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Borehole gravity surveys in native-sulfur deposits, Culberson and Pecos Counties, Texas

by

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Native-sulfur deposits in west Texas are heterogeneous, with sulfur content and formation properties varying significantly over small vertical and horizontal distances. The zone of recovery of the Frasch process extends tens or even hundreds of feet around each recovery well, but the investigation depth of most wire-line logs is measured in inches. Consequently, the analysis of drill cores is still the primary method for the evaluation of sulfur deposits.

In these circumstances, the borehole gravity meter, with a radius of investigation comparable to the recovery radius of the Frasch process, offers advantages in the evaluation of native-sulfur deposits. The borehole gravity meter is a density logging tool that is not significantly influenced by casing, borehole rugosity, or formation damage caused by drilling. Variations in heterogeneous formations are averaged into the density determination.

Fundamentals of borehole gravity logging and data interpretation, considerations of the effective radius of investigation, and applications to geologic problems have been discussed in the literature by Smith (1950), Goodell and Fay (1964), Howell, Heintz, and Barry (1966), McCulloh (1966), Healey (1970), Beyer (1971), Jageler (1976), Hearst and McKague (1976), and Schmoker (1977a,b; 1978). In the absence of complicating structural factors, the relationship between formation density and measurements of gravity in a borehole is given by:

$$\rho = 39.185(F - \Delta g/\Delta z) \qquad (1)$$

where ρ is the average formation density between two vertically separated points in the borehole (g/cm^3), F is the free-air vertical gradient of gravity (mgals/ft), Δg is the difference in gravity between the vertically separated points (mgals), and Δz is the vertical separation (ft).

The U.S. Geological Survey - LaCoste and Romberg[1/] borehole gravity meter (described by McCulloh and others, 1967a, b) was used to carry out borehole gravity surveys in four wells penetrating the native-sulfur deposit at the Duval Corporation's Culberson property, Culberson County, Texas. A fifth borehole gravity survey was conducted at the Duval Corporation's Heiner sulfur mine (shut in) near Fort Stockton, Pecos County, Texas. Figure 1 locates the two areas of investigation.

Prior to each borehole gravity survey, a gamma-ray log was run for stratigraphic correlation. Gravity stations were located where the gamma-ray log or driller's log indicated variations in formation properties. Drift control was established by station reoccupations, and tidal corrections, terrain corrections, and drift corrections were applied to the borehole gravity data.

The data associated with each subsurface gravity station in the five wells are given in Tables 1 through 5. Column headings are explained in the following list:

Station number:	A numbering of borehole gravity stations in order of increasing depth.
Depth:	Depth of stations in feet and (meters), relative to ground level.

[1/] Use of brand names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

Uncorrected gravity:	Observed gravity in milligals, referenced to an arbitrary base.
Tide correction:	Theoretical correction for earth tides in milligals.
Drift correction:	A correction in milligals for instrument drift based on station reoccupations. (Each station of the P-270 and C-211 wells was occupied twice, and the "Drift correction" for these wells was incorporated into the "Uncorrected gravity" at the time of initial data reduction).
Terrain correction:	Terrain correction in milligals calculated for a density of 2.67 g/cm^3 out to a distance of 71,996 ft (21,944 m), which corresponds to zone M of Hammer's terrain correction system (Hammer, 1939).
Corrected gravity:	Observed gravity in milligals, referenced to an arbitrary base, corrected for tide, drift, and terrain effects.
Well temperature: (C-211 only)	Temperature in ^{o}C, measured with a commercially available temperature probe.

Rocks of post-Permian age are thin in the survey areas and are underlain in descending order by the Rustler, Salado, and Castile Formations of Late Permian age. The Castile Formation is characterized by alternating laminae of white anhydrite and brown calcite that are usually assumed to reflect annual cycles of sedimentation (Anderson and others, 1972).

Davis and Kirkland (1970) postulate the following sequence of events leading to the formation of sulfur deposits in west Texas:

1) Solution porosity develops in anhydrite.
2) Petroleum, probably from the underlying sandstones of the Bell Canyon Formation of Late Permian age, migrates into pores and fractures developed in the anhydrite.
3) Sulfate-reducing bacteria oxidize petroleum and use sulfate ions from anhydrite as hydrogen acceptors to generate large volumes of hydrogen sulfide and carbon dioxide.
4) Calcite precipitates from carbon dioxide to form replacement limestone, and oxidation of hydrogen sulfide by oxygen in ground water leads to sulfur deposition.

The actual distribution of sulfur in the replacement limestone is irregular because hydrogen sulfide is highly mobile and tends to migrate prior to oxidation (Bodenlos, 1973).

Sulfur ore in Pecos County is controlled by local structural highs along a major regional anticline and is confined to the Salado Formation (McNeal and Hemenway, 1972). Plans were made to obtain borehole gravity data in three or more wells at Duval's Fort Stockton property (Figure 1), which had been mined using standard Frasch techniques but is presently shut in. Unfortunately, hole conditions were poor and the borehole gravity meter could not be safely used in the ore zones.

The #327 well was logged in casing above the sulfur, however, and for the sake of completeness the data are presented here. Figure 2 shows the gamma-ray log and borehole-gravity densities obtained in the #327 well.

Densities were computed from the data of Table 1 using equation 1 and a "normal" free-air gradient of 0.09406 mgals/ft (0.30860 mgals/m). In situ formation densities were obtained for surficial material, the Rustler Formation, and part of the Salado Formation.

Locations of the four borehole gravity surveys conducted in Culberson County (Public School Land Block 111) are shown in Figure 3. The sites lie to the west of present sulfur production and are not affected by the hot waters of the Frasch process. Sulfur occurs in both the Salado and Castile Formations.

Figures 4, 5, 6, and 7 show gamma-ray logs and borehole-gravity densities obtained in the four Culberson County wells. Densities were computed from the data of Tables 2, 3, 4, and 5 using equation 1 and an empirically determined free-air gradient of 0.09219 mgals/ft (0.30246 mgals/m), about 2 percent lower than the "normal" value. The gamma-ray log for the #352 well (Figure 6) is anomalously high between 335 and 485 ft (102-148 m). This does not reflect the natural radioactivity of the formation, but is due either to materials used in drilling and completing the well or to the deposition of minerals when the well was used for water withdrawal.

The rocks underlying the Rustler Formation (Figures 4, 5, 6, and 7) have been affected by sulfate-reducing bacteria and include zones of possible sulfur deposition. Table 6 lists densities of common constituents of the sulfur-bearing formations of west Texas, and illustrates the wide range of formation densities that are possible. The situation is simplified in zones of sulfur ore, however, which typically comprise only three volume-significant components - limestone matrix (2.71 g/cm^3), sulfur (2.03 g/cm^3), and water (about 1.0 g/cm^3). The large density contrasts between these components make the in situ formation density quite sensitive to sulfur content.

The formation density, ρ, in sulfur-ore zones can be expressed as

$$\rho = \phi_s(2.03) + \phi_w(1.0) + \phi_m(2.71) \tag{2}$$

where ϕ_s, ϕ_w, and ϕ_m are the fractional volumes of sulfur, water, and limestone matrix, respectively. Because

$$\phi_s + \phi_w + \phi_m = 1.00 \tag{3}$$

equation 2 can be written as

$$\rho = \phi_s(2.03) + \phi_w(1.0) + (1 - \phi_s - \phi_w)(2.71) \tag{4}$$

Maximum possible sulfur contents can be estimated from equation 4 using borehole-gravity densities and assuming all interstices to be sulfur filled ($\phi_w = 0.0$). If assumptions regarding average ratios of sulfur to water can be made, the actual sulfur content of the rocks sensed by the borehole gravity meter can be estimated.

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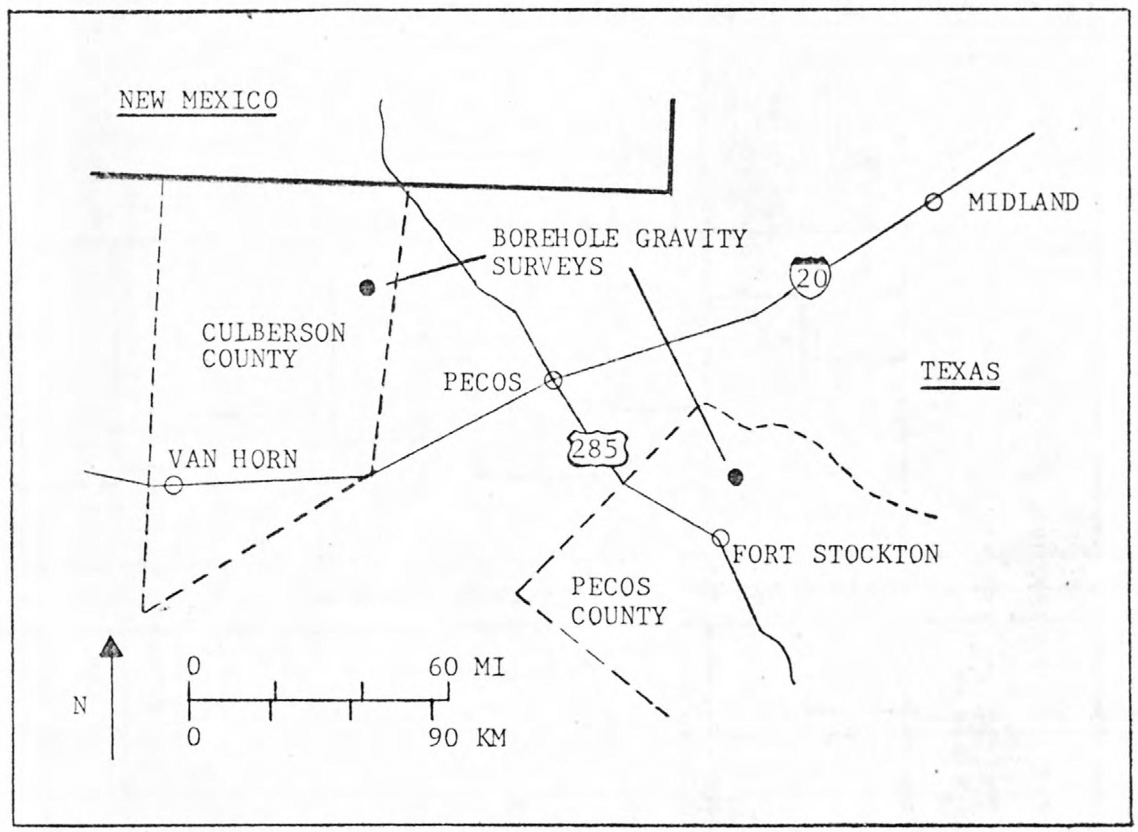

Figure 1. Regional locations of west Texas borehole gravity surveys.

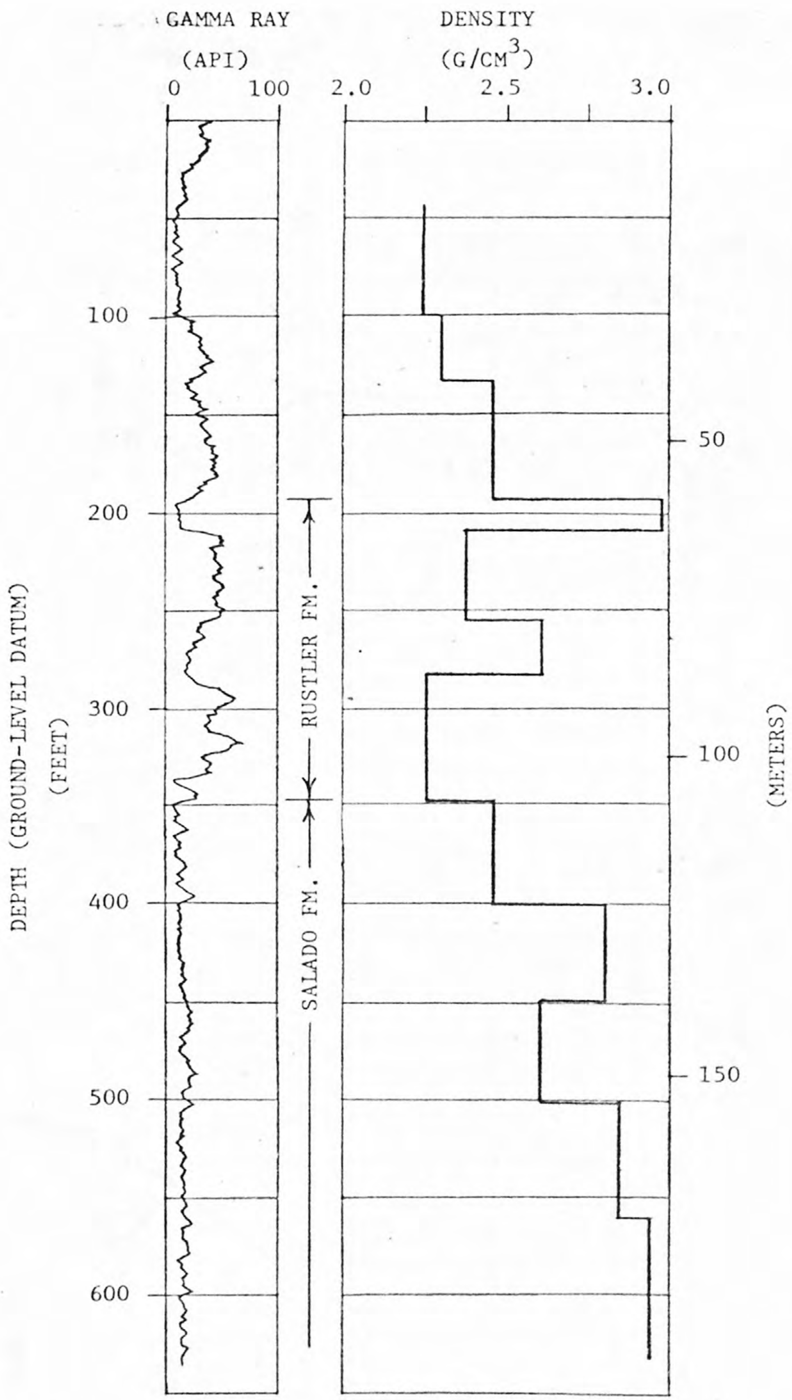

Figure 2. Gamma-ray intensity and borehole-gravity density, Duval #327 well, Pecos County, Texas.

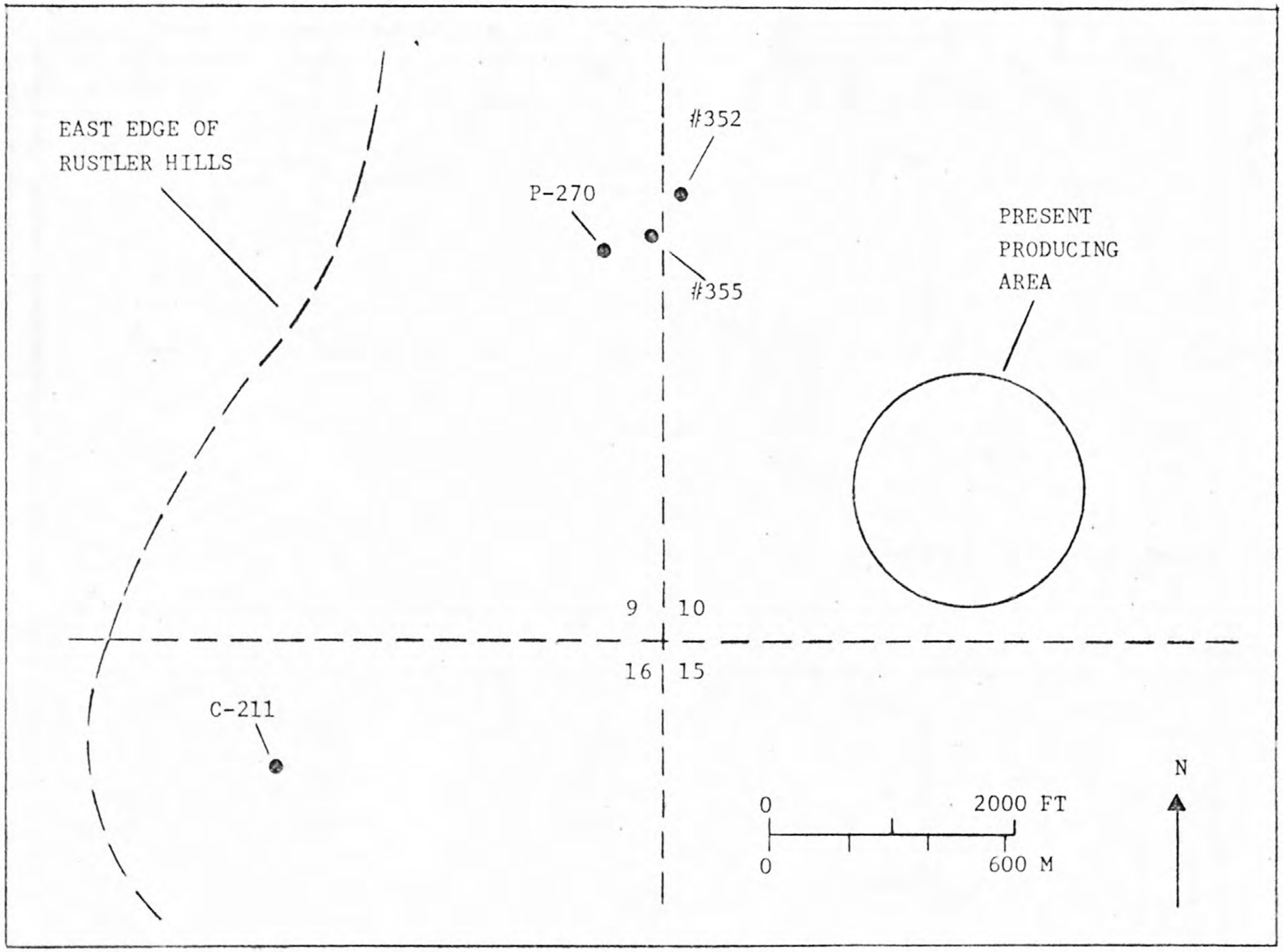

Figure 3. Locations of borehole-gravity surveys at the Duval Culberson property, Culberson County, Texas.

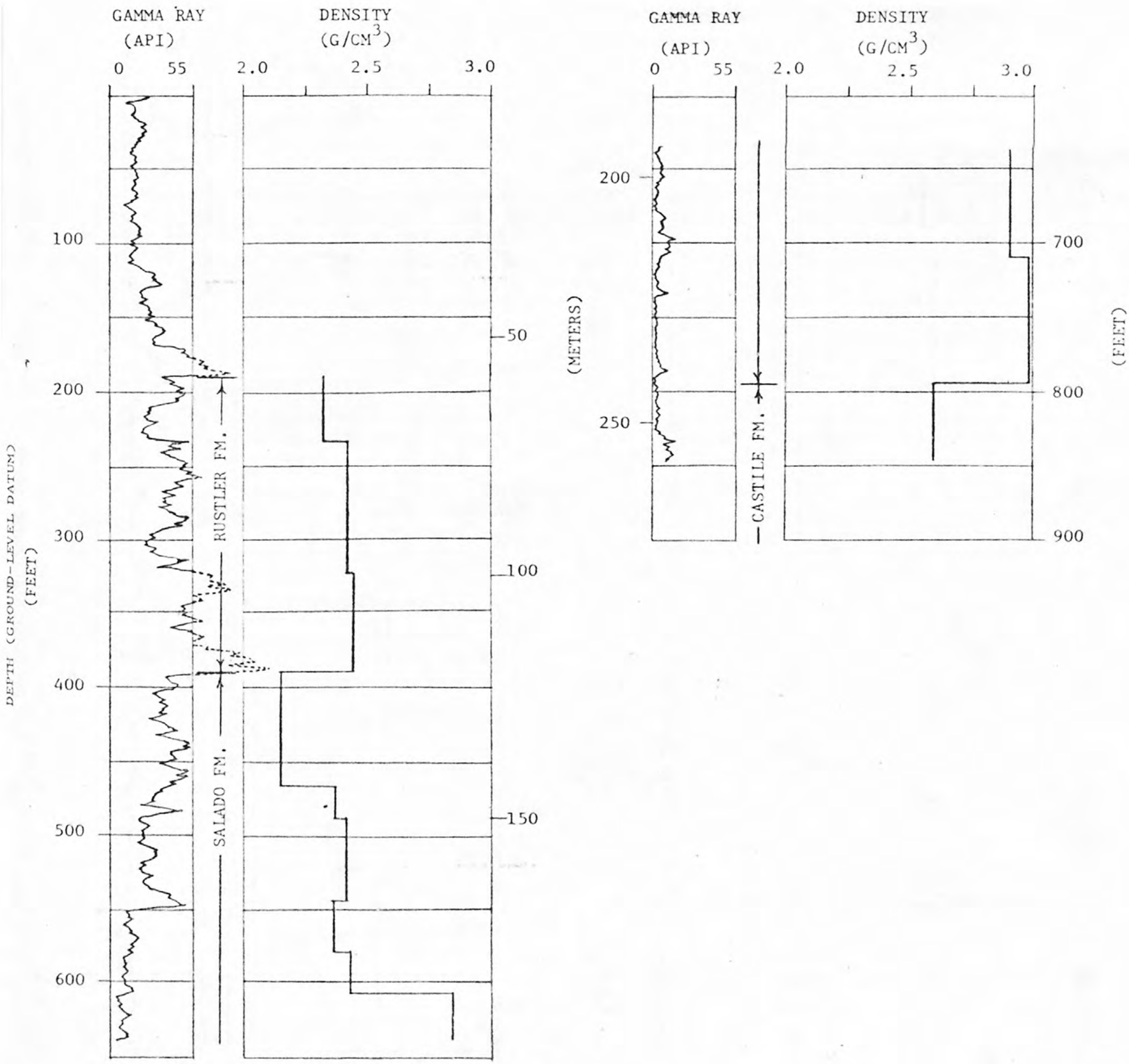

Figure 4. Gamma-ray intensity and borehole-gravity density, Duval P-270 well, Culberson County, Texas.

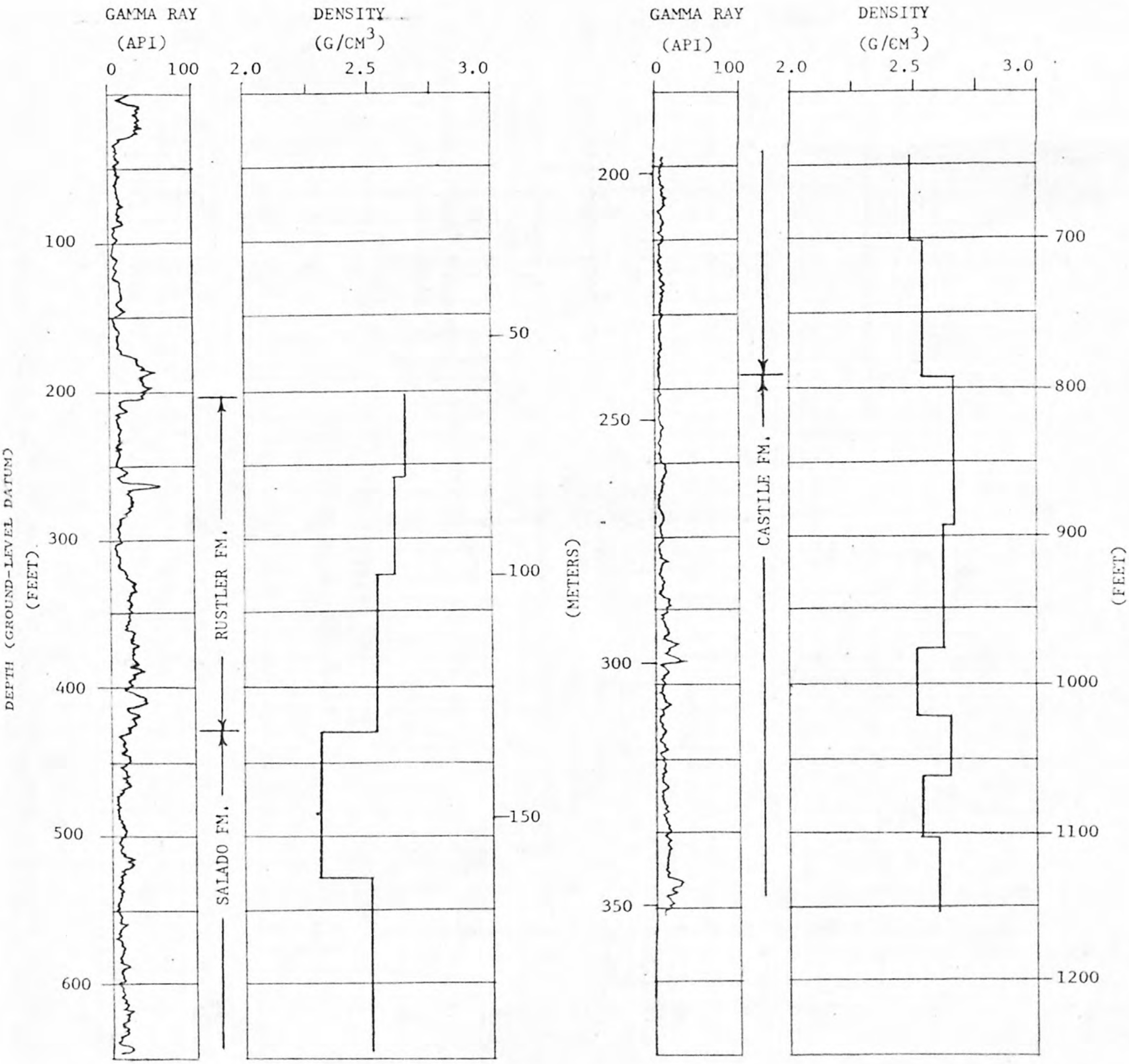

Figure 5. Gamma-ray intensity and borehole-gravity density, Duval C-211 well, Culberson County, Texas.

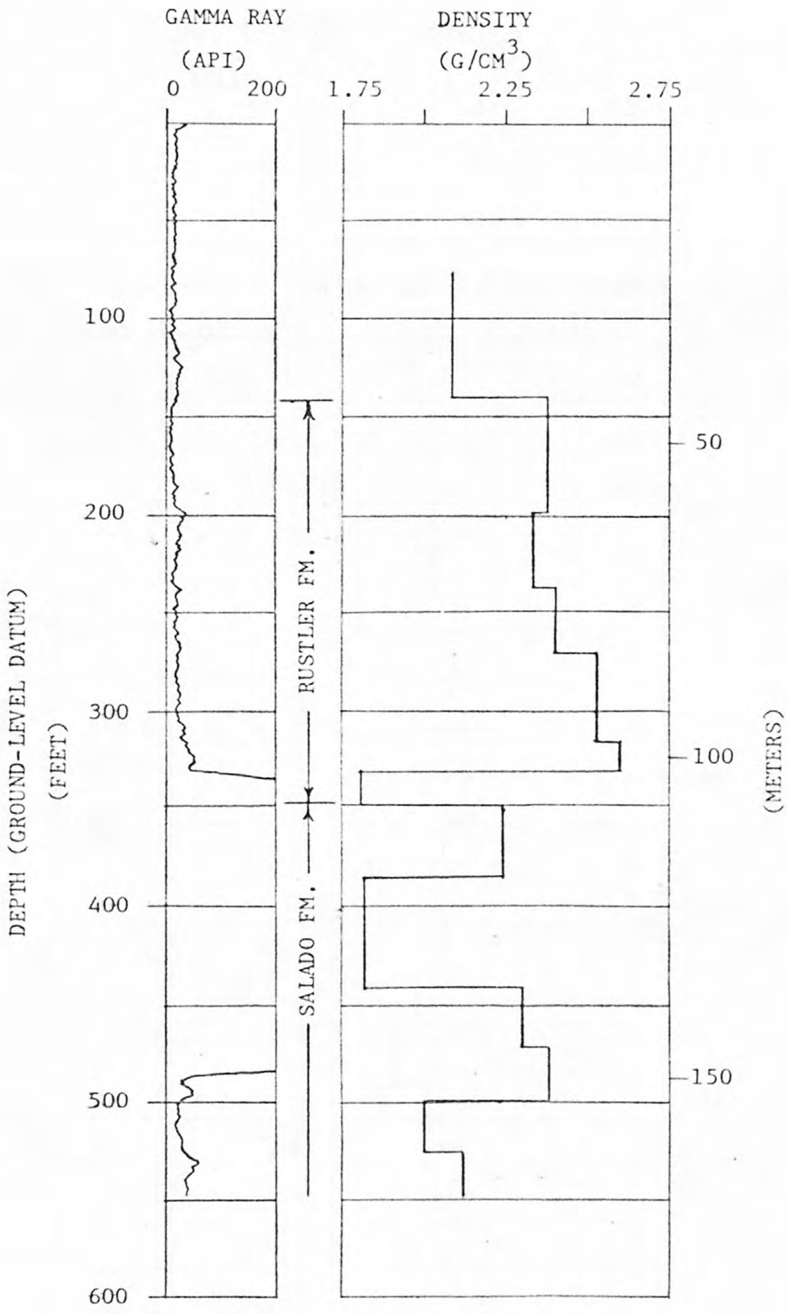

Figure 6. Gamma-ray intensity and borehole-gravity density, Duval #352 well, Culberson County, Texas.

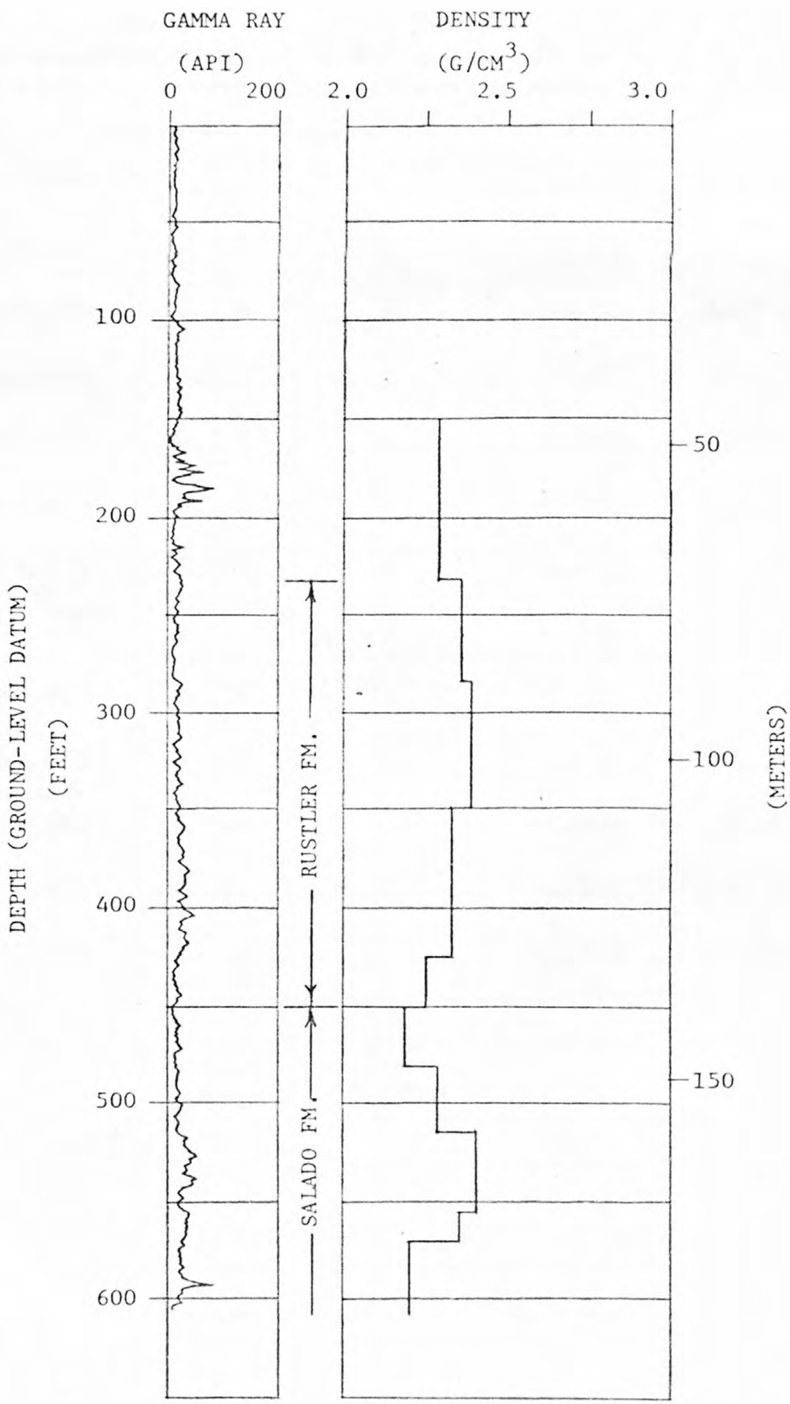

Figure 7. Gamma-ray intensity and borehole-gravity density, Duval #355, Culberson County, Texas.

Station number	Depth ft	(m)	Uncorrected gravity	Tide correction	Drift correction	Terrain correction	Corrected gravity
1	43.0	(13.1)	57.053	0.109		0.019	57.181
2	100.0	(30.5)	59.137	0.115	N	0.025	59.277
3	131.0	(39.9)	60.230	0.118	E	0.026	60.374
4	194.0	(59.1)	62.004	0.119	G	0.029	62.152
5	209.0	(63.7)	62.466	0.121	L	0.030	62.617
6	254.0	(77.4)	63.963	0.123	I	0.032	64.118
7	282.0	(86.0)	64.732	0.124	G	0.033	64.889
8	347.0	(105.8)	67.104	0.125	I	0.035	67.264
9	399.0	(121.6)	68.720	0.126	B	0.037	68.883
10	448.0	(136.6)	69.811	0.126	L	0.039	69.976
11	500.7	(152.6)	71.263	0.126	E	0.041	71.430
12	560.0	(170.7)	72.532	0.126		0.042	72.700
13	632.5	(192.8)	73.917	0.126		0.044	74.087

Table 1. Duval Corp. #327 well, Pecos County, Texas. Logged 8/13/78.

Station number	Depth ft	(m)	Uncorrected gravity	Tide correction	Terrain correction	Corrected gravity
1	190	(57.9)	16.550	- 0.063	0.768	17.255
2	233	(71.0)	17.880	- 0.062	0.850	18.668
3	322	(98.1)	20.434	- 0.059	1.019	21.394
4	385	(117.3)	22.194	- 0.058	1.137	23.273
5	467	(142.3)	25.098	- 0.046	1.287	26.339
6	487	(148.4)	25.694	- 0.045	1.323	26.972
7	540	(164.6)	27.217	- 0.035	1.418	28.600
8	578	(176.2)	28.344	- 0.015	1.485	29.814
9	608	(185.3)	29.198	- 0.013	1.537	30.722
10	636	(193.9)	29.699	- 0.012	1.585	31.272
11	710	(216.4)	30.907	- 0.002	1.710	32.615
12	794	(242.0)	32.067	0.008	1.848	33.923
13	845	(257.6)	33.284	0.025	1.930	35.239

Table 2. Duval Corp. P-270 well, Culberson County, Texas. Logged 8/18/77.

Station number	Depth ft (m)	Uncorrected gravity	Tide correction	Terrain correction	Corrected gravity	Well temp., °C
1	204 (62.2)	12.335	0.029	0.762	13.126	20.1
2	260 (79.2)	13.600	0.024	0.877	14.501	20.4
3	324 (98.8)	15.132	0.020	1.004	16.156	20.9
4	428 (130.5)	17.824	0.016	1.201	19.041	21.8
5	527 (160.6)	20.955	0.013	1.377	22.345	22.9
6	645 (196.6)	24.102	0.005	1.572	25.679	23.9
7	702 (214.0)	25.655	0.002	1.662	27.319	24.4
8	792 (241.4)	27.992	- 0.005	1.797	29.784	25.2
9	892 (271.9)	30.259	- 0.012	1.938	32.185	25.9
10	977 (297.8)	32.288	- 0.015	2.051	34.324	26.6
11	1,020 (310.9)	33.439	- 0.017	2.106	35.528	26.9
12	1,062 (323.7)	34.419	- 0.020	2.158	36.557	27.3
13	1,102 (335.9)	35.469	- 0.021	2.206	37.654	27.8
14	1,155 (352.0)	36.752	- 0.028	2.268	38.992	28.8

Table 3. Duval Corp. C-211 well, Culberson County, Texas. Logged 8/20/77.

Station number	Depth ft	(m)	Uncorrected gravity	Tide correction	Drift correction	Terrain correction	Corrected gravity
1	80.0	(24.4)	84.910	0.167	- 0.001	0.520	85.596
2	142.0	(43.3)	87.219	0.163	- 0.003	0.639	88.018
3	197.0	(60.0)	88.859	0.159	- 0.005	0.745	89.758
4	238.0	(72.5)	90.125	0.155	- 0.007	0.824	91.097
5	270.0	(82.3)	91.063	0.150	- 0.008	0.885	92.090
6	315.0	(96.0)	92.234	0.145	- 0.010	0.970	93.339
7	331.0	(100.9)	92.626	0.140	- 0.012	1.000	93.754
8	350.0	(106.7)	93.479	0.135	- 0.014	1.036	94.636
9	386.8	(117.9)	94.716	0.130	- 0.015	1.105	95.936
10	441.0	(134.4)	97.131	0.116	- 0.019	1.204	98.432
11	471.0	(143.6)	98.095	0.109	- 0.022	1.258	99.440
12	498.0	(151.8)	98.902	0.103	- 0.023	1.307	100.289
13	525.0	(160.0)	99.982	0.096	- 0.025	1.355	101.408
14	548.0	(167.0)	100.829	0.088	- 0.027	1.396	102.286

Table 4. Duval Corp. #352 well, Culberson County, Texas. Logged 8/16/78.

Station number	Depth ft	(m)	Uncorrected gravity	Tide correction	Drift correction	Terrain correction	Corrected gravity
1	150.0	(45.7)	96.201	0.164	- 0.023	0.655	96.997
2	230.0	(70.1)	98.736	0.170	- 0.014	0.808	99.700
3	285.0	(86.9)	100.376	0.174	- 0.008	0.913	101.455
4	350.0	(106.7)	102.293	0.176	0.000	1.036	103.505
5	425.0	(129.5)	104.604	0.178	0.006	1.175	105.963
6	450.0	(137.2)	105.422	0.179	0.011	1.220	106.832
7	482.0	(146.9)	106.528	0.180	0.018	1.278	108.004
8	515.0	(157.0)	107.580	0.180	0.024	1.338	109.122
9	555.0	(169.2)	108.754	0.180	0.013	1.409	110.356
10	570.0	(173.7)	109.219	0.179	0.005	1.435	110.838
11	607.0	(185.0)	110.499	0.177	- 0.003	1.499	112.172

Table 5. Duval Corp. #355 well, Culberson County, Texas. Logged 8/17/78.

Mineral or Pore Fluid	Apparent Log Density, g/cm^3
Anhydrite	2.98
Calcite	2.71
Dolomite	2.88
Gypsum	2.35
Halite	2.03
Quartz	2.65
Sulfur	2.03
Water - fresh	1.00
Water - 100,000 ppm NaCl	1.07
Water - 200,000 ppm NaCl	1.14

Table 6. Density of formation water and common minerals in the Rustler, Salado, and Castile Formations (after Tixier and Alger, 1970).