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PETROLOGY AND MINERAL RESOURCES OF THE WIND MOUNTAIN LACCOLITH, CORNUDAS MOUNTAINS, NEW MEXICO AND TEXAS

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ABSTRACT

The Wind Mountain laccolith is one of many intrusive bodies found in the Cornudas Mountains. These intrusive bodies comprise the northern part of the Trans-Pecos alkaline magmatic province in southern New Mexico and southwestern Texas. Ten laccoliths and stocks, along with numerous dikes, sills, and smaller plugs of varying textures, have intruded Permian limestone and other sedimentary rocks in the Cornudas Mountains area. Nepheline syenite predominates, although phonolite, trachyte, and syenite are common. The Wind Mountain laccolith is texturally and mineralogically zoned, whereas the other intrusive bodies in the Cornudas Mountains seem homogeneous. Wind Mountain consists of two textural varieties of nepheline syenite porphyry and four textural varieties of syenite porphyry. The zonation is attributed to crystal fractionation, volatile separation, and cooling history, not to different pulses of magma. Feldspar crystallization under initially hypersolvus conditions can account for most of the chemical variation in the volumetrically larger nepheline syenite zones. Subsolvus conditions of feldspar crystallization, coupled with the separation of a volatile phase, was responsible for the chemical and mineralogical variation within the capping syenite units, which form a rind at the top of the pluton. The Cornudas Mountains have been examined for potential economic deposits of gold, silver, beryllium, rare-earth elements, niobium, and uranium, but no production has occurred. The nepheline syenite porphyry at Wind Mountain is being considered as raw material for use in dark-colored glass, flatglass, and ceramics.

Keywords: Cornudas Mountains, Wind Mountain laccolith, nepheline syenite, syenite, alkaline rocks, New Mexico, Texas.

SOMMAIRE

The laccolite de Wind Mountain est un parmi plusieurs massifs intrusifs affleurant dans les montagnes Cornudas, à l'extrémité nord de la province magmatique alcaline de Trans-Pecos, dans le sud du Nouveau-Mexique et le sud-ouest du Texas. En tout, dix laccolites et plutons, ainsi que plusieurs filons, filons-couches et petits massifs à texture variable recoupent les calcaires et autres roches sédimentaires d'âge permien de la région. La syénite néphélinique est prédominante, quoique la suite contient aussi phonolite, trachyte et syénite. Le pluton de Wind Mountain, le plus imposant, est zoné en texture et en minéralogie, tandis que les autres massifs intrusifs semblent plutôt homogènes. Nous décrivons deux variétés texturales de syénite néphélinique porphyrique et quatre variétés de syénite porphyrique. La zonation semble due à la cristallisation fractionnée, la séparation d'une phase volatile, et le taux variable de refroidissement, plutôt qu'à des venues distinctes de magma. La cristallisation de feldspath à des conditions tout d'abord hypersolvus peut expliquer la plupart de la variation chimique parmi les différentes venues volumineuses de syénite néphélinique. Les conditions propices à une cristallisation subsolvus et à la séparation d'une phase volatile rendent compte des variations chimique et minéralogique parmi les unités supérieures de syénite, qui constituent une carapace au sommet du massif. La chaîne Cornudas a fait l'objet de recherches pour des anomalies en or, argent, béryllium, terres rares, niobium et uranium, mais sans découvertes dignes d'exploitation. Récemment, on a initié un programme d'exploration et de développement de la syénite néphélinique porphyrique pour son potentiel dans la fabrication de verre foncé, verre en panneaux, et céramique; ce matériau aurait aussi un potentiel dans la fabrication de granules pour toitures et d'abrasifs, et dans l'industrie des pierres taillées.

(Traduit par la Rédaction)

Mots-clés: chaîne de montagnes Cornudas, laccolite de Wind Mountain, syénite néphélinique, syénite, roches alcalines, Nouveau-Mexique, Texas.

Introduction

Wind Mountain is one of ten Tertiary intrusive alkaline bodies that form the Cornudas Mountains in the Otero and Diablo plateaus in southern New Mexico and southwestern Texas (Fig. 1). These intrusive bodies represent the northern extent of the Trans-Pecos magmatic province. The Cornudas Mountains were originally mapped in the early 1940s and 1950s as homogeneous plutons or laccoliths (Zapp 1941, Timm 1941, Clabaugh 1941, Warner *et al.* 1959). Subsequent petrological and geochemical studies along with

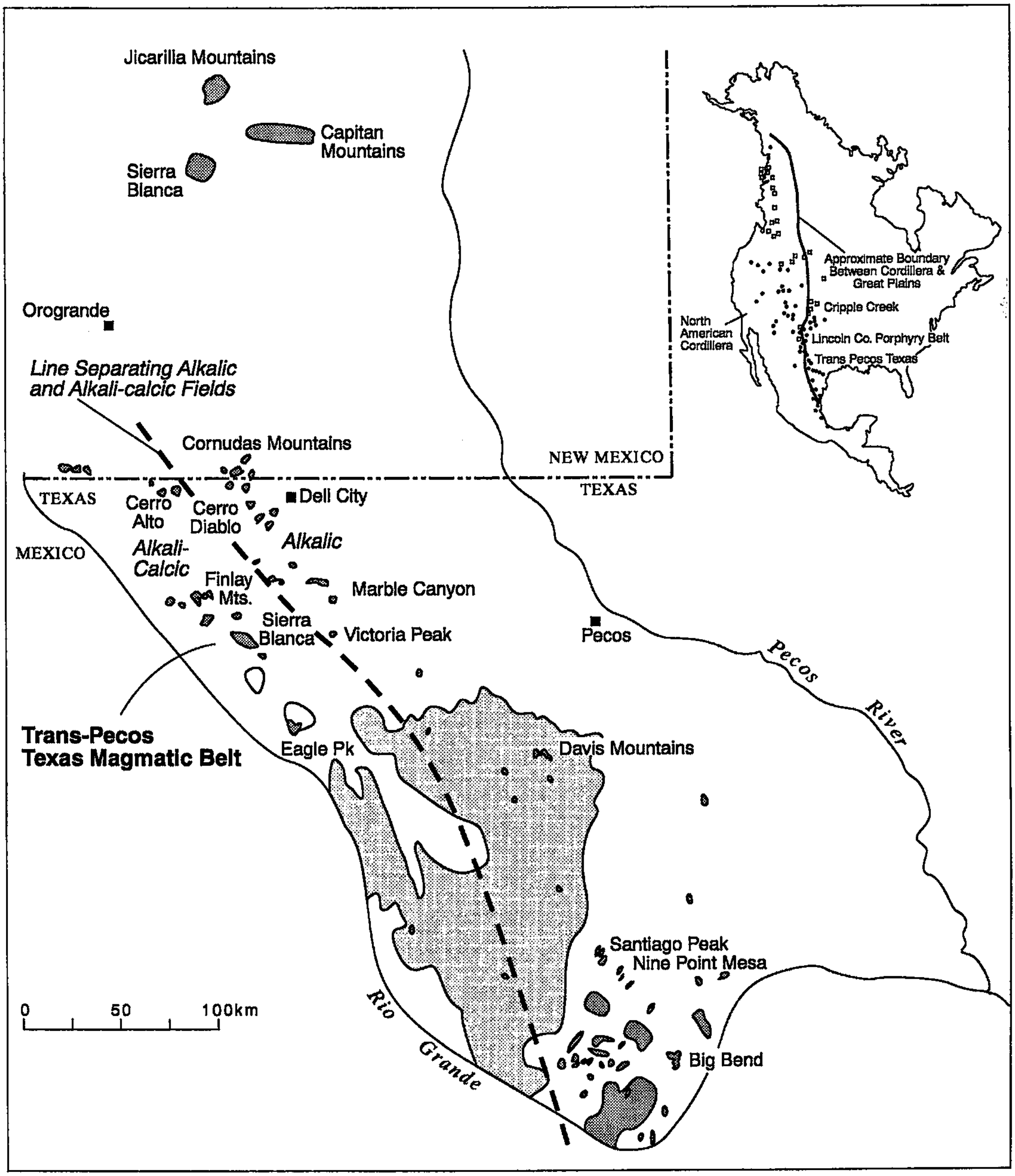

FIG. 1. Trans-Pecos magmatic province, New Mexico and Texas (modified from Barker 1987, Price *et al.* 1987). The inset map shows the North American Cordilleran belt of alkaline igneous rocks (Woolley 1987, Mutschler *et al.* 1991).

examination of the Wind Mountain nepheline syenite by geologists of Addwest Minerals, Inc. revealed that this unit is texturally and mineralogically zoned (McLemore & Guilinger 1993, McLemore *et al.* 1994, 1996).

The purpose of this paper is to 1) summarize the petrology and mineralogy of the Wind Mountain laccolith, 2) describe the zones in the laccolith, 3) determine the cause of zonation, and 4) describe the mineral resource potential.

Regional Setting

The Cornudas Mountains and the Trans-Pecos magmatic province form part of the southern portion of the North American Cordilleran alkaline igneous belt. This belt is a diffuse region of Cenozoic igneous rocks that extends along the eastern margin of the North American Cordillera from Alaska and British Columbia southward into Trans-Pecos Texas and eastern Mexico (Fig. 1; Barker 1987, Mutschler *et al.* 1985, 1991, Woolley 1987).

The Trans-Pecos magmatic province is a regional belt of alkaline and metaluminous igneous rocks that lie within an area defined by the Rio Grande on the west and south, the Pecos River on the east, and an east–west line approximately 12 km north of the state boundary between New Mexico and Texas (Fig. 1). The province contains more than 200 intrusive bodies having an outcrop area exceeding 1 km^2 (Barker 1977, 1979, 1987). The Trans-Pecos magmatic province is the eastern limit of Cenozoic magmatic activity in southwestern United States and Mexico. The magmatism occurred in the region nearly continuously from 48 to 17 Ma (Price *et al.* 1987). Compositions of igneous rocks vary from alkaline in the eastern portions of the province, including the Cornudas Mountains, to calc-alkaline westward into Mexico (Fig. 1; Barker *et al.* 1977, Barker & Hodges 1977, Barker 1987, Price & Henry 1984, Cameron & Cameron 1985, Price *et al.* 1987, Clark 1989).

Early genetic interpretations suggested an analogy between the Trans-Pecos province and the Kenya portion of the East African rift (Barker 1977). However, subsequent work has shown that much of the Cenozoic faulting in Trans-Pecos Texas, earlier considered to be associated with rifting, actually post-dates igneous activity (Barker 1987, Henry *et al.* 1991). Trans-Pecos magmatic activity began at the end of the Laramide compressional tectonic period and may be linked to progressive shallowing of the subduction of the Farallon plate beneath the North American plate with time (Coney 1972, Barker 1987, Damon *et al.* 1981, Campa & Coney 1983, Henry *et al.* 1989, 1991). It is also possible that some Trans-Pecos magmatic activity is related to back-arc spreading (Barker 1987).

Geological Setting

Wind Mountain is one of ten larger sills, plugs, and laccoliths (Table 1, Fig. 2) and smaller dikes and plugs in the Cornudas Mountains that intrude relatively flat-lying limestone and other sedimentary rocks of the Hueco Limestone and Bone Spring Limestone (Permian). Other dikes, sills, and plugs are buried by sedimentary cover, as indicated by subsurface drilling (King & Harder 1985), geophysical surveys, and structural anomalies (*i.e.*, anticlines, synclines, faults) in the overlying sedimentary rocks. These intrusive bodies vary in size from less than 700 m to 2.5 km in diameter. Wind Mountain is one of the largest (Fig. 2), with a reported thickness of 0.25 km, an area of 4.3 km^2, and a minimum volume of 1.1 km^3 (Barker *et al.* 1977).

Barker *et al.* (1977) divided the lithologies found in the Trans-Pecos magmatic province into nine types on the basis of mineralogy and texture: 1) nepheline-bearing augite syenite, 2) nepheline-bearing trachyte, 3) syenite, 4) nepheline syenite, 5) porphyritic nepheline syenite, 6) phonolite, 7) foliated porphyritic nepheline syenite, 8) quartz-bearing syenite, and 9) quartz-bearing trachyte. All nine types are found in the Cornudas Mountains; however, the predominant lithology is porphyritic nepheline syenite. The largest laccoliths consist of dark gray to pink, fine- to coarse-grained equigranular to porphyritic nepheline syenite.

TABLE 1. DESCRIPTION OF IGNEOUS INTRUSIVE BODIES IN THE CORNUDAS MOUNTAINS*

Name	Predominant Lithology	Form	Age in Ma	References
Alamo Mountain	phonolite, foliated porphyritic nepheline syenite	discordant sheet or sill	36.8 ± 0.6 (K/Ar on biotite)	Barker *et al.* (1977), Clabaugh (1941), Henry *et al.* (1986)
Flat Top Mountain	phonolite, augite syenite dike	sill	–	Barker *et al.* (1977), Clabaugh (1941)
Cornudas Mountain	quartz–bearing syenite, syenite, trachyte	plug or laccolith	34.6 ± 1.5 (K/Ar on biotite)	Barker *et al.* (1977), Zapp (1941), Henry *et al.* (1986)
Wind Mountain	nepheline syenite, phonolite, porphyritic nepheline syenite	laccolith	–	Barker *et al.* (1977), Warner *et al.* (1959), McLemore & Guilinger (1993)
San Antonio Mountain	nepheline syenite	laccolith	–	Timm (1941), Barker *et al.* (1977)
Deer Mountain (Little Wind Mountain)	nepheline syenite	plug or laccolith	33.0 ± 1.4 (K/Ar on biotite	Barker *et al.* (1977), Clabaugh (1941, 1950), Henry *et al.* (1986)
Chatfield Mountain	phonolite	sill	–	Timm (1941), Barker *et al.* (1977)
Black Mountain	porphyritic nepheline syenite	sill	–	Barker *et al.* (1977)
Washburn Mountain	porphyritic nepheline syenite	sill	–	Timm (1941), Barker *et al.* (1977)
Unnamed hill	nepheline–bearing augite syenite	plug	36.8 ± 0.6 (K/Ar on biotite)	Barker *et al.* (1977), Clabaugh (1941), Henry *et al.* (1986)

* Bodies as shown in Figure 2.

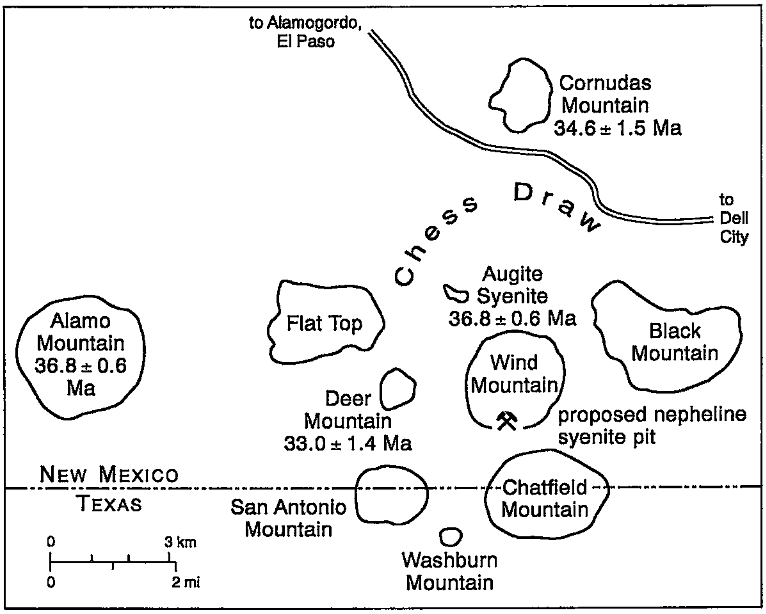

FIG. 2. Reference map of Cornudas Mountains.

THE WIND MOUNTAIN LACCOLITH

Geology and petrology

Wind Mountain is the only pluton mapped in detail in the Cornudas Mountains and is mineralogically and texturally zoned (Figs. 3, 4; McLemore & Guilinger 1993). The laccolith consists of six zones (Fig. 3), although some of the zones vary only in texture. The rocks are typically gray- to cream-colored and weather to darker colors. Accessory minerals form dark-colored aggregates dispersed throughout the rock. A crude to well-developed trachytic texture defined by feldspar is present in all rock types. In addition, the laccolith displays an igneous foliation that dips steeply away from the center of the intrusive body, roughly parallel to the observed slope surface. Feldspar lineations vary by 90° in the plane of this foliation. These feldspar orientations represent a magmatic lineation that formed subparallel to the walls of the intrusion.

The outermost zone consists of medium-grained nepheline syenite porphyry ($TNSP_2$). The rock is comprised of alkali feldspar phenocrysts (15% by volume) up to 2 cm long, that occur in a fine- to medium-grained matrix (grain size less than 0.5 cm). The entire rock is composed predominantly of alkali feldspar (77%) and interstitial nepheline (12%), with minor analcime (2%). Other accessory minerals form dark-colored aggregates (less than 0.5 cm long) and include aegirine (4%), sodic amphibole (2%), biotite (1%), and magnetite (2%). All percentages are based on modal analysis by optical determination from point counts (1000 points). At the contact with the Hueco Limestone, a thin zone of diopside hornfels is locally present. Within the intrusive rock, schlieren-like mafic segregations and zones of finer-grained textures are present in the contact zone for one meter into the intrusive rock. Small xenoliths of hornfels material also are present in this zone.

The outer nepheline syenite porphyry ($TNSP_2$) grades into a coarse-grained nepheline syenite porphyry ($TNSP_1$), which consists of larger and more abundant (29% of the rock mass) alkali feldspar phenocrysts (up to 3 cm) in a coarse-grained matrix (0.5 to 3 cm). Modal analysis shows the rock is predominantly alkali feldspar (70%) and interstitial nepheline (10%), with minor analcime (8%). Accessory minerals in larger dark-colored aggregates (up to 1 cm long) include aegirine (5%), sodic amphibole (3%), biotite (2%), and magnetite (2%). The contact zone between $TNSP_2$ and $TNSP_1$ is marked by a zone of schlieren approximately 10 m wide.

The nepheline syenite porphyry ($TNSP_1$) grades into syenite porphyry ($TSPfg_4$), which consists of K-feldspar phenocrysts (up to 1 cm long) in a fine-grained matrix of K-feldspar and albite. Most of the rock consists of K-feldspar (63%) and albite (19%), with interstitial analcime (3%). Accessory minerals form small aggregates (less than 2 mm long) and include aegirine (6%), sodic amphibole (3%), clay (2%), biotite (1%), and magnetite (3%). This syenite porphyry is typically darker colored than the lighter gray or cream-colored nepheline syenite porphyry ($TNSP_1$, $TNSP_2$). The contact zone between $TNSP_1$

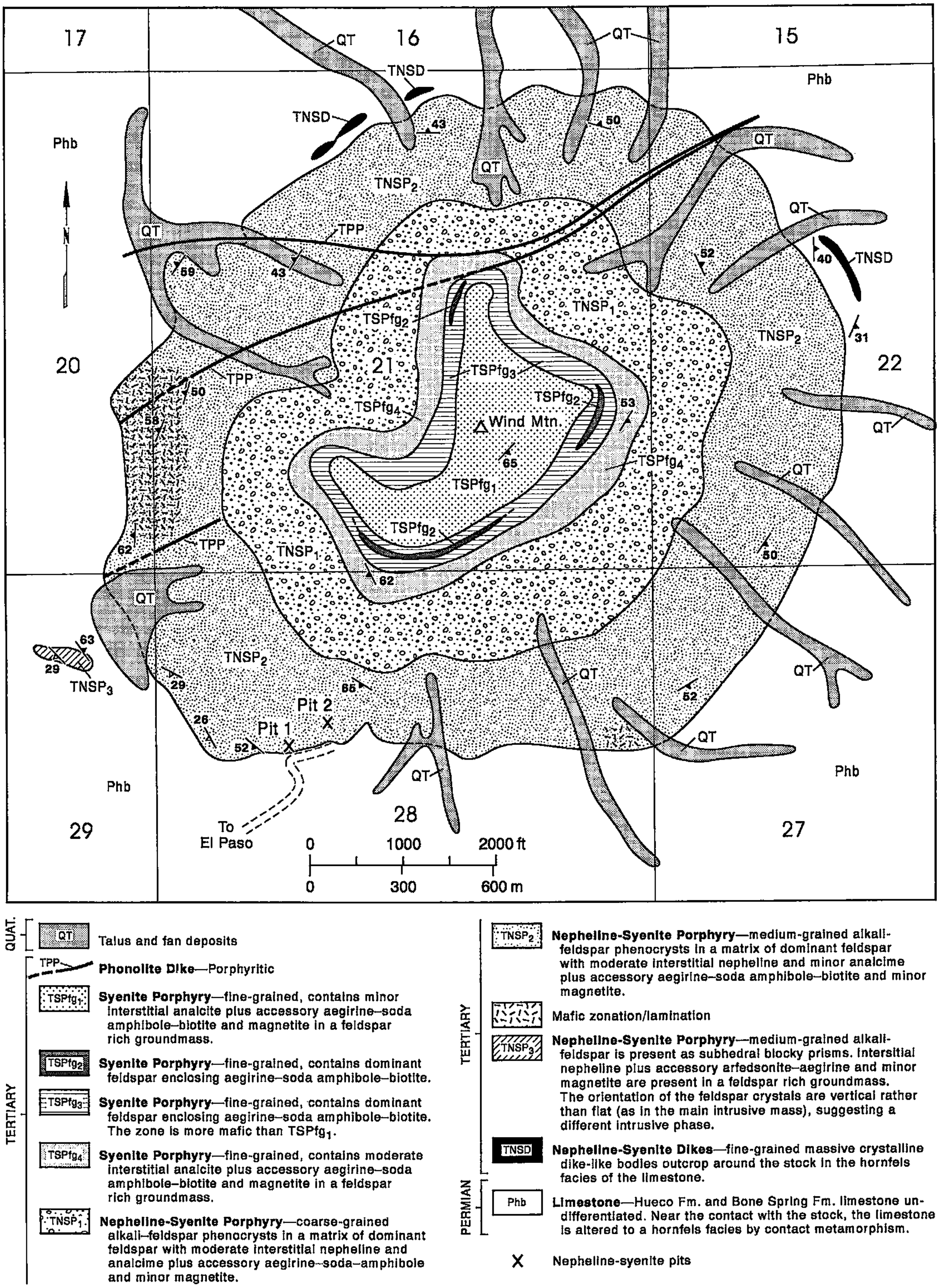

FIG. 3. Geological map of Wind Mountain (P. Graseah, field mapping, July 1992).

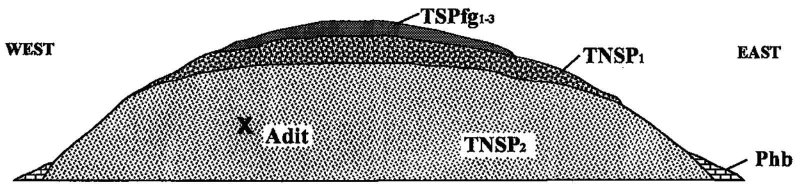

FIG. 4. Schematic cross-section of the Wind Mountain laccolith.

and $TSPfg_4$ is a narrow zone of schlieren between 1 and 2 m wide.

The fine-grained syenite porphyry ($TSPfg_4$) grades into a more mafic-looking syenite porphyry ($TSPfg_3$). This syenite porphyry is similar in grain size to $TSPfg_4$, except that it contains larger phenocrysts (up to 1 cm long) of K-feldspar in a fine-grained matrix of predominantly K-feldspar and albite. Feldspar proportions in the entire rock are 54% K-feldspar and 20% albite. $TSPfg_3$ contains accessory aegirine (5%), sodic amphibole (4%), biotite (1%), clay (1%) and magnetite (1%) as discrete grains as well as in mineral aggregates. Analcime is most abundant in this phase of the pluton, comprising 14% of the rock. The contact between $TSPfg_4$ and $TSPfg_3$ is very gradational and not readily recognized in the field.

Several thin, discontinuous zones of less mafic, lighter colored, fine-grained syenite porphyry ($TSPfg_2$) occurs within the syenite porphyry ($TSPfg_3$). This syenite porphyry consists of smaller (less than 2 mm) K-feldspar and albite phenocrysts in a fine-grained matrix. The rock consists of K-feldspar (57%), albite (20%), analcime (8%), aegirine (8%), sodic amphibole (2%), biotite (2%), and magnetite (1%). Also within this zone are thin and discontinuous dark (in outcrop) dikes that appear more mafic on weathered outcrop but are actually light colored on fresh surfaces. The contact between $TSPfg_2$ and $TSPfg_3$ is sharp.

The mafic syenite porphyry ($TSPfg_3$) grades into the uppermost cap of syenite porphyry ($TSPfg_1$). The syenite porphyry is similar to $TSPfg_4$ and consists of K-feldspar phenocrysts (up to 1 cm long) in a fine-grained matrix. The unit is predominantly K-feldspar (58%), albite (20%), analcime (8%), and accessory aegirine (4%), sodic amphibole (3%), biotite (2%), clay (2%), and magnetite (3%). The accessory minerals form crystal aggregates up to 1 cm long. This phase of the pluton contains numerous miarolitic cavities lined with crystals of feldspar, analcime, occasionally natrolite, and more rarely, zirconium silicates. The contact between $TSPfg_3$ and $TSPfg_1$ is gradational and subtle.

The Wind Mountain laccolith is cut by two dikes of porphyritic phonolite that coalesce into one dike. Eudialyte occurs locally in these dikes (Zapp 1941, Clabaugh 1950, Warner *et al.* 1959). The dikes are matrix-supported, with large phenocrysts of anorthoclase and, more rarely, nepheline. In addition, several thin dikes and sills (less than 1 m) of nepheline syenite porphyry intrude along bedding planes and fractures in the Permian limestone. Locally, thin zones of chlorite–epidote hornfels are developed along the contacts (McLemore & Guilinger 1993).

Mineralogy

Feldspar-group minerals constitute the most abundant species, and are represented by two distinctly different textures and compositions. Alkali feldspar typically occurs as medium- to coarse-grained microperthitic phenocrysts in the nepheline syenite porphyry units; these phenocrysts are characteristic of hypersolvus conditions during crystallization. Phenocrysts are commonly turbid and are occasionally altered to analcime, natrolite, or clay. In the groundmass, alkali feldspar is typically less altered and turbid than the phenocrysts. The groundmass feldspar also is microperthitic. Two primary feldspars are present in the syenites, representing subsolvus conditions of crystallization. Albite and microcline (determined optically, based on twinning and extinction angle) coexist with smaller laths of albite surrounding the subhedral K-feldspar phenocrysts in the syenite units. Discrete grains of albite and microcline also are present in the matrix. Most of the feldspar grains in the syenite units are turbid and partially altered to analcime, natrolite, or clay minerals. Feldspar alteration is more pervasive in the syenite units than in the nepheline syenite. Minor amounts of muscovite were observed in the syenite as a product of deuteric alteration of the microcline.

Nepheline is found in all zones at Wind Mountain, as well as in several other laccoliths in the Cornudas Mountains (Tables 1, 2). Nepheline is typically euhedral to subhedral, interstitial to the feldspars, and locally altered to clay minerals and analcime. Larger grains poikilitically enclose bleb-shaped inclusions of mafic minerals, usually aegirine. Locally in the nepheline syenite, the outer edges of the nepheline grains display extensive alteration to clay. Significantly less nepheline is present in the syenite units and, where present, is typically corroded and altered to clay or analcime.

TABLE 2. SELECTED MINERALS REPORTED FROM THE CORNUDAS MOUNTAINS AND THEIR MODE OF OCCURRENCE

Mineral	Occurrence	Reference
analcime	replaces nepheline, lines vugs, vesicles and miarolitic cavities	Barker & Hodges (1977), Boggs (1985)
natrolite	replaces nepheline and feldspars	Barker & Hodges (1977)
olivine	mineral aggregates of ferromagnesian minerals and magnetite	Barker & Hodges (1977)
aenigmatite	in nepheline syenite	Barker & Hodges (1977)
eudialyte	in dikes, sills, and laccoliths and in miarolitic cavities	Barker & Hodges (1977), Clabaugh (1950), Boggs (1985, 1987)
catapleiite	miarolitic cavities	Boggs (1985)
georgechaoite	miarolitic cavities	Boggs (1985), Boggs & Ghose (1985)
aegirine	miarolitic cavities	Boggs (1985, 1987)
monazite	miarolitic cavities	Boggs (1985)
thomsonite	miarolitic cavities	Zapp (1941), Boggs (1985)
chabazite	miarolitic cavities	Boggs (1985)
parakeldyshite	nepheline syenite, Wind Mountain	this report
pyrite	aggregates of ferromagnesian minerals	this report
fluorite	breccia	Barker *et al.* (1977)

Chemical formulae of rare species: eudialyte: $Na_4(Ca,Ce)_2(Fe^{2+},Mn^{2+},Y)ZrSi_8O_{22}(OH,Cl)_2$, catapleiite: $Na_2ZrSi_3O_9 \cdot 2H_2O$, georgechaoite: $NaKZrSi_3O_9 \cdot 2H_2O$, parakeldyshite: $Na_2ZrSi_2O_7$.

TABLE 3. WHOLE-ROCK CHEMICAL COMPOSITION OF REPRESENTATIVE SAMPLES FROM THE WIND MOUNTAIN LACCOLITH

	CORN 31	CORN 33	CORN 34	$TNSP_1$	$TSPfg_1$	$TSPfg_2$	$TSPfg_3$	$TSPfg_4$
SiO_2 wt.%	60.10	59.40	58.00	58.67	59.00	59.20	59.00	59.50
TiO_2	0.18	0.18	0.08	0.19	0.26	0.13	0.24	0.24
Al_2O_3	17.70	18.40	17.70	17.80	18.10	18.50	18.00	18.30
Fe_2O_3*	5.09	5.64	4.58	5.96	4.75	4.78	4.73	4.65
MnO	0.21	0.27	0.27	0.28	0.23	0.26	0.24	0.23
MgO	0.24	0.48	0.19	0.44	0.53	0.49	0.46	0.35
CaO	1.16	1.28	0.73	1.19	1.50	0.94	1.45	1.19
Na_2O	6.83	7.72	8.04	8.12	7.28	7.66	7.00	6.72
K_2O	5.44	5.33	5.48	5.33	5.20	5.31	5.13	5.27
P_2O_5	0.09	0.09	0.08	0.10	0.12	0.06	0.12	0.11
LOI	1.02	2.06	3.35	2.20	1.79	3.27	1.67	1.64
Total	98.06	100.85	98.50	100.28	98.76	100.60	98.04	98.20
Ba ppm	182	103	89	106	442	nd	370	439
Cr	30	22	13	28	47	nd	31	36
Zn	105	184	353	208	121	216	132	107
Ga	27	29	32	29	23	30	24	24
Pb	15	31	55	29	22	38	28	18
Th	8	38	77	39	22	46	30	16
Rb	115	160	200	157	121	165	133	122
Sr	60	64	62	69	203	109	130	135
Y	24	53	138	65	40	65	44	36
La	61	123	184	116	84	nd	107	84
Cs	13	18	23	26	13	nd	18	17
Zr	744	1759	2843	1994	1165	2135	1326	949
Nb	96	214	360	239	157	250	178	126

* Total iron as Fe_2O_3. nd: no data. Samples CORN 31, 33, and 34 are taken from unit $TNSP_2$.

Analcime locally replaces nepheline and feldspar and also occurs as linings or discrete crystals in miarolitic cavities in the syenite units (notably $TSPfg_1$). Where present as a primary phase in the nepheline syenite, analcime is anhedral and intersertal to the feldspars and may represent an alteration phase. Analcime is most abundant in the finer-grained syenite units. In the syenite, analcime is disseminated throughout the entire rock and varies in texture from euhedral to anhedral grains intersertal to feldspars.

A variety of mafic and other accessory and trace minerals occur in the Wind Mountain laccolith (Tables 2, 3). Mafic minerals include sodic amphibole, aegirine, biotite, and magnetite (Table 3). Hematite and clays are common products of alteration that can constitute up to 12% of the sample. The mafic aggregates within the nepheline syenite units ($TNSP_1$ and $TNSP_2$, Fig. 5) allow for easy removal by magnetic separation. Primary magnetite is intimately associated with aegirine, commonly observed as inclusions in the pyroxene. Fluorite is reported as breccia filling and as small replacement bodies at Wind Mountain (Barker *et al.* 1977) and may represent a fluorine-rich derivative from the laccolith.

A large number of less common minerals are reported to occur in the Cornudas Mountains, and specifically at Wind Mountain (Table 3). Many of these occur within miarolitic cavities, although some also are present in the matrix. Recently, parakeldyshite, a rare Na–Zr silicate, was identified by X-ray diffraction in a heavy-mineral separate of the Wind Mountain nepheline syenite ($TNSP_2$). A number of other Na–Zr silicates have been found in miarolitic cavities in the laccolith. Wind Mountain is the type locality for the mineral georgechaoite (Boggs & Ghose 1985).

Geochemistry

Individual samples from each zone of the Wind Mountain laccolith, except the phonolite dikes, were crushed and ground following standard practices. Whole-rock and trace-element geochemical analyses were obtained using a Philips PW 2400 X-ray-fluorescence unit utilizing standard operating procedures. Fused glass disks were used for major-element analysis (Hallet & Kyle 1993). Pressed powder briquettes were prepared for trace-element determinations (Norrish & Hutton 1969). U.S. Geological Survey rock standards were used to calibrate the instrument.

Chemical variation among individual map-units within the laccolith cannot be readily discerned by utilizing major-element oxides (Table 3). Only TiO_2 values reveal any significant variation between the two rock types. Normative calculations based on whole-rock compositions reveal a more important

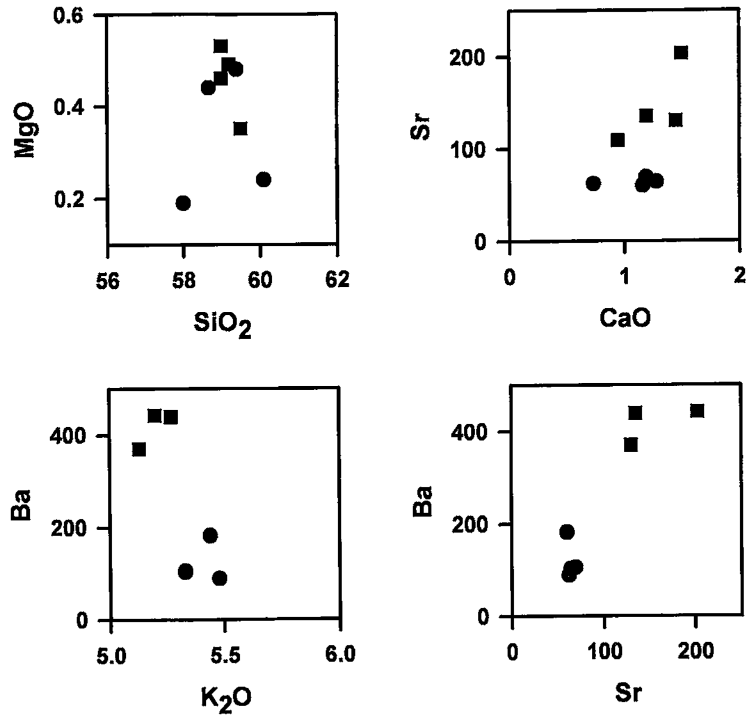

FIG. 5. MgO – SiO_2, Sr – CaO, Ba – K_2O, and Ba – Sr variation diagrams for the various zones in the Wind Mountain laccolith. Oxide values are reported as weight percent, trace elements as ppm. Symbols: ●: nepheline syenite, ■: syenite.

discriminating factor: proportion of normative anorthite. The nepheline syenite units lack normative anorthite. This is also seen in the lack of modal plagioclase in the petrographic analysis of the rocks. Syenite units contain up to 5% normative anorthite, and also contain modal albite. No mafic mineral fractionation was apparently involved in the transition from syenite to nepheline syenite (Fig. 5).

Although the different units within the Wind Mountain laccolith are chemically similar on the basis of major-element oxides, significant chemical differences in Sr and Ba concentrations are observed between the nepheline syenite and syenite units. The syenite units generally contain twice as much Sr as the nepheline syenite (Fig. 5). Barium concentrations display even greater contrast between the two major rock-types. The variation in Ba and Sr (Fig. 6) is a result of crystallization and removal of feldspars from the melt (Weaver *et al.* 1972). The feldspar-rich products are considered to form at or migrate toward the top of the magma chamber, and form a capping syenite. The compositional gap in Ba and Sr is further evidence of differential cooling, which is also manifested by textural variation between the two units. The syenite is consistently finer-grained than the nepheline syenite units.

Trace-element variation between the two main rock-types is not apparent in incompatible element concentrations (Fig. 6). The distribution of Cs, La, Nb, and Rb as a function of Zr does not indicate partitioning of the incompatible elements between the major rock-units, although the use of Zr as a conserved element in this system could be problematic since Zr-rich phases are present in the intrusion (Weaver *et al.* 1972). The large variation in Zr between individual map-units is due to the precipitation of Zr-silicates throughout the laccolith. However, the linear variation in Nb/Zr, La/Zr, and Rb/Zr suggests that all the rock units are comagmatic. This is similar to the case of other alkaline igneous intrusive bodies in Trans-Pecos Texas (Barker 1987). The scatter in the Cs/Zr plot, less so in the La/Zr plot, may be the result of the development of a volatile phase during crystallization (Weaver *et al.* 1972). The alteration of the feldspars and mantling of phenocrysts by albite in syenite units also suggest the possibility of a post-magmatic metasomatic alteration event similar to that described by Martin & Bowden (1981). The alteration of nepheline to analcime further indicates Na metasomatism of the syenites.

The high alkalinity of the melt, coupled with the high initial concentrations of Zr and a lack of free silica, allowed for the formation of a suite of the rare zirconium silicates, which occur throughout the intrusion, without the formation of zircon. The concentration of zirconium silicates in the late-stage phonolite dikes (Zapp 1941, Clabaugh 1950, Warner *et al.* 1959) suggests an overall buildup of Zr during crystallization. However, the presence of significant amounts of zirconium silicates accompanied by analcime and natrolite in miarolitic cavities would also indicate concentration during the separation of a volatile phase.

The formation of the various units in the Wind Mountain laccolith appears to be the result of fractional crystallization and the development of a volatile phase, which separated over time. Initial formation of the nepheline syenite units involved crystallization under hypersolvus conditions. As the magma continued to crystallize, subsolvus conditions developed in the upper portions of the magma chamber due to the

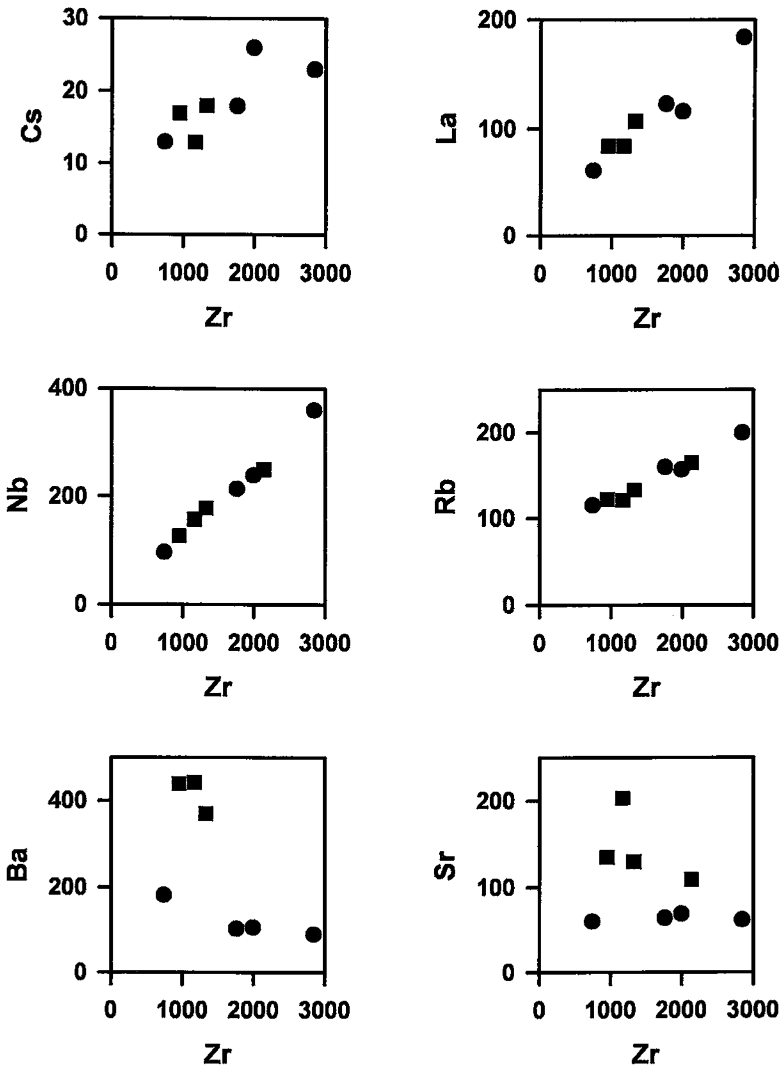

FIG. 6. Cs, La, Nb, Rb, Ba, Sr – Zr trace element variation diagrams for the various zones in the Wind Mountain Laccolith. All values are in ppm. Symbols: ●: nepheline syenite, ■: syenite.

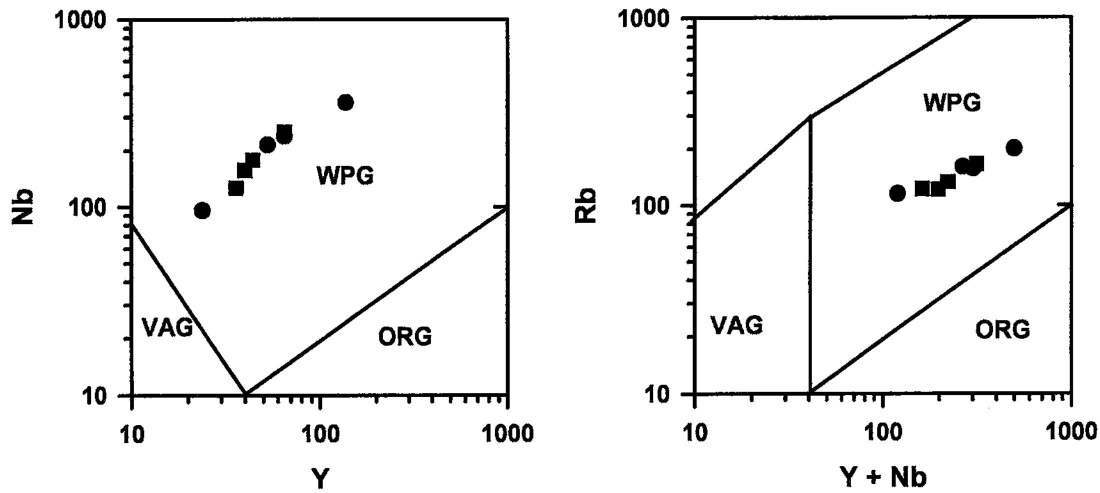

FIG. 7. Log Nb–Y and log Rb–(Y + Nb) diagrams for the various zones in the Wind Mountain Laccolith after Pearce *et al.* (1984). All values are in ppm. Symbols: ●: nepheline syenite, ■: syenite.

concentration of volatiles, and resulted in the formation of syenite units. The progressive build-up of residual fluid in the upper zones of the pluton during crystallization of the nepheline syenite culminated in the formation of mineralogical and textural zones, deuteric alteration, and minor expulsion of fluid, which escaped into the country rock, forming the skarn and hornfels units adjacent to the pluton. The various zones at the top of the laccolith probably reflect various zones of volatile concentration, which also explains the tendency for these various zones to be separated by schlieren, and not sharp contacts. The syenite unit displaying sharp contacts ($TSPfg_2$) represents injections of more fractionated magma along dikes during late-stage crystallization. The migration of residual fluids also deuterically altered the syenite units, and in particular reduced the nepheline to analcime and clay. Additional mapping of the pluton and more detailed petrography may lead to the identification of fluid pathways through the earlier-formed units, similar to the alteration stages described by Martin & Bowden (1981), and so better constrain the timing of alteration. Residual fluids trapped at the apex of the laccolith also contributed to the formation of zirconium-silicate-rich miaroles within the nepheline syenite, described by Boggs (1985), during crystallization of the syenite units. The two-feldspar, eudialyte-bearing dike that intrudes both the laccolith and the country rocks represents a late-stage magma formed by the same processes (Boggs 1987).

The Wind Mountain laccolith is classified as a Within-Plate Granite using the classification of Pearce *et al.* (1984) (Fig. 7). In accordance with these types of intrusions, the magmas probably originated in the mantle and acquired a significant enrichment in lithophile-group elements during its movement through continental crust. These data are consistent with either continental rift or subduction-related back-arc extension settings. Additional studies are required to further constrain the origin of the magmas to a particular tectonic setting.

Mineral Deposits

The Cornudas Mountains have been examined in the past for potential deposits of gold, silver, beryllium, rare-earth elements, niobium, thorium, and uranium (McLemore & Guilinger 1993, McLemore *et al.* 1996), but there has been no production. In the 1950s, prospectors located several areas of anomalously high radioactivity in the Cornudas Mountains and attributed these to the presence of uranium and thorium. Shallow prospect pits were dug on many claims in the area; however, assay results were very low, and the claims were later dropped. The potential for economic uranium and thorium deposits in the area seems low because of low assays in areas of anomalously high radioactivity and a depressed uranium market (McLemore & Chenoweth 1989).

Beryllium was first reported from the Cornudas Mountains during the 1940s. A few samples assayed were found to contain as much as 0.2% BeO (Warner *et al.* 1959). The limited development of a metasomatic aureole and apparent lack of large-scale metasomatism on the margins of the pluton would suggest that Wind Mountain may only contain limited beryllium potential, in comparison to the mineralized laccoliths near Sierra Blanca, Texas.

A variety of deposits containing gold and silver are associated with alkaline igneous rocks in New Mexico (Great Plains Margin deposits; North & McLemore 1986, 1988, McLemore 1991) and elsewhere along the North American Cordilleran alkaline igneous belt (Fig. 1, Mutschler *et al.* 1991, Thompson 1991, 1992). Consequently, numerous companies have examined the Cornudas Mountains for similar gold–silver deposits, but without success (McLemore & Guilinger 1993). The lack of significant evidence for hydrothermal alteration (*i.e.*, large zones of skarn, complex alteration assemblages, *etc.*) associated with the emplacement of the Wind Mountain laccolith suggests that the potential for precious metal deposits is low (McLemore & Guilinger 1993).

A few companies have examined the Cornudas Mountains unsuccessfully for high concentrations of rare-earth elements, niobium, zirconium, and titanium. U.S. Borax sampled and drilled in the Chess Draw area, but their assays of mineralized limestone and syenite dikes were low (up to 0.06% total rare-earth oxides, 10–1400 ppm Nb, 10–3000 ppm Zr, 230–13,000 ppm F). Results of an analysis reported by McLemore *et al.* (1988a, b) contain 1235 ppm Ce, 700 ppm La, 270 ppm Nd and 242 ppm Y. Zirconium silicates are common in the area (Table 2) and are well distributed throughout the pluton. Three claims for zirconium deposits are located immediately east of Wind Mountain.

Addwest Minerals, Inc. is developing the Wind Mountain nepheline syenite for use as a constituent in amber-colored beverage containers, ceramics, and flatglass. The nepheline syenite contains high iron compared to other commercial sources of nepheline syenite, but, when the Wind Mountain nepheline syenite is crushed and passed through a specialized rare-earth magnet, the resulting nonmagnetic product is similar in composition to Grade-B product specified by Unimin Canada Ltd. Specifications and description of the industrial applications of the Wind Mountain nepheline syenite are provided by McLemore *et al.* (1996) and McLemore & Guilinger (1996). Emission spectroscopy indicates that the magnetic fraction contains 20 to 30% Fe_2O_3, but is low in rare-earth elements (100 ppm La), beryllium (5 ppm), yttrium (100 ppm) and zirconium (2000 ppm). The magnetic fraction can be sold as millite, an iron-rich additive required for controlling the color of glass. Several other consumers have tested the nepheline syenite and found it suitable for use in ceramics, fiberglass, and flatglass. The lack of free silica as quartz also enables use of the Wind Mountain nepheline syenite as a silica-free abrasive. Interesting textural variations in the main mass of the syenite, and the presence of wisps of finer-grained material in the rock, also make it an attractive building stone.

Summary

The Wind Mountain laccolith is mineralogically and texturally zoned. All six zones in the pluton vary in texture, but are chemically similar. Nepheline syenite porphyry forms the outermost zones of the Wind Mountain laccolith and may constitute much of the mountain (Fig. 4), although drilling has not yet reached the center of the laccolith. Thin zones of syenite porphyry cap the laccolith. The zonation in the Wind Mountain laccolith appears to have been controlled by crystal fractionation, separation of volatiles, and cooling history, rather than different pulses of magma. Feldspar fractionation can account for most of the chemical variation in the different zones. The syenites crystallized under subsolvus conditions as indicated by feldspar mineralogy and the presence of metasomatic alteration phases (muscovite and zeolites). A late-stage hydrothermal event is indicated in all rock types by the alteration of nepheline to analcime and clay.

Additional mineral resource potential in the Cornudas Mountains is limited. The nepheline syenite of Deer and San Antonio Mountains (Fig. 2) may have potential use for glass or ceramic use. The other laccoliths, dikes, plugs, and sills are not suitable for glass or ceramic use because of high iron contents and heterogeneous composition. The lack of large-scale hydrothermal alteration associated with the emplacement of the laccoliths in the region suggests that the potential economic mineralization may be limited. However, the abundant rare minerals at Wind Mountain suggest that the area has potential for deposits of rare-earth elements, niobium, and zirconium.

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