone Mountain [LM], Jones Camp dike [JCD], Three Rivers stock [TRS]; triangles—hybrid alkalic/silica-oversaturated complexes of the Gallinas Mountains [GAL], Jicarilla Mountains [JIC] and the Tecolote Hills [TEC]; squares—alkalic complexes of Sierra Blanca [SBC] and Black Mountain [BMC], the Railroad Mountain dike [RRMD] and the Quaternary Carrizozo basalts [CBF].)

The primitive alkalic rocks of the region have relatively unradiogenic initial $^{87/86}Sr$ isotopic values of 0.70395 to 0.7049 and $^{143/144}Nd$ isotopic ratios near $CHUR_{(T)}$ (epsilon Nd = +0.5 to −1.9; DePaolo and Wasserburg, 1976). Although these data are consistent with derivation of these rocks from a primitive mantle source ("bulk earth" Rb/Sr and Nd/Sm ratios), the LREE-enrichment displayed by these rocks indicates a recent modification of the mantle source. Within the older alkalic complexes that contain hybridization of the two magma suites (i.e., Tecolote Hills, Jicarilla Mountains, Gallinas Mountains), more radiogenic Sr values (>.705) and more negative epsilon Nd isotopic values (<−2.8) are associated with the more felsic units. A positive correlation of initial Sr values with silica content is seen in Fig. 14. These trends are consistent with evolution of primitive alkalic magma to silica-saturated felsic magmas via assimilation of lower crustal material during fractional crystallization.

Discussion

Enigmatically, mafic alkalic and felsic silica-oversaturated rocks of the LCPB, particularly of the Capitan lineament, have high and LREE-enriched REE abundances, which makes their relationship via fractional crystallization or partial melting unlikely. Since geochemical and isotope data require that these two magma types were derived from different sources, a process whereby melting of compositionally diverse sources resulted in similarly REE-enriched magmas must be sought. Although LREE-enrichment in the granitic LCPB rocks may be produced by partial melting of a crustal (REE-enriched) source or a garnet-bearing

TABLE 2. Summary of isotope data from igneous rocks of the Ruidoso region, New Mexico.

Feature/complex	rock type	87/86 Sr_I	Nd(CHUR$_T$)	source
	Quaternary igneous rocks			
Carrizozo volcanic field				
Little Black Peak	basalt	.70482	+0.2	1
Broken Back Crater	basalt	.70477	+0.7	1
	Igneous rocks from 26 to 30 Ma			
Capitan pluton	granite	.70801	-5.0	1
Carrizo Mountain (at 27 Ma)	granite	.70735	-5.8	1
Lone Mountain (at 27 Ma)	granite	.70673	-3.7	1
Three Rivers stock	granite	.70670	-1.4	2,1
Jones Camp dike	syenite	.70715	-5.5	1
Railroad Mountain dike	syenogabbro	.70411	+0.5	1
	Igneous rocks older than 30 Ma			
Sierra Blanca intrusives	nepheline syenite	.70395	-	1
	essexite	.70438	-	1
Sierra Blanca volcanic rocks	trachybasalt	.70446	-1.6	1
Black Mountain complex	alkali gabbro	.70485	-0.3	1
	gabbro xenolith	.70432	-1.9	1
Tecolote Hills (at 37 Ma)	pyroxenite	.70490	-0.8	1
	syenite	.70513	-0.3	1
Jicarilla Mountains	syenogabbro	.70569	-3.5	1
	syenite	.70578	-3.7	1
	tonolite	.70565	-4.8	1
Gallinas Mountains (at 37 Ma)	quartz syenite	.70610	-2.8	1

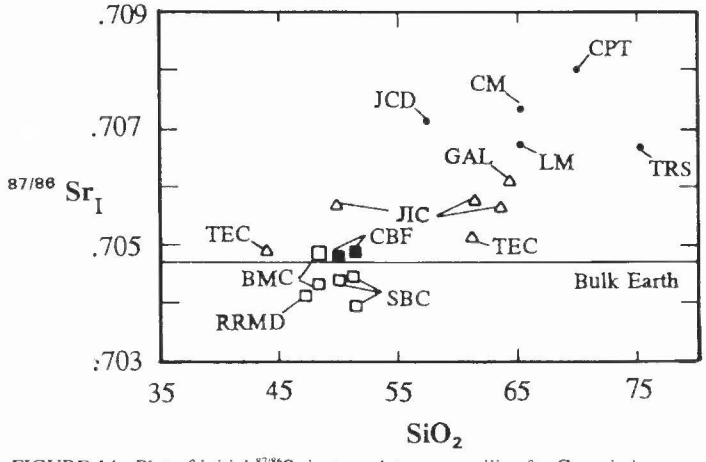


FIGURE 14. Plot of initial $^{87/86}Sr$ isotope data versus silica for Cenozic igneous rocks of the Ruidoso region, New Mexico. (Symbols as in Fig. 13.)

(LREE-fractionating) source (Kay and Gast, 1973; Hanson, 1978, 1980), production of coeval mafic magma of similarly high REE content (La_{cn} = 210–220) through partial melting of an underlying chondritic or depleted mantle source is implausible (Cullers and Graf, 1984). An enriched source is necessary for their generation. However, epsilon Nd values near "bulk earth" requires that enrichment must have occurred recently, since high Nd/Sm ratios over time would result in lower (negative) epsilon Nd values.

LREE-enrichment is commonly displayed by alkalic rocks, especially kimberlites and lamprophyres (Cullers and Graf, 1984). Models of mantle metasomatism have been used to explain the petrogenesis of these alkalic rocks (Nielson and Noller, 1987; Wilshire, 1987). The evidence for, and nature of, mantle metasomatism has been presented elsewhere (Fitton and Upton, 1987; Morris and Pasteris, 1987; Menzies and Hawkesworth, 1987). Some models propose that LREE and alkali enrichment of alkalic magmas results from fluxing of volatiles (especially CO_2, H_2O and F) or volatile-rich magmas into an upper mantle source region, and partitioning of LREE into melts generated subsequently (Eggler, 1987; Nielson and Noller, 1987; Spera, 1987; Wilshire, 1987). Experimental studies have shown that melts generated under CO_2-rich mantle conditions are LREE-enriched and alkalic (Wendlandt and Harrison, 1979; Mysen, 1979, 1983; Wendlandt and Eggler, 1980).

Apatite and other REE-rich accessory minerals are commonly observed in metasomatized mantle xenoliths and their alkalic rock hosts (Lloyd and Bailey, 1975; Menzies and Wass, 1983; Smith, 1987). In these rocks, apatite is the dominant host of the REE, and thus controls their REE patterns (Menzies et al., 1987). Fesq et al. (1974) and Beswick and Carmichael (1978) believed that the reservoir for LREE in the mantle may be less refractory carbonate and phosphate minerals that provide large quantites of LREE to magmas during partial melting. Both the mafic alkalic rocks as well as least-differentiated granitic rocks of the LCPB contain significant quantities of microphenocrystic apatite (1–4%). Much of the REE content of these rocks is due to their apatite

content (Fig. 15). Given the requirement for enrichment of the mantle in the generation of the alkalic LCPB magmas, it is plausible that the overlying crust also underwent metasomatic enrichment, which resulted in the generation of similarly LREE-enriched granitic melts.

It has been demonstrated that source regions beneath other alkalic provinces underwent metasomatism and LREE enrichment just prior to generation of alkalic magmas (Menzies and Murthy, 1980; Futa and Armbrustmacher, 1987; Roden, 1987). The source and origin of a metasomatic fluid/magma are difficult to constrain. One mechanism might involve fluids released during subduction via the breakdown of the more refractory volatile-rich minerals, such as pargasite, phlogopite and apatite (Boettcher et al., 1973; Olafsson and Eggler, 1983; Bailey, 1987; Tronnes et al., 1988). In this region of the RMAP, evidence exists for contribution of material to alkalic magmas from the Farallon plate as it underwent low-angle subduction beneath this region (Schulze et al., 1987; Smith, 1987).

Reduced metasomatic input to the mantle source as subduction waned may be reflected by differences between Tertiary and Quaternary mafic rocks. The Quaternary Carrizozo basalts are the least alkali and LREE-enriched mafic igneous rocks in the Ruidoso region, but have Sr and Nd isotope systematics nearly equivalent to the Tertiary Railroad Mountain dike, consistent with their derivation from the same source. The lower alkali and REE contents of the basalts may be due to: (1) reduced metasomatic influx, (2) depletion of the mantle source by the prior Tertiary melting, or (3) a larger degree of melting of the mantle source.

TECTONIC IMPLICATIONS

Any model proposed for the generation of alkalic and oversaturated magmas in this region of New Mexico must account for the presence of post-compressional alkalic rocks throughout the RMAP and the Trans-Pecos province of Texas and Mexico. Though textures, compositions and isotope systematics vary from region to region, the consistent presence of alkalic centers to the east of a calc-alkalic magmatic arc implies a common tectonic process. The association of alkalic and silica-oversaturated rocks at some locations within the RMAP must also be accounted for. Where interpretations of field observations and petrographic and major-element geochemical data might lead to the conclusion of cogenesis of magmas through fractionation, REE and isotopic data are invaluable in distinguishing mantle and crustal magma sources (Jahn et al., 1979; Barker et al., 1977).

Igneous activity in the LCPB was initiated at about 38.2 Ma, and includes the mafic alkalic complexes distributed along the north-trending Pedernal arch. Evolution of mafic to felsic alkalic rocks of the LCPB persisted until about 36.5 Ma. At the same time, voluminous calc-alkalic lava flows and ash sheets were erupted from caldera complexes in western New Mexico. The paleo-stress model of Price et al. (1987) indicates that south-central New Mexico was under some north-

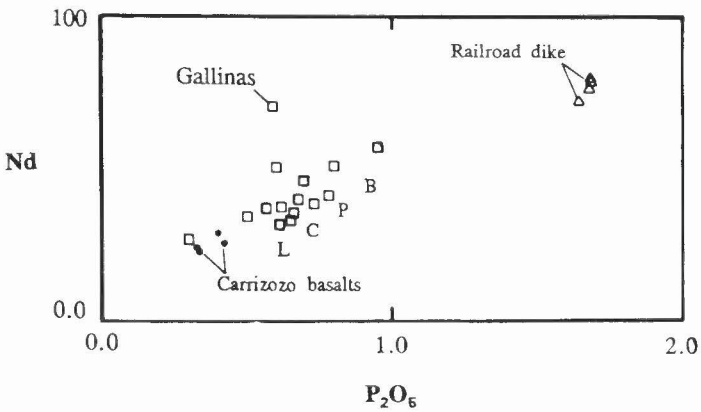


FIGURE 15. Plot of Nd (parts per million) versus P_2O_5 (weight percent) for Cenozoic mafic rocks (silica <52%) of the Ruidoso region, New Mexico. (Squares—LCPB alkalic complexes; triangles—Railroad Mountain dike; dots—Carrizozo basalts.)

east-directed compression during this time, due to the waning stages of subduction. This regime is consistent with the intrusion of the northeast-trending Black Mountain dike swarm (Moore et al., 1985, 1988a), and the northeast trends of intrusions in the Tecolote Hills and Jicarilla Mountains (Kelley and Thompson, 1964). This stress regime may have inhibited rapid transport of alkalic magmas to the surface and allowed time for some crustal contamination. The northeasterly compression, however, inhibited opening of east-west fractures along the Capitan lineament during this time.

The transition from plate convergence to transform motion along the western margin of North America relieved northeast-directed compression in south-central New Mexico and allowed for development of east-west extension. Thus, a second period (28–26.5 Ma) of igneous activity was initiated in the Ruidoso region, which was concentrated along the Capitan lineament. This widespread bimodal activity, which included alkalic gabbros (i.e., Railroad Mountain, Jones Camp, Pie Town dikes) and granites (i.e., Capitan, Carrizo Mountain, Lone Mountain and Anchor Canyon/Nitt plutons), indicates the large areal extent of partial melting beyond the axis of the rift during early rifting. The granitic rocks of the Capitan lineament are concentrated near the present-day axial basins of the rift, whereas the alkali gabbros occur on either side. This may reflect some structural control for tapping of separate crustal and mantle sources, or may reflect more intensive melting along the rift axis which included the crust.

Isotope and REE data indicate that generation of the LCPB magmas required a recent event whereby at least the mantle source for the mafic alkalic magmas, and possibly the lower crust, were alkali and LREE enriched. Whether these magmas were generated as a direct result of: (1) fluxing of overlying mantle by devolatization of the subducted plate, or (2) fluxing due to arching of the crust and decompression and/or subduction-caused mantle upwelling, may be difficult to ascertain. Nevertheless, volatile and alkali fluxing in both pre-rift and early-rift magmatic episodes is indicated. For further discussion of these processes, see Bailey (1970, 1972, 1974), Fyfe and McBirney (1975), Lloyd and Bailey (1975), Gupta and Yagi (1980), Wyllie (1981), Boullier et al. (1986) and Lameyre (1987).

In the Ruidoso region of New Mexico, we believe that shallow subduction of the Farallon plate caused arching, folding and fracturing of the crust. Melting of mantle below this region occurred as a result of volatile and alkali enrichment through devolatilization of the subducted plate and/or fluxing due to arching. Alkalic, LREE-enriched, mafic magmas with primitive isotopic signatures migrated through, and variably interacted with, lower crust. Fractionating magmas were emplaced in high-level chambers through northeast-trending fractures during the waning stages of compression (38.2–36.5 Ma). The transition to extension and rifting caused additional influx of volatiles into mantle and crustal magma-source regions, elevated geotherms, melting, and intrusion of bimodal mafic-alkalic and granite magmas into open fractures along the Capitan lineament. Basalts recently erupted along the lineament show less metasomatic input.

IMPLICATIONS FOR MINERAL DEPOSITS

Recognition of the tectonic setting and differentiation processes that control formation of certain igneous rock suites can aid in defining metallogenic provinces and predicting the occurrences of mineral deposits. Important mineral deposits (e.g., Cripple Creek gold district) are spatially and genetically related to the igneous rocks of the RMAP. The study of the petrogenesis of the LCPB has provided information concerning the origin of certain mineral deposit types, which may be useful in exploration for these deposits in the RMAP and in other alkalic magmatic provinces. Metallic mineral deposits are intimately associated with the igneous rocks of the LCPB. They are divided into four major types based on geologic setting and commodity produced: iron-skarn deposits, REE-fluorite deposits, molybdenum porphyry and gold breccia-vein deposits. The occurrence of some deposits appears to be unrelated to rock type, whereas others are specifically related to a particular magma suite.

Iron-skarn deposits are associated with intrusions of both magma

suites represented in the LCPB. Their occurrence is determined primarily by shallow intrusion of magma into a favorable carbonate host lithology, and subsequent development of an adequate fracture-controlled hydrothermal system. The importance of a magma-derived fluid as a source for iron or as a metasomatizing agent of the carbonate host is untested at this time. However, study of fluid inclusions in quartz from veins and in quartz within miarolitic samples of the roof zone of the Capitan pluton, which supports the largest LCPB iron deposit, indicates that iron oxides and salts were significant components in late-stage magmatic fluids (Phillips, 1990; A. R. Campbell, personal comm.).

Fluorine-rich REE deposits of the LCPB occur in both the older alkalic complex of the Gallinas Mountains and in the younger Capitan granite pluton. Though the styles of mineralization are different in each setting, the REE deposits appear to be related to magmatic/hydrothermal fluids derived from the igneous rocks. The igneous rocks at both locations are LREE-enriched, and thus provided REE-rich sources from which to derive REE-rich hydrothermal fluids. It might be concluded that this REE mineralization is independent of magma suite, but isotopic data from the Gallinas Mountains complex indicate significant contamination by a crustal component, thereby confounding this conclusion. Differences in the commodities present at each locality, such as gold and copper-sulfide minerals in the Red Cloud district, suggest that the deposits in the Gallinas and Capitan Mountains represent different types. Additional study is necessary to determine the factors that controlled mineralization in each deposit type.

Molybdenum porphyry deposits are related to the late stages of the emplacement of the Sierra Blanca complex. These stockwork vein deposits are intimately related to the igneous rocks which host them, and their similarity to the Climax-type deposits of Colorado and Questa, New Mexico strongly suggests a magmatic origin (Giles and Thompson, 1972; White et al., 1981; Stein and Hannah, 1985; Carten et al., 1988; Hannah and Stein, 1990). The data presented here indicate that the molybdenum-bearing rocks of the Sierra Blanca complex were derived much later and from a distinctly different source (lower crust) than the spatially associated alkalic rocks of the complex. Plutons hosting molybdenum deposits in the Colorado mineral belt have pronounced negative Eu anomalies and radiogenic Sr isotopic compositions relative to similar, but unmineralized, plutons (Simmons and Hedge, 1978; Stein, 1985). The ore-bearing plutons formed via differentiation of magmas derived from the lower crust (Stein and Hannah, 1985; Stein et al., 1987). The REE and isotope data for the youngest Sierra Blanca intrusives are also consistent with their derivation from the lower crust.

The gold deposits of the Ruidoso region are almost exclusively related to alkalic complexes. Gold deposits are closely related to igneous rocks in the White Oaks district of the Baxter Mountain complex, in the Jicarilla Mountains complex, and in the Gallinas Mountains complex, where gold-bearing veins, and intrusive and hydrothermal breccias are localized within and adjacent to the intrusive rocks of the complexes. In the Nogal and Bonito districts within the Sierra Blanca complex, complicated intrusive and hydrothermal histories leave relationships of mineralization to igneous rock type equivocal. The similarity in geochemistry and tectonic setting of the alkalic complexes of the LCPB to those at Cripple Creek, Colorado, and Ortiz, New Mexico, suggests a similar petrogenesis. At the latter two locations, gold mineralization has been linked to evolution of alkalic igneous rocks of each complex (Thompson et al., 1985; Mutschler et al., 1985; Saunders, 1986; Kay, 1986; Maynard et al., 1990).

Giles (1983) compiled information on several gold deposits related to the igneous centers of the northern RMAP, and lists many common characteristics. Deposits typically occur in vertically extensive vein systems or breccia pipes. They contain dominantly gold relative to silver or base metals, but may contain telluride and tungsten ores. Gangue minerals often include pyrite, quartz, fluorite and adularia. Argillic alteration is often intense but may be quite limited in extent away from veins. Many of these features also characterize the gold deposits of the LCPB. Mutschler et al. (1985) and Rock et al. (1987) compiled data on unaltered alkalic igneous rocks related to gold districts, which show significant enrichment of gold in these rocks relative to crustal averages. Gold contents of some igneous rocks of the LCPB compared to those of Cripple Creek are presented in Table 3. Enrichment above crustal average is indicated.

The process whereby these rocks were enriched in gold is unknown but may depend upon magma source (mantle) and/or metasomatism of that source. Studies of meteorites have shown that they contain high gold and platinum-group element contents (Baedecker and Ehman, 1965; Fouche and Smales, 1967; Schaudy et al., 1967; Jones, 1968). This is interpreted to indicate that during the early differentiation of the earth, these metals were preferentially partitioned to the mantle and core. Tapping of mantle by deeply generated magmas could result in the gold enrichments displayed by many mafic alkalic rocks. However, differences in isotope systematics of alkalic complexes that host gold deposits in the RMAP indicate a variety of source compositions and histories (Birmingham, 1987; Musselman, 1987; M. S. Allen, unpubl. data), indicating that melting of primitive mantle is not required to produce gold-enriched magmas. Hamlyn et al. (1985) believed that remelting of previously melted mantle may be necessary to generate gold-enriched magmas, due to gold's tendency to remain in the residual sulfide fraction during first-stage melting.

Metasomatism of gold-enriched continental lithosphere may provide

TABLE 3. Gold contents of samples of igneous rocks from the Lincoln County porphyry belt, New Mexico, and Cripple Creek complex, Colorado. Values are in parts per billion. Samples from Cripple Creek were collected by Carl Eriksson (1987) and analyzed by the USGS for this study. Crustal data from Rose et al. (1979).

Complex/pluton	Rocktype	Sample	Au content
Black Mountain	alkali gabbro	BMS-3A	4.7
"	alkali gabbro	BMS-6	3.3
"	gabbro xenolith	BMS-22E	18.3
Sierra Blanca	essexite	TRS-1	10.5
"	nepheline syenite	TRS-8	7.7
"	nepheline syenite	TRS-11	3.4
Three Rivers	syenite	TRS-5	9.2
"	syenite	TRS-13	6.1
"	syenite	TRS-15	5.9
"	syenite	TRS-16	5.1
"	quartz syenite	TRS-14	<1.0
"	alkali granite	TRS-3	<1.0
Bonito Lake	syenodiorite	BLS-7	5.4
Rialto	syenodiorite	RS-2	1.9
White Oaks	syenogabbro	WO-3	2.8
Gallinas Mountains	syenodiorite	GAL-11	4.9
"	alt. syenite	GAL-12	4.2
"	quartz syenite	GAL-8	2.4
Jicarilla Mountains	syenogabbro	JIC-1	1.0
"	syenodiorite	JIC-9	1.0
"	syenite, tonalite	(5 samples)	<1.0
Tecolote Hills	gabbro, syenite	(4 samples)	<1.0
Jones Camp dike	syenite	JCD-2	13.0
"	syenite	JCD-11	7.8
Railroad Mountain dike	syenogabbro	RRMD-3	5.9
Capitan	granite	(19 samples)	<1.0
Lone Mountain	granite	(3 samples)	<1.0
Carrizo Mountain	granite	(4 samples)	<1.0
Cripple Creek	alkali basalt	CCS-24	2.4
"	alkali basalt	CCS-45	23.4
"	phonolite	PP-2	8.2
"	phonolite	CCN-9	14.5
Crustal Average			
	ultramafic		3.2
	mafic		3.2
	granite		2.3

the correct combination of factors to generate gold-rich magmas. Although the partitioning of gold in mantle materials under high pressure and volatile-rich conditions has not been tested, it is interesting to note that gold in its +1 oxidation state has an ionic radius almost identical to that of potassium. Potassium-rich minerals and alkali-rich metasomatic fluids or magmas might be agents of gold storage and mobilization, thereby providing a mechanism for enrichment of gold in alkalic magmas. Though much is yet to be learned concerning the processes of gold-enrichment of magmas, and the subsequent formation of gold deposits, alkalic igneous complexes within the LCPB, and throughout the RMAP are favorable targets for hosting gold deposits. Additionally, alkalic magmatic arcs worldwide may have potential for hosting alkalic-related gold deposits (Wyman and Kerrich, 1988).

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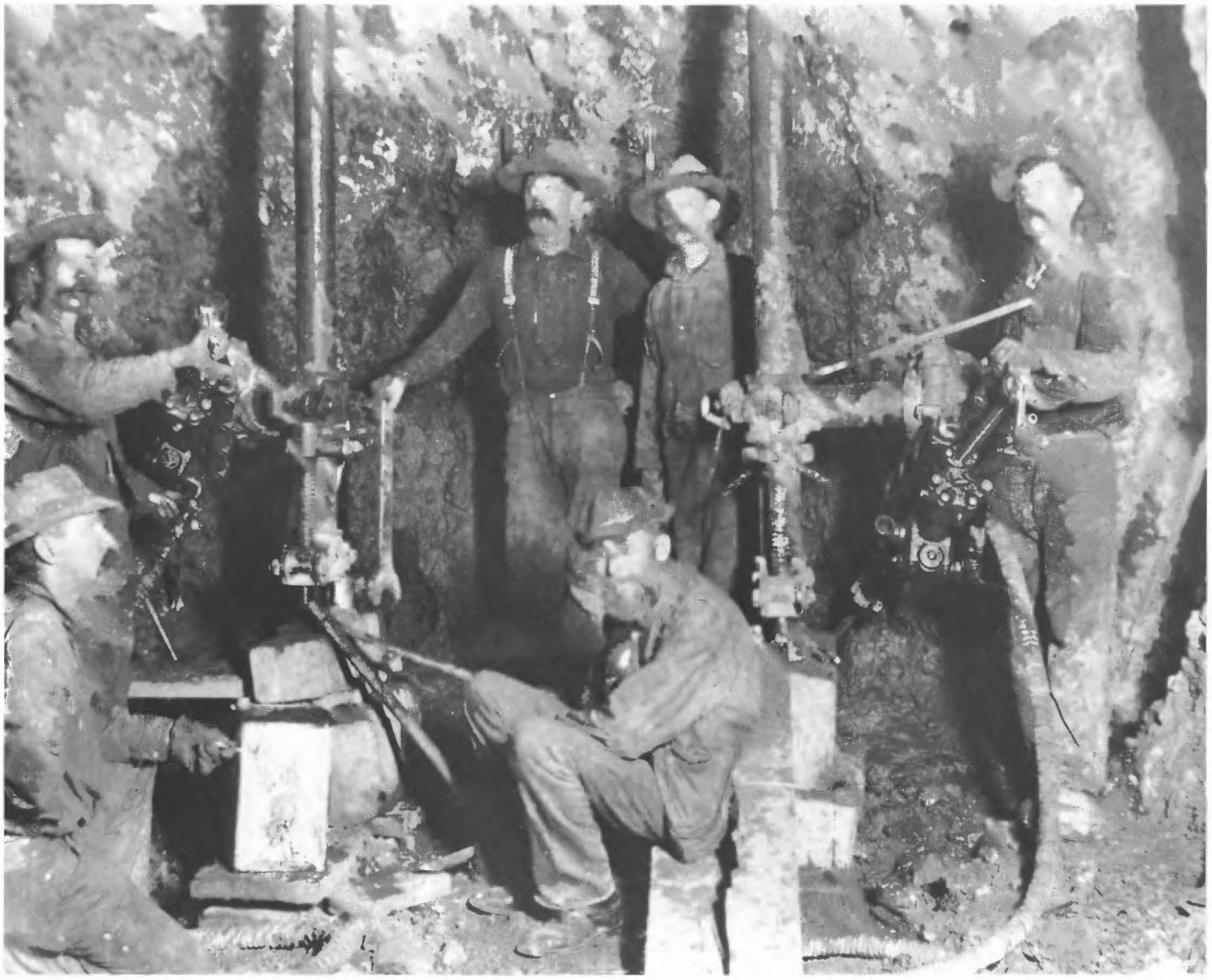
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While cutting a shaft station on the 1000-ft level on the Old Abe mine about 1893, many of White Oaks' finest pose for the photographer. Standing, l-r, are Oliver Parker, Forest Smith, Al Curtis and George Wilkerson. Seated, l-r, are A. P. Green and mine owner John Y. Hewitt. Note the lack of protective headgear and the use of candles—their sole source of illumination. New Mexico Bureau of Mines collection No. 1664, courtesy of Richard H. Jahns and John Kelt.