Geochemistry of micas from Precambrian rocks of northern New Mexico

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Abstract

Average concentrations of 10 minor elements (Nb, Rb, Ni, Fe, Mn, Ba, Ga, Ti, Zn and Ca) were determined for 53 mica samples from eight mining districts, areas, and isolated mines in northern New Mexico (the Petaca district, Ojo Caliente district, Elk Mountain district, Aspen Basin area of the Cordova district, Harding mine, Mom area, Priest mine and MICA mine). Minor-element composition of muscovites from the entire Petaca mining district is uniform, suggesting that all pegmatites in that district formed metasomatically during regional metamorphism. In five of the remaining seven areas muscovite composition is similar, hinting of similar emplacement. The exception is the Harding pegmatite which, because of its enrichment in Li, Be, Nb, Ta and F, depletion of Fe, and textural and compositional zoning, appears to have formed differently than the other pegmatites of northern New Mexico. Minor-element geochemistry of the micas supports a syntectonic emplacement for the Harding pegmatite. Differing minor-element concentrations, in particular Rb, Mn, Nb and Zn, among the eight areas suggest that the sources were not interconnected.

Regionally, California muscovites exhibit more uniform minor-element composition than do New Mexico muscovites, but a regional shift in TiO_2 and BaO concentrations in California could not be identified in New Mexico muscovites. However, when compared with the isolated and compositionally complex California Isinglass pegmatite, New Mexico pegmatitic muscovites show little minor-element variation within each deposit. In general, the MnO and ZnO concentrations of New Mexico muscovites are much higher, with weight percent of MnO up to 0.45 and ZnO up to 0.12, in contrast with California values of 0.06 and 0.02. Substitution of smaller ions in New Mexico 2M, muscovites has resulted in a smaller average unit cell with basal spacings of about 19.920 A, as compared with the standard 20.058 A. Little biotite is present in pegmatites of northern New Mexico, but analyses of the two biotites included in this geochemical study show a lower equivalent FeO content than in California biotites.

Minor-element geochemistry of micas may to be useful in the study of the origin and sources of pegmatites. Variations in elemental composition may indicate the same or different sources and/or times of emplacement and may help in the identification of extensions to known pegmatites and in the discovery of new pegmatites.

Introduction

The purposes of this geochemical investigation of mica deposits in northern New Mexico are: (1) to determine the minor-element chemistry and degree of chemical uniformity of muscovites in each mining district; (2) to compare mica compositions among these mining districts; (3) to compare the chemical compositions of New Mexico micas with those of better known California micas; and (4) to judge the usefulness of mica chemistry in determining sources of minor elements and rock genesis.

Previous work

Published studies of mica and pegmatite deposits in New Mexico date back more than 100 years. Broad aspects of the mica resources of New Mexico were first described by Clarke (1885), who reported that mica was being mined from the Cribbenville mica mines in the Petaca district and near Las Vegas (Fig. 1). A more detailed description of mica mining in New Mexico was made by Sterrett (1913). He described mica mines in the southernmost Sangre de Cristo Mountains ("Glorieta Mountains") of San Miguel County and in the Petaca area of Rio Arriba County, and mica prospects near Ojo Caliente in Rio Arriba County. Later Sterrett (1923) compiled a more complete list of mica mines, which included the mines in Rio Arriba County, in the "Glorieta Mountains," and in Mora County near the town of Mora.

A reconnaissance study of the Picuris and Petaca mining districts by Just (1937) was followed by Jahns' (1946) in-depth study of the more than 74 mines in the Petaca mining district, which included detailed descriptions of the mica deposits in the Ojo Caliente and Elk Mountain districts. Northrop (1959) listed additional small muscovite deposits. Lesure (1965) summarized mica mining in New Mexico, including a large pegmatite dike swarm in the Cordova district in Santa Fe County south of Chimayo. Beckman (1982) discussed New Mexican mica deposits as part of a summary of mica resources in the western United States. At present, mica schist is mined by Franklin Industrial Minerals at the MICA mine (formerly the M.I.C.A. mine, and before that the Tojo mine) near Vadito in southern Taos County (Ferro and Stewart, 1988; Austin et al., 1990).

Proterozoic rocks host the eight mica districts and important mines discussed in this paper. The general geology of Proterozoic rocks of northern New Mexico is summarized by Bauer and Williams (1989), Williams (1990), and Robertson et al. (in press). Geochronologic summary data are available in Brookins (1974, 1982), Wobus (1984), Bauer and Williams (1989), Williams (1990), Grambling and Dallmeyer (1990), Ward (1990), and Robertson et al. (in press).

Interelemental correlations of trace elements in muscovites may identify different modes of origin, and some trace elements in muscovites help in determining temporal relationships among rocks. A relationship between the minor-element composition of micas and tin mineralization was shown by Bradshaw (1967) for selected granites from Great Britain. Olade (1979) used biotite from British Columbia in a similar study. Gres-

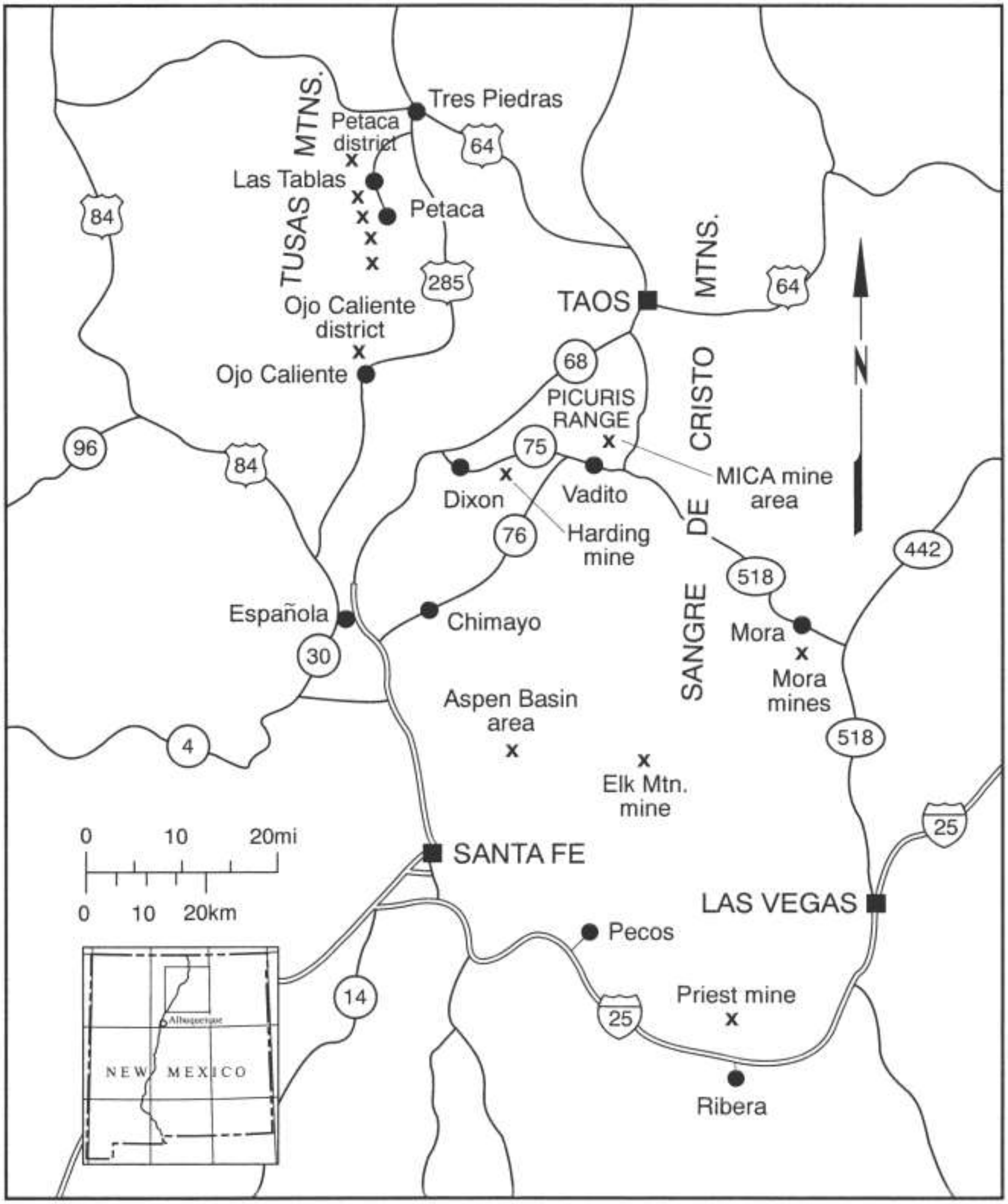

FIGURE 1—Index map of towns and mica deposits (x) in northern New Mexico.

ens (1967) and Gresens and Stensrud (1974) discussed the origin of muscovite in both pegmatites and mica schists in northern New Mexico based on detailed studies of their geochemistries. An additional study of red muscovite followed (Gresens and Stensrud, 1977). Elemental compositions for samples from two muscovite locations in the northern Petaca area (Kiawa Group) reported by Gresens (1967) and Stensrud (1970) are compared in Table 1. An investigation of California mica deposits by Post (1988) discussed variations in minor-element chemistry of muscovite. Post's study showed the usefulness of minor elements, particularly Rb, Ni, Zn, and Ti, for evaluating geochronology and indicating nearby economic concentrations of rare-earth elements and zinc. Post (1988) also demonstrated that adjacent but poorly exposed gneiss and granodiorite in the Santa Catalina and Rincon Mountains of Arizona could be differentiated on minor-element composition of muscovites.

TABLE 1—Calculated oxide contents for chemical compositions of muscovites from the Kiawa area. Data by Gresens (1967) using emission spectrographic analysis, and Stensrud (1970) using absorption spectrophotometry.

Gresens (1967) Median - 6 specimens			Stensrud (1970) Median - 4 specimens		
SiO_2	48	(wt. %)			(wt.%)
TiO_2	0.64		TiO_2	0.67	
Al_2O_3	27		A1203	32.9	
Fe_2O_3	6.30		Fe_2O_3	5.03	
MnO	0.24		MnO	0.34	
MgO	0.90		MgO	0.28	
CaO	0.040		Na_20	0.46	
$Zr0_2$	tr	(ppm)			(m)
Cr_2O_3	20		Cr_2O_3	45	
Sc_2O_3	15		$L1_20$	395	
V_20_3	96		Rb_2O	695	
Y_20_3	30		ZnO	853	
BeO	89		CuO	25	
SrO	20				
BaO	290				
CuO	7				
NiO	tr				

Gresens (1967) and Gresens and Stensrud (1974) suggested a metasomatic origin for the muscovite in Kiawa Group pegmatites of the Petaca district and for the mica-schist muscovite in the Las Tablas area and in the Picuris Range farther to the southeast (Fig. 1). During metasomatism, Mg, Li and Ti(?) are added to the rock, whereas Na, Ca and Cu(?) are removed and Si, Al, Fe, Mn and Zn concentrations remain unchanged. However, this also is a time of muscovite growth, and muscovite takes up available Zn, Li, Mn, Mg and Ti; K and Rb, normally mobile elements whose values otherwise would decrease during metasomatism, also are taken up by muscovite. Gresens and Stensrud (1974) indicated that much of their data supports a closed-system "dilution model" for progressive metasomatic growth of muscovite, in which the whole-rock concentrations of Zn, Li, Mn, Mg, Ti, K and Rb remain unchanged during metasomatism. Consequently, as the amount of muscovite grew larger, the weight fraction of each of these elements in muscovite grew smaller. They also asserted that the progenitor for quartz-muscovite schist in the Petaca and Picuris districts is metarhyolite rather than a metasediment. This conclusion was based on the similarity of minor-element compositions of muscovites and textural evidence across the pegmatites, schist and adjacent rock.

The details of the geochemical studies by Gresens (1967) and Gresens and Stensrud (1974), who investigated 220 mica samples and 65 whole-rock samples, are beyond the scope of this report. However, as a follow-up to their studies, it is logical to ask whether all the pegmatitic micas in the Petaca district and elsewhere in northern New Mexico were formed metasomatically and how are they related in time and by source to each other.

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Overview of New **Mexico mining districts**

Petaca district

The Petaca district (Rio Arriba County), approximately 40 km (25 mi) west of Taos, has five groups of mines that form a belt approximately 1.6-7.0 km (1-4.3 mi) wide and 24 km (15 mi) long (Fig. 2). The five groups are the Kiawa, Persimmon Peak-Las Tablas, La Jarita-Apache, Cribbenville and Alamos. Elevations in the district are between 2500 and 2800 m (8200-9190 ft). Pegmatite bodies, with Rb-Sr ages for muscovite of 1425 ± 15 Ma (Long, 1972), and quartz veins are found throughout the Precambrian exposures, although most are present in quartz-mica schist. More than 74 mica mines and prospects exist in the five mine areas, and structural and petrogenetic relationships between the pegmatites and the country rocks are complex (Jahns, 1974).

The most abundant minerals in the pegmatites are microcline, albite and quartz. Nearly 50 minerals have been recognized in the Petaca district, most in minor amounts. Minerals that have been mined include mica, beryl, monazite, samarskite and columbite-tantalite (Jahns, 1946, 1974). The pegmatites contain abundant muscovite and minor biotite.

The Cribbenville mica deposits in the Petaca district were first worked during the 17th century to provide window panes in Santa Fe and Espanola. In the 1870s commercial-scale mining began supplying mica for stove doors. Mining for scrap mica began about 1900. By 1912 there was a demand for electrical sheet mica, and

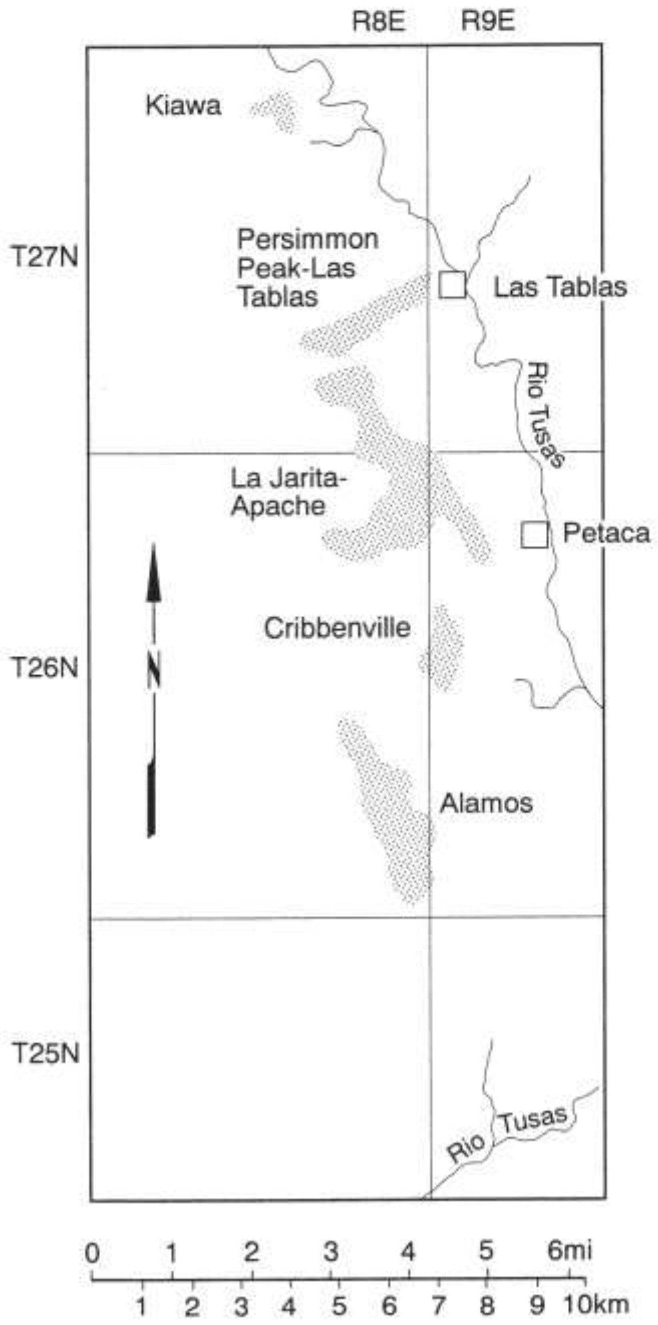

FIGURE 2—Location map of the five groups of mica mines in the Petaca district, including more than 74 mines and prospects.

a dozen mines eventually became important producers. During World War II strategic-grade material was produced from at least 20 deposits, but by 1945 the Petaca district was almost deserted and only the Globe mine was operating. Jahns (1946) estimated that more than 380 mt (419 st) of plate mica and 16,000 mt (17,630 st) of scrap mica were produced. Between 1956 and 1962 some mica was mined for the U.S. Government critical materials stockpile.

Ojo Caliente district

The Ojo Caliente district (Rio Arriba County) is 3 km (2 mi) north of Ojo Caliente at an elevation of approximately 2000 m (6560 ft). The pegmatites are in amphibolites of the early Proterozoic Moppin Complex. The Moppin Complex has not been dated directly, but Barker (1958) and Wobus and Hedge (1982) concluded that the Moppin is intruded by the Maquinita Granodiorite, which has been dated at 1755 Ma by the U—Pb zircon dating method (reported by Bauer and Williams, 1989). However, the contact may not be intrusive (Williams, 1990), in which case the Moppin Complex could be considerably younger.

Muscovite is present in books up to 8 cm in diameter, with some larger scattered books. Most of the books are severely ruled, broken and crushed, and are of scrap grade only. Some beryl is present. Jahns (1946) reported that between 1905 and 1932 the Joseph deposit produced several thousand short tons of scrap mica, and the nearby Star deposit, with other small deposits, produced some additional scrap.

Elk Mountain district

The Elk Mountain mine (San Miguel County), 1.6 km (1 mi) northeast of Elk Mountain, is in the southern Sangre de Cristo Mountains 33 km (20 mi) northwest of Las Vegas, at an elevation of approximately 3200 m (10,500 ft). The pegmatite bodies are in Precambrian schist of the Pecos Complex dated at 1720 Ma (Bowring and Condie, 1982; Bauer and Williams, 1989; Robertson and Condie, 1989).

Between 1942 and 1958 production estimates were 410 mt (450 mt) of sheet mica and 19 mt (21 st) of scrap mica (Redmon, 1961). Both the Elk Mountain mine and a pegmatite deposit 4 km (2.5 mi) southwest of Elk Mountain, the Guy No. 1 deposit, produced small amounts of columbite. Mica shoots, typically along the boundary between the core and outer zone at the Elk Mountain mine, are 1-5 m (3-17 ft) thick and have approximately 55% muscovite (Jahns, 1946; Moench and Lane, 1988). Many books of muscovite are 25 cm (10 in.) or more in diameter, but most are severely ruled, broken or marked by "A" structure, with prepared mica sheets not exceeding 5 x 5 cm (2 x 2 in.).

Harding mine

The Harding mine (Taos County), 10 km (6 mi) east of Dixon in the Picuris mining district at an elevation of 2300 m (7550 ft), was first described by Roos (1926). Two excellent summaries of the development of the Harding mine were prepared by Jahns and Ewing (1976) and Brookins et al. (1979). The Harding pegmatite is a series of complex, well-zoned pegmatite bodies that crop out in a broad, west-trending belt 800 m (2620 ft) long (Northrup and Mawer, 1990). The age of the pegmatite is poorly constrained. Brookins et al. (1979) reported the average Rb—Sr isotope age of 1366 Ma. However, they also pointed out that late redistribution of Rb and Sr in pegmatites could have reset the isotopic systems. S. A. Bowring (pers. comm. to P. W. Bauer in 1990) reported a preliminary U—Pb isotopic age of about 1100 Ma on a single large zircon from the pegmatite. Northrup and Mawer (1990) suggested that the Harding pegmatite emplacement was syntectonic with respect to late-stage regional deformation.

The Harding mine was discovered in 1910 and produced mainly lepidolite from about 1919 to 1930, microlite from 1942 to 1947, and beryl from 1950 to 1958. Production of lepidolite, which was used mainly in glass, was valued at nearly $59,000 during 1928 (Jahns, 1946). According to Roos (1926), the price for ground lepidolite varied between $30 and $45 per short ton. As the world's largest concentration of microlite, 10,000 kg (22,000 lbs) of microlite concentrate containing 68% Ta_2O_5 and 7% Nb_2O_5 were produced in the 1940s. During the last period of mining, when beryl was the principal ore mineral, 622 mt (690 st) of ore containing 11.2% BeO and 167 kg (185 st) containing 5.5% BeO were produced.

MICA mine area

Mica schist, from the Rio Pueblo Schist (Miller et al., 1963), is mined by by Franklin Industrial Minerals about 15 km (9 mi) east of the Harding Mine and approximately 5 km (3 mi) northeast of Vadito, Taos County. A similar feldspathic muscovite schist near the Comales Campground, 5 km (3 mi) southeast of the mine, yielded a preliminary U–Pb zircon age of about 1680 Ma (Austin et al., 1990). During 1987 (when the mine was operated by Mineral Industrial Commodities of America, Inc., or M.I.C.A.) approximately 18,000 mt (20,000 st) of dry ground mica were produced, principally **for making wallboard joint cement (Austin et al.,** 1990). A flotation plant is used to improve the recovery of mica from the deposit.

Mora mines

Large, mainly concordant, coarse-crystalline quartz and quartz–feldspar pegmatites intrude Proterozoic country rocks in the Mora district 2.5 km (1.5 mi) southeast of Mora, Mora County (O'Neill, 1990). Mica mines in these pegmatites were active mainly during 1911-1912 and supplied muscovite of good quality for electrical applications. Manufactured products included cut washers, disks, punched parts, stove mica, grade mica and scrap for grinding. Mining and Engineering World (1912) described the Mora mica mines in a 1912 volume, but the amount of production is unknown.

Priest mine

The Priest mine (San Miguel County) is 13 km (8 mi) north of Ribera at an elevation of 2290 m (7500 ft) in the southeastern Sangre de Cristo Mountains (identified as the "Glorieta Mountains" by some authors). Ward (1990) showed that the pegmatites are related to granites that yield U–Pb and Rb–Sr isotopic ages of about 1450 Ma. Some books of muscovite from the Priest mine were used by early settlers for making windows, but much of the mica was ruled and deformed. The mine was worked as early as 1909, but production data are not available (Sterrett, 1913); there was moderate production of scrap mica before World War II (Jahns, 1946).

Aspen Basin area

The Aspen Basin area (Santa Fe County) in the Cordova district 14 km (9 mi) northeast of Santa Fe yielded only one specimen for analysis from a mica mine in a pegmatite (NW1/4 SE1/4 sec. **1, T18N, R10E).** Metcalf (1985) and Moench and Lane (1988) showed that the nearby country rocks are stratified pelitic schist, gneiss and migmatite of early Proterozoic age. The geochronology of the plutonic rocks is not well constrained, but some volcanism occurred about 1670-1600 Ma (Grambling et al., 1988; Williams, 1990). Lesure (1965) described the Aspen Basin pegmatite as an extension of a large pegmatite dike swarm to the north. Some scrap mica was produced in the Cordova district, but mine production is unknown.

Analytical method

Muscovite samples from pegmatites in the eight mining districts or large areas were collected for chemical analyses. The maps, mine names, and numbers given by Jahns (1946) were used to locate the sites in the Petaca district, because most of the mines are not shown on U.S. Geological Survey topographic maps.

Specimens of clean mica from the collected books were cut into ribbons and ground with a mullite mortar and pestle to pass a no. 140 sieve. The standard preparation for XRD powder samples was used by **front-loading ground mica into the sample holder and** smoothing the surface with the edge of a glass slide. XRD patterns were made to check the mica species and polytypes.

Geochemical analysis of micas is complex, due to elemental and mineralogical interference as well as matrix variability. For the XRF analyses, the specimens, previously analyzed by XRD, were packed into spexcaps 29.64 mm in inside diameter and 4.80 mm deep. Specimens were analyzed for Ca, K, Si, Al and Mg using a He path Picker model 816 spectrometer with a Cr x-ray tube operating at 36 kV and 20 mA. The secondary beam was collimated by means of an incident beam of 2° divergence, and 0.39° divergence for the analyzed beam, with an ADP, EDDT or LiF analyzing crystal. The secondary fluorescence signal was detected by an argon gas-flow counter whose output was processed by linear amplifier and ratemeter. Pulse height discrimination removed unwanted signals. Ti and all heavier elements were analyzed using a W or Mo x-ray tube at 36 kV and 20 mA in conjunction with a scintillation counter, along with the LiF analyzing crystal in an air path. Specimen scan rates were 1°2θ/minute. Analog data were output to a stripchart recorder, and background was subtracted by linear extrapolation through determinations on either side of each analytical peak. Peak areas were measured by polar planimetry.

All analyses were done by close-bracketing methods, except for Ca and Mg which required calibration curves—the Ca because of excess K interference and

TABLE 2—XRF analyses for minor- and trace-element oxide contents of micas (muscovite unless specified otherwise) from northern New Mexico. Iron concentrations for muscovite and zinnwaldite reported as Fe_2O_3 and for biotite as FeO.

	Nb_2O_5	Rb_2O	NiO	Fe_2O_3 wt. %	MnO	BaO	Ga_2O_3	TiO_2	ZnO	CaO
Petaca district										
KIAWA AREA										
Kiawa mine, #2	0.022	0.11	0.005	5.52	0.45	0.03	0.028	0.63	0.199	0.08
	0.019	0.09	0.004	5.33	0.36	0.07	0.017	0.80	0.114	0.07
	0.026	0.10	0.004	5.16	0.46	0.01	0.023	0.53	0.191	0.05
PERSIMMON PEAK–LAS TABLAS AREA										
Silver Spur mine, #6	0.038	0.13	0.007	6.25	0.30	0.04	0.022	0.32	0.146	0.04
	0.047	0.12	0.005	6.77	0.28	0.04	0.023	0.41	0.142	0.11
LA JARITA–APACHE AREA										
Lonesome mine, #16	0.038	0.25	0.009	4.26	0.82	0.01	0.024	0.21	0.175	0.08
	0.033	0.16	0.008	6.65	0.41	0.02	0.024	0.31	0.134	0.10
El Contento mine, #14	0.054	0.17	0.008	5.94	0.43	0.02	0.024	0.27	0.201	0.07
Conquistador mine, #23	0.034	0.18	0.007	5.60	0.22	0.03	0.017	0.27	0.147	0.06
Coyote mine, #29	0.030	0.28	0.006	3.73	0.62	0.03	0.022	0.24	0.188	0.09
Sandoval mine, #30	0.036	0.22	0.007	4.80	0.62	0.02	0.027	0.17	0.157	0.05
	0.039	0.18	0.010	4.70	0.48	0.02	0.026	0.23	0.140	0.08
Apache mine, #31	0.037	0.16	0.009	6.20	0.41	0.03	0.019	0.37	0.188	0.07
Queen mine, #34	0.042	0.12	0.005	6.90	0.30	0.05	0.017	0.59	0.090	0.06
Coats mine, #35	0.038	0.11	0.005	5.08	0.64	0.03	0.029	0.26	0.129	0.11
CRIBBENVILLE AREA										
Fridlund mine, #38	0.034	0.14	0.006	6.13	0.30	0.03	0.016	0.35	0.106	0.06
Cribbenville mine, #48	0.035	0.12	0.003	6.74	0.30	0.04	0.022	0.39	0.091	0.07
Capitan mine, #45	0.036	0.11	0.003	6.51	0.29	0.06	0.017	0.34	0.091	0.08
	0.038	0.12	0.003	7.08	0.28	0.03	0.016	0.45	0.087	0.07
	0.022	0.11	0.004	6.38	0.32	0.02	0.021	0.32	0.089	0.06
	0.030	0.09	0.004	6.52	0.25	0.05	0.019	0.40	0.084	0.07
ALAMOS AREA										
Globe mine, #60	0.029	0.23	0.004	4.18	0.48	0.01	0.024	0.21	0.180	0.06
	0.040	0.24	0.004	5.55	0.36	0.04	0.032	0.29	0.158	0.05
	0.013	0.32	0.007	1.79	0.56	0.02	0.036	0.13	0.132	0.08
Carmelita mine, #62	0.028	0.26	0.006	4.13	0.48	0.04	0.029	0.18	0.168	0.08
Guadalupe mine, #63	0.035	0.23	0.005	5.15	0.29	0.02	0.038	0.25	0.135	0.07
Ojo Caliente district										
San Texas mine	0.041	0.16	0.007	5.05	0.33	0.04	0.016	0.30	0.064	0.15
	0.032	0.15	0.007	4.05	0.34	0.02	0.020	0.40	0.047	0.07
	0.035	0.15	0.009	4.34	0.33	0.02	0.008	0.49	0.045	0.09
Joseph mine	0.025	0.15	0.007	3.94	0.42	0.04	0.017	0.46	0.041	0.40
Elk Mountain district										
Elk Mountain mine	0.031	0.41	0.013	4.34	0.55	0.02	0.030	0.12	0.133	0.08
	0.025	0.51	0.016	3.66	0.55	0.02	0.032	0.13	0.183	0.03
	0.021	0.56	0.018	3.30	1.05	0.03	0.028	0.10	0.210	0.04
	0.046	0.37	0.014	4.78	0.45	0.03	0.030	0.20	0.205	0.14
	Zinnwaldite									
	tr	0.64	0.019	8.31	0.44	0.04	0.005	1.22	0.041	0.64
	Biotite			(FeO)						
	0.000	0.40	0.006	13.77	0.35	0.17	0.004	0.93	0.062	0.22
Cordova mining district				(Fe_2O_3)						
ASPEN BASIN AREA	0.073	0.28	0.009	4.81	0.20	0.03	0.017	0.19	0.068	0.06

TABLE 2 continued

	Nb_2O_5	Rb_2O	NiO	Fe_2O_3 wt. %	MnO	BaO	Ga_2O_3	TiO_2	ZnO	CaO
Other areas and mines										
Harding mine	0.012	1.62	0.012	1.02	1.02	0.02	0.027	0.07	0.116	0.11
	0.005	1.13	0.006	0.11	0.08	0.02	0.036	tr	0.017	0.07
	0.012	0.95	0.006	1.86	0.54	0.03	0.022	0.11	0.101	0.19
	0.013	1.62	0.010	0.41	0.74	0.04	0.031	0.03	0.060	0.09
	0.015	0.69	0.003	2.13	0.07	0.05	0.029	0.13	0.056	0.18
	0.015	0.79	0.009	2.65	0.81	0.03	0.010	0.26	0.075	0.10
	Biotite			(FeO)						
	tr	1.06	0.018	11.07	0.42	0.00	0.046	1.02	0.080	0.17
	Zinnwaldite			(Fe_2O_3)						
	0.019	0.86	0.012	6.72 (6.05% FeO)	0.40	0.03	0.019	0.80	0.049	0.20
Mora area	0.026	0.11	0.006	3.72	0.05	0.03	0.015	0.22	0.018	0.10
	0.071	0.21	0.008	4.35	0.16	0.02	0.013	0.21	0.070	0.05
	0.088	0.15	0.005	4.74	0.15	0.03	0.012	0.21	0.081	0.06
	0.093	0.14	0.005	4.25	0.08	0.02	0.011	0.30	0.058	0.04
Priest mine	0.070	0.15	0.006	4.66	0.06	0.03	0.011	0.51	0.036	0.04
	0.080	0.15	0.009	4.92	0.07	0.06	0.015	0.54	0.036	0.06
MICA MINE AREA										
(Mica schist) (0.08% ZrO_2, 0.03% Y_2O_3)	0.009	0.03	0.009	5.80	0.09	0.18	0.012	0.67	0.042	0.68
(Pegmatite)	0.034	0.07	0.002	4.68	0.10	0.04	0.015	0.46	0.075	0.07

Mg when present in Fe-rich micas. Two analyzed muscovite specimens and one analyzed phlogopite specimen (Lin and Clemency, 1981a, b) were made available by C. V. Clemency, State University of New York, Buffalo; one specimen of analyzed phlogopite and one of analyzed biotite (Abbey, 1983), from the French CRPG micas, were secured from the Geology Department, University of Arizona; and two analyzed specimens of biotite (Dodge et al., 1982) were obtained from F. C. W. Dodge, U.S. Geological Survey, Menlo Park.

All mica books are zoned during formation so that only an average analysis is possible without using an electron microprobe. The likely variance in results may be primarily from consecutive analyses of the same specimen or from using two different standard materials for comparison. Voltage changes and gas-flow changes also affect the results.

Based on the results of several years of analyses by the senior author, the following variances are assumed for muscovite data:

Element	Variance (wt. %)
Ni, Ga	±0.001
Zn, Ca, Nb, Mn	±0.01
Rb, Ti, Ba	± 0.02
Fe, K	± 0.05
Si, Al, Mg	±0.1

Calibration curves must be made during each analysis to be fully effective. Hence, when possible, close bracketing is a more efficient analytical procedure.

Seven elements (Rb, Fe, Mn, Ba, Ti, Zn and Ca) were among those identified earlier in New Mexico muscovites (Gresens, 1967; Gresens and Stensrud, 1974, 1977). Two elements (Nb and Ni) were among the 10 used in a study of California muscovite (Post, 1988). Ga concentrations in the present study were determined using the second order GaKa reflections, although this peak occurs in conjunction with the CsLB reflection. However, the GaKa peak is much stronger. Although no Cs*K*a peaks were observed for any specimen, one California sample (Specimen 1, Table 5) was analyzed by neutron activation to check the analytical procedure for the concentrations of both Ga and Cs; the results were 0.040% Ga_2O_3 and 0.002% Cs_2O.

For the Rio Pueblo Schist mined at the MICA mine, a mica concentrate was prepared from a whole-rock sample of pulverized mica schist by suspension in water. The whole-rock specimen contained approximately 35% quartz; the suspension still contained nearly 20% quartz.

Analytical results

Forty-nine muscovite, two biotite, and two zinnwaldite specimens from eight mining districts or areas were analyzed by XRF for 10 minor and trace elements (Table 2). The entire Fe content of muscovite is expressed as equivalent Fe_2O_3, and of biotite as FeO. For the mica schist from the MICA mine, in which the

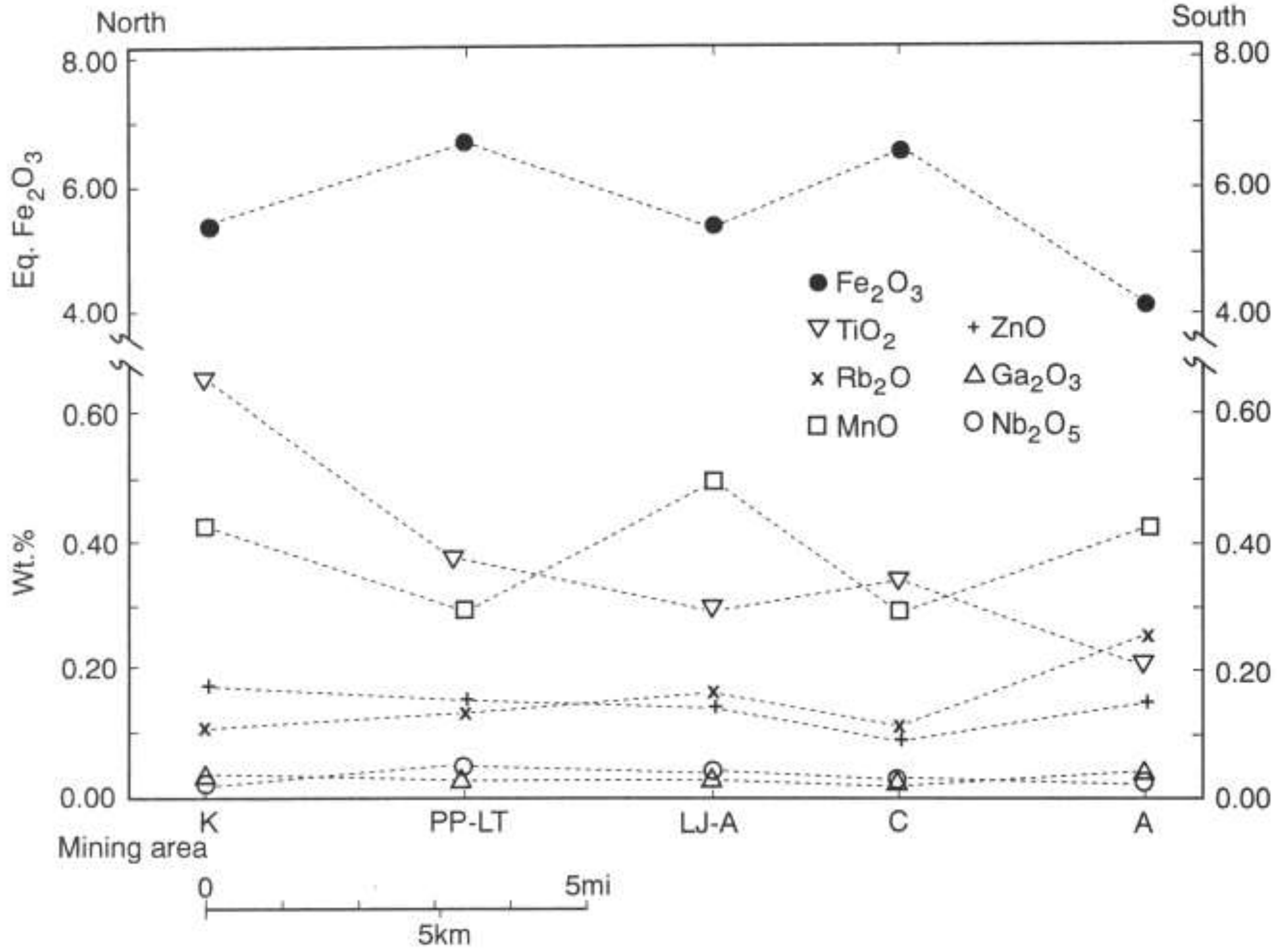

FIGURE 3—Plot of the six average minor-element and iron (as Fe_2O_3) concentrations in muscovite specimens from the five groups of mica mines (north to south) in the Petaca district (K = Kiawa, PP–LT = Persimmon Peak–Las Tablas, LJ–A = La Jarita–Apache, C = Cribbenville, A = Alamos). Vertical scale is condensed relative to Figs. 5 and 6.

analyzed material retained quartz, the analytical results were adjusted to a quartz-free basis. Muscovite from a small pegmatite adjacent to the MICA mine was also analyzed, and the results are included (Table 2). A graphic presentation shows the average minor-element content of muscovites from the five different mine areas in the Petaca district (Fig. 3).

Thirty-six muscovite samples (all $2M_1$ polytype), primarily from the Petaca area but also from the Mora and Cordova districts and the Harding, Elk Mountain, and Priest mines, were analyzed by x-ray diffraction (XRD) for cell dimensions. In micas the c-dimension is the most sensitive to ionic substitution. The average c-dimension for the New Mexico muscovites was 19.920 A as measured from the 002 reflection, but c-dimensions ranged from 19.884 to 20.004 A, smaller than the 20.058 A commonly accepted for $2M_1$ muscovites (Bailey, 1984).

Chemical analyses (by XRF) of a typical muscovite from the Capitan mine in the Cribbenville area of the Petaca district and biotite from the Elk Mountain mine are presented (Table 3); we have included the unit-cell cation contents for each. The data for the two biotites (Tables 2 and 3) explore the minor-element composition of other New Mexico micas and permit comparison with published data on California biotites. Post (1988) reports an average of 16.16 wt.% FeO for 10 samples of biotites from 10 California locations, with a range of 19.59-12.40 wt.%. The two New Mexico biotites from pegmatites reported here have lower equivalent FeO contents (13.77 and 11.07 wt.%) than all but one of the California biotites.

For purposes of comparison, a summary of the minor-element compositions for 74 California muscovites (Post, 1988), corrected for NiO and Ga_2O_3 contents and with the CO content deleted, is presented in this report (Table 4). The original published data have been recast to use the eight physiographic provinces with pegmatitic muscovite for denoting source area, according to the procedure given by Lesure (1966). Post's (1988) data summary for these 74 muscovites lists 38 sites with the number of analyses for each site ranging from one to 15 specimens.

Minor-element compositions of the Petaca and other New Mexico muscovites can be compared to those of 15 samples from a typically zoned pegmatite body, the Isinglass mine, Siskiyou County, California (Table 5, Fig. 4). Graphic presentations of the Rb_2O, MnO, ZnO, Nb_2O_5, and Gap, contents in muscovites (Figs. 5, 6) cross the site approximately along north—south and west—east transects. Four additional analyses (nos. 12-15) by the senior author augment the original 11 analyses published by Post (1988).

TABLE 3—XRF analyses of a typical but separate muscovite from the Capitan mine the Cribbenville area, Petaca district (by the New Mexico Bureau of Mines & Mineral Resources X-ray Laboratory), and of a biotite from the Elk Mountain mine (by the senior author). Unit-cell cation contents by structural sheets are listed below.

		Capitan muscovite			Elk Mountain biotite	
	SiO_2	46.05 (wt. %)			37.13 (wt. %)	
	Ga_2O_3	0.021			0.004	
	TiO_2	0.29			0.93	
	Al_2O_3	31.31			17.46	
	Fe_2O_3	6.46		(FeO)	13.77	
	MgO	0.13			15.46	
	MnO	0.26			0.35	
	ZnO	0.089			0.062	
	NiO	0.004			0.006	
	Nb_2O_5	0.022			0.000	
	K_2O	10.08			9.66	
	Na_2O	0.34			----	
	CaO	0.05			0.22	
	Rb_2O	0.12			0.40	
	BaO	0.02			0.17	
	H_2O+	4.43			4.14	
	TOTAL	99.58			99.76	
Tetrahedral	Si	3.115		Si	2.756	Site occupancies calculated on the basis of 12 oxygen atoms
	Al	0.885		Al	1.244	
Octahedral	Al	1.609	1.958	Al	0.283	2.926
	Fe	0.324		Fe	0.855	
	Mg	0.013		Mg	1.710	
	Ti	0.004		Ti	0.052	
	Mn	0.004		Mn	0.022	
	Zn	0.004				
Interlayer	K	0.869	0.927	K	0.915	0.966
	Na	0.045		Na	----	
	Ca	0.008		Ca	0.032	
	Rb	0.005		Rb	0.019	

Discussion

Minor-element distributions of the Petaca district muscovites taken from any available zone of individual pegmatites show uniform composition (Fig. 3). According to Jahns (1946), the mica products from different Petaca mines sometimes were mixed because of the dark color (amber) of some books, but the actual equivalent Fe_2O_3 contents of muscovites do not vary much among the mines. The lack of variation in muscovite composition in the Petaca pegmatite bodies suggests that individual bodies are not isolated from each other and that pegmatitic mineralization may be more extensive in the subsurface. Similarly, the uniformity of minor-element composition across the Petaca mining district and the paucity of internal and marginal deformation suggest that, as with the Kiawa pegmatite area (Gresens, 1967), all the Petaca pegmatites apparently formed metasomatically during regional metamorphism (Gresens and Stensrud, 1974).

In contrast, the isolated California Isinglass pegmatite structure contains a concentration plume with the highest concentration of minor elements in muscovite midway along the north—south traverse near the pegmatite's eastern margin (Fig. 5). The minor-element content also decreases west from the plume along the west—east traverse (Fig. 6). Near the western edge of the pegmatite, specimen 8 is deficient in all five minor elements, with no enrichment from the adjacent serpentine mass. The pegmatite also is depleted in Ti, with TiO_2 contents as low as 0.01% along the western border and below detection limits in the northeast (Table 5). The pattern of minor-element concentrations suggests emplacement from a source near the plume along the eastern border.

The variations in average minor-element compositions of muscovites among the eight New Mexico mining districts (Table 6) suggest that the source material was different in each mining area. Particularly with Zn, Rb, Nb and Mn, the amounts of elements taken up by muscovite during metasomatism vary considerably among the districts, but within each district are similar (Table 2). Fe and Ti contents vary widely even in muscovites from the same mining area and thus are not as useful for comparison. There is little evidence of country rock mixing with the pegmatites by uptake or removal of mobile elements such as Ca and Ti (Table 2).

The Harding mine pegmatites are textually and compositionally zoned. Harding minerals are noted for the enrichment of Li, Be, Nb, Ta and F, and depletion of Fe (Jahns and Ewing, 1976). Muscovite trace-element compositions are markedly different from any other mica mining area in northern New Mexico (Table 6). Compared with other New Mexico pegmatites, the Harding muscovite is enriched in Rb and Mn and depleted in Nb, Fe and Ti (Tables 2, 6). Both biotite and muscovite from the Harding mine contain significant amounts of Li, as shown by unusually small cell dimensions determined by XRD methods (Table 7); however, Li-bearing zinnwaldite was collected from both the Harding and Elk Mountain mines (Table 2).

We agree with Jahns (1946), who suggesed that the Harding pegmatite bodies had been emplaced in a manner different from other northern New Mexico pegmatites, which appear to be of metasomatic origin. Jahns and Ewing (1976, p. 274) believed that "the Harding pegmatite bodies are best explained as products of highly differentiated rest-liquid derived from granitic magma and injected into already deformed and regionally metamorphosed host rocks." However, Northrup and Mawer (1990) considered it unlikely that forceful intrusion of a liquid into a strongly foliated host would result in large, flattened tabular bodies that cut across the prominent foliation at a high angle such as at the Harding mine. They concluded that the pegmatitic

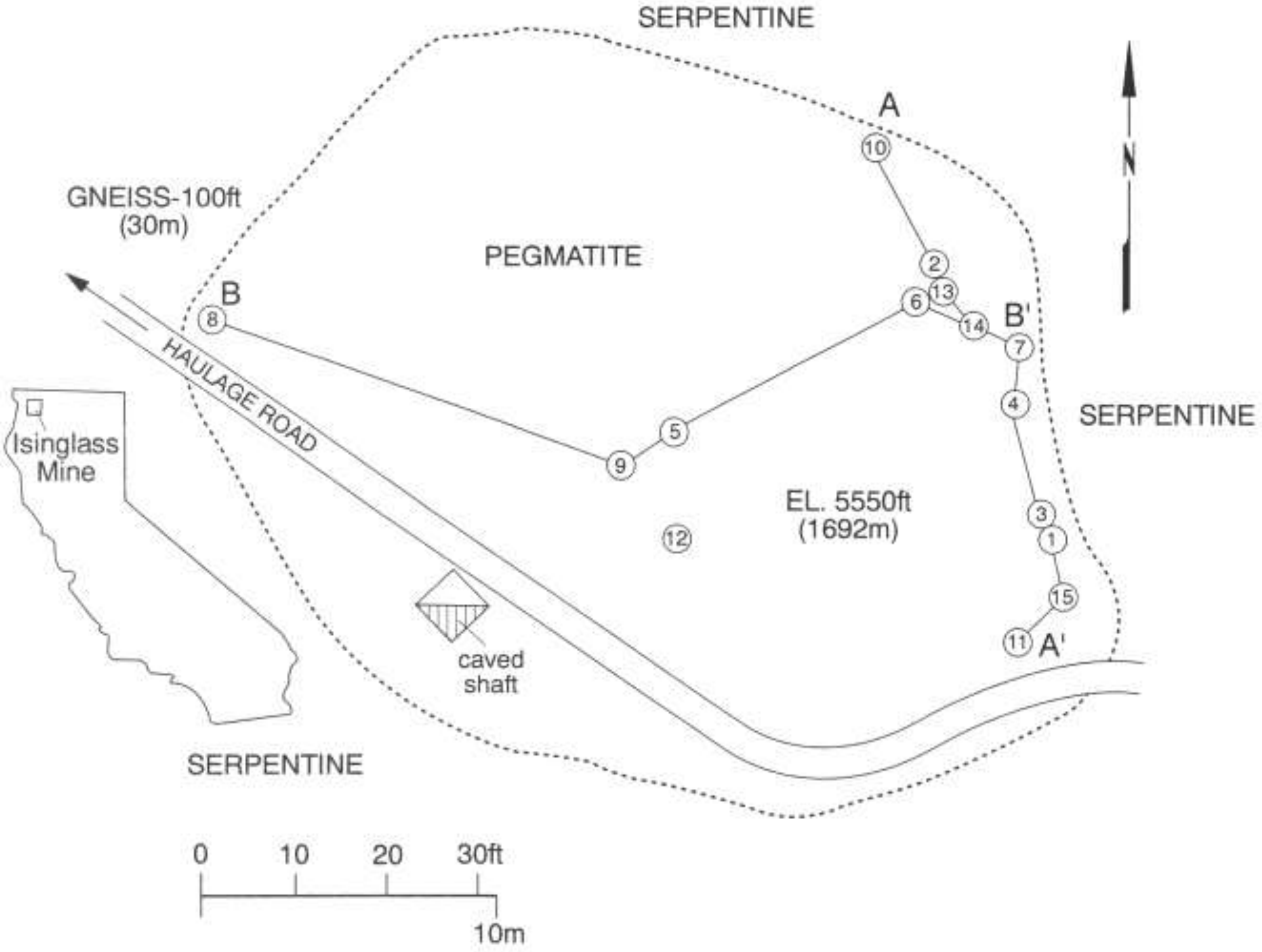

FIGURE 4—Locations of the 15 sample sites in the Isinglass mine (sec. 36, T44N, R11W) in the Klamath Mountains, Siskiyou County, California, showing an exposed pegmatite body in serpentine host rock. A–A' and B–B' represent approximate north–south and west–east transects along which samples were taken.

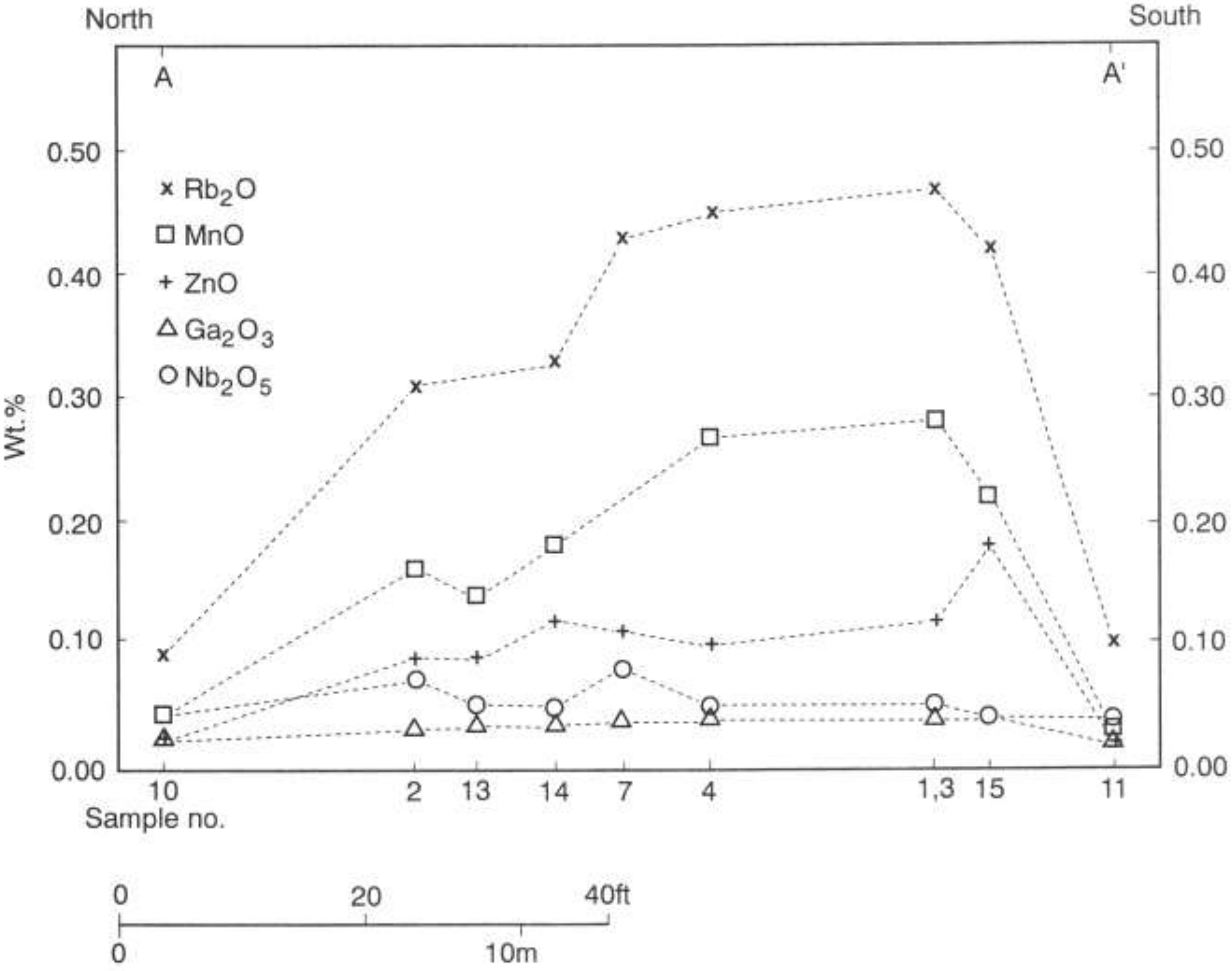

FIGURE 5—Plot of five minor-element concentrations in muscovite specimens from 10 samples (nos. 10–11) sites (north to south) in the Isinglass mine.

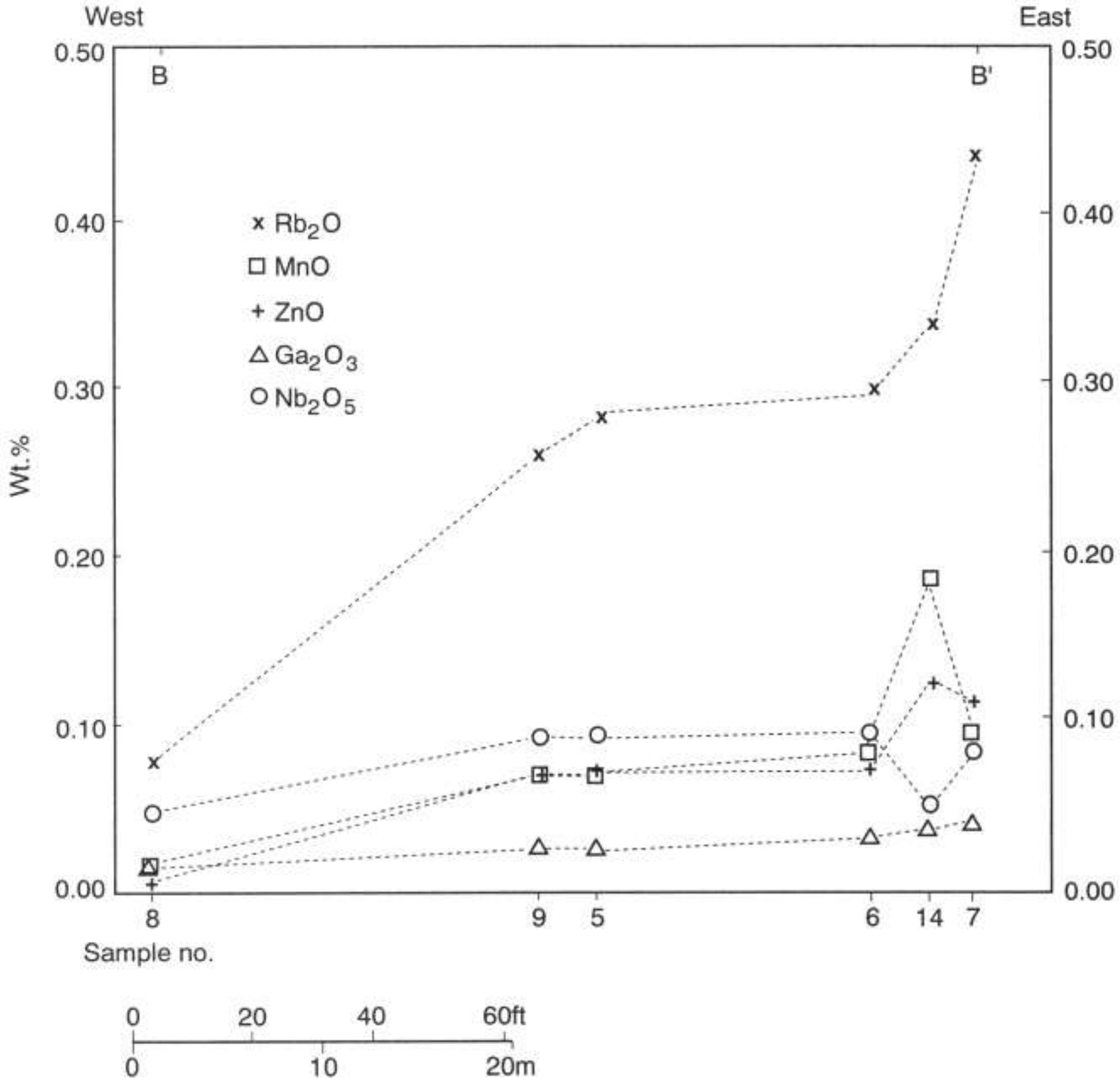

FIGURE 6—Plot of five minor-element concentrations in muscovite specimens from six samples (nos. 8–7) sites (west to east) in the Isinglass mine.

TABLE 4—XRF analyses of average minor-element compositions of muscovites from the physiographic provinces of California (see Fig. 4). After Post (1988).

Nb_2O_5	Rb_2O	NiO	Fe_2O_3 wt.%	MnO	BaO	Ga_2O_3	TiO_2	ZnO	CaO
Sierra Nevada Province - 11 sites									
0.02	0.15	0.006	3.96	0.05	0.18	0.013	0.39	0.01	0.11
Klamath Mountain Province - 2 sites									
0.05	0.21	0.007	3.88	0.09	0.02	0.031	0.35	0.05	0.05
Peninsular Ranges, San Diego County - 9 sites									
0.05	0.17	0.006	3.48	0.04	0.03	0.026	0.09	0.03	0.09
Coast Ranges, Ventura County - 2 sites									
0.07	0.19	0.007	4.03	0.07	0.02	0.020	0.10	0.03	0.09
Transverse Ranges, Los Angeles County - 2 sites									
0.11	0.10	0.004	3.81	0.03	0.02	0.021	0.26	0.02	0.08
Mojave Desert, San Bernardino County - 4 sites									
0.08	0.27	0.010	5.38	0.11	0.03	0.020	0.46	0.03	0.16
Great Basin Province, Inyo County - 8 sites									
0.02	0.13	0.006	3.16	0.06	0.05	0.011	0.45	0.01	0.23

TABLE 5—XRF oxide analyses of muscovite from the Isinglass mine, Klamath Mountains, Siskiyou County, California. After Post (1988, table 4).

Sample	Nb_2O_5	Rb_2O	NiO	Fe_2O_3	MnO	TiO_2	ZnO	CaO	Ga_2O_3	BaO
1	0.05	0.47	0.013	3.43	0.28	0.014	0.12	0.06	0.040	-0.00-
2	0.07	0.31	0.010	4.13	0.16	0.006	0.09	0.04	0.033	0.01
3	0.06	0.47	0.012	3.43	0.25	0.012	0.14	0.05	0.040	-0.00-
4	0.05	0.45	0.010	3.49	0.27	0.014	0.10	0.06	0.040	0.01
5	0.09	0.28	0.007	4.13	0.07	0.011	0.07	0.05	0.031	-0.00-
6	0.09	0.29	0.008	4.27	0.08	0.013	0.07	0.06	0.031	0.06
7	0.08	0.43	0.013	3.74	0.09	0.016	0.11	0.05	0.039	0.01
8	0.05	0.08	0.003	3.91	0.02	0.101	0.01	0.05	0.017	0.06
9	0.09	0.26	0.006	4.22	0.07	0.011	0.07	0.06	0.027	0.04
10	0.04	0.09	0.005	3.22	0.04	0.054	0.02	0.07	0.020	-0.00-
11	0.04	0.10	0.004	2.83	0.03	0.066	0.02	0.07	0.018	0.04
12	0.06	0.23	0.007	4.36	0.12	0.010	0.07	0.06	0.026	0.03
13	0.05	0.20	0.007	4.40	0.14	0.000	0.09	0.07	0.036	0.07
14	0.05	0.33	0.011	3.64	0.18	0.007	0.12	0.08	0.035	0.05
15	0.04	0.42	0.012	3.20	0.22	0.009	0.18	0.06	0.039	0.04

TABLE 6—XRF analyses of average minor-element compositions of muscovites from mica mining areas of northern New Mexico.

	Nb_2O_5	Rb_2O	NiO	Fe_2O_3	MnO	BaO	Ga_2O_3	TiO_2	ZnO	CaO
						wt.%				
Petaca district										
Kiawa area - 3 spec.	0.022	0.10	0.004	5.34	0.42	0.04	0.023	0.65	0.168	0.07
Persimmon Peak–Las Tablas area - 2 spec.	0.043	0.13	0.006	6.51	0.29	0.04	0.023	0.37	0.144	0.08
La Jarita–Apache area - 10 spec.	0.038	0.18	0.007	5.39	0.48	0.03	0.023	0.29	0.155	0.08
Cribbenville area - 6 spec.	0.033	0.12	0.004	6.56	0.29	0.04	0.019	0.38	0.091	0.07
Alamos area - 5 spec.	0.029	0.26	0.005	4.16	0.43	0.03	0.032	0.21	0.155	0.07
(Average for Petaca mining district - 26 spec.)	0.034	0.17	0.006	5.50	0.40	0.03	0.024	0.34	0.141	0.07
Other areas										
Ojo Caliente mining district - 4 spec.	0.033	0.15	0.007	4.35	0.36	0.03	0.015	0.41	0.049	0.18
Elk Mountain mine - 4 spec.	0.031	0.46	0.015	4.02	0.65	0.03	0.030	0.14	0.183	0.07
Harding mine - 6 spec.	0.012	1.13	0.008	1.36	0.54	0.03	0.026	0.10	0.071	0.12
Mora mining area - 4 spec.	0.070	0.15	0.006	4.27	0.11	0.03	0.013	0.24	0.057	0.06
Priest mine - 2 spec.	0.075	0.15	0.008	4.79	0.07	0.05	0.013	0.53	0.036	0.05
Aspen Basin area - 1 spec.	0.073	0.28	0.009	4.81	0.20	0.03	0.017	0.19	0.068	0.06

bodies are internally deformed but show little evidence of rotation since crystallization, and they thus preferred a syntectonic emplacement. We believe the geochemistry supports a syntectonic emplacement from a granitic source (Jahns and Ewing, 1976) that was isolated from sources of the other northern New Mexico pegmatites.

In general, New Mexico pegmatitic muscovites (Table 6) are richer in MnO and ZnO than California muscovites (Table 4); most of the equivalent Fe_2O_3 contents also are larger. The substitution of smaller ions in New Mexico muscovites has resulted in a somewhat smaller average unit cell with basal spacing of about 19.920 A. In California, the average minor-element compositions of muscovites are uniform except for more BaO in the Sierra Nevada province and an increase in TiO_2 toward the eastern part of the state. No similar trends are observed in the New Mexico muscovite districts; only the Harding muscovite has minor-element contents that are considerably different from the other pegmatites analyzed.

TABLE 7—Lattice spacings in biotite from the Elk Mountain mine and Harding mine biotites based on x-ray diffraction analysis.

Elk Mountain mine		Harding mine	
001	10.026 Å	001	9.987 Å
020	4.600 Å	020	4.498 Å
060	1.534 Å	060	1.529 Å

Conclusions

The average minor-element compositions of muscovites from eight mining districts of northern New Mexico suggest that the source material was different for each district; Rb, Mn, Nb and Zn contents vary considerably. However, Fe and Ti contents vary widely in muscovites within each mining area and are not useful for comparison, except for the Harding mine micas. If the muscovite composition of pegmatite bodies in the Petaca district is compared with muscovites of the isolated California Isinglass pegmatite, the Petaca bodies appear to be interrelated, with similar minor-element contents. Northern New Mexico muscovite deposits are richer in MnO and ZnO than California pegmatites. In general, the equivalent Fe_2O_3 contents are also higher, and the New Mexico $2M_1$ muscovites have an average unit cell basal spacing of only about 19.920 A.

The Harding pegmatite bodies, noted for their enrichment in Li, Be, Ta and F, and depletion of Fe, were emplaced from a different source (probably a highly differentiated liquid derived from a granitic magma) and in a different manner (probably syntectonically) than other New Mexico pegmatites. Both the Harding biotite and muscovite contain significant amounts of Li as shown by the small cell dimensions. The high levels of Li in the Harding micas are unusual but not unique in northern New Mexico pegmatites.

Little biotite is present in the northern New Mexico mica deposits. Two biotites, one from the Elk Mountain and and one from the Harding mines, were analyzed for trace elements. The New Mexico biotites have lower equivalent FeO contents than do most of the 10 California biotites analyzed by Post (1988).

Minor-element geochemistry of micas, particularly muscovite, can be useful in the study of origin and sources of pegmatites. Similarity of elemental compositions may indicate a connection or relationship among pegmatites, and variation of elemental compositions may indicate different sources and/or time of emplacement. A regional approach to mica geochemistry may prove of value in the search for associated minerals (such as tin) and for extensions to known pegmatites, and in discovering new pegmatites.

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Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, µm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

**Divide by* the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

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Typesetting: Lynne Hemenway
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Text—Black
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