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A Geothermal Investigation of Low-Temperature Mineralized Fluids

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WATER GEOCHEMISTRY OF THE LUCERO UPLIFT, NEW MEXICO
A Geothermal Investigation of Low-Temperature Mineralized Fluids

by

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ABSTRACT

A detailed geochemical investigation of 27 waters of the Lucero uplift, central New Mexico, was performed to determine if the fluids originate from a high-temperature geothermal system along the Rio Grande rift. Two types of mineralized water issue from the Lucero region: a relatively saline (high-Cl, high-SO₄) type and a relatively dilute (low-Cl, high-SO₄) type. Emergence temperatures of both types range from 12 to 26°C. Chemical data and thermodynamic and geothermometer calculations all indicate that both water types are in equilibrium with carbonate and evaporite minerals found in local Colorado Plateau rocks at surface temperatures or slightly higher. Stable isotope data do not indicate high-temperature rock-water interaction. Although we do see evidence for mixing between mineralized waters and dilute surface waters, we see no evidence for mixing of a deep hot fluid and surface waters. Dilute mineral waters, which issue from a large area of Chinle Formation on the west side of the Lucero uplift, may be useful for low-temperature geothermal applications with appropriate design of equipment. Saline mineral waters, which leak from a zone of faulted and folded rocks along the Comanche fault zone, do not appear to have much, if any, geothermal potential due to their low-temperature, restricted distribution, and high concentration of dissolved solids. We see no evidence that saline mineral waters are associated with Quaternary faults of the Rio Grande rift or Quaternary basaltic volcanism within the immediate area.

I. INTRODUCTION

The Lucero uplift is an arid region of low mountains and mesas that locally forms the western topographic and structural boundary of the Albuquerque Basin, Rio Grande rift (Callender and Zilinski 1976). The rift is a major physiographic feature of the southwestern United States, stretching from Colorado to northern Mexico. It is characterized by active extensional tectonics, late-Tertiary to recent basaltic volcanism, high regional heat flow, and above-normal thermal gradients (Chapin et al. 1978; Reiter et al. 1975, 1978). Basaltic flows and cinder cones as young as 0.32 Myr have erupted in the Lucero uplift (Bachman and Mehnert 1978; Baldrige et al. 1980) and gravity investigations by Ander and Huestis (in prep.) suggest that mafic magma less than 2 Myr has been injected as a laccolith beneath the Lucero uplift and its boundary with the Rio Grande rift (Fig. 1).

Fig. 1.

Sketch map of the Albuquerque Basin of the Rio Grande rift, New Mexico, showing locations of the Lucero uplift region and other features mentioned in text.

The Lucero uplift is also characterized by an unusual suite of mineralized low-temperature waters (12 to 26°C) that issue from faulted rocks along the rift margin and from relatively undeformed rocks to the west (Wright 1946; Trainer and Lyford 1979). Calculated subsurface reservoir temperatures using the normal Na-K-Ca chemical geothermometer (Fournier and Truesdell 1973) exceed 100°C. Because of these calculations and the association of the waters with Quaternary faulting and volcanism, and high regional heat flow, some investigators have suggested that the mineralized fluids are derived in part from geothermal reservoirs of deep origin (Callender and Zilinski 1976; Trainer and Lyford 1979). This report investigates in detail the chemistry and origin of these fluids and evaluates the geothermal potential of the Lucero uplift. This work is designed to support regional hot dry rock (HDR) and low-temperature geothermal investigations being conducted by Los Alamos National Laboratory in the Rio Grande rift.

II. GEOLOGIC OVERVIEW

The Lucero monocline, which dips to the east and plunges to the north, was formed by compressional tectonics during the Laramide orogeny (Kelly and Wood 1946). It is not clear whether the broad structural features of the region formed entirely during the period of Laramide tectonism or whether some structural uplift occurred during Quaternary intrusion of the postulated laccolith of Ander and Huestis (in prep.). The entire structural block is roughly 50 x 20 km in dimension (Fig. 2). Late-Tertiary high-angle faults created during formation of the Rio Grande rift are now superimposed on the Lucero monocline (Kelly and Clinton 1960; Ducshatko 1953). To the north lies the Rio Puerco fault zone (Slack and Campbell 1976), whereas to the southeast lies the Ladron Mountains, an uplifted fault block exposing Precambrian basement. Two recently identified northeast-trending linear features defined by various geologic structures and geophysical and volcanic alignments apparently cross the Colorado Plateau-Rio Grande rift boundary north and south of the Lucero uplift (Fig. 1). These linears may possibly form tectonic boundaries to the uplift (Ander and Huestis in prep.).

A. Stratigraphy

Rocks of the Colorado Plateau that extend into the Lucero uplift region are composed mainly of about 2000 m of Paleozoic to Mesozoic carbonates,

Fig. 2.

Simplified geologic map of the Lucero uplift region, New Mexico; Lucero monocline axis is shown only on northeast edge of map. Numbers adjacent to spring and well symbols correspond with sample numbers in tables. Remaining numbers show dip of sedimentary rocks. Map modified from Kelly and Wood (1946), Wright (1946), Jicha (1958), and Callender and Zilinski (1976).

sandstones, shales, and evaporites (Fig. 2). Thickness of the sequence increases to the west due to the gentle dip of the west flank of the Lucero monocline. These older rocks are juxtaposed against unconsolidated late-Tertiary sediments of the Rio Grande rift (Callender and Zilinski 1976). Small intrusions of gabbro, diorite, and monzonite of Oligocene age have been injected along various stratigraphic horizons and faults within and bordering the Lucero uplift (Jicha 1958; Gambill 1980).

Carbonate and evaporite rocks of the uplift are noteworthy because they may be the source of soluble minerals producing the unusual chemistry of local groundwaters (Wright 1946; Titus 1963). For example, the Madera and San

Andreas limestones consist of up to 600 m of limestone and dolostone, while beds of gypsum 3 m or more in thickness occur in the Yeso and Chinle Formations (Jicha 1958; Hunter 1980).

B. Structure

Callender and Zilinski (1976) divided the structural evolution of the eastern Lucero uplift into four episodes starting with formation of the monocline and ending with rift-style faulting. The Lucero monocline becomes an undulating thrust fault in the south part of the study area, and this thrust is cut by later high-angle reverse to normal faults. We refer to all these complex faults as the Comanche fault zone because they appear to be a closely related group of structures. During our field work in May 1980, we noted that mineral springs of the eastern Lucero uplift discharge only from faults comprising the Comanche fault zone.

The Santa Fe fault, just east of the Comanche fault zone, is a high-angle normal fault forming the tectonic margin of the Rio Grande rift. Offset along this fault is roughly 3500 m on the basis of exposed stratigraphy to the west and downhole stratigraphy of the Shell Santa Fe No. 2 drilled 12 km to the east. Latest movements on the Santa Fe fault are Quaternary (Kelly and Wood 1946). We found no active springs or old spring deposits aligned along the Santa Fe fault although the fault cuts older travertines formed along the Comanche fault zone to the west.

Geologic structure on the western side of the Lucero uplift is much simpler, consisting of relatively undeformed rocks cut by a few normal faults of small displacement. Mineralized springs and wells discharge from rocks of the Chinle Formation in arroyos between high mesas. Springs in Arroyo Colorado appear to issue from a northeast trending fault or fracture zone also utilized by a chain of late Tertiary to Quaternary basaltic eruptions.

C. Late-Tertiary Volcanism

The latest episode of igneous activity in the Lucero uplift region produced tholeiitic to alkali-rich basaltic flows, plugs, and cinder cones ranging from 7.2 to 0.32 Myr in age (Baldrige et al. 1980; Bachman and Mehnert 1978; see also Jicha 1958). Older flows of this group cap mesas throughout the area and are interbedded with scattered deposits of travertine, some of considerable volume (Jicha 1958; Wright 1946).

A large positive residual Bouguer gravity anomaly of >25 mgals straddling the Lucero monocline-Rio Grande rift boundary is interpreted by Ander and Huestis (in prep.) to be caused by a basaltic intrusive body emplaced across the Santa Fe fault. The source of this anomaly is apparently not more than 1.25-km deep but the gravity contours are not noticeably offset by the fault, thus, the intrusive is estimated to be <2 Myr. However, there is no evidence for enhanced spring activity or other geothermal phenomena above or surrounding this buried intrusion, suggesting that it has long since cooled to the regional geothermal gradient temperature.

III. MINERAL WATERS

A. Sampling and Analysis

All water samples were collected in early May 1980 except for LUC-1 (Table I), which was sampled the previous January. Field and laboratory procedures for the collection, preservation, and analysis of water samples are described in a previous report (Goff et al. 1982). Al was determined using a modification of a procedure of Barnes (1975), and field Eh was measured by standardizing the meter with Quinhydrone (Kodak 217) mixed in pH4 and pH9 buffer solutions. Field data, major and trace element chemistry, and D and ¹⁸O isotopic data of waters are listed in Tables I and II. Samples of spring precipitates were analyzed by x-ray diffraction (Table III). Field and chemical data were entered as input to the computer code SOLMNEQ (Kharaka and Barnes 1973) to calculate thermodynamic values of typical rock-forming and secondary minerals that may be in equilibrium with mineralized fluids (Table IV).

B. Geochemistry and Geohydrology

All mineral fluids of the Lucero uplift region are composed of sodium-calcium sulfate-chloride-bicarbonate water but two very distinct chemical types can be distinguished on a trilinear plot of major anions (Fig. 3) and on chloride variation diagrams (Fig. 4): a relatively saline, high-SO₄, high-Cl type (type S) that issues along the Comanche fault zone, and a relatively dilute, high-SO₄, low-Cl type (type D) that discharges from Arroyo Colorado and adjacent valleys west and northwest of the Lucero monocline (see also Trainer and Lyford 1979). Type S saline springs leak eastward down arroyos and steep canyons in the structurally complex Lucero monocline. These fluids

TABLE I
FIELD DATA AND CHEMICAL ANALYSES OF 27 MINERAL AND "POTABLE" WATERS OF THE LUCERO UPLIFT REGION, NEW MEXICO
(analyses reported in mg/l; locations on Fig. 2)

Field No.	Name	Water Type ^a	Rock Type ^b	Flow, l/min	Temp, °C	Field pH	Field Eh, mv	Conduc., umho/cm	SiO ₂	Al	Ca	Mg	Na	K	Li	HCO ₃	SO ₄	Cl	F	B
LUC-1	Unnamed Salt Spg ^c	S	Pm	20	12	6.40	--	28400	18	0.190	723	313	5370	85	3.80	2370	2910	7470	0.78	3.80
LUC-2	Crane Spg ^d	D	Trc	6	19	7.08	110	3700	21	0.200	593	108	238	20	0.84	395	2120	114	1.80	0.89
LUC-3	Eddleman Spg	D	Trc	3	15	7.20	70	3700	12	0.070	555	107	225	20	0.78	448	1980	99	2.20	0.87
LUC-4	Unnamed Salt Lick ^e	S	Pm, Py	seep	18	7.40	-15	17000	23	0.021	470	399	2900	28	0.92	819	2470	4390	0.97	2.45
LUC-5	Unnamed Salt Spg	S	Pm	1/2	23	6.58	75	>20000	20	0.013	840	192	8070	180	8.00	1560	4490	10600	1.26	9.20
LUC-6	Unnamed Windmill	P	Tsf	0-6	18	7.32	--	5500	18	--	490	265	509	2.5	0.30	266	2860	531	1.15	1.18
LUC-7	Red Windmill	P	Trc	0-8	16	6.9	--	2900	18	--	379	144	141	8.0	0.45	487	1200	115	0.06	0.96
LUC-8	Lucero Spg ^f	D	Trc	12	16	6.60	-185	4400	23	0.078	634	155	293	13	0.78	467	1900	298	1.28	0.82
LUC-9	Romero Windmill	P	Pa	0-8	15	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
LUC-10	Seis-Wilson Windmill	P	Trc	0-30	17	7.4	--	1640	14	--	10.7	3.18	338	4.8	0.08	586	247	48	1.64	1.20
LUC-11	Salado Spg	D	Trc	2	25	6.46	25	3800	15	0.032	670	92.4	195	21	0.52	425	1990	156	1.87	0.68
LUC-12	Apache Spg	D	Trc	2	19	6.60	-270	3900	19	0.022	584	89.6	300	22	0.905	459	1990	141	2.43	0.80
LUC-13	Lonely Windmill	D	Trc	0-10	20	7.72	--	3800	15	--	600	101	245	24	0.875	327	2140	130	2.29	0.80
LUC-14	Hiyi Windmill	P	Trc	0-20	20	7.65	--	5000	13	--	56	10.6	1100	1.2	0.38	515	2100	157	1.87	1.30
LUC-15	Unnamed Windmill	P	Trc	0-20	18	7.68	--	700	19	--	32.4	16.8	87	1.0	0.04	243	126	14	0.61	0.34
LUC-16	Red Spg	P	Tb, Trc	seep	17	7.5	--	1010	17	--	4.6	2.51	227	0.3	0.024	414	49	7.9	2.8	0.60
LUC-17	Artesian Well	D	Trc	10	26	6.82	-200	4000	15	--	450	85.7	475	10.3	0.94	475	2070	145	2.1	1.03
LUC-18	Dog Hole Windmill	P	Trc	0-10	16	8.68	--	1680	17	--	5.6	1.41	351	0.2	0.052	407	368	127	0.91	0.68
LUC-19	Field Artesian Well ^g	D	Trc	40	25	6.30	-295	3700	14	0.034	624	93.1	214	22	0.77	376	2080	211	2.4	0.78
LUC-20	Ojo Terna	P	Jd	2	14	7.30	--	1150	19	--	12.2	6.80	216	1.8	0.86	288	326	26	0.56	0.32
LUC-21	Rock Tank Windmill	P	Tb	0-5	18	6.73	--	1100	17	--	112	41.2	98	6.2	0.15	272	323	23	1.54	0.41
LUC-22	Ojo Monte Largo ^h	S	Pm	20	14	6.68	-40	>20000	15	0.040	440	283	12200	295	9.0	3250	6500	17000	3.31	10.7
LUC-23	Ojo Pato	S	Pm	10	21	6.42	-110	>20000	21	0.016	660	230	5500	22	3.74	1640	3100	9600	3.9	4.79
LUC-24	Unnamed Windmill	P	Pm	0-8	19.5	6.8	--	1240	18	--	171	56.8	131	5.4	0.165	536	183	46	0.26	0.14
LUC-25	Ojo Saladito	S	Pm	20	24	6.82	5	12000	12	0.012	355	123	1990	46	1.30	740	1170	2960	2.0	1.69
LUC-26	East Tank Windmill	P	Tsf	0-10	23	6.5	--	7000	15	--	76	42.7	1290	44	0.38	476	815	1740	2.7	1.82
LUC-27	Unnamed Salt Spg ⁱ	S	Jm	10	18	7.28	90	>20000	36	--	340	129	8230	250	10.5	1720	6200	9800	3.0	14.5

^a S = Saline mineral type, D = dilute mineral type, P = "potable" waters, either from separate sources or derivatives of types S and D.
^b Jd = Dakota Sandstone, Jm = Morrison Formation, Pa = Abo Formation, Py = Yeso Formation, Pm = Madera Limestone, Trc = Chinle Formation, Tb = Tertiary basalt, Tsf = Santa Fe Formation.
^c See also Trainer and Lyford, 1979, analysis 15, p. 300.
^d See also Wright, 1946, analysis 203, p. 453.
^e See also Wright, 1946, analysis 173, p. 453.
^f See also Wright, 1946, analysis 196, p. 453.
^g See also Jicha, 1958, analysis 23844, p. 58.
^h See also Wright, 1946, analysis 171, p. 453.
ⁱ See also Wright, 1946, analysis 186, p. 453.

TABLE II

TRACE ELEMENT CHEMISTRY AND ISOTOPIC ANALYSES OF 27 MINERAL AND "POTABLE" WATERS IN THE LUCERO UPLIFT REGION, NEW MEXICO (analyses reported in mg/ℓ; locations on Fig. 2)

Field No.	Name	Ba	Fe	Pb	Sr	U ^a	Zn	NO ₃	PO ₄	Br	δD, ‰	δO, ‰
LUC-1	Unnamed Salt Spg	0.026	0.022	--	13.4	0.63	0.025	--	--	--	-83.6	-10.8
LUC-2	Crane Spg	0.007	0.15	0.026	10.5	--	<0.002	<0.2	<0.2	<0.2	-105.1	-14.2
LUC-3	Eddleman Spg	0.004	0.065	0.024	10.2	<0.24	<0.002	<0.2	<0.2	<0.2	-104.0	-14.05
LUC-4	Unnamed Salt Lick	0.004	0.002	0.200	16.3	0.55	<0.002	<0.2	<0.2	1.9	-76.8	-10.45
LUC-5	Unnamed Salt Spg	0.008	<0.001	0.450	13.2	<0.36	<0.002	<0.5	<0.2	3.3	-84.0	-11.0
LUC-6	Unnamed Windmill	0.004	<0.001	0.020	10.6	--	0.002	15.4	<0.2	<0.2	60.0	-8.60
LUC-7	Red Windmill	0.022	<0.001	0.010	6.95	--	0.140	11.0	<0.2	<0.2	-63.8	-9.35
LUC-8	Lucero Spg	0.007	0.59	0.030	11.4	<0.24	<0.002	<0.2	<0.2	<0.2	-70.9	-10.05
LUC-9	Romero Windmill	--	--	--	--	--	--	--	--	--	-76.0	-10.5
LUC-10	Seis-Wilson Windmill	0.002	0.021	0.006	0.35	--	0.060	10.6	<0.2	<0.2	-74.2	-10.1
LUC-11	Salado Spg	0.003	5.83	0.024	9.42	<0.24	0.004	<0.2	<0.2	<0.2	-88.1	-12.15
LUC-12	Apache Spg	0.022	11.2	0.030	8.27	--	<0.002	<0.2	<0.2	<0.2	-94.0	-12.75
LUC-13	Lonely Windmill	0.007	0.27	0.026	8.80	--	0.008	<0.2	<0.2	<0.2	--	--
LUC-14	Hiyi Windmill	--	0.67	0.048	2.32	--	0.110	<0.2	<0.2	<0.2	--	--
LUC-15	Unnamed Windmill	0.010	0.045	0.024	1.12	--	0.200	14.0	<0.2	<0.2	-52.7	-7.80
LUC-16	Red Spg	0.005	0.019	0.016	0.16	--	0.005	7.4	<0.2	<0.2	--	--
LUC-17	Artesian Well	0.008	31.7	0.034	8.04	--	<0.002	<0.2	<0.2	<0.2	--	--
LUC-18	Dog Hole Windmill	0.058	0.144	0.038	0.16	--	0.050	<0.2	<0.2	<0.2	--	--
LUC-19	Field Artesian Well	0.009	4.70	0.023	9.33	--	0.025	<0.5	<0.5	<0.5	-96.5	-13.20
LUC-20	Ojo Ternerera	0.008	0.038	0.044	0.54	--	0.019	2.4	<0.2	<0.2	--	--
LUC-21	Rock Tank Windmill	0.010	0.045	0.006	2.50	--	0.300	<0.2	<0.2	<0.2	--	--
LUC-22	Ojo Monte Largo	0.010	0.80	0.410	9.84	--	0.024	<1.0	<1.0	12.3	--	--
LUC-23	Ojo Pato	0.022	0.36	0.220	12.1	--	0.003	<1.0	<1.0	4.1	--	--
LUC-24	Unnamed Windmill	0.077	0.034	0.004	2.60	--	0.064	19.0	<0.2	<0.2	--	--
LUC-25	Ojo Saladito	0.070	0.114	0.076	7.17	--	0.010	3.2	<0.5	1.6	-66.6	-9.15
LUC-26	East Tank Windmill	0.030	0.106	0.080	1.96	--	0.170	9.9	<0.5	<0.5	--	--
LUC-27	Unnamed Salt Spg	0.010	0.074	0.220	12.3	--	0.055	<1.0	<1.0	9.3	--	--

^a Samples obtained October 1981 and analyzed by G. Bayhurst, Los Alamos National Laboratory.

TABLE III

MINERAL DEPOSITS OF SIX SPRINGS ISSUING IN THE LUCERO UPLIFT REGION, NEW MEXICO
(mineral identification by x-ray diffraction; locations on Fig. 2)

Sample No.	Name	Description	Mineral Phases
<u>Type S Mineral Waters</u>			
LUC-1a	Unnamed Salt Spg	poorly crystallized white travertine	aragonite, halite, calcite, quartz
LUC-4a	Unnamed Salt Lick	crusty white deposit	aragonite, halite, gypsum, calcite
LUC-4b1	Unnamed Salt Lick	red earthy deposit	quartz, calcite, halite, aragonite
LUC-4b2	Unnamed Salt Lick	travertine	aragonite, calcite, halite
LUC-4c	Unnamed Salt Lick	massive travertine	aragonite, calcite
LUC-5a	Unnamed Salt Spg	fine-grained travertine	calcite, quartz
LUC-5b	Unnamed Salt Spg	white coral-like deposit	thenardite, halite
LUC-5c	Unnamed Salt Spg	white stalactite	halite, thenardite
<u>Type D Mineral Waters</u>			
LUC-2a	Crane Spg	coral-like travertine	gypsum, calcite, quartz
LUC-3a	Eddleman Spg	'wormy' travertine	calcite, gypsum
LUC-8a	Lucero Spg	'wormy' travertine	gypsum, calcite, quartz

TABLE IV
REACTION STATES OF MINERAL SPRING AND WELL WATERS WITH RESPECT TO SELECTED MINERALS;
VALUES IN kcal CALCULATED USING SOLMNEQ
(sample locations on Fig. 2, data from Tables I and II)

	Type S Mineral Waters						Type D Mineral Waters					
	LUC-1	LUC-4	LUC-5	LUC-22	LUC-23	LUC-25	LUC-2	LUC-3	LUC-8	LUC-11	LUC-12	LUC-19
<u>Secondary Non-Silicates</u>												
Aragonite	0.27	0.95	0.51	0.45	0.22	0.22	0.40	0.52	-0.14	-0.20	-0.15	-0.54
Barite	0.14	-0.95	-0.77	-0.33	0.17	0.36	-0.36	-0.60	-0.37	-1.05	0.27	-0.37
Brucite	-9.6	-6.4	-9.0	-8.9	-9.2	-8.2	-7.9	-7.8	-9.1	-9.3	-9.2	-9.7
Calcite	0.31	1.0	0.57	0.50	0.27	0.28	0.45	0.57	-0.09	-0.14	-0.10	-0.48
Celestite	-0.62	-0.40	-0.61	-0.67	-0.71	-1.1	-0.35	-0.37	-0.38	-0.46	-0.51	-0.44
Cerrusite	--	2.1	1.4	1.6	0.84	0.88	0.85	1.1	0.35	-0.06	0.37	-0.39
Dolomite	0.80	2.6	0.99	1.4	0.64	0.64	0.59	0.86	-0.33	-0.74	-0.60	-1.4
Fe(OH) ₃	--	-10	-14	-10	-11	-9.6	-8.8	-9.1	-10	-8.7	-8.2	-9.5
Fluorite	-1.3	-1.1	-0.56	0.22	0.69	-0.19	0.08	0.38	-0.28	0.15	0.48	0.39
Gypsum	0.15	-0.02	0.24	-0.01	0.06	-0.42	0.39	0.35	0.35	0.41	0.35	0.39
Strontianite	1.4	2.2	1.1	1.6	1.0	1.1	1.3	1.6	0.84	0.53	0.62	0.23
Witherite	0.56	0.24	-0.33	0.40	0.18	1.2	-0.13	-0.15	-0.61	-1.5	-0.01	-1.2
<u>Primary Silicates</u>												
Albite High	0.20	1.4	-0.75	-1.2	-2.7	-1.9	0.42	-0.91	-1.2	-3.8	-3.2	-5.0
Anorthite	-3.6	-0.16	-4.4	-6.5	8.5	-4.1	1.34	-0.45	-2.6	-5.2	-6.0	-7.5
Microcline	2.5	3.6	1.8	-1.5	-0.09	0.68	3.8	2.6	1.9	-0.37	0.09	-1.6
Muscovite	17	19	14	13	9.1	14	21	19	17	12	12	9.1
Quartz	0.93	0.93	0.75	0.76	0.86	0.43	0.83	0.58	0.94	0.53	0.77	0.49
<u>Secondary Silicates</u>												
Albite Low	1.5	2.9	0.70	0.29	-1.2	-0.40	1.9	0.58	0.32	-2.4	-1.8	-3.5
Analcime	-1.4	-0.03	-2.0	-2.4	-4.0	-2.8	-0.91	-2.0	-2.6	-4.9	-4.5	-6.0
Chlorite	-1.6	15	-0.07	-1.8	-5.2	2.9	9.7	8.1	1.2	-3.2	-3.4	-7.3
Chrysotile	-13	-3.4	-11	-11	-12	-9.7	-8.0	-8.2	-11	-13	-12	-14
Kaolinite	6.6	7.1	4.3	3.3	1.0	4.2	9.2	7.5	6.8	3.6	3.1	1.8
Montmorillinite	7.5	8.6	4.7	3.5	1.1	4.2	10	8.1	7.5	3.3	3.1	1.1
Zoisite	-2.0	4.5	-3.0	-5.8	-9.3	-2.3	6.4	3.9	-0.99	-4.4	-5.2	-8.1

Fig. 3.

Trilinear plot of major anions in equivalents for all water types of the Lucero uplift region, New Mexico.

discharge either from travertine mounds or from alluviated arroyos that may be partly filled with a labyrinth of travertine pools (Fig. 5). Obvious discharge of CO₂ was noted at only three of these springs (LUC-1, 22, and 23; Table I). Type D mineral waters all issue from relatively undeformed Chinle Formation. They flow from broad grass-covered travertine mounds up to 10 m high and 1/2 km across or from a variety of artesian wells. Some of the waters deposit copious amounts of iron hydroxides. Obvious discharge of CO₂ occurs only at Lucero Spring (LUC-8).

Other systematic chemical differences besides SO₄ and Cl distinguish the two water types. For example, although the absolute concentration of B and Li is greater in type S waters, the B/Cl and Li/Cl ratios are considerably higher in type D waters. These chemical characteristics are apparent in the chloride variation diagrams of Fig. 4.

Additional chemical features are noteworthy. Concentrations of SiO₂ are ≤ 36 mg/l in all water samples, considerably less than silica concentrations in

Fig. 4.

Chloride variation diagrams of six selected species for mineral waters of the Lucero uplift region, New Mexico; numbered points refer to saline type S waters. Please note broken scale on chloride concentration axes and sodium axis.

high-temperature geothermal waters. The concentration of Ca + Mg is 2 to 3 times greater than Na concentration in type D waters, and is high in all mineralized waters, up to 1000 mg/l. The mole ratio of Na/Cl averages 1.09 for saline type S waters but averages 2.88 in more dilute type D waters to the west. Concentrations of Fe may exceed 30 mg/l in dilute type D mineral waters because they issue from iron-rich redbeds of the Chinle Formation. Sr concentration increases with Ca + Mg whereas Br increases with Cl.

From examination of this chemical data, we conclude as Wright (1946) and Titus (1963) have, that mineral waters of the Lucero uplift region are dissolving gypsum, limestone, dolostone, and evaporite minerals from stratified

Fig. 5.

Photo of travertine pools in Arroyo Salado, 200 m downstream (east) of Unnamed Salt Spring, LUC-1. Ridge in background is composed of west-dipping Madera Limestone (Pennsylvanian).

rocks of the Colorado Plateau section. We add, however, that saline waters of the Lucero monocline are dissolving halite from some unknown source that is not available to type D waters. Five of the mineral springs listed in Tables I and II were previously sampled by Wright (1946, pp. 452-453). Comparison of his data with ours indicates that mineral waters of the Lucero uplift have not varied significantly in major element chemistry for the last 35 years.

Most "potable" waters throughout the region (that is, water used for stock and human consumption) also contain solutes derived from older sedimentary rocks (Table I) and appear to grade chemically with type D waters (Fig. 3). In general, waters containing the least amount of dissolved solids issue either from or near the base of basalt flows (LUC-15, 16, and 21) or from sandstones stratigraphically above the Chinle Formation (LUC-20).

A plot of δD vs $\delta^{18}O$ (Fig. 6) shows that all mineral and potable waters of the region fall along the Craig meteoric water line (Craig et al. 1956). However, the range in isotopic values is remarkable for a sampling area of only 1200 km^2 having a maximum elevation difference of only 600 m. The two mineralized water types plot along different sections of the Craig line, but even these two groups of points display considerable scatter. Possibly, the waters are relatively old and their original isotopic conditions have changed with time. We conclude that neither mineralized water type originates from

Fig. 6.

Plot of deuterium vs oxygen-18 for all water types of the Lucero uplift region, New Mexico; triangles = type S waters, squares = type D waters, dots = "potable" waters. Numbers refer to sample numbers in tables.

one large aquifer having a unique recharge area of constant isotopic composition.

All type S waters that were sampled display a slight enrichment of ^{18}O with respect to the Craig meteoric water line. We do not know if this subtle enrichment is due to normal isotopic variations caused by the arid climate, due to a small amount of evaporation, or due to presence of a very small proportion of connate water being leached from pores of marine carbonate rocks. If the ^{18}O shift arises from connate water, the shift is very tiny compared to ^{18}O shifts displayed by other connate waters of similar salinity (White et al. 1973; Lesniak 1980). We strongly doubt, based on arguments discussed in Section III-D, that the ^{18}O shift is due to high-temperature (>100°C) rock-water interaction in a deep geothermal environment.

The relationship between $\delta^{18}\text{O}$ and altitude is displayed in Fig. 7a. Five potable waters from locations scattered throughout the Lucero uplift produce a trend of decreasing ^{18}O with increasing emergence altitude. From examination of topographic maps and using our geologic knowledge of the area, we estimated recharge elevations for the five waters, shown by additional points to the right of numbered points. A linear regression curve fit of these

estimated points (line A) has a coefficient of determination, $r^2 = 0.92$ and a gradient (slope), $m = -1.3 \text{ } \delta^{18}\text{O}/100 \text{ m}$ (Fontes 1980). Type S and type D mineral waters plot as distinct but diffuse clusters of points below line A. We do not know if horizontal extrapolations of individual points in these groups to line A (as shown by thin dashed line B in Fig. 7a) yield reliable estimates of recharge elevation. However, in the case of type D waters, these estimates of recharge elevation are reasonable because rocks of the Chinle Formation and San Andreas limestone crop out along the crest of the Sierra Lucero at elevations approaching 2400 m and dip westward into the valleys where type D springs and wells discharge. The artesian behavior of LUC-17 and LUC-19 is easily explained by a recharge zone of high elevation and fluid flow down the dip of stratified rocks (Fig. 8). Such a model can also explain the recharge elevations of type S waters although their structural setting is more complex.

Figure 7b is a plot of $\delta^{18}\text{O}$ versus Cl (please note the broken scale on the Cl concentration axis). The five potable waters shown in Fig. 7a plot

Fig. 7.

Plot of oxygen-18 vs altitude (Fig. 7a) and chloride (Fig. 7b); symbols same as Fig. 6. Numbers in Fig. 7a refer to sample numbers of five potable waters listed in tables. Points to right of numbered points are estimated recharge elevations of the potable waters and line A is a linear regression curve fit of these points. Line B shows the extrapolation of recharge elevation from emergence elevation of one of the type D waters, LUC-19. Lines C and D in Fig. 7b are linear regression curve fits to data of type D and type S waters, respectively.

with no correlation on Fig. 7b and, thus, are not shown. However, type S and type D mineral fluids plot as two distinct trends with opposite slopes. This suggests different origins for the two water types. Linear regression curve fits to these trends (lines C and D) yield coefficients of determination, $r^2 = 0.71$ and 0.76 , respectively.

We do not see any chemical or isotopic evidence for mixing between type S and type D mineral fluids. First, each water type plots as a unique cluster of points in different corners of the trilinear diagram of major anions (Fig. 3). Second, chloride variation diagrams (Fig. 4) show that type D waters have very restricted compositions and different chemical trends compared with type S waters. Third, the diagram of $\delta^{18}O$ versus chloride (Fig. 7b) indicates each water type has a unique correlation of these parameters although we cannot explain why this is so. On the other hand, chloride variation diagrams reveal that type S waters possess reasonable linear relationships with Na, Li, HCO_3 , SO_4 , and B and that these relationships point toward the origins of the diagrams. These facts suggest that type S waters are diluted with surface meteoric waters having relatively low dissolved solids.

From examination of our data and the regional geology, we conclude that the two mineralized waters of the Lucero uplift have different hydrologies as well as different chemistries (Fig. 8). Type D mineral waters flow within a broad area on the west, gently dipping flank of the Lucero monocline and they issue from some wells and from springs. Examination of the driller's log of the Field Artesian Well (LUC-19) shows that approximately 4.2×10^4 gal/min of water were originally produced at a depth of 200 m from the base of the Chinle Formation and the top of the underlying San Andreas limestone (Jicha 1958, p. 34). In contrast, saline type S waters of the Lucero monocline discharge only from the Comanche fault zone and appear to originate at depth within the complexly deformed narrow fault blocks between the Comanche and Santa Fe faults. Saline water does not apparently circulate in limestone west of the Comanche fault (LUC-24), but it does leak east from this fault into sediments of the Rio Grande rift (LUC-6 and 26; see Titus 1963). On the other hand, it is possible that rocks west of the Comanche fault zone provide recharge to the system.

Trainer and Lyford (1979) have suggested that mineral waters of the Lucero region originate in regional ground-water flow from the San Juan Basin

to the northwest. Regional flow could explain the puzzling range of stable isotope variations observed in Fig. 6.

C. Spring Deposits and Rock-Water Interaction

Mineral phases found depositing from mineral waters of both chemical types are listed in Table III. Calcite, gypsum, and quartz were found in deposits of both types while aragonite, halite, and thenardite (Na_2SO_4) were found only in deposits of saline springs. Biological activity by algae probably induces deposition of both crystalline forms of CaCO_3 from saline waters. Both forms are thermodynamically stable as discussed below. Deposition of soluble sodium salts in crusts and small stalactites occurs only because of the high-evaporation rates in the arid climate.

Chemical analyses of six saline and six dilute mineral waters were processed through the computer code SOLMNEQ to investigate the free energies of various minerals that could be reacting with or produced by the fluids (Table IV). Positive values listed in Table IV mean that the mineral in question is oversaturated with respect to a given fluid while negative values indicate undersaturation. A value of zero indicates saturation. We stress that calculations of this type only tell us what is thermodynamically reasonable; they do not necessarily tell us if an oversaturated mineral will actually precipitate. Also, SOLMNEQ cannot deal with sulfate-chloride interactions that may perturb its predictive capability. However, logical analysis of rock petrology and the data in Table IV can help determine what reactions between coexisting waters and rocks have taken place.

For example, the data of Table IV indicate that most mineral waters of the Lucero region are saturated to oversaturated with calcite, gypsum, and quartz. Calcite, dolomite, and aragonite deposition is more favored from saline type S waters (greater free energy) while gypsum deposition is favored from type D waters. This information correlates very well with the observed spring deposits (Table III). In addition, many of the mineral waters are oversaturated with barite, cerrusite, fluorite, strontianite, and witherite. In contrast, all waters are undersaturated with brucite, celestite, and $\text{Fe}(\text{OH})^3$. We conclude that mineral waters of the Lucero region are reacting with carbonate and evaporite minerals within sediments of the Colorado Plateau.

Are mineral waters of the Lucero region altering local sandstones and shales? We did not observe any alterations around the mineral springs during

Fig. 8.

Schematic cross-section showing postulated geologic and hydrologic environment of type S and type D low-temperature geothermal waters, Lucero uplift region, New Mexico; symbols same as Fig. 2 except pc = Precambrian basement.

May 1980, but petrographic work by Hunter and Ingersol (1981) reveals that many of the sandstones of the Permian Yeso Formation contain authigenic quartz and calcite cements, clay coatings, and minor albite along grain boundaries. In general, the sandstones are composed primarily of quartz and K-spar with lesser quantities of altered plagioclase, sericite (muscovite), and metamorphic rock fragments. In support of these observations, examination of data in Table IV indicates that mineral waters of the Lucero region could contribute to low-temperature diagenesis. Quartz and muscovite are oversaturated in all waters while K-spar is oversaturated in most, thus, the mineral fluids do not dissolve these primary silicates. On the other hand plagioclase is consistently undersaturated; thus, it could slowly react with mineral fluids to help produce authigenic quartz, calcite, albite, and clays observed in the rocks. All the latter phases, with the possible exception of albite, are generally oversaturated. Although these mineral fluids could contribute to observed diagenetic reactions, the diagenetic minerals probably formed soon after the rocks were formed.

Another problem is presented by small bodies of altered Oligocene-age gabbro, diorite, and monzonite that locally intrude Colorado Plateau rocks of the Lucero uplift. These magmas have intruded as dikes, sills, and plugs and are surrounded by contact aureoles of hornfelsed sandstone and shales up to 10 m thick (Jicha 1958). The intrusions have been named "spilites" (Duschatko and Poldervaart 1955) or "sodaclase diorites" (Jicha 1958) because the original feldspars have been changed to albite and clinozoisite. Gambill (1980) has observed that original feldspars and mafic minerals of gabbro and

monzonite have been converted to a mineral assemblage that includes albite, analcime, chrysotile, chlorite, and brucite. Although Gambill suggested that present bicarbonated mineral waters of the Lucero region may have participated in these alterations, the data of Table IV do not support this interpretation. All mineral waters are undersaturated with analcime, chrysotile, and brucite whereas most waters are undersaturated with chlorite and zoisite. Thus, the observed alteration minerals will dissolve in the presence of the mineral fluids rather than precipitate from them. Formation of chrysotile and brucite probably needs both higher temperatures and, more important, higher pH as suggested by Barnes et al. (1973). We conclude that hydrothermal alterations preserved in these intrusive bodies occurred during different (and much earlier) conditions of fluid chemistry, temperature, and pressure than those displayed by present mineral waters.

D. Chemical Geothermometry

Subsurface aquifer temperatures of hot-water geothermal systems can be estimated using the concentrations of temperature-dependent species such as SiO_2 , Na, K, Ca, and Li (Fournier and Rowe 1966; Fournier and Truesdell 1973; Fouillac and Michard 1981). Several assumptions must be satisfied, however, before the direct application of the geothermometers can yield meaningful results (Fournier et al. 1974; Ellis 1979). These include water-rock equilibrium at depth, negligible re-equilibration as the water rises toward the surface, and no mixing of deep hot and cold surface fluids. Because of such restraints, the application of the geothermometers to real systems may be very difficult, particularly without drillhole control.

The quartz geothermometer of Fournier and Rowe (1966) or of Mahon (1966) is considered reliable for hot-water systems in excess of 180°C . However, hot spring systems that equilibrate at 180°C or more will commonly deposit silica sinter at their orifices. Such deposits have not formed around mineral springs of the Lucero region, which precipitate instead carbonates, gypsum, and minor disseminated quartz (Table III). The lack of siliceous sinter merely reflects the low-silica content of the fluids. Either these waters never equilibrated at such high temperatures or the waters are mixtures of deep hot fluids and surface meteoric waters. Because chloride variation diagrams and isotopic evidence (Figs. 4 and 7) do not yield evidence for

mixing or of existence of a deep hot fluid, we conclude the waters have never equilibrated above 180°C.

Quartz (conductive) temperatures ranging from 46 to 87°C were computed (Table V) for comparison of type S and type D mineral waters. Silica concentrations and, thus, quartz temperatures are essentially the same for both water types. The computed temperatures can be considered estimates of maximum equilibration temperatures because it is more likely that the fluids are in equilibrium with more soluble silica phases such as chalcedony or cristobalite.

The empirical Na-K-Ca geothermometer of Fournier and Truesdell (1973) contains a factor β that is dependent on whether or not the water equilibrated above 100°C ($\beta = 1/3$) or below 100°C ($\beta = 4/3$). This geothermometer is most reliable for geologic environments where ample feldspar is available for reaction and where the fluids contain abundant Ca. The $\beta = 1/3$ case is not usually calculated if the $\beta = 4/3$ temperature is <100°C, the $\log (Ca^{1/2}/Na)$ in equivalents is >0, or if the fluids contain substantial Mg. A Mg-correction procedure for this geothermometer has been recently devised (Fournier and Potter 1979) which is applicable if the normal Na-K-Ca temperature calculation is >70°C and the factor $R = Mg/(Mg + Ca + K) \times 100$ in equivalents is <50. The

TABLE V
CHEMICAL GEOTHERMOMETRY OF MINERAL WATERS OF THE LUCERO UPLIFT REGION,
NEW MEXICO
(locations on Fig. 2)

Field No.	Name	Measured Temp., °C	Quartz	Na-K-Ca			Na-Li
				$\beta = 4/3$	$\beta = 1/3$	Mg-Corrected	Cl < 0.3M
<u>Type S Mineral Waters</u>							
LUC-1	Unnamed Salt Spg	12	60	144	120	40	59
LUC-4	Unnamed Salt Lick	18	69	102	96	20	25
LUC-5	Unnamed Salt Spg	23	64	183	140	65	76
LUC-22	Ojo Monte Largo	14	53	250	155	25	61
LUC-23	Ojo Pato	21	66	165	135	45	57
LUC-25	Ojo Saladito	24	46	123	127	42	55
LUC-27	Unnamed Salt Spg	18	87	241	161	51	90
<u>Type D Mineral Waters</u>							
LUC-2	Crane Spg	19	66	58	--	--	159
LUC-3	Eddleman Spg	15	46	59	--	--	158
LUC-8	Lucero Spg	16	69	47	--	--	138
LUC-11	Salado Spg	25	53	55	--	--	138
LUC-12	Apache Spg	19	62	64	--	--	147
LUC-13	Lonely Windmill	20	51	64	--	--	160
LUC-17	Artesian Well	26	53	51	--	--	117
LUC-19	Field Artesian Well	25	51	59	--	--	161

calculated Na-K-Ca temperature estimates for type S and type D mineral waters of the Lucero region are listed in Table V for comparison with quartz temperatures.

We note that the Na-K-Ca temperatures fall into two distinct groups correlating with the two mineral water types. Calculated $\beta = 4/3$ and $\beta = 1/3$ temperatures of type S fluids are considerably higher than quartz temperatures and generally $>100^{\circ}\text{C}$. We attribute the higher estimated temperatures in type S saline springs to solution of halite and other soluble salts from local sources. Thus, total Na concentration is not a function of temperature and addition of excess Na causes the resulting temperature estimates of type S waters to be too high. Similar problems in application of the Na-K-Ca geothermometer were noted by Goff and Donnelly (1978) for a suite of 45 thermal/mineral waters of The Geysers-Clear Lake region, California. Many of these waters contain connate Na-rich fluids, thus, some Na-K-Ca temperature estimates are unreasonably high ($>500^{\circ}\text{C}$).

When the Mg-correction of Fournier and Potter (1979) is applied to type S mineral waters, Na-K-Ca temperatures are again comparable to quartz temperatures. Many of the resulting Na-K-Ca temperatures of both water types are within 25°C of the measured discharge temperatures suggesting the waters have equilibrated at low temperatures, not in a deep high-temperature geothermal environment (Fournier et al. 1974). In addition, high concentrations of Ca and Mg carbonates indicate the waters have not equilibrated at high temperatures due to the inverse solubility relationship of these minerals with increasing temperature (Garrels and Dyer 1952).

Fouillac and Michard (1981) have developed an empirical Na-Li geothermometer using much data from explored geothermal fields. This geothermometer has two forms depending on whether or not the fluid is of low-to-moderate salinity ($\text{Cl} < 0.3\text{M}$) or of high salinity ($\text{Cl} > 0.3\text{M}$), but in both forms, the estimated temperature is inversely proportional to $\log (\text{Na/Li})$. Salinities of all waters of the Lucero region (Table I) are less than 0.3M in Cl except LUC-22, thus, the low salinity form of the Na-Li geothermometer was applied (Table V).

Na-Li temperatures fall into two distinct groups correlated again with the two types of mineral waters. Saline type S waters, which have an average Li/Na of 0.0008, yield calculated temperatures of 25 to 90°C , bracketing quartz and Na-K-Ca (Mg-corrected) temperatures. Dilute type D fluids have an

average Li/Na of 0.0031 and yield calculated temperatures well over 100°C. Because none of our other data indicates equilibration temperatures in excess of 100°C, we propose that Li concentrations in mineral fluids of the Lucero region are controlled by solution of Li-bearing evaporite minerals from Colorado Plateau rocks rather than by equilibration temperature. If such is the case, the Na-Li geothermometer is not applicable to this region and the fortuitously close agreement (in type S mineral waters) between the Na-Li temperatures and other geothermometers is caused by excess concentrations of Na from minerals such as halite.

IV. CONCLUSIONS: GEOTHERMAL POTENTIAL OF LUCERO UPLIFT MINERAL WATERS

Although chloride variation diagrams (Fig. 4) show two distinct types of mineral waters issuing from the Lucero region, our field evidence presented above plus isotopic data (Fig. 6), reaction states of the fluids (Table IV) and chemical geothermometry (Table V) indicate equilibration of both fluids at temperatures not exceeding the solubility of quartz; i.e. $\leq 60^{\circ}\text{C}$. Probably the fluids are in equilibrium with chalcedony or cristobalite. Additionally, we see no evidence indicating mixing between a deep hot geothermal fluid and surface waters.

Type D mineral waters circulate in layered evaporite- and carbonate-bearing rocks, primarily Chinle Formation, on the west flank of the Lucero uplift. Abundant water (as much as 4.2×10^4 l/min) at temperatures of 25°C is available from artesian and normal aquifers such as tapped by the Field Well (LUC-19) at moderate depths (Jicha 1958). Based on our geochemical evidence, we do not believe that type D waters will exceed 30°C in temperature anywhere in the Lucero uplift. With proper hardware, scaling prevention, heat pumps, and consideration of the relatively clear sunny weather that prevails in the Lucero region, dilute type D mineral waters could be used for greenhouse applications. Close proximity to the large population center of Albuquerque, New Mexico, could provide a market for this type of energy utilization.

Type S mineral waters present a more difficult problem in interpretation of geothermal potential. These fluids leak from the complex Comanche fault zone and associated fault blocks within the Lucero monocline. Flow rates and emergence temperatures of type S waters are generally less than those of type D waters. We do not know where the excess salt originates that is dissolved

in type S waters. Possibly it is leached from evaporites of the upper Yeso Formation, which is known to contain beds of halite about 100 km to the south (Hunter and Ingersoll 1981). Saline mineral waters are not obviously associated with the Rio Grande rift because we observed no spring activity on the Quaternary Santa Fe fault. We also do not see any evidence for enhanced spring activity or elevated temperatures in the vicinity of the buried mafic intrusion, interpreted by Ander and Huestis (in prep.) to be injected across this fault. Based on our geochemical evidence, we do not believe that saline waters have ever equilibrated above 60°C and doubt they have equilibrated above 30°C. The high concentrations of Na, Ca, Cl, SO₄, and HCO₃ would make most of these saline fluids undesirable for geothermal applications. If at some future time, an exploratory well is drilled to investigate the deep hydrology, hypothetical mixing, and geologic setting of type S saline waters, we recommend drilling to Precambrian basement somewhere in the fault blocks east of the Lucero monocline and west of the Santa Fe fault.

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