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Mineralogy and geochemistry of altered rocks associated with Lemitar carbonatites, central New Mexico, U.S.A.

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ABSTRACT

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The intrusion of more than 100 Cambrian–Ordovician carbonatite dikes caused minor alteration of Proterozoic granitic and mafic rocks in the Lemitar Mountains, although hematization, carbonatization and fenitization caused extensive alteration locally. Ampibolites within 15–20 m of the carbonatite dike contacts were highly altered by carbonatization. Locally the Lemitar diorite/gabbro adjacent to some carbonatites were altered in a thin, discontinuous zone by sodic–potassic fenitization. The granite at Polvadera Peak was locally altered by potassic fenitization. Most of the altered rocks have been further altered by hematization and carbonatization.

The altered rocks show increases in loss on ignition and in one or more of the elements Ca, K, Na and Al. Only granitic fenites in the Lemitar Mountains lost silica and some diorite/gabbro fenites gained silica. Petrologic and geochemical studies clearly indicate that the types and degree of alteration differ notably in different rock types. The fenitizing fluids were oxidizing, slightly acidic, high in volatiles (especially CO_2) and possibly fairly low in alkali elements.

Introduction

Cambrian–Ordovician carbonatite dikes (minimum age of 449±16 Ma, K–Ar on biotite, McLemore, 1982, 1987a) intrude a complex Proterozoic metamorphic terrain in the Lemitar Mountains, 11 km north of Socorro, New Mexico in the southwestern United States (Fig. 1). The Proterozoic rocks in the Lemitar Mountains are described by McLemore (1980, 1982) and Bowring et al. (1983). The younger rocks were mapped and the structural setting was described by Chamberlin (1982, 1983). The petrology and chemistry of the Lemitar carbonatites were described by McLemore (1980, 1982, 983, 1987a). The intrusion of the carbonatites used minor alteration of the Proterozoic rocks al- ough hematization, carbonatization and fenitization caused extensive alteration locally.

Today, fenitization is recognized in more diverse country rock types than previously described (Brögger, 1921; Von Eckermann, 1948; Heinrich, 1966). Although some workers restrict the term fenite to only leucocratic, feldspathic, metasomatic rocks (Borodin and Pavlenko, 1974; Carmichael et al., 1974; Bates and Jackson, 1987), we prefer a more liberal definition. For our report, we define fenitization as the in-situ alkali metasomatism of country rocks associated with the intrusion of carbonatites or alkalic rocks (Heinrich, 1966; Le Bas, 1977; Garson et al., 1984; Kresten and Morogan, 1986). Fenites are the products of fenitization and in general decrease in Si and increase in one or more of the elements Ca, Al, Na and K (McKie, 1966; Heinrich, 1966; Robins and Tysseland, 1979). Ver-

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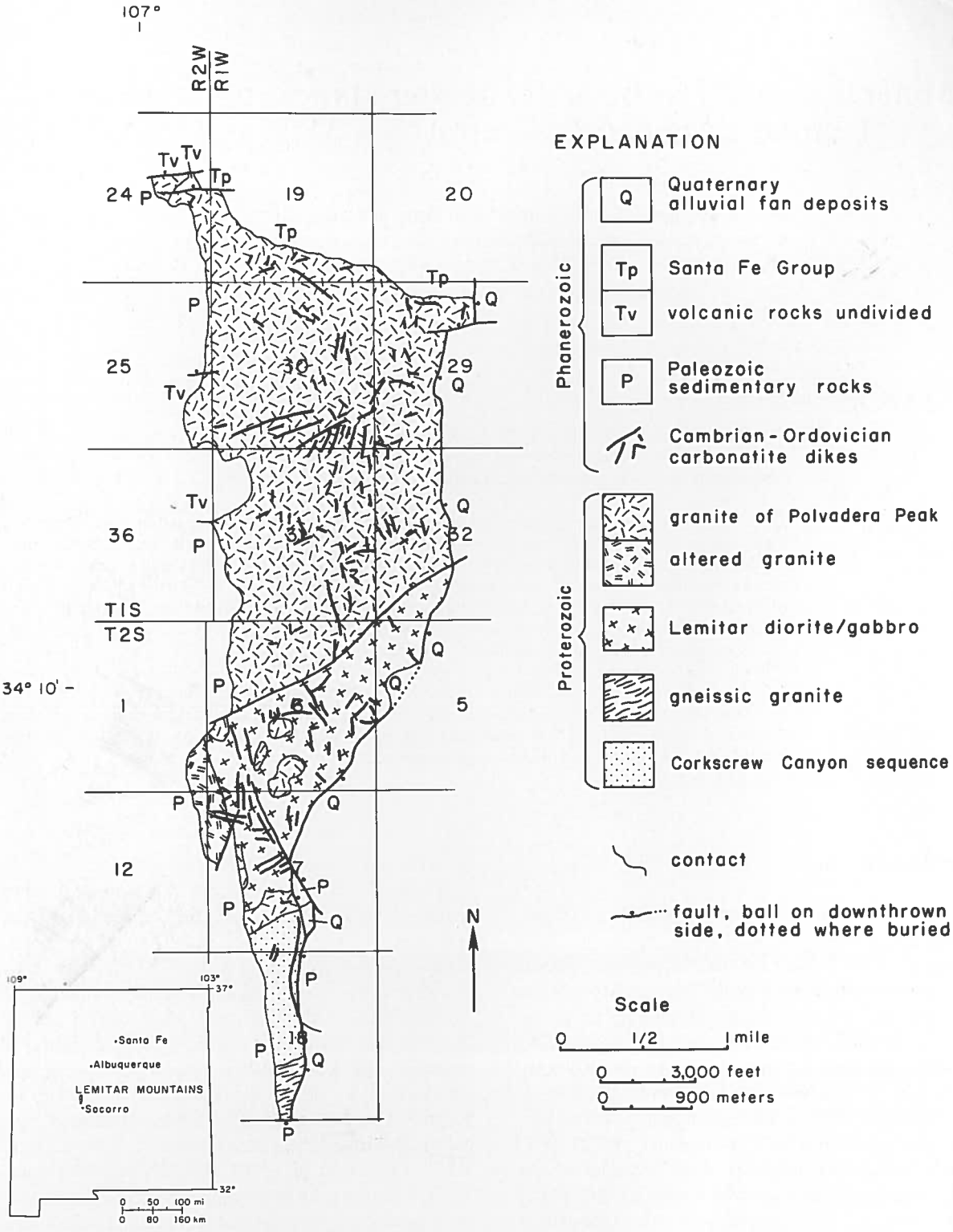

Fig. 1. Geologic map of the Lemitar Mountains. Note the distribution and trends of carbonatite dikes (simplified from McLemore, 1982).

woerd (1966) observed that a decrease in Si is less pronounced in mafic fenites than in granitic fenites. Many styles of fenitization are associated with carbonatites. Le Bas (1977) describes at least six styles of fenitization, four of which occur in the Lemitar Mountains: potassic–sodic fenitization (feldspathization), sodic fenitization, hematization and carbonatization.

The mechanisms of fenitization and the nature of the fenitizing solutions are not well understood even though there are numerous studies of fenitization in the literature (McKie, 1966; Verwoerd, 1966; Currie and Ferguson, 1971; Le Bas, 1977; Rubie and Gunter, 1983; Kresten and Morogan, 1986). One way to better understand fenitization is to study more areas exhibiting low-grade fenitization. Low-grade fenitization preserves textures and primary minerals, including original quartz, feldspar, and biotite (Vartiainen and Woolley, 1976; Kresten and Morogan, 1986). In medium-grade fenites, primary textures and minerals are rare; replacement and recrystallization are common.

The Lemitar Mountains are one of the few areas in the world where we can study the effects of low-grade fenitization on both granitic and mafic rocks in which aureole fenites are absent. This report presents new petrologic, mineralogic and geochemical data that characterize the alteration of different rock types in the Lemitar Mountains associated with the intrusion of carbonatites. These data are presented to aid in our understanding fenitization.

Analytical techniques

Whole-rock chemical analyses were determined by X-ray fluorescence spectrometry (XRF) on fused discs at the New Mexico Bureau of Mines and Mineral Resources following the procedure of Norrish and Hutton (1969). Trace elements were determined by XRF using pressed powder briquettes. Cathodoluminescence (CL) was observed using a Technosyn Cathodoluminescence Stage (McLemore and Barker, 1987). Any use of trade product of firm names is for descriptive purposes only and does not imply endorsement by the U.S. or New Mexico governments. Electron microprobe analyses were determined on a ARL-SEMQ Electron Microprobe at the U.S. Geological Survey in Denver. Analyses were made using standard techniques.

Geologic setting

The oldest rocks in the Lemitar Mountains are metamorphosed sedimentary rocks of Proterozoic age known as the Corkscrew Canyon sequence (Fig. 1). The Corkscrew Canyon sequence was intruded by gneissic granite (1648 ± 3 Ma; Bowring et al., 1983), the Lemitar diorite/gabbro and the granite at Polvadera Peak. The older rocks are intruded by amphibolite and pegmatite dikes. In the Lemitar Mountains, the Proterozoic rocks and carbonatites are unconformably overlain by Mississippian and Pennsylvanian sedimentary rocks.

Carbonatites

More than 100 silicocarbonatite and ferrocarbonatite dikes intruded the Proterozoic rocks after

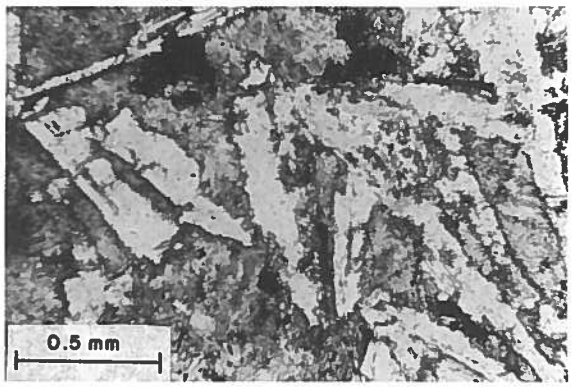

Fig. 2. Photomicrograph of unaltered amphibolite that has subophitic textures, in plane light. Field of view is about 2 mm.

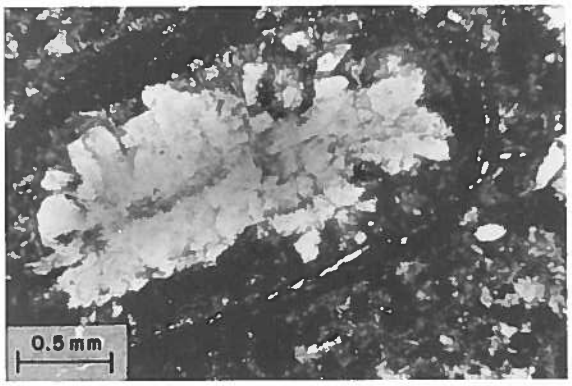

Fig. 3. Photomicrograph of altered plagioclase phenocryst in altered amphibolite almost completely replaced by calcite and iron oxides, in plane light. Field of view is about 3 mm.

regional amphibolite-grade metamorphism. The dikes range in thickness from a few centimeters to more than a meter and are as much as 600 m long. The silicocarbonatites consist of calcite and dolomite matrix (greater than 50%), magnetite (5–15%), layer silicates (biotite, phlogopite, muscovite, and chlorite; 10–20%), apatite (5–10%) and various amounts of accessory minerals. The silicocarbonatites are classified on the basis of petrology, mineralogy and chemistry as primary-magmatic and replacement silicocarbonatites (Armbrustmacher, 1979; McLemore, 1987a). The relict textures in replacement silicocarbonatites are identical to textures found in unaltered amphibolite dikes or unaltered Lemitar diorite/gabbro, which suggests that carbonatite magma or fluid partially replaced these country rocks. Ferrocarbonatites, previously called rodbergs (McLemore, 1987a), are carbonatites that consist of iron-rich carbonate minerals (Heinrich, 1966; Anderson, 1984; Woolley and Kemp, 1989). The Lemitar ferrocarbonatites consist mostly of dolomite, ankerite, hematite and goethite and lesser calcite, barite, fluorite, quartz and other accessory minerals. Ferrocarbonatites intrude the silicocarbonatites. Carbonatite intrusion was followed by emplacement of hydrothermal calcite and barite–fluorite veins, although the age and origin of these veins are uncertain. The veins may represent hy-

TABLE I

Chemical analyses of unaltered and altered amphibolites. Degree of alteration is based on amount of carbonate present and cathodoluminescence characteristics

	Unaltered			Degree of alteration Altered		Highly altered	
	LEM 11	LEM 406	LEM 407	LEM 408	LEM 209	LEM 404	LEM 409
SiO_2	47.2	48.8	47.9	46.3	46.6	42.4	24.0
TiO_2	2.79	3.41	1.95	2.06	0.99	0.93	3.95
Al_2O_3	12.4	12.3	14.4	14.8	13.4	12.7	4.50
Fe_2O_3*	19.0	17.4	14.1	16.2	11.5	11.0	13.9
MgO	6.22	3.39	8.05	6.78	9.26	8.72	7.43
CaO	8.38	8.02	9.11	7.72	10.2	10.8	23.8
Na_2O	2.41	3.37	2.61	2.22	2.11	1.76	0.90
K_2O	0.79	0.66	0.66	1.76	1.79	1.95	0.50
MnO	0.30	0.29	0.23	0.29	0.18	0.19	0.41
P_2O_5	0.30	1.47	0.18	0.25	0.17	0.17	1.85
LOI	0.62	0.75	1.35	2.78	3.27	9.93	19.4
Total	100.41	99.86	100.54	101.16	99.47	100.55	100.64
Ba	182	194	221	553	331	1103	218
Rb	33	21	24	50	119	110	33
Sr	152	231	156	173	198	450	359
Y	67	94	46	42	29	22	80
Nb	10	15	9	10	7	8	256
Zr	185	225	136	171	90	103	655
Cr	54	64	361	146	240	886	765
Pb	13	14	57	259	11	18	15
V	530	130	325	341	251	275	323
U	4	4	3	3	4	6	7
Th	4	5	3	7	2	9	25
Ga	21	18	19	17	18	14	14
Zn	193	207	196	326	102	114	122
Cu	77	13	83	39	71	72	70
Ni	41	5	129	96	136	247	286
Dist.	400	80	20	15	5	4	1

Dist. approximate distance in meters from the intrusive contact of a carbonatite.
*Total iron calculated as Fe_2O_3. All major and trace elements analyses by x-ray fluorescence, except LOI (loss on ignition), C.M. McKee, analyst, New Mexico Bureau of Mines and Mineral Resources. Major elements in percent; trace elements in parts per million.

drothermal activity related to the emplacement of the carbonatites because some are enriched in U and Th; but other veins are probably much younger than the Paleozoic carbonatites based on field relationships (McLemore, 1982).

Carbonate stocks, plugs and ring structures typical of many carbonatite complexes in the world are absent in the Lemitar Mountains. The Lemitar carbonatites are not locally associated with any alkalic rocks (McLemore, 1983, 1987a). However, the Lemitar carbonatites are part of a regional Cambrian–Ordovician alkalic magmatic event that includes rocks from southern Colorado and New Mexico. This event is characterized by emplacement of carbonatites, syenites, alkali granites and mafic dikes and by associated alkali metasomatism (McLemore, 1987b; Evans and Clemons, 1988; McLemore and McKee, 1988, 1989).

Petrology and geochemistry

Contact and vein fenites formed locally in the Proterozoic rocks due to carbonatite intrusion. Contact fenites formed adjacent to the carbonatites, whereas vein fenites formed when fenitizing solutions filled cracks, fractures and other zones of structural heterogeneities (Kresten, 1988). Four styles of fenitization, as defined by Le Bas (1977), were active locally in the mafic rocks and granite at Polvadera Peak: hematization, carbonatization, sodic-potassic fenitization and potassic fenitization. Metasedimentary rocks of the Corkscrew Canyon sequence are little or not altered. The gneissic granite has not been been fenitized because carbonatites do not intrude this granite.

Hematization was locally pervasive and resulted in thin veins and disseminated hematite and carbonate that cut the Proterozoic rocks and fill preexisting fractures. Thin sections show that extensive hematization near ferrocarbonatites obscured primary textures and mineralogy in the altered rock. However, hematization is not only associated with the ferrocarbonatites, but also occurs with other styles of fenitization.

Carbonatization occurred in the amphibolite dikes typically within 15–20 m of the carbonatite contact. Iron oxide–carbonate and iron oxide–carbonate–feldspar veinlets fill crosscutting fractures and other structural heterogeneities in the host rock. These veinlets are less than 10 cm wide and occur within a few meters of the carbonatite. Some car-

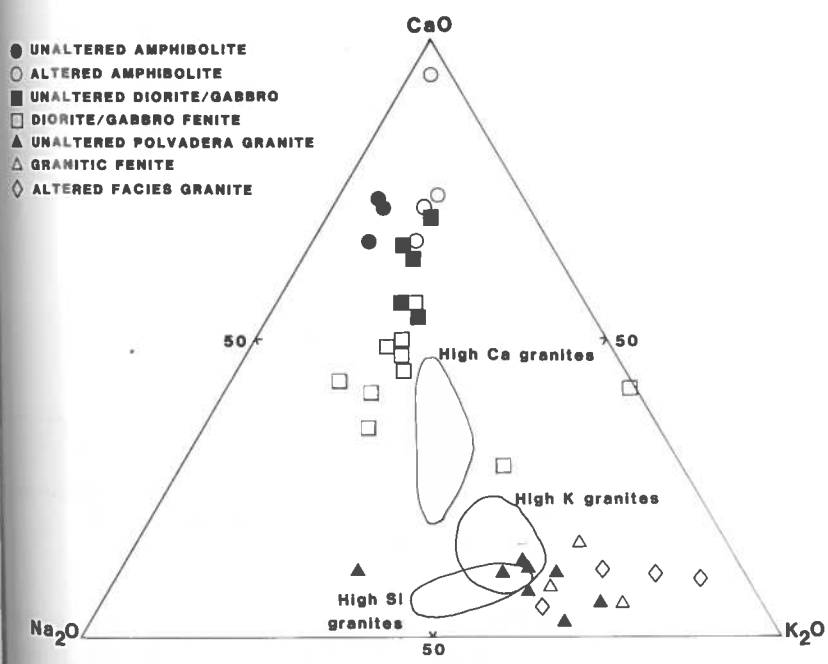

Fig. 4. CaO–Na_2O–K_2O diagram (in weight percent) of unaltered and altered rocks in the Lemitar Mountains. Granitic fields from Condie (1978).

bonatization occurred in the diorite/gabbro and granite.

Sodic–potassic fenitization occurred in the Lemitar diorite/gabbro along the contact with carbonatite dikes. Potassic fenitization, although weak, occurred locally in the granite at Polvadera Peak.

Amphibolites

The most pervasive alteration associated with the carbonatites is carbonatization of amphibolite dikes. The amphibolites are metamorphosed basaltic or gabbroic dikes that intrude the Proterozoic rocks in the Lemitar Mountains. Carbonatization occurred locally, where carbonatites intrude across or along the contacts of amphibolite dikes. The amphibolite dikes may show alteration even though the adjacent country rocks show no recognizable alteration.

The amphibolite dikes ae greenish black, fine grained and typically less than 2 m wide, although a few dikes are as wide as 5 m. Length along strike varies because many dikes are faulted or pinch out. The dikes consist of green hornblende (35–40%), plagioclase (30–35%), green and brown biotite (10–

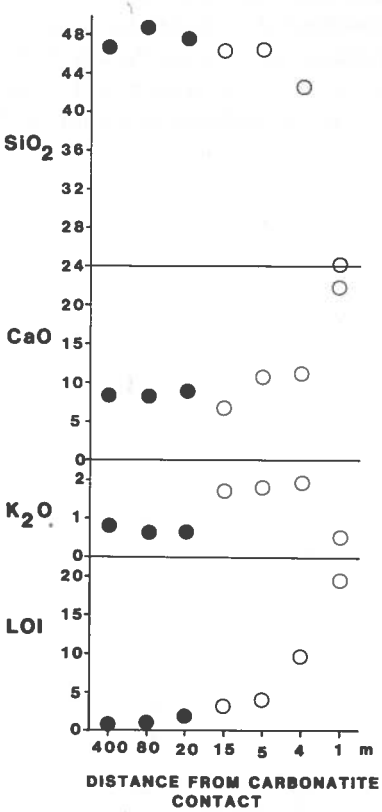

Fig. 5. Chemical oxides (in wt.%) of unaltered (dots) and altered (circles) amphibolites versus distance from the carbonatite contact. LOI, loss on ignition.

TABLE 2

Representative chemical analyses of feldspars in amphibolites. Feldspars in sample LEM 409 (nearest the carbonatite contact) were completely replaced by calcite

	Feldspars in LEM 11 (unaltered)				Feldspars in LEM 408 (altered)
Type of Feldspar	Plag.	Plag.	Plag.	Plag.	Plag.*
BaO	0.02	0.04	0.02	0.01	–
K_2O	1.06	0.26	0.17	0.12	0.35
Na_2O	4.14	7.36	6.73	6.24	0.00
SiO_2	52.89	59.83	58.08	57.42	41.23
SrO	0.10	0.12	0.14	0.14	–
Fe_2O_3	0.63	0.44	0.58	0.45	7.03
CaO	11.59	7.10	8.23	9.15	26.81
Al_2O_3	30.07	25.92	26.54	27.50	25.86
Total	100.50	101.07	100.49	101.03	101.28
An	57	34	40	44	–
Ab	37	64	59	55	–
Or	6	1.5	1	0.7	–
Color of CL	White	Blue	Blue	Blue	Red

	Feldspars in LEM 209 (altered)				
Type of Feldspar	Plag.	Plag.	Plag.	Plag.	Kspar
BaO	0.03	0.04	0.02	0.01	0.34
K_2O	1.52	2.07	0.16	0.75	9.84
Na_2O	8.53	6.99	7.84	7.39	3.35
SiO_2	63.83	60.31	61.66	60.69	63.21
SrO	0.19	0.19	0.15	0.15	0.12
Fe_2O_3	0.75	0.79	0.19	0.44	0.93
CaO	2.10	3.73	6.21	6.02	1.96
Al_2O_3	23.85	25.75	25.19	25.62	21.36
Total	100.80	99.87	101.42	101.07	101.11
An	11	20	30	30	10
Ab	80	67	69	66	31
Or	9	13	1	4	59
Color of CL	Red	Red	Orange	Orange	Red

Analyses by electron microprobe (in percent), P.J. Modreski, analyst, U.S. Geological Survey.
Plag–plagioclase, Kspar–K-feldspar; Molecular proportions: An–anorthite, Ab–albite, Or–orthoclase, CL–cathodoluminescence.
*Calcite partially replacing the feldspar; –Not analyzed.

20%), magnetite (5–10%) and various amounts of quartz, chlorite, hematite, garnet, fluorite, carbonate and apatite. Some amphibolite dikes show minor foliation in thin section and have subophitic or porphyritic textures (Fig. 2).

Seven samples of an amphibolite intruded by a carbonatite were sampled along strike at various distances from the carbonatite. Altered amphibolites are similar in appearance to unaltered amphibolites. The amphibolite was extensively altered next to the carbonatite, where fine-grained carbonatite partially or completely replaced and corroded magnetite, hornblende and plagioclase. Altered plagioclase is turbid and typically surrounded by a rim of iron oxides, clays and/or sericite (Fig. 3). In the highly altered amphibolites, fine-grained calcite partially replaces plagioclase as determined by electron microprobe studies. The highly altered amphibolite contains some K-feldspar, but the structural state of the K-feldspar has not been determined. The altered amphibolites always contains carbonate minerals and carbonate concentration decreases with increase in distance away from the carbonatite. Apatite crystals are larger in the altered amphibolite than in the unaltered amphibolite. Subophitic textures were preserved. Alteration diminishes in the samples farthest from the carbonatite contact.

Fenitization causes mineralogical effects that can be observed using cathodoluminescence (CL; Mariano, 1978; Marshall, 1988). The matrix of the most altered sample (LEM 409) adjacent to the carbonatite luminesces bright red. The red luminescence is due to Fe^{3+} activated feldspars (Telfer and Walker, 1978; White et al., 1986; Marshall, 1988), Mn^{+2} activated carbonate minerals and possibly activated quartz in the matrix and may suggest an oxidizing environment during fenitization. Less altered amphibolites farther from the carbonatite contact have only thin veinlets of red luminescing carbonate or feldspar cutting across brown luminescing matrix. The feldspars in unaltered or slightly-altered amphibolite luminesce blue to blue-white; such blue luminescence has been attributed to Ti^{+4} or Eu^{+2} (Mariano and Ring, 1974; Mariano, 1978; Marshall, 1988). Red luminescence is absent in the unaltered amphibolite samples.

The unaltered amphibolites are classified as gabbro–diorite and monzogabbro according to the geochemical classification of De la Roche et al. (1980). The altered amphibolite increases in LOI, CaO,

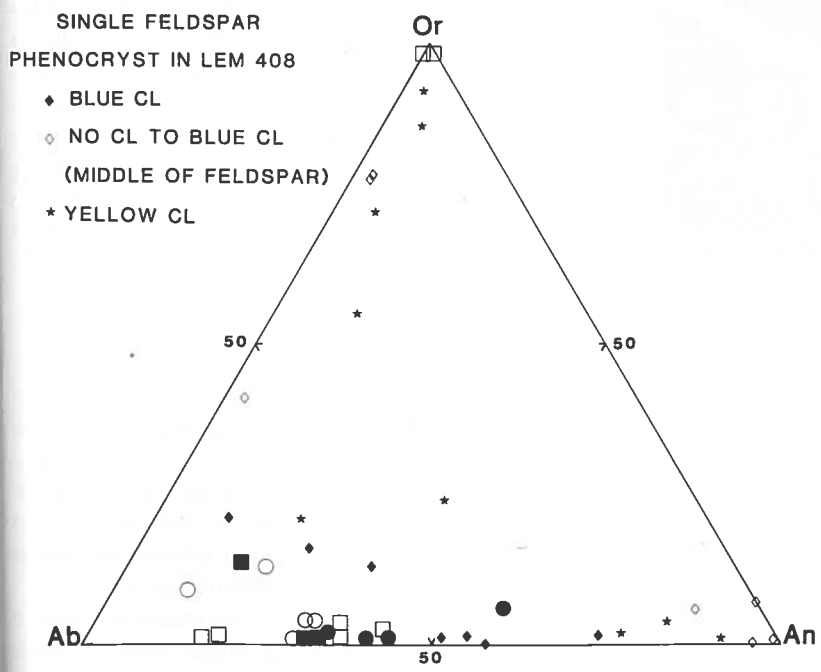

Fig. 6. Ab–An–Or diagram (molecular proportions) of feldspars in altered and unaltered amphibolites and diorite/gabbro in the Lemitar Mountains. Symbols explained in Fig. 4.

TABLE 3

Representative chemical analyses of feldspars in Lemitar diorite/gabbro

Type of Feldspar	LEM 449 (unaltered)			LEM 8365 (fenite)					LEM 506 (fenite)		
	Plag.	Plag.	Plag.	Plag.	Plag.	Plag.	Kspar	Kspar in vein	Plag.	Plag.	Plag.
Bao	0.04	0.03	0.00	0.03	0.02	0.05	0.58	0.83	0.04	0.03	0.02
K_2O	0.07	0.06	2.29	0.49	0.12	0.25	15.86	15.32	0.43	0.26	0.17
Na_2O	7.92	7.72	7.54	7.00	7.48	7.19	0.13	0.16	6.23	9.06	9.37
SiO_2	61.14	60.68	60.74	59.86	60.57	59.70	65.50	65.22	57.41	63.91	64.55
SrO	0.15	0.19	0.14	0.13	0.13	0.14	0.09	0.12	0.10	0.16	0.15
Fe_2O_3	0.01	0.00	0.25	0.23	0.13	0.18	0.00	0.09	0.18	0.09	0.21
CaO	6.41	6.76	3.03	7.09	7.01	7.43	0.07	0.01	8.51	3.87	3.52
Al_2O_3	25.13	25.43	25.09	26.10	25.54	25.88	18.52	18.66	27.59	23.35	22.90
Total	100.87	100.87	99.08	100.93	101.00	100.82	100.75	100.41	100.49	100.73	100.89
An	31	33	16	35	34	36	0.3	–	42	19	17
Ab	69	67	70	62	65	63	1.2	1.6	55	80	82
Or	0.4	0.3	14	3	0.7	1	98	98	2.5	1.5	1
Color of CL	Blue	Blue-White	White	Blue	Blue	Blue	White	Red	Blue	Red	Red

Analyses by electron microprobe (weight percent), P.J. Modreski, analyst, U.S. Geological Survey. Plag.–plagioclase, Kspar–K feldspar; Molecular proportions: An–anorthite, Ab–albite, Or–orthoclase; CL–cathodoluminescence.

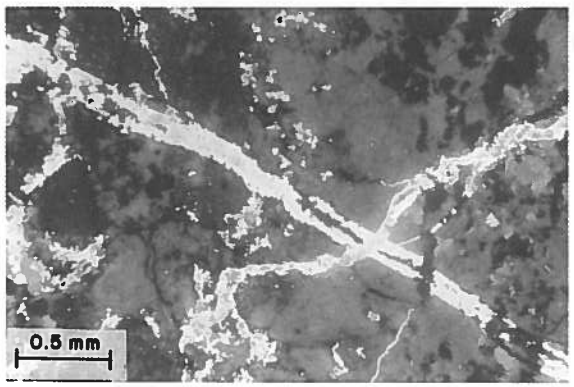

Fig. 7. Photomicrograph of calcite veins cutting diorite/gabbro fenite under cathodoluminescence. The veins luminesce red to orange. The light gray (actually brown or blue) is plagioclase. Field of view is about 3 mm.

K_2O, Rb, Sr and Ba and decreases in TiO_2, Na_2O, SiO_2 and total iron compared with unaltered amphibolites (Table 1, Figs. 4, 5). The sample closest to the carbonatite, LEM 409, shows increases in LOI, CaO, TiO_2, P_2O_5, Sr, Nb, Zr, Cr and Th and decreases in Na_2O, SiO_2, Al_2O_3, total iron and K_2O. Feldspars in unaltered amphibolite are labradorite to andesine (Table 2, Fig. 6), whereas feldspars in altered amphibolite are bytownite to oligoclase and K-feldspar. In addition to the microprobe analyses given in Table 2, partial analyses (for Na, K, Ca) from a traverse across a plagioclase feldspar crystal showing zoned cathodoluminescence (blue core to yellow rim) in fenitized amphibolite sample LEM-408 are plotted in Fig. 6. They show an increase in Ca:Na in the plagioclase, from andesine in the unaltered core to bytownite in the rim and patchy development of yellow-luminescent potassium feldspar in the outer part of the crystal. Both of these trends (increase in Ca and in K) are consistent with the trend in overall chemistry observed in the fenitized amphibolites.

Diorite/gabbro

A thin, discontinuous zone of sodic–potassic fenitization with minor carbonatization and hematization is developed locally in the Lemitar diorite/gabbro along the contact of some carbonatite dikes. This zone is typically less than several centimeters wide. In places, vein fenites in fractures and joints are several meters from the carbonatite contact.

Unaltered diorite/gabbro appears speckled due to the white phenocrysts of plagioclase (about 2–5mm long) in a dark matrix of hornblende and biotite. Lithologically, the diorite/gabbro ranges from gab-

Chemical analyses of unaltered and altered Lemitar diorite/gabbro

	Unaltered Lemitar diorite/gabbro†					Fenitized Lemitar diorite/gabbro									
	LEM 148	LEM 439	LEM 449	LEM 501	LEM 503	LEM 8352†	LEM 8364†	LEM 8370†	LEM 8373†	LEM 532*	LEM 533*	LEM 8365*	LEM 8368*	LEM 8369*	LEM 8355*
SiO_2	51.2	54.5	51.0	59.1	51.0	57.4	57.0	56.1	57.0	55.2	59.0	57.8	57.2	57.2	52.8
TiO_2	2.88	1.46	2.29	1.17	2.99	1.27	1.27	1.47	1.10	1.18	1.24	1.08	1.19	1.22	2.32
Al_2O_3	11.1	12.1	9.26	11.8	10.6	14.3	14.9	12.9	13.1	13.7	14.6	13.9	14.2	13.7	12.1
Fe_2O_3*	18.2	17.7	21.1	15.9	18.6	14.1	13.0	16.5	14.5	12.8	10.0	11.5	14.5	12.3	15.9
MgO	3.08	1.01	2.58	0.98	3.12	1.15	1.43	1.21	1.36	2.89	1.56	1.72	1.22	1.31	2.99
CaO	7.63	6.10	7.97	5.34	7.43	4.72	4.73	5.89	5.42	3.74	3.90	2.68	5.28	3.76	2.26
Na_2O	2.43	2.83	1.73	2.53	2.43	3.41	3.14	2.80	3.14	3.75	3.57	2.33	3.45	4.47	0.16
K_2O	1.50	1.90	1.50	2.03	1.65	2.42	2.12	2.11	2.22	1.14	1.88	4.17	1.95	2.31	2.87
MnO	0.20	0.31	0.33	0.32	0.27	0.30	0.28	0.36	0.35	0.16	0.14	0.17	0.33	0.26	0.11
P_2O_5	–	–	–	–	–	0.32	1.29	0.45	0.36	0.25	0.40	0.25	0.26	0.24	1.23
LOI	1.21	1.48	2.47	1.47	1.50	0.68	1.79	0.94	0.72	4.50	3.36	4.34	1.34	3.02	6.49
Total	99.43	99.39	100.23	100.64	99.59	100.07	99.95	100.74	99.87	99.31	99.65	99.65	100.91	99.79	99.23
Ba	415	754	480	952	463	743	851	822	718	286	731	1314	807	603	986
Rb	61	82	76	75	74	114	120	79	81	38	82	156	73	98	125
Sr	236	364	161	223	215	226	272	196	236	213	196	223	227	176	40
Y	88	103	172	110	88	111	110	149	115	68	91	98	121	162	115
Nb	7	31	8	10	10	14	8	19	16	16	19	12	12	32	33
Zr	191	554	1024	1331	2121	611	597	1349	929	1527	1461	1387	1450	1779	723
Cr	186	235	171	379	43	86	116	121	105	90	115	105	119	122	74
Pb	BD	15	13	17	10	41	27	27	23	19	21	20	31	26	231
V	70	39	55	30	51	46	40	23	22	41	33	36	27	35	77
U	5	BD	3	4	5	3	4	BD	5	4	4	3	9	4	9
Th	6	10	10	7	10	11	9	12	11	5	11	11	6	11	11
Ga	22	21	12	18	20	21	21	10	20	–	19	14	17	111	22
Zn	162	224	250	264	178	248	237	305	263	–	166	180	223	105	350
Cu	61	48	56	63	80	57	30	43	68	–	27	18	46	48	38
Ni	52	89	48	102	6	8	7	4	6	–	35	7	6	13	26

All major and trace elements analyses by XRF, C.M. McKee, analyst, New Mexico Bureau of Mines and Mineral Resources, except LOI (loss on ignition). Major elements in percent. Trace elements in parts per million. –Not analyzed.

*Total iron calculated as Fe_2O_3.

†white feldspars.

*red feldspars.

bro and diorite to quartz gabbro and quartz diorite (McLemore, 1980). The diorite/gabbro typically consists of plagioclase (30–50%), dark blue-green and brown hornblende (30–50%), biotite (10–20%) and trace amounts of quartz, garnet, apatite, magnetite, zircon and chlorite. Maximum quartz content is 15%. The plagioclase varies from andesine to labradorite (Table 3, Fig. 6). Textures include subophitic, ophitic (diorite) and hypidiomorphic granular (gabbro).

Fenitized diorite/gabbro may contain large, orange-pink to red andesine to albite crystals instead of the white labradorite to andesine phenocrysts normally found in the unaltered diorite/gabbro (Fig. 6). The reddish color is due to finely disseminated hematite within the feldspar crystal and is thought to result from oxidation and exsolution of iron originally within the feldspar lattice (Von Eckermann, 1948, p. 29). When the fenitized diorite/gabbro contains only white feldspars, it can still be recognized as fenite by proximity to the carbonatite, composition differences and red cathodoluminescence. In thin section, the feldspars are turbid due to iron oxide, clay and sericite disseminations. Some turbid feldspars have a core of clear, relict feldspar. Modal quartz content appears to decrease in the fenites; however, chemical analyses show Si increases in some samples. Electron microprobe studies indicate that quartz is hidden in small aggregates of hornblende, calcite, chlorite and feldspar. Small calcite crystals or thin veinlets of calcite cut across larger feldspar and hornblende crystals (Fig. 7). A few fenitized diorite/gabbro samples contain larger zircons than in unaltered samples; similar observations were reported by Strauss and Truter (1950) and Heinrich (1966).

Fenitization is easily recognized using CL. Parts of the hornblende–calcite–chlorite–feldspar aggregates within the diorite/gabbro fenite luminesce red and thin veinlets of calcite and plagioclase along crystal boundaries in the fenite also luminesce red. The plagioclase feldspars in the unaltered diorite/gabbro luminesce gray to white to blue. There is no red luminescence in the unaltered diorite/gabbro. Apatites vary considerably in chemical composition and CL (V.T. McLemore and P.J. Modreski, unpubl. data). In the fenites, the apatites luminesce green to gray to yellow-white, whereas in the unaltered diorite/gabbro, they luminesce yellow. Apatites in the Lemitar carbonatites luminesce green to gray to blue to occasionally yellow-white.

The unaltered diorite/gabbro varies in chemical composition as a result of variations in mineralogic composition, especially quartz content (Table 4). Chemically, samples of the diorite/gabbro are classified as monzogabbro, gabbro–diorite, diorite, monzodiorite and monzonite according to the chemical classification of De la Roche et al. (1980). Geochemically, the diorite/gabbro fenite is typically higher in LOI, Na_2O, Al_2O_3, and Rb and lower in total iron, CaO, Cr and Ni than unaltered diorite/gabbro (Table 4, Fig. 5). In addition, erratic but slight increases in K_2O and Pb and slight decreases in MgO are observed in some fenites. Changes in Si are erratic; some samples show increases in SiO_2. Plagioclase in unaltered diorite/gabbro ranges from andesine to labradorite, whereas feldspars in the fenites are andesine to albite and K-feldspar (Table 3, Fig. 6). The structural state of the K-feldspar has not been determined.

Granite at Polvadera Peak

The unaltered granite at Polvadera Peak is medium to coarse grained, pale red and locally slightly foliated. The granite consists of equal amounts of quartz (30–35%), plagioclase (25–30%) and K-feldspar (25–30%) and various amounts of biotite, hornblende, magnetite, apatite, chlorite and zircon. Hypidiomorphic-granular textures are preserved.

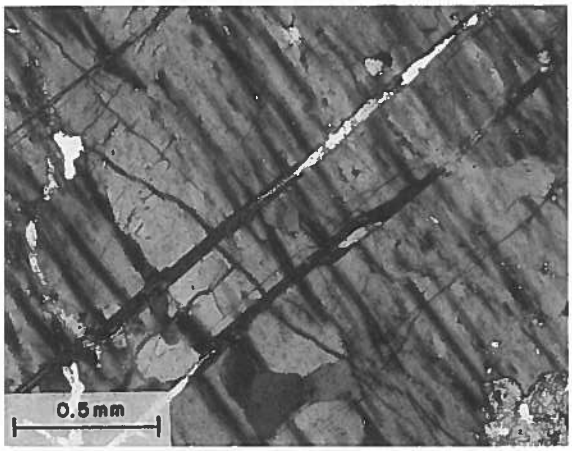

Fig. 8. Photomicrograph of calcite veins cutting microcline in granitic fenite, in polarized light. Field of view is about 2 mm. Note that microcline has no grid-iron twinning. Many microclines in fenites lose the grid-iron twinning (Heinrich and Moore, 1970).

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TABLE 5

Chemical analyses of unaltered and altered granite of Polvadera Peak

	Unaltered granite of Polvadera Peak								Fenitized granite of Polvadera Peak			Altered facies of the granite of Polvadera Peak			
	LEM 84	LEM 108	LEM 126	LEM 423	LEM 446	LEM 8456	LEM 511	LEM 8375	LEM 813	LEM 817	LEM 8394	LEM 906	LEM 8358	LEM 8360	LEM 8036
SiO_2	73.2	72.2	72.2	73.8	75.0	77.0	72.4	76.0	70.0	69.7	71.8	70.3	58.6	69.3	71.3
TiO_2	0.41	0.50	0.32	0.33	0.03	0.05	0.42	0.12	0.42	0.53	0.44	0.58	2.53	0.75	0.36
Al_2O_3	12.8	14.8	13.5	13.2	11.3	11.8	12.9	12.4	13.5	13.1	13.2	12.7	12.2	10.4	13.9
Fe_2O_3*	4.46	3.35	4.15	3.02	2.99	1.39	3.78	1.76	2.27	4.18	3.43	5.82	11.3	9.55	1.35
MgO	0.40	0.38	BD	0.40	0.36	0.28	0.41	0.38	0.27	0.88	0.89	1.23	2.07	1.31	0.15
CaO	1.22	0.99	0.93	0.98	0.48	0.17	1.08	0.71	1.81	0.62	0.83	0.46	0.69	0.41	1.42
Na_2O	2.92	2.53	4.51	2.41	1.97	2.56	3.20	2.77	2.29	1.87	2.49	2.29	0.88	0.27	2.32
K_2O	5.08	4.54	2.75	5.42	6.23	5.82	5.09	5.17	6.90	7.00	5.47	4.40	4.95	3.20	7.58
MnO	0.10	0.05	0.01	0.05	0.06	0.02	0.06	0.04	0.06	–	0.06	–	0.08	0.08	0.01
P_2O_5	0.11	0.16	0.43	0.12	0.03	0.01	0.18	0.11	0.10	–	0.11	–	0.30	0.15	0.08
LOI	0.48	1.48	0.28	0.58	1.19	0.43	1.30	0.59	2.11	2.23	0.96	2.39	4.25	4.07	1.44
Total	100.98	100.98	99.08	100.31	99.91	99.53	100.98	100.05	99.73	100.11	99.68	100.17	97.85	99.49	99.82
Ba	919	1009	570	775	31	136	752	76	–	737	711	1050	4244	2100	–
Rb	189	178	59	232	223	156	253	271	–	411	274	113	256	216	–
Sr	74	129	73	58	50	34	74	40	–	54	59	51	76	54	–
Y	164	52	48	95	128	97	98	100	–	108	106	77	67	104	–
Nb	24	20	13	16	10	41	71	11	–	20	14	25	6	8	–
Zr	612	258	295	247	398	136	350	76	–	404	347	445	185	920	–
Cr	398	331	441	323	47	201	523	196	–	103	164	561	171	110	–
Pb	30	28	17	38	37	30	34	44	–	22	70	29	26	20	–
V	15	44	17	16	16	19	26	15	–	30	24	26	392	46	–
U	30	5	11	7	4	6	6	10	–	7	4	8	5	3	–
Th	14	19	15	31	18	30	34	145	–	35	44	23	4	4	–
Ga	18	19	19	16	15	20	18	18	–	15	18	20	20	14	–
Zn	130	40	26	45	75	28	59	24	–	72	142	127	253	258	–
Cu	46	46	50	43	64	56	84	56	–	53	21	34	23	27	–
Ni	127	80	101	108	12	11	172	10	–	15	11	173	37	16	–

*Total iron calculated as Fe_2O_3. All major and trace elements analyses by XRF, C.M. McKee, analyst, New Mexico Bureau of Mines and Mineral Resources, except LOI (loss on ignition). Major elements in percent. Trace elements in parts per million.
–no data.

An altered facies southwest of the main body (Fig. 1), although poorly exposed and badly weathered, is medium to fine grained and is pale red with black aggregates of hornblende, magnetite and hematite. The altered granite consists of quartz (25–30%), plagioclase (20–25%), perthitic K-feldspar (30–35%), biotite and chlorite (10–20%), and various amounts of hornblende, magnetite, and hematite. Thin veinlets and disseminations of quartz, feldspar, barite, galena, calcite and secondary copper minerals occur locally within the altered granite. This altered facies may, in part, result from fenitization, although hydrothermal alteration associated with nearby Tertiary barite and fluorite mineralization may have been superimposed over the fenitization (McLemore, 1980, 1982).

The granite at Polvadera Peak next to or near some carbonatites contain small irregular zones (up to several meters diameter) of pink to red granitic fenites, consisting of predominantly albite and/or K-feldspar. These fenites are slightly radioactive, two or four times average background. The fenites are fine grained, lower in quartz and mafic minerals and contain more iron oxides, carbonate and K-feldspar than unaltered granite at Polvadera Peak. The feldspars are turbid (sericitic alteration) and characterized by the presence of finely disseminated hematite. The feldspars in one sample of granitic fenite were almost completely replaced by carbonate. Hemitization occurred along the contacts of ferrocarbonatites.

The granitic fenites, including the altered facies in the Lemitar Mountains (Fig. 8), typically have red-luminescing veinlets of carbonate, quartz and/or feldspar surrounding and cutting original crystals. A red-luminescing calcite vein cutting a granitic fenite is shown in a color photograph in McLemore and Barker (1987, fig. 3). Feldspars in these fenites typically luminesce brown to gray to red, whereas feldspars in the unaltered granite at Polvadera Peak luminesce white to blue. Unaltered granites do not luminesce red.

Chemical composition changes erratically between the granitic fenites, the altered facies and unaltered granites (Table 5, Fig. 4). Unaltered granites are similar in composition to Proterozoic granites elsewhere in New Mexico and are classified as either high K or high Si (Condie, 1978). The granites are classified as granite and alkali granite according to the geochemical classification of De la Roche et al. (1980). Typically, granitic fenites and the altered facies show increases in LOI, MgO and total iron and decreases in SiO_2 and possibly Na_2O. The granitic fenite is higher in K_2O than the unaltered granite, whereas the altered facies is lower in CaO and K_2O than the unaltered granite. Geochemical trends and CL characteristics suggest that the altered facies may be a product of fenitization. The compositional differences between the fenite and the altered facies probably result from later hydrothermal alteration associated with nearby Tertiary Mississippi Valley-type barite–fluorite mineralization.

Discussion

The alteration of the Proterozoic rocks in the Lemitar Mountains is minimal and is local along the contacts of some carbonatites and along fractures, joints, faults and other structural heterogeneities near carbonatites. The Proterozoic rocks were metamorphosed to amphibolite-grade (temperatures about 450°–700°C; Winkler, 1974) prior to intrusion of the Lemitar carbonatites and subsequent alteration. The Lemitar carbonatites are the source of the fenitizing solutions, because alteration occurred only at contacts of the carbonatites and along fractures, joints, faults and other structural heterogeneities within a few meters of the carbonatites. Replacement silicocarbonatites in the Lemitar Mountains are formed by replacement of country rock by the carbonatite magma, yet original textures and some minerals may be preserved (McLemore, 1987a). Similar replacement carbonatites occur in the Wet Mountains, southern Colorado (Armbrustmacher, 1979). These replacement silicocarbonatites and replacement of minerals in the country rocks by carbonate from fenitizing solutions in the Lemitar Mountains also indicate the carbonatites were the source of fenitizing solutions.

When the Proterozoic rock sin the Lemitar Mountains were altered as a result of the intrusion of the carbonatites, different rock types showed different compositional changes. Most altered rocks in the Lemitar Mountains show increases in LOI, probably due to addition of CO_2 and other volatiles and in one or more of the elements Ca, K, Na and Al. Carbonatization occurred in the amphibolites and is characterized by a significant increase in Ca

and a decrease in Si and Na. Sodic–potassic fenitization occurred in the Lemitar diorite/gabbro and is characterized by an increase in na, Al and sometimes a slight increase in K. Many diorite/gabbro fenites show a decrease in Ca; however, calcite was introduced into the rock, which suggests a complex chemical system in which Ca was mobile. Potassic fenitization, although poorly-developed, occurred in the granite at Polvadera Peak and is characterized by an increase in K and Mg and a decrease in Si. Hematization and carbonatization are common in most of the Lemitar fenites. Chemical changes are summarized in Table 6.

Desilicification during fenitization has been emphasized by previous workers (Heinrich, 1966; McKie, 1966; Heinrich and Moore, 1970); however, in the Lemitar Mountains, only the granitic fenites show a decrease in quartz and Si (Tables 1, 3, 5). The mafic fenites change very little in quartz or Si unless highly altered (for example, sample LEM-409); but some diorite/gabbro fenites actually increase in quartz and Si. A similar silicification occurred in the Melteig fenites at Fen, Norway (Kresten and Morogan, 1986) and in gabbroic fenite xenoliths from the Oldoinyo Lengai carbonatitic volcano in Tanzania (Morogan and Martin, 1985).

It is beyond the scope of this paper to examine fully the chemical conditions required during fenitization to produce the different styles and degrees of fenitization observed in the Lemitar Mountains. However, we can make some observations on the nature of the fenitizing solutions from this study. Pervasive hematization and cathodoluminescence characteristics suggest that the fenitizing solutions were oxidizing. The presence of sericitic alteration of feldspars in the Lemitar fenites suggests that the fenitizing solutions may have been slightly acidic (Currie and Ferguson, 1971).

The composition of the fenitizing solutions is more difficult to determine because the composition of these solutions changes rapidly with variations in temperature, pressure, oxidation state and activities of the various elements in the solutions. Certainly the fenitizing solutions were enriched in volatiles, specially CO_2, because the fenites increase in LOI and calcite with respect to the parent rock. Woolley (1982) and Le Bas (1981) believed the dramatic increase in alkalis observed in areas of aureole fenites (McKie, 1966; Verwoerd, 1966; Currie, 1971; Kresten and Morogan, 1986) suggested the carbonatite magma was once enriched in these elements. The magma lost the alkalis to the fenites

TABLE 6

Summary of trends in chemistry of fenites relative to unaltered rocks in the Lemitar Mountains

Altered rock	Bulk rock chemical composition		Feldspar chemical composition	Feldspar CL		Style of fenitization
	Increase	Decrease		Unaltered	Altered	
amphibolite (except LEM 409)	Ca, K, Ba, Rb, Sr*, LOI	Si, Ti, Fe, Na	<>Na, <>Ca, >K	blue, white	red, orange	carbonatization
amphibolite (LEM 409)	Ca, P, Ti, Sr, Nb, Zr, Cr, Th, LOI	Si, Al, Fe, Na, K	NA replaced by carbonate	NA	red, orange	extensive carbonatization
diorite/ gabbro	Al, Na*, K*, Rb, Pb, LOI	Ca, Cr, Ni, Fe*, Mg*	>Na, <Ca, >K	blue, white	red, blue	sodic-potassic fenitization, minor carbonatization and hematization
granitic	K, Mg, Fe*, LOI	Si	no data	blue, white	blue, white to brown to red, orange	potassic fenitization, hematization and carbonatization near ferrocarbonatites
altered facies	Mg, Fe, LOI	Si, Ca, Na*, K*	no data	NA	blue, white to brown to red, orange	potassic fenitization with possible overprinting by hydrothermal alteration

*only small changes were observed.
NA–not applicable.
CL–cathodoluminescence.
<>–both increase and decrease observed.
>–increase observed.
<–decrease observed.

and, therefore, the carbonatites found in the field are low in alkalis. Because the Lemitar fenites do not dramatically increase in alkalis, perhaps the fenitizing solutions in the Lemitar Mountains were not enriched in alkalis.

The absence of aureole fenites in the Lemitar Mountains could be explained by the physicochemical conditions during fenitization. The fenitizing solutions derived from the Lemitar carbonatite dikes may not have been hot enough to alter extensive areas in the metamorphosed Proterozoic rocks. Le Bas (1981) suggested that one way of dissolving granite or other silicate material is to add sodium carbonate and heat. If the fenitizing solutions in the Lemitar Mountains were low in alkalis, especially sodium, then aureole fenites may not have formed.

Even though the Lemitar fenites are low-grade, the data presented here indicate that fenitization is a complex process dependent upon temperature, pressure, oxidation state, composition of the fenitizing solutions and composition of the parent rocks. These data are consistent with theories suggesting that the Lemitar carbonatites are distant from a main carbonatite pluton at depth or faulted away by the Rio Grande rift (McLemore, 1982, 1987a).

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