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Introduction

The Fenton Hill granodiorite is one of the most distinctive Precambrian lithologic units encountered during deep drilling at the Los Alamos National Laboratory Hot Dry Rock (HDR) geothermal site west of the Valles caldera (Laughlin et al., 1983). Although it differs both mineralogically and chemically from most other Precambrian plutons in central and northern New Mexico, petrologic, chemical, and geochronological data suggest that it is similar to surface exposures of the Sandia pluton in the Sandia Mountains east of Albuquerque. If these rocks are pieces of the same pluton, a right-lateral offset of approximately 80 km (50 mi) along a precursor fault to the Rio Grande rift is suggested. The sense and amount of this displacement is in agreement with earlier estimates by Chapin and Cather (1981) and Chapin (1983).

Fenton Hill granodiorite

The Fenton Hill granodiorite is not exposed at the surface and has only been encountered in deep geothermal wells at Fenton Hill, New Mexico and in the Continental Scientific Drilling Program (CSDP) well VC–2B in the Valles caldera. The HDR geothermal site at Fenton Hill is in Sandoval County, New Mexico about 32 km (20 mi) west of Los Alamos (Fig. 1). The site is in the Jemez Mountains, west of the western rim of the Valles caldera. Four deep wells, GT–2, EE–1, EE–2 and EE–3, were drilled at Fenton Hill; the deepest of these, EE–2, has a true vertical depth of 4.39 km (14,417 ft). Cores, cuttings, and random samples from a "junk basket" run behind the drill bit were used by Laughlin et al. (1983) to characterize the Precambrian basement rocks at the site (Fig. 2).

Precambrian basement rocks were encountered at a depth of approximately 730 m (1,748 ft) in the four Fenton Hill wells. From 730 m (1,748 ft) to 2,590 m (8,498 ft) the Precambrian section consists of a metamorphic complex of various gneisses and schists. Between 2,590 m (8,498 ft) and 3,000 m (9,843 ft) the Fenton Hill granodiorite was encountered as a single, continuous intrusive body (Fig. 2). Smaller bodies of the granodiorite were encountered at greater depths. The granodiorite is a homogeneous, typically nonfoliated, sphene-bearing, biotite-rich granitic rock. The major minerals are quartz, sericitized plagioclase (An_{33}), microcline, and biotite. Accessory minerals include the ubiquitous sphene (1–3%), zircon, opaque oxides, myrmekite, and apatite. Epidote and calcite are also present as alteration minerals.

The CSDP well VC–2B was drilled in 1988 to a depth of 1,762

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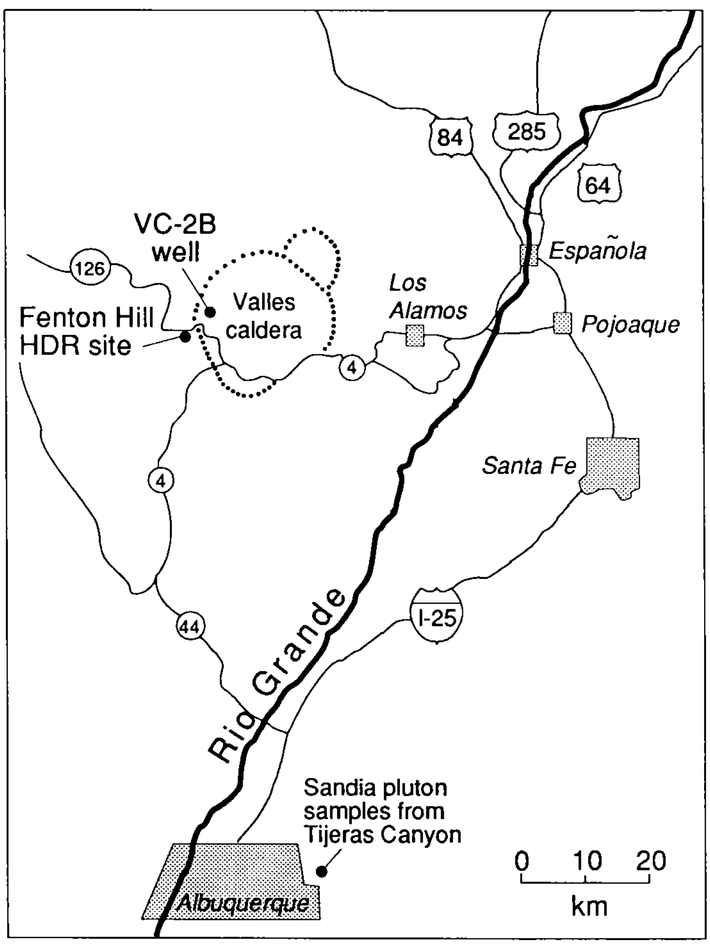

FIGURE 1—Index map showing the Fenton Hill hot dry rock (HDR) site, Continental Scientific Drilling Program (CSDP) well VC–2B, and the Sandia pluton.

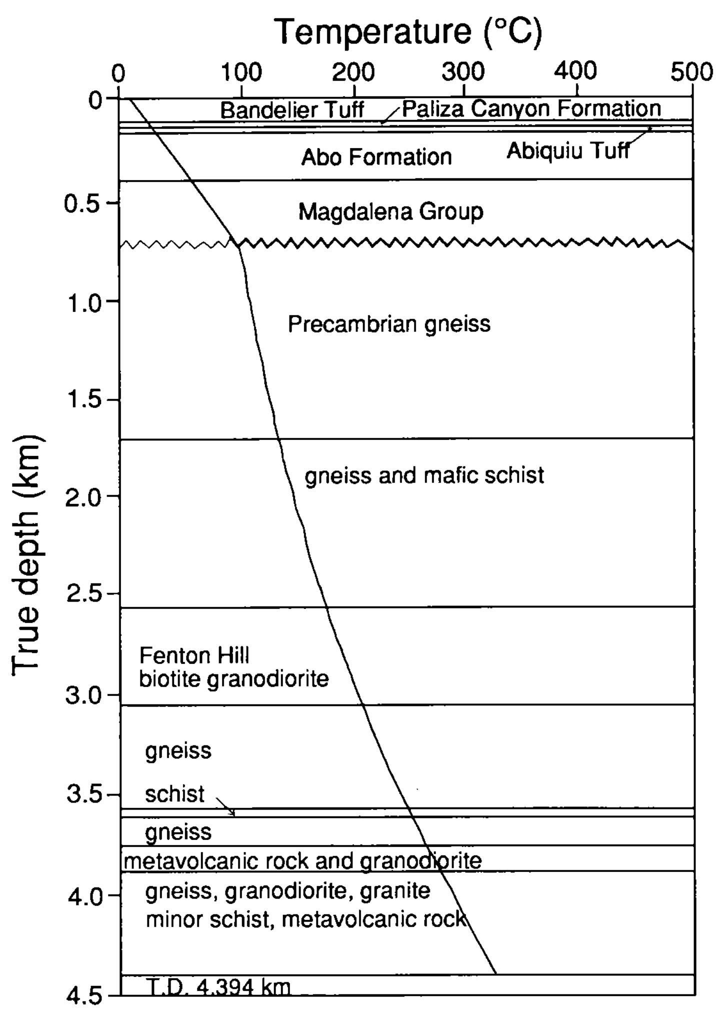

FIGURE 2—Simplified stratigraphic column at the Fenton Hill hot dry rock site.

m (5,781 ft) in the Sulphur Springs area of the western Valles caldera. Sulphur Springs is about 7.5 km (4.7 mi) northeast of the Fenton Hill site. Precambrian quartz monzonite was encountered at a depth of 1,556 m (5,105 ft) in VC–2B, which had been continuously cored. The major minerals in this Precambrian quartz monzonite are quartz, plagioclase, microcline, and biotite. The plagioclase is moderately sericitized and the biotite is strongly chloritized. Accessory minerals include sphene, opaque oxides, zircon, and apatite. The subhedral to euhedral sphene is strongly altered to leucoxene. Epidote, calcite, chlorite, and sericite are present as alteration minerals.

A summary of the whole-rock chemistry of the Fenton Hill granodiorite from both the Fenton Hill and VC–2B wells is given in Table 1. Results of neutron activation analysis of trace elements are presented in Table 2. The biotite granodiorite is characterized by high Fe_2O_3, FeO, TiO_2, K_2O, P_2O_5, and SrO. The high TiO_2 and P_2O_5 values are reflected by the high modal contents of sphene and apatite, whereas the high Fe_2O_3, FeO, and K_2O values are reflected by the high biotite contents.

Sandia granite

The Sandia granite, actually quartz monzonite to granodiorite, is exposed in the western escarpment of the Sandia Mountains, east of Albuquerque. Surface exposures of the granite are commonly weathered. Some of the best exposures are found in Tijeras Canyon where the granodiorite is in contact with the Cibola gneiss. The northern part of the Sandia granite is in intrusive contact with the Juan Tabo series (Brookins and Majumdar, 1989). On the basis of modal and compositional data from only four samples, Condie and Budding (1979) suggested that the Sandia granite consists of two plutons; the North Sandia pluton and the South Sandia pluton (Fig. 3). Rocks of both plutons are typically homogeneous and medium to coarse grained. Modal compositions

TABLE 1—Composition of Sandia granite and Fenton Hill granodiorite. All values expressed as percentages.

Column	1 NSP N=4**	2 SSP N=5	3 NSP N=14	4 SSP N=13	5 NSP N=6	6 SSP N=2	7 SSP TC-1 N=1	8 SSP AWL-8-81 N=1	9 Fenton Hill granodiorite N=6	10 VC-2B N=2
SiO_2	69.2	66.3	68.0	66.87	69.4	66.6	66.64	63.36	64.27	66.00
TiO_2	0.76	1.03	0.88	0.95	0.79	1.05	0.94	1.10	0.95	0.76
Al_2O_3	13.7	13.9	14.23	14.24	13.9	14.3	13.52	15.15	14.48	14.59
Fe_2O_3	4.81*	6.85*	5.35*	5.92*	2.29	2.3	2.74	3.14	2.96	2.39
FeO	n/a	n/a	n/a	n/a	3.10	3.1	3.04	3.35	2.92	2.62
MgO	1.00	1.33	1.17	1.33	0.95	1.24	1.36	1.50	1.39	1.26
MnO	n/a	n/a	0.11	0.17	n/a	n/a	0.11	0.12	0.098	0.083
CaO	2.75	3.73	2.82	2.90	2.29	3.21	3.13	3.55	3.11	2.93
Na_2O	3.29	3.11	3.24	3.32	3.34	3.06	3.17	3.28	3.32	3.34
K_2O	3.99	3.25	4.34	3.00	3.71	4.02	3.51	3.82	4.23	4.02
H_2O^+	n/a	n/a	n/a	n/a	0.73	0.81	1.03	0.87	0.98	1.60
H_2O^-	n/a	n/a	n/a	n/a	0.06	0.06	0.01	0.04	0.07	0.04
P_2O_5	n/a	n/a	0.31	0.31	0.30	0.30	0.34	0.37	0.57	0.35
SrO	0.024	0.023	0.022	0.024	0.025	0.026	0.01	0.02	0.04	0.09

Columns 1 and 2—Condie and Budding (1979).
Columns 3 and 4—Majumdar (1985).
Columns 5 and 6—Enz et al. (1979).
Columns 7, 8 and 10—This work.
Column 9—Laughlin and Eddy (1977).
*Total Fe as Fe_2O_3
**N = number of samples. All results are averaged, except those in columns 7 and 8.

TABLE 2—Trace-elements in Sandia granite and Fenton Hill granodiorite, analyzed by neutron activation.

	Sandia granite		Fenton Hill granodiorite			
	AWL-8-81	TC-1	9519-1	9520-3	8538-1b	9529-2
Ba	800.1	685.5	1109	1652	1829	1374
Dy	11.00	8.131	10.90	15.19	17.55	17.85
U	4.219	3.699	5.582	5.465	2.87	6.224
Sm	11.68	6.386	14.85	16.02	11.53	17.12
W	3359	333.0	457.6	n/a	n/a	n/a
Sc	16.59	14.43	16.42	17.44	3.316	16.14
Cr	27.70	n/a	19.41	37.99	72.30	82.07
Co	24.55	25.14	26.43	12.34	9.915	14.51
Zn	n/a	n/a	n/a	167.8	88.59	146.5
Rb	155.0	155.0	125.4	117.9	n/a	111.3
Cs	5.582	6.575	5.725	4.406	n/a	3.966
Ce	149.7	119.2	209.1	237.1	224.2	251.3
Eu	2.442	1.702	2.772	2.888	1.807	3.21
Tb	1.171	n/a	1.398	1.410	1.248	1.589
Yb	1.029	5.85	8.954	13.35	6.739	14.67
Lu	0.9219	0.5859	1.089	1.312	0.5499	1.46
Hf	11.82	8.857	13.07	17.33	12.19	18.57
Ta	10.88	3.065	7.799	4.284	n/a	3.500
Th	13.02	9.847	13.57	13.21	13.96	17.75

are shown in a K-feldspar/quartz/plagioclase ternary plot (Fig. 4) modified from Condie and Budding (1979). The two Sandia plutons plot near the boundary between the granodiorite and quartz monzonite fields, and away from most of the other 29 New Mexico Precambrian plutons reported by Condie and Budding (1979). The Fenton Hill granodiorite plots close to the Sandia pluton or plutons within the granodiorite field.

Brookins and Majumdar (1982, 1989) and Majumdar (1985) have reexamined the question of whether the Sandia granite is made up of one or two plutons. They present the results of whole-rock chemical analysis of 28 samples of the granite; 13 from the South Sandia pluton and 15 from the North Sandia pluton. Variation diagrams plotted from these data strongly suggest that there is only a single pluton. Four of these variation diagrams are reproduced here as Fig. 5 with the analyses of the Fenton Hill granodiorite plotted for comparison.

To supplement the chemical data presented by Condie and Budding (1979) and Brookins and Majumdar (1989), two samples of the Sandia pluton were collected in Tijeras Canyon. Analyses of major and trace elements in all the samples are given in Tables 1 and 2. Chemically, the Sandia pluton, like the Fenton Hill granodiorite, is characterized by high Fe_2O_3, FeO, K_2O, TiO_2, and P_2O_5.

Geochronology of the Fenton Hill granodiorite and the Sandia granite

Extensive geochronological work has been done on the Fenton Hill granodiorite, the Sandia granite, and the gneisses into which they were intruded. Although a wide variety of isotopic dating methods have been applied to the Fenton Hill granodiorite and the Sandia granite, the emplacement ages can be determined most ☞

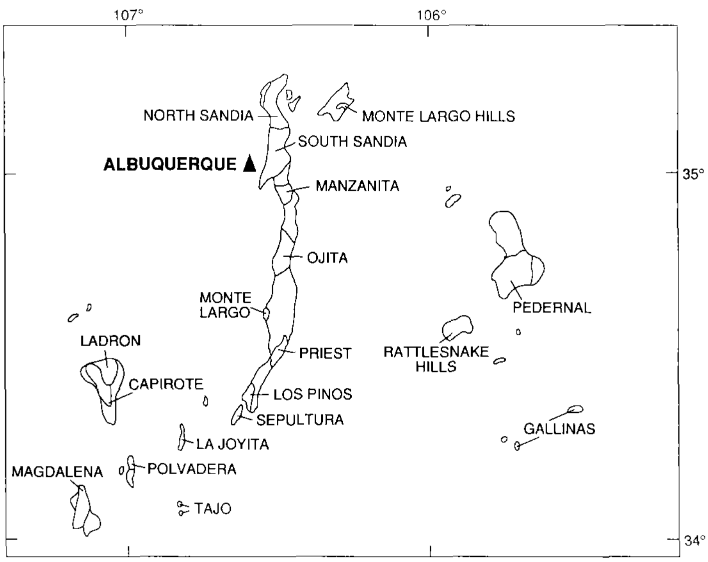

FIGURE 3—Sandia and associated Precambrian plutons of central New Mexico. Modified from Condie and Budding (1979).

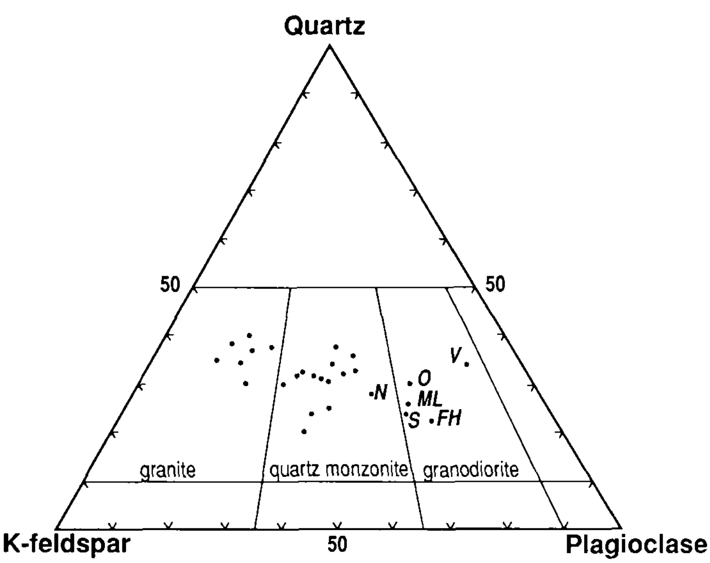

FIGURE 4—Ternary diagram of Precambrian plutons in central and south-central New Mexico. Plutons are: N, North Sandia; S, South Sandia; FH, Fenton Hill; V, VC–2B; O, Ojita; and ML, Monte Largo. Modified from Condie and Budding (1979).

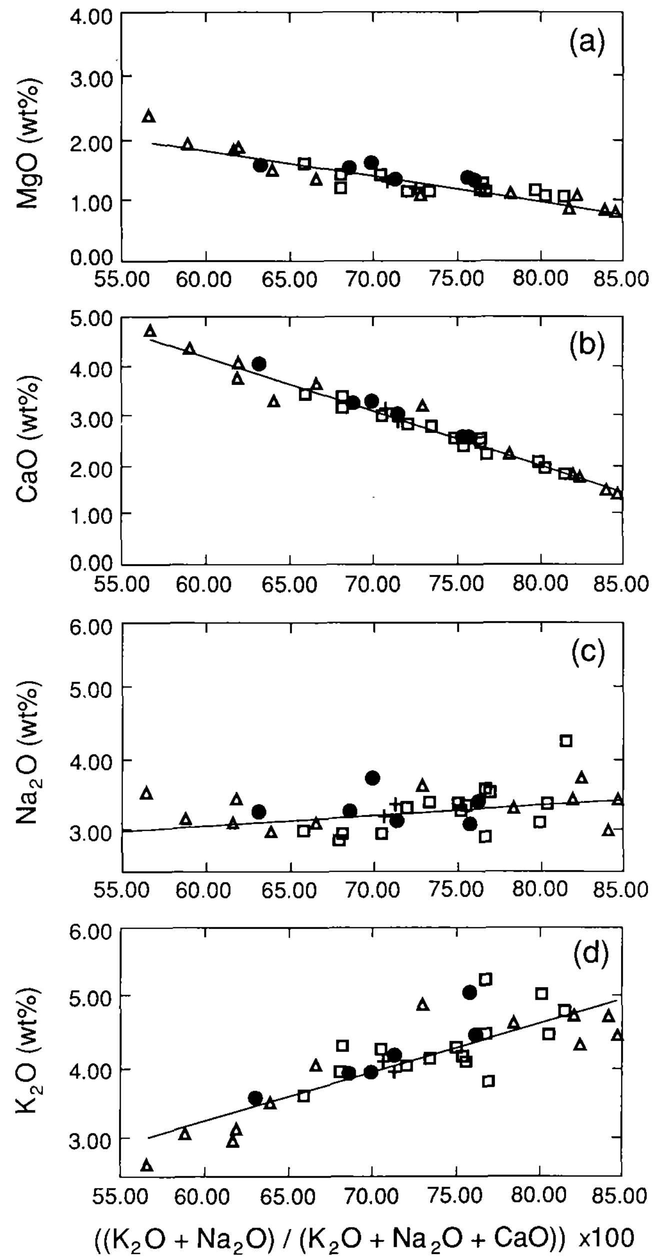

FIGURE 5—Variation diagrams for Sandia and Fenton Hill plutons. Modified from Majumdar (1985). (a)–(d), component vs felsic index. □, Sandia pluton; Δ, South Sandia pluton; ●, Fenton Hill granodiorite; +, VC–2B granodiorite (Fenton Hill).

accurately by the Rb/Sr and U/Pb isotopic methods. High temperatures resulting from nearby volcanism (Fenton Hill) and/or deep burial (Fenton Hill and Sandia Mountains) would lead to argon loss and fission-track annealing and, thus, K/Ar and fission-track ages that are less than the crystallization ages. Such perturbations for the Fenton Hill samples have been discussed by Brookins et al. (1977). Two K/Ar ages of 1.35 and 1.40 Ga have been obtained from a sample of the Precambrian rocks from VC–2B by Laughlin and Shafiqullah (unpub. data). This sample was undoubtedly affected by the present high in situ temperature of almost 300°C.

Brookins and Laughlin (1983) reported Rb/Sr isochron ages of 1.50 ± 0.12 Ga for the Fenton Hill granodiorite and 1.62 ± 0.04 Ga for the adjacent gneisses. The large error on the granodiorite is the result of the small spread in Rb/Sr ratios of the homogeneous granodiorite. A suite of samples from VC–2B has been collected for Rb/Sr analysis by D. G. Brookins and work is in progress on these samples. Taggert and Brookins (1975) reported Rb/Sr isochron ages (corrected for the new decay constant) of 1.47 ± 0.02 Ga for the Sandia granite and 1.58 ± 0.07 Ga for the Cibola gneiss, and Brookins and Majumdar (1982) report a Rb/Sr isochron age of 1.44 ± 0.04 Ga for the Sandia granite.

The Rb/Sr isochron age of 1.50 Ga on the Fenton Hill granodiorite was confirmed by the Pb/Pb model age results of Zartman (1979). His results from sphene and zircon indicate an age of 1.50 ± 0.02 Ga. He also calculated a model age of 1.50 Ga for microcline from the granodiorite. The Sandia granite Rb/Sr isochron is also confirmed by lead isotopic data. The Pb^{207}/Pb^{208} dates of Tilton et al. (1962), Steiger and Wasserburg (1969), and Tilton and Grunenfelder (1968) average 1.47 ± 0.02 Ga. Steiger and Wasserburg (1969) suggested an original age of formation between 1.49 and 1.64 Ga. This large range resulted from the model used for episodic lead loss and from the material analyzed. All lead isotopic results were summarized by Brookins (1974).

Equivalence of the Fenton Hill granodiorite and the Sandia granite

Although it is difficult to prove that two plutonic rocks are comagmatic without continuity in outcrop, a number of mineralogical, chemical, and geochronological lines of evidence can be brought to bear to suggest that the correlation is probable. Clearly, these two units are similar and probably crystallized at about 1.50 Ga. They are chemically and mineralogically very similar and have undergone related magmatic histories. The probability of correlation is increased because the two units are compositionally distinct from other plutons in the region.

Both plutonic rocks are chemically similar in both major and trace elements. They are distinctive in having high TiO_2 and K_2O relative to SiO_2. On a ternary diagram of quartz/k-feldspar/plagioclase modal mineralogy, the Fenton Hill granodiorite plots close to the Sandia pluton. Plutons with similar modal mineralogy, reported by Condie and Budding (1979), include the Monte Largo and Ojita plutons. The Sandia, Monte Largo, and Ojita plutons crop out within a relatively small area east of Albuquerque and could be connected at depth. The Sandia, Fenton Hill, Monte Largo, and Ojita plutons are the most plagioclase-rich of the 32 plutons shown in Fig. 4.

Another point of similarity between the Sandia granite and the Fenton Hill granodiorite is presented in table 5 of Condie and Budding (1979). These authors show that the North and South Sandia plutons, in contrast to 28 other plutons in central and south-central New Mexico, are characterized by high (1–1.5%) sphene contents. Only one other pluton, the White Sands, contained more than a trace of sphene. Bauer and Lozinsky (1986), however, have reported high sphene contents in a Proterozoic pluton in the Caballo Mountains. As discussed above, the Fenton Hill granodiorite is also characterized by high sphene contents.

No available chemical, mineralogic, or geochronological evidence refutes the suggestion that the Fenton Hill granodiorite and the Sandia pluton are equivalent.

Discussion

Several workers have suggested that the Colorado Plateau was translated north–northeastward during Laramide deformation (Woodward and Callendar, 1977, Chapin and Cather, 1981, and Chapin, 1983). To evaluate the magnitude of this translation they have examined evidence for offset of various geologic features across the zone of decouping, i.e. the Rio Grande rift, focusing on features that intersect the zone at a high angle. Chapin and Cather (1981) found that although the Jemez lineament is well defined southwest of the Valles caldera and may continue to the Taos area, it is poorly defined northeast of Taos. Because a line drawn through the volcanic fields of northeastern New Mexico projects southwestward to the Tijeras–Canyoncito fault system near Albuquerque, they suggested that this fault system is a right-lateral offset of the Jemez lineament. If this interpretation is correct, 90–120 km (56–75 mi) of offset are suggested.

Chapin and Cather (1981) also estimated the magnitude of the displacement from the offset of the Precambrian province boundary that trends northeastward across New Mexico. This boundary, which separates 1.72–1.80 Ga supracrustal rocks in the north from 1.65–1.72 Ga supracrustal rocks in the south, is approximately coincident with the Jemez lineament. The boundary is offset approximately 80 km (50 mi) right laterally across the Rio Grande rift.

Chapin and Cather (1981) also obtained an estimate of 65 km (41 mi) of right-lateral offset of the Capitan lineament as it crosses the Rio Grande rift onto the Colorado Plateau. A correlation of similar Precambrian and early Paleozoic rocks across the rift in the Caballo Mountains area yielded an estimate of 120 km (75 mi) of right-lateral translation.

Chapin and Cather (1981) state, "The above correlations of possible offset features along the eastern Colorado Platea margin are highly speculative but may serve as a starting point in the search for more reliable data." I hope that the data presented in this short note meet the criteria for more reliable data and contribute to our understanding of early displacement along the Plateau margin.

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Yeso Formation

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Grassy Lookout quadrangle

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