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CARBON DIOXIDE IN UNION AND HARDING COUNTIES

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Abstract—Naturally occurring carbon-dioxide (CO_2) gas has been produced from three fields in Union and Harding Counties: the Bravo Dome and Bueyeros fields of southern Union and southern Harding Counties and the Des Moines field of northwestern Union County. Only the Bravo Dome and Bueyeros fields are presently active. Development of the Bravo Dome and Bueyeros fields was slow until the 1980's when CO_2 became useful for enhanced recovery of oil in the Permian Basin of southeastern New Mexico and western Texas. Current CO_2 production from the Bravo Dome and Bueyeros fields is approximately 100 billion ft^3/yr. Estimates of recoverable reserves in the Bravo Dome and Bueyeros fields range from 5.3 to 9.8 trillion ft^3/yr.

The main reservoir in the Bravo Dome and Bueyeros fields is the Tubb sandstone (Permian) at depths of 2,000–2,500 ft (600–750 m). Other reservoirs are arkosic sandstones and conglomerates of the Abo Formation (Permian) at depths of 2,500–3,000 ft (750–900 m) and Santa Rosa sandstones (Triassic) at depths less than 1,000 ft (300 m). The main reservoirs in the Des Moines field are arkosic conglomerates of the Abo Formation (Permian) at depths of 2,060–2,600 ft (630–790 m). Other secondary reservoirs are in the Alibates Dolomite (Permian) at a depth of approximately 1,200 ft (370 m).

INTRODUCTION

Naturally occurring carbon-dioxide (CO_2) gas has been produced from three fields in Union and Harding Counties (Fig. 1): Bravo Dome field, Bueyeros field and Des Moines field. Those CO_2 fields are located on two basement-cored uplifts, the Bravo dome and the Sierra Grande uplift. The Bravo dome is a southeast-trending projection of the north-east-trending Sierra Grande uplift. The Dalhart basin of the Texas Panhandle protrudes into eastern Union County. The shallowest, northern part of the Tucumcari basin occupies the southernmost part of Harding County.

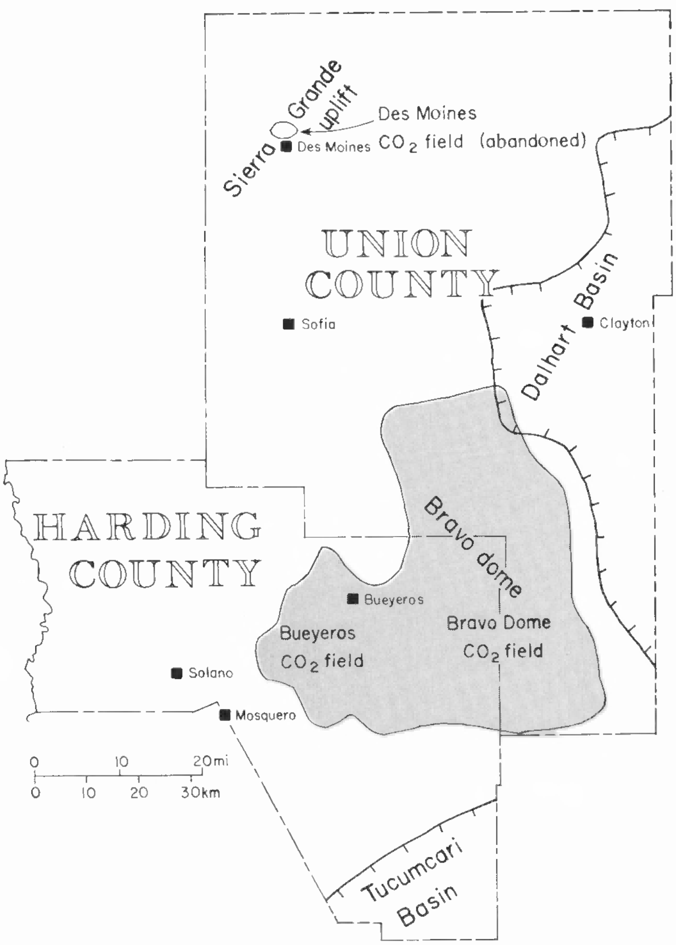

FIGURE 1. Major tectonic elements present in Union and Harding Counties and locations of known CO_2 gas fields.

The Sierra Grande uplift, Bravo dome, Dalhart basin and Tucumcari basin are tectonic features of Middle Pennsylvanian to Wolfcampian (Permian) age. Early Pennsylvanian and pre-Pennsylvanian strata have been eroded from the Bravo dome and Sierra Grande uplift (Fig. 2). Cambrian, Ordovician, Mississippian and Early-Middle Pennsylvanian marine sedimentary rocks have been preserved in the Dalhart basin (Montgomery, 1986). Mississippian and Middle Pennsylvanian marine sedimentary rocks have been preserved in the Tucumcari basin (Broadhead and King, 1985).

Middle Pennsylvanian to Wolfcampian strata on the Bravo dome and Sierra Grande uplift consist of arkosic sandstone, conglomerate and shale. The arkosic sediments were derived from the granitic core of these two positive elements and were deposited as alluvial fans and fan deltas. These arkosic sediments constitute the Abo Formation (Fig. 2). Orange, fine- to medium-grained, arkosic to quartzose sandstone of the Tubb sandstone overlies the Abo and appears to be mostly reworked Abo sediment deposited in shallow-marine and marginal-marine environments. The Tubb buried the highest parts of the Bravo dome and Sierra Grande uplifts and marks the end of major tectonic uplift. Precambrian structure (Fig. 3) strongly controlled Abo deposition, but as the late Paleozoic uplifts were buried, their effect on sedimentation became progressively less pronounced. By Mesozoic time, those structures did not exhibit a primary control on depositional environments.

Structure of the Sierra Grande uplift and Bravo dome appears to have been controlled primarily by high-angle normal and reverse faults. Those faults were not contoured for Figure 3 because of a paucity of subsurface control. Structure is thought to be similar to structure found at the northern boundary of the Tucumcari basin in Guadalupe, San Miguel and southern Harding Counties.

Carbon dioxide has many commercial uses. The principal use of CO_2 is for enhanced recovery of oil (Foster, 1980; Taber and Martin, 1983; Broadhead, 1985); CO_2 gas is injected into oil reservoirs to recover oil that cannot be produced efficiently by primary production or conventional waterflood techniques. CO_2 injection is usually begun after oil production with waterflood techniques and is no longer economically attractive. The CO_2 is soluble in crude oil at reservoir pressures; when injected into the reservoir, it mobilizes oil not recoverable by conventional processes (Taber and Martin, 1983).

Other uses of CO_2 are in refrigeration (dry ice), carbonation of beverages, meat processing, cryogenics and as a chemical-inert shield. A major use of CO_2 is by the petroleum industry; CO_2 is used in place of

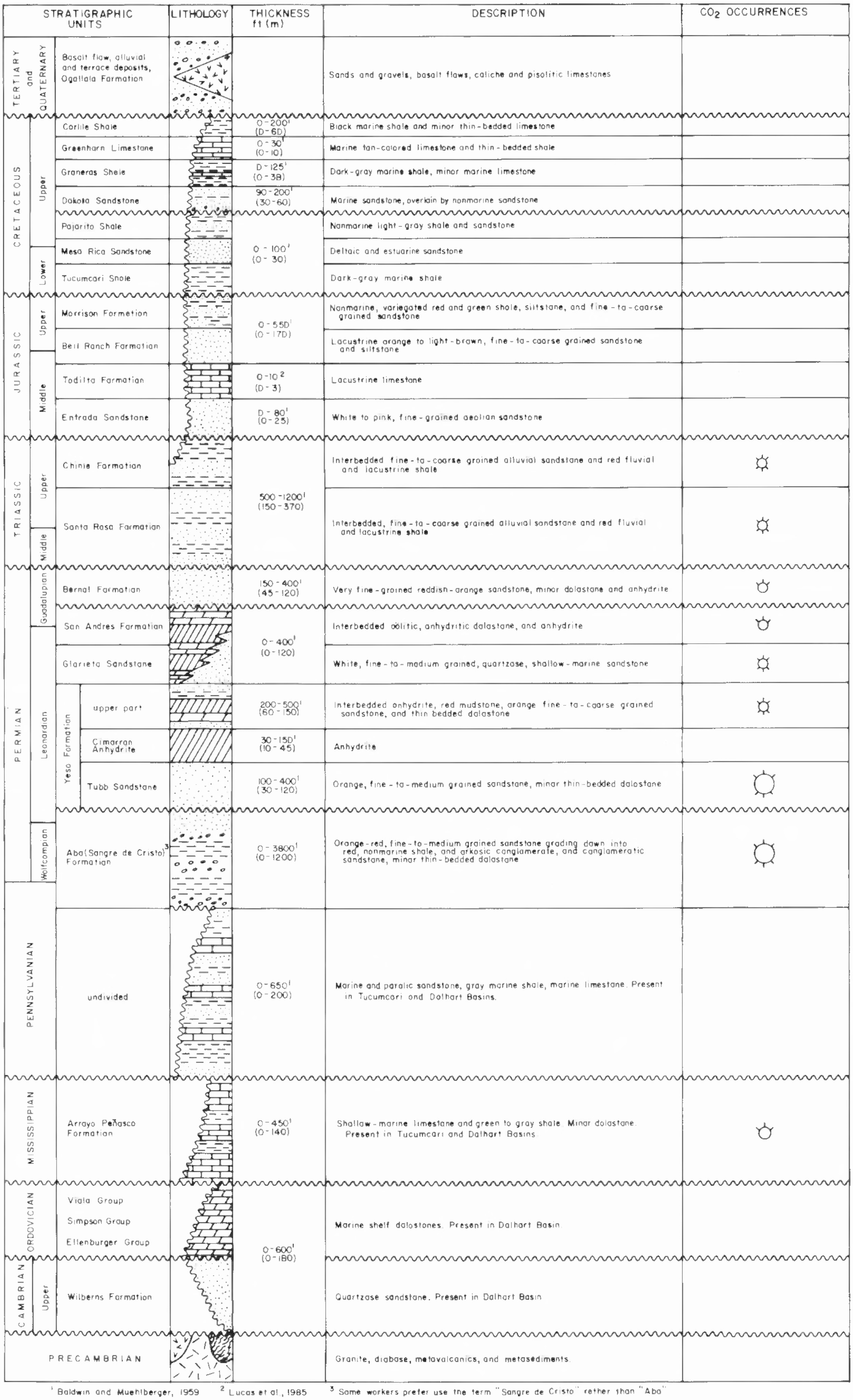

FIGURE 2. Stratigraphic column of Union and Harding Counties and stratigraphic occurrence of carbon dioxide.

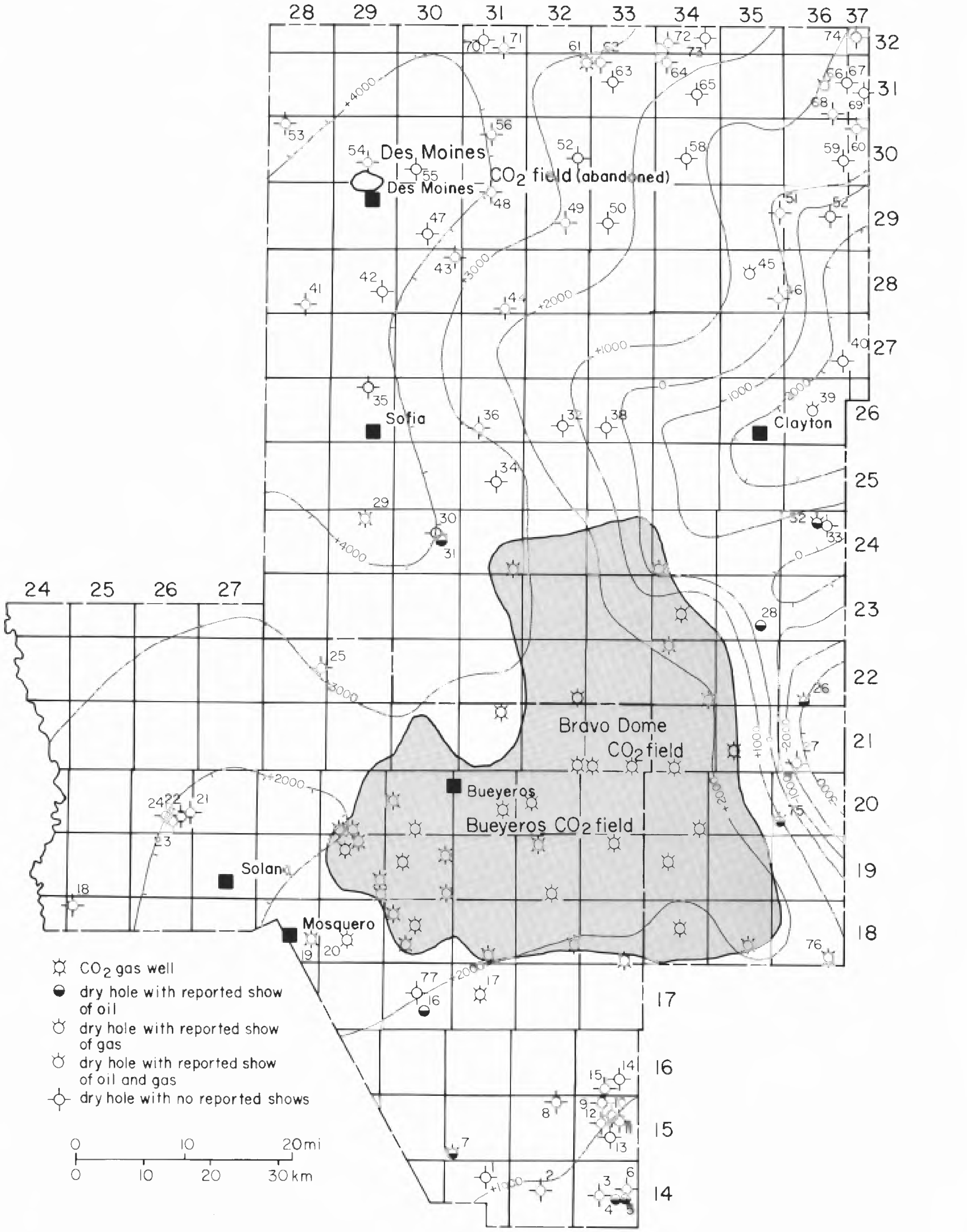

FIGURE 3. Known CO_2 fields, significant petroleum and CO_2 exploration wells and structure contours on the Precambrian. Numbers refer to wells listed in Table 2.

TABLE 1. Carbon dioxide production and number of active CO_2 wells in Union and Harding Counties, 1964–1985. Data from New Mexico Oil & Gas Engineering Committee (1983, 1984, 1985, 1986), New Mexico Energy and Minerals Department (1985) and New Mexico Taxation and Revenue Department. MMCF, million ft^3; NA, not available. Data prior to 1982 are for sales volumes, which are approximately 85% of production volumes.

Year	CO_2 production, MMCF	Number of active CO_2 wells at end of year
1964	806	NA
1965	704	NA
1966	774	NA
1967	781	NA
1968	747	NA
1969	801	NA
1970	704	NA
1971	770	NA
1972	691	NA
1973	608	NA
1974	540	NA
1975	562	NA
1976	606	NA
1977	542	NA
1978	1,081	NA
1979	1,095	NA
1980	776	NA
1981	691	NA
1982	1,067	16
1983	1,065	20
1984	13,349	195
1985	101,227	258

water as a medium to fracture artificially reservoirs that contain swelling clays. The use of CO_2 will prevent swelling of those clays, and therefore prevent a loss of matrix permeability.

HISTORY OF CO_2 DEVELOPMENT

Carbon dioxide was first discovered in Harding County in 1916 by the American Production Corp. No. 1 Bueyeros, located in sec. 32, T20N, R31E. That well was drilled as an oil test. CO_2 was encountered at 2,000 ft (600 m), and the potential was reported to be 25 million ft^3 per day (Anderson, 1959). The well blew open for one year and was plugged in 1917 because a market did not exist for the CO_2. The No. 1 Bueyeros was the discovery well of the Bueyeros field. A market for CO_2 arose in the 1930's, and the Bueyeros field was finally developed. It has produced since the 1930's.

The Des Moines field of northwestern Union County was discovered in 1935 by the Sierra Grande Oil Corp. No. 1 Rogers, located in sec. 4, T29N, R29E; the No. 1 Rogers found CO_2 at a depth of 2,245 ft (684 m) in the Abo (or Sangre de Cristo) Formation and had a reported potential of 6 million ft^3 per day (Anderson, 1959). The field was not produced or developed until the 1950's and was abandoned in the 1960's.

Main development of CO_2 in Union and Harding Counties occurred in the 1980's when several oil fields in the western Texas part of the Permian Basin were piloted for enhanced oil recovery with CO_2. The Bravo Dome CO_2 field, an eastern extension of the Bueyeros field, was extensively developed in the 1980's and was unitized under the direction of Amoco and Cities Service. Annual CO_2 production and the number of active CO_2 wells (Table 1) reflect the increased CO_2 production that resulted from the onset of flooding Permian-Basin oil fields with CO_2.

CO_2 OCCURRENCES

Three CO_2 gas fields have been discovered in Union and Harding Counties (Fig. 3): Bravo Dome, Bueyeros and Des Moines. The geology of each field is discussed below. The Bravo Dome and Bueyeros fields are essentially different parts of the same field; the boundary between the two fields is more legal than geologic. Therefore, the two fields are discussed together. Seventy-seven significant exploration wells have been drilled outside of the three known fields (Fig. 3); several of those wells encountered either CO_2 or hydrocarbons (Table 2).

The Bravo Dome and Bueyeros fields are located on the Bravo dome. Those fields produce CO_2 from the Tubb sandstone (Permian), the Abo Formation (Permian) and the Santa Rosa Formation (Triassic: Fig. 2). The main producing reservoir is the Tubb sandstone, which is present

TABLE 2. Significant CO_2 exploration wells and petroleum exploration wells drilled in Union and Harding Counties. Data from New Mexico Bureau of Mines and Mineral Resources. D&A, dry and abandoned; MCFGPD, thousand ft^3 gas per day; BWPD, bbls water per day; DST, drill-stem test; KB, Kelly bushing; DF, derrick floor; GL, ground level.

No. on Fig 1	Operator, well number, and lease	Location (section-township-range, county)	Elevation ft (m)	Total depth ft (m)	Year completed	Comments
1	Waddell & Crosthwait No. 1 Mathes	10-14N-31E, Harding	4179 (1274)	2445 (745)	1939	D&A
2	Sunray Mid-Continent No. 1 State N	16-14N-32E, Harding	3926 (1197) KB	2850 (869)	1958	D&A
3	Underwood No. 1 Cornett	21-14N-33E, Harding	3990 (1216)	1370 (418)	1938	Completed as water well.
4	Sanders No. 1 Sanders	22-14N-33E, Harding	3969 (1210)	4475 (1364)	1938	D&A
5	Sanders No. 3 Sanders	22-14N-33E, Harding		1365 (416)	1938	D&A. Slight oil show and salt water from 1210-1220 ft & 1355-1360 ft.
6	Underwood No. 2 Sanders	22-14N-33E, Harding		1208 (368)	1938	D&A
7	Waddell & Crosthwait No. 1 Peters	31-15N-31E, Harding	4265 (1300)	2025 (617)	1939	D&A. Odor of oil at 470 ft. Broken CO_2 shows from 1675-2025 ft.
8	Edmonds & Peters No. 1 State	2-15N-32E, Harding		1050 (320)	1970	D&A. Water at 700 ft.
9	Conley & Associates No. 3 Cain (OWDD)	4-15N-33E, Harding	4320 (1316)	1176 (358)	1976	D&A

TABLE 2 (continued).

No. on Fig 1	Operator, well number, and lease	Location (section-township-range, county)	Elevation ft (m)	Total depth ft (m)	Year completed	Comments
10	James A. Talley No. 1 Cain	10-15N-33E, Harding		2891 (881)	1968	D&A
11	Jack F. Conley No. 1 Cain	10-15N-33E, Harding	4292 (1308) GL	1484 (452)	1976	D&A
12	Beck Production Co. No. 1 State	16-15N-33E, Harding	4293 (1309) KB	1500 (457)	1970	D&A
13	Edmonds & Peters No. 2 Cain (OWWO)	22-15N-33E, Harding	4140 (1262) GL	1430 (436)	1972	D&A. Perforated, acidized, & swabbed 427-428, 620-622, 971-972, 1254-1255, 1284-1285, 1327-1328, 1357-1358 ft with no shows.
14	Astro Tex Corp. No. 1X Olympic State	27-16N-33E, Harding	4225 (1288) KB	2906 (886)	1975	D&A. Perforated 2174-2194 ft (Yeso), acidized, no show. Perforated 1284-1321 ft (San Andres), acidized, no show.
15	Beck Production Co. No. 1 McCarthy State	33-16N-33E, Harding	4385 (1337)	1600 (488)	1970	D&A
16	Law & Eckerd No. 1 Gallegos	27-17N-30E, Harding	4249 (1295)	1996 (608)	1938	D&A. Gas shows at 130, 310, 350-360 ft. Oil & gas show at 1550 ft.
17	Amoco Production Co. No. 161 BDCDGU 1731	16-17N-31E, Harding	4342 (1323) KB	4342 (1323)	1985	CO_2 well. Producing through perforations from from 2172-2996 ft (Tubb).
18	Quinn N. Sowell No. 1 Maddox (OWDD)	6-18N-25E, Harding	5827 (1776) DF	3238 (987)	1961	D&A
19	Texas Pacific No. 1 Trujillo	23-18N-28E, Harding	5510 (1679) KB	3070 (936)	1982	CO_2 well. Producing through perforations from 1408-1478 ft (Santa Rosa), IPF 33 MCFGPD. CO_2 gas shows from 2858-2992 ft (Tubb).
20	Cities Service No. 1 Smith A	21-18N-29E, Harding	5435 (1657) GL	3212 (979)	1981	CO_2 well. Producing through perforations from 2927-2994 ft (Tubb), IPF 250 MCFGPD.
21	Mae Belcher Trustee No. 1 Lula Gambrel	24-20N-26E, Harding		1500 (457)	1960	D&A
22	Morad No. 1 Gambrel	23-20N-26E, Harding		250 (76)		
23	Morad No. 3 Gambrel	26-20N-26E, Harding		1213 (370)	1956	D&A
24	Morad No. 1 Foster (OWDD)	27-20N-26E, Harding		886 (270)	1956	D&A
25	Amoco Production Co. No. 1 State FB	13-22N-28E, Harding	5672 (1729) KB	2630 (802)	1974	D&A
26	Ridgeway Petroleum No. 1 AB Hughes	33-22N-36E, Union	4521 (1378) GL	410 (125)	1975	D&A. Oil & gas show through perforations from 370-380 ft (Dakota).
27	Oil Exploration Inc. No. 1 Irwin A	29-21N-36E, Union	4526 (1380) KB	7360 (2243)	1956	D&A. DST 3141-3204 ft (Abo), strong blow.

TABLE 2 (continued).

No. on Fig 1	Operator, well number, and lease	Location (section-township-range, county)	Elevation ft (m)	Total depth ft (m)	Year completed	Comments
28	R. L. Nunn & Co. No. 1 Jim Hopson	26-23N-35E, Union	4743 (1446)	969 (295)	1952	D&A
29	Energy Oil No. 1 Sadler	3-24N-29E, Union	5962 (1817) GL	2640 (805)	1979	CO_2 well. Producing through perforations from 1767-1938 ft (Glorieta), IPF 580 MCFGPD. CO_2 shows from 836-868 ft & 2200-2226, 2388-2390 ft (Abo); oil show from 2480-2488 ft (Abo).
30	Galbreath & Associates No. 1 Britt et al.	14-24N-30E, Union		2603 (793)	1957	D&A
31	Pasamonte No. 1 Herring	14-24N-30E, Union	5790 (1765)	2787 (849)	1924	D&A. Gas show from 1923-2016 ft; oil show at 2025 ft.
32	Buffalo Oil Syndicate No. 1 Odiorine Texline	3-24N-36E, Union	4687 (1429)	2171 (662)	1924	D&A. Gas shows from 148-185, 600-652, 2048-2055 ft; oil shows from 430-431, 530-557, 1255-1293 ft.
33	Continental Oil Co. No. 1 Federal Land Bank 2	2-24N-36E, Union	4691 (1430) KB	5308 (1618)	1957	D&A
34	Amoco Production Co. No. 1 State EZ	22-25N-31E, Union	5762 (1756) KB	2338 (713)	1974	D&A
35	Amoco Production Co. No. 1 State EW	3-26N-29E, Union	6429 (1960) DF	2163 (659)	1973	D&A
36	Amoco Production Co. No. 1 State EY	29-26N-31E, Union	5874 (1790) KB	2973 (906)	1973	D&A
37	Hoxsey Oil Co. & Bryan Edwards No. 1 Grover-Jones	27-26N-32E, Union		3898 (1188)	1956	D&A
38	Western Oil & Gas Co. No. 1 Federal	29-26N-33E, Union	5477 (1669) KB	5053 (1540)	1959	D&A
39	Geoponic Resources No. 2 Kay State	16-26N-36E, Union	4748 (1447) GL	7283 (2220)	1983	D&A. Methane shows from 3920-4060, 4570-4670, 5030-5300 ft (Abo).
40	Herndon No. 1 Mock	25-27N-36E, Union	4802 (1464)	4555 (1388)	1945	D&A
41	Texaco No. 1 Click	34-28N-28E, Union	6560 (1999) GL	3183 (970)	1980	D&A
42	Amoco Production Co. No. 1 State EV	26-28N-29E, Union	6589 (2008) KB	2530 (771)	1973	D&A
43	Texaco No. 1 Springhill B NCT-1	1-28N-30E, Union	6097 (1858) GL	4000 (1219)	1980	D&A. Perforated 2022-2188, 2284-2290, 2370-2376, 2456-2463, 2505-2510, 2546-2558, 2670-2742, 2802-2838, ft with no show.
44	Snorty-Cobbler No. 1	35-28N-31E, Union		527 (161)	1924	D&A. Water sands at 270-280, 283-310 ft.
45	Skelly No. 1 NM Van Pelt	9-28N-35E, Union	5162 (1573) KB	4387 (1337)	1958	D&A. DST at 3778 ft (Mississippian), recovered CO_2 gas at 5 MCFGPD.

TABLE 2 (continued).

No. on Fig 1	Operator, well number, and lease	Location (section-township-range, county)	Elevation ft (m)	Total depth ft (m)	Year completed	Comments
46	Morad No. 1 Campbell	25-28N-35E, Union		600 (183)	1956	D&A
47	Texaco No. 1 Springhill NCT-1	28-29N-30E, Union	6259 (1908) GL	3844 (1172)	1980	D&A. Perforated 1582-1604, 1635-1643, 1704-1711, 1841-1850 ft (Glorieta) with no show. Perforated 2647-3543 ft (Abo), with no show.
48	Amerada Hess No. 1 Wilkinson	4-29N-31E, Union	6049 (1844) GL	3960 (1207)	1980	D&A. Perforated & fractured 849-999 ft with no show.
49	Wayne Freeman Jr. No. 1 Smith	22-29N-32E, Union	5900 (1798)	2959 (902)	1952	D&A
50	HNG Fossil Fuels No. 3 Excel	20-29N-33E, Union	5560 (1695) GL	3032 (924)	1980	D&A
51	Gregg Oil Co. No. 1 Witt	13-29N-35E, Union		4283 (1305)	1961	D&A
52	Texaco No. 1 Cruz	14-29N-36E, Union	4835 (1474) KB	6460 (1969)	1964	D&A. DST 4355-4440 ft (Pennsylvanian), rec salt water.
53	Farrel No. 1	5-30N-28E, Union		480 (146)	1925	D&A
54	Texaco No. 1 Bennett	27-30N-29E, Union	6560 (1999) GL	2868 (874)	1980	D&A
55	Texaco No. 1 Brown NCT-1	29-30N-30E, Union	6410 (1954) GL	2998 (914)	1980	D&A. Perforated 940-1212 ft (Triassic) with no show. Perforated 1480-1749 ft (Glorieta-San Andres) with no show.
56	Amerada Hess No. 1 Burner	9-30N-31E, Union	6052 (1845) GL	3728 (1136)	1984	D&A. Perforated, acidized, fractured 1560-1618 ft (Glorieta) with no show.
57	HNG Fossil Fuels No. 2	23-30N-32E, Union	5700 (1737) GL	3144 (958)	1979	D&A
58	Gulf Oil Corp. No. 1 Jolla Land & Cattle Co.	21-30N-34E, Union	5306 (1617) KB	4190 (1277)	1966	D&A
59	Gregg Oil Co. No. 1 Northcutt	24-30N-36E, Union	4556 (1389) KB	3887 (1185)	1961	D&A
60	Pure Oil Co. No. 2 Black Mesa	6-30N-37E, Union	4424 (1348)	3564 (1086)	1947	D&A. DST 3431-3564 ft (Mississippian), rec salt water.
61	HNG Fossil Fuels No. 1 Excel	1-31N-32E, Union	5135 (1565) KB	2475 (754)	1980	CO_2 well. Perforated 688-720, 746-770 ft (Glorieta), IPF 85 MCFGPD.
62	United Oil Co. No. 2 Baker	6-31N-33E, Union	5062 (1543) KB	2725 (831)	1919	D&A. Water at 108, 860-880, 903-935 ft.
63	Gulf Oil Corp. No. 1 Union State B	17-31N-33E, Union	5311 (1619) KB	2855 (870)	1970	D&A
64	M. H. Farr No. 3 Farr	6-31N-34E, Union	4752 (1448)	768 (234)	1968	D&A. Drilled fault from 616-660 ft, flowed gas.

TABLE 2 (continued).

No. on Fig 1	Operator, well number, and lease	Location (section-township-range, county)	Elevation ft (m)	Total depth ft (m)	Year completed	Comments
65	Gulf Oil Corp. No. 1 Jolla Land & Cattle Co.	22-31N-34E, Union	5287 (1611) KB	4083 (1244)	1970	D&A
66	Guy F. Atkinson No. 1 Hobart Quinby	15-31N-36E, Union	4432 (1351) DF	3014 (919)	1957	D&A. DST 2200-2220 ft (Mississippian), rec 130 ft gas-cut mud + 710 ft fresh water.
67	Pure Oil Co. No. 1 Black Mesa Unit	13-31N-36E, Union	4366 (1331)	3514 (1071)	1947	D&A
68	Gregg Oil Co. No. 1 Harris	35-31N-36E, Union	4555 (1388) KB	3639 (1109)	1961	D&A
69	Ramsey Petroleum No. 1 Black Mesa	20-31N-37E, Union	4419 (1347) KB	3446 (1050)	1970	D&A
70	Trend Petroleum Inc. No. 1 Brown	29-32N-31E, Union		3586 (1093)	1957	D&A
71	Hopkinson No. 1 Hopkinson	34-32N-31E, Union		302 (92)	1954	Completed as water well.
72	Harvest Queen Mill & Elevator Co. No. 1 Like B	30-32N-34E, Union	4882 (1488) GL	1000 (305)	1966	D&A
73	Harvest Queen Mill & Elevator Co. No. 1 Like	26-32N-34E, Union		1220 (372)	1966	Completed as water well.
74	Gulf Oil Corp. No. 1 Huber State	19-32N-37E, Union	4512 (1375) KB	3244 (989)	1975	D&A
75	R. L. Nunn & Co. No. 1 Wallace	30-20N-36E, Union		762 (232)	1952	D&A. Oil & gas show from 580-592 ft.
76	Amoco Production Co. No. 1 State LZ	36-18N-36E, Union	4875 (1486) DF	2900 (884)	1981	CO_2 well. Producing through perforations from 2237-2298 ft (Tubb), IPF 317 MCFGPD + 3 BWPD.
77	Cities Service No. 1 State DP	16-17N-30E, Harding	4342 (1323) KB	2400 (732)	1981	D&A

at depths of 2,000–2,500 ft (600–750 m). At the end of 1985, there were 240 producing wells in the Bravo Dome field and 18 producing wells in the Bueyeros field (New Mexico Oil & Gas Engineering Committee, 1986). Most wells in the Bravo Dome field have been drilled since 1983. On the Bravo Dome, the Tubb consists of interbedded lenticular sandstones, mudstones and minor thin-bedded dolostones and anhydrites. Sandstones are the principal reservoirs of CO_2. They are orange to white in color, fine to very coarse grained and poorly cemented. The orange sandstones contain small amounts of orange-colored clay matrix. Porosity of productive sandstones generally ranges from 10 to 20%. Average permeability is 42 millidarcies (Johnson, 1983). Productive sandstone beds are generally 5–20 ft (1–6 m) thick, but several beds generally produce within a single well so that the gross thickness of productive Tubb may be 200 ft (60 m) or more. Porous sandy zones are generally perforated and acidized; they may also be artificially fractured. Initial potential of wells that produce from the Tubb is generally 500–2,000 MCFGPD (thousand ft^3 gas per day). Mudstones are interbedded with the sandstones and are mostly red or orange in color, but some are greenish gray. The dolostones are thin bedded and light gray; some are porous and probably act as reservoirs. Anhydrites are white, nonporous and microcrystalline.

The Abo Formation on the Bravo dome consists of interbedded lenticular sandstones and red mudstones. The sandstones are very fine to very coarse grained and arkosic. Sandstones in the lower part of the Abo are generally coarse grained and conglomeratic, whereas sandstones in the upper part of the Abo are finer grained. Porosity is variable. Some sandstones are poorly cemented and porous; other sandstones have been cemented by clays or carbonate and are relatively impermeable. Individual sandstone beds are generally 5–20 ft (1–6 m) thick, but several beds generally produce within a single well so that the gross thickness of productive Abo may be 200 ft (60 m) or more. However, the Abo is generally less than 200 ft (60 m) thick on the Bravo dome; it rests unconformably on the Precambrian.

The Santa Rosa Formation produces CO_2 in the Bueyeros field. Most Santa Rosa production is from T21N, R30E in Harding County. Depth to production is less than 1,000 ft (300 m). The Santa Rosa consists of lenticular, fine- to coarse-grained alluvial sandstones and interbedded red, alluvial and lacustrine mudstones. Initial potential of Bueyeros wells that produce from the Santa Rosa is approximately 1,500 MCFGPD. Some wells appear to produce from both the Santa Rosa and from discontinuous sandstones in the lower part of the Chinle Formation (Triassic). The Santa Rosa has been tested only sparsely in the Bravo dome field because wells are generally drilled to completion in the deeper, more prolific Tubb sandstone.

Estimates of recoverable reserves in the Bravo Dome and Bueyeros fields range from 5.3 to 9.8 trillion ft^3 gas (Johnson, 1983). The gas is composed of 98.6–99.8 mole percent CO_2, minor amounts of nitrogen and trace amounts of noble gases (Johnson, 1983; Table 3).

The Des Moines field is located on the Sierra Grande uplift. Five wells produced at the Des Moines field, but all five wells have been abandoned, and the field is presently inactive. The main producing reservoir is the Abo Formation, which rests unconformably on Precambrian granite. Pay zones are 20–30 ft (6–9 m) thick beds of lenticular arkosic conglomerate (Foster and Jensen, 1972). Depth to productive conglomerates ranges from 2,060 to 2,600 ft (630 to 790 m). Initial potential from the Abo is good, ranging from 100 to 1,000 MCFGPD.

Gas was encountered in a shallower unit than the Abo in three of the wells drilled in the Des Moines field. Depth to this shallow gas is approximately 1,200 ft (370 m). At the time those wells were drilled in the early 1950's, it was thought that the reservoir for the shallower gas was the Santa Rosa Formation. However, Foster and Jensen (1972) believed the reservoirs are the Alibates Dolomite (Permian) and a Permian section immediately beneath the Alibates. The term Alibates is used in the Texas Panhandle; in the Des Moines area, the Alibates is thought to be correlative with a dolostone bed in the lower part of the Bernal Formation. One well, the Gruemmer Indian Carbonic No. 2 Gruemmer apparently established production from the Alibates.

Reserves and cumulative productive of CO_2 in the Des Moines field are not known. The gas produced from the field in the Sierra Grande Oil Corp. No. 1 Rogers consisted of 98.6% CO_2, 1.2% N_2 and 0.4% O_2 (Table 3; Moore, 1976). The nitrogen and oxygen caused problems with processing the gas at the small plant constructed at the field (Anderson, 1959). However, gases produced from wells in the Bueyeros field have compositions similar to the gas produced at Des Moines (Table 3) and were successfully processed. The Des Moines CO_2 field was abandoned apparently for economic reasons, and not because reserves were depleted.

Wells drilled outside the productive fields in Union and Harding Counties have also encountered natural gases (Fig. 3, Table 2). Generally, gases encountered by wells drilled on the Sierra Grande uplift and on the Bravo dome have been rich in CO_2; gases encountered by wells drilled in adjacent basinal areas have been rich in hydrocarbons. Three wells, the Energy Oil No. 1 Sadler (Fig. 3, no. 29; Table 2, no. 29), the HNG Fossil Fuels No. 1 Excel (Fig. 3, no. 61; Table 2, no. 61) and the Texas Pacific No. 1 Trujillo (Fig. 3, no. 19; Table 2, no. 19) were completed as productive CO_2 wells but are currently shut in (presumably because of lack of a pipeline connection to processing facilities). The Glorieta Sandstone (Permian) is the reservoir in the Sadler and Excel wells. The Santa Rosa Formation is the reservoir in the Trujillo well. Noncommercial shows of CO_2 have been encountered in Mississippian sedimentary rocks by the Skelly No. 1 New Mexico Van Pelt (Fig. 3, no. 45; Table 2, no. 45).

Wells drilled on the Bravo dome and Sierra Grande uplift have been generally barren of hydrocarbons, but shows of hydrocarbons have been reported in wells drilled in the Tucumcari and Dalhart basins (Fig. 3; Table 2). Shows of oil and hydrocarbon gases have been encountered in the Dakota Sandstone (Cretaceous), the Abo Formation (Permian) and in the Mississippian. Marginally economic hydrocarbon production has been established in Triassic and Pennsylvanian strata of the Tucumcari basin south of the area mapped in Figure 3 (Broadhead, 1984; Broadhead and King, 1985). The Dalhart basin produces hydrocarbons in the Texas Panhandle; production is from Pennsylvanian and Permian reservoirs (Montgomery, 1986).

SOURCE OF CO_2

The source of the CO_2 produced in Union and Harding Counties has not been positively identified, but four hypotheses have been suggested (Foster and Jensen, 1972): (1) juvenile magmatic CO_2; (2) chemical breakdown of carbonate rocks by adjacent igneous intrusions; (3) groundwater solution of carbonate rocks; and (4) bacterial or thermal decomposition of organic matter. Although it is beyond the scope of this report to investigate the possible origins of CO_2 in northeastern New Mexico, geologic and geochemical aspects of the four hypotheses will be reviewed briefly.

Juvenile magmatic CO_2 could have been introduced into Bravo dome reservoirs as volcanic emanations or it could have migrated into its present traps from a deeper source through the deep-seated basement faults that form the Bravo dome and Sierra Grande tectonic elements. Phinney et al. (1978) found support for a juvenile magmatic origin by analyzing isotopes of noble gases (He, Ne, Ar, Kr and Xe) that occur with the CO_2 in the Bravo dome area. Although Phinney et al.'s analyses indicate the noble gases may have a juvenile magmatic source, it is not certain that the CO_2 has the same source as the noble gases. A problem with the volcanic origin is that the areas with the most volcanic rocks and the areas with the largest known CO_2 occurrences are mutually exclusive. Very little volcanic activity has occurred in and around the Bravo Dome and Bueyeros fields; most of the volcanic centers are located in northwestern Harding and northern Union Counties (Dane

TABLE 3. Chemical analyses of natural gas recovered from wells drilled in Union and Harding Counties.

Operator, well number, and lease	Location (section-township-range, county)	Depth of sample ft (m)	Stratigraphic unit	Composition, mole percent							Reference
				CO_2	He	H_2	Ar	O_2	N_2	hydrocarbons	
Amoco Production Co. No. 1 Heimann	3-19N-33E, Harding	2,370 (722)	Tubb (Permian)	98.8	0.01	0	Tr	0.1	1.0	Tr	Hertweck and Fox, 1984
Amoco Production Co. No. 1 Cain E	22-19N-35E, Union	2,060 (628)	Tubb (Permian)	99.0	0.02	0	Tr	Tr	0.8	Tr	Hertweck and Fox, 1984
Waddell & McFann et al. No. 1 Baca	19-20N-31E, Harding	1,706 (520)	Santa Rosa (Triassic)	99.4	0	0	0	0	0.6	0	Moore, 1976
Lula Gambrel No. 1	24-20N-36E, Harding	1,137 (347)	Chinle (Triassic)	18.8	1.80	0.1	1.2	0.1	77.7	0.2	Moore, 1976
Kummbaca Oil & Gas Co. No. 1 Kerlin	34-21N-30E, Harding	940 (287)	Triassic	98.2	0	0	0	0.4	1.4	0	Moore, 1976
Powers-Marshall Co. No. 1 Powers-Marshall	34-21N-30E, Harding	1,900 (579)		99.7	0.01	Tr	Tr	Tr	0.2	0	Moore, 1976
Sierra Grande Oil Corp. No. 1 Rogers	4-29N-29E, Union	1,188 (362)	Bernal (Permian)	98.4	0	0	0	0.4	1.2	0	Moore, 1976

TABLE 4. Carbon-dioxide processing plants in Union and Harding Counties.

Operator	Plant	Location	Products	Capacity
Amerigas, Inc.	Valley plant	northeast of Mosquero	liquid CO_2	100 tons/day
Amerigas, Inc.	Schwarz plant (shut down)	south of Bueyeros	dry ice	100 tons/day
CO_2-in-Action	Bueyeros plant	northwest of Bueyeros	liquid CO_2, dry ice	50 tons/day
Ross Carbonics	Ross Carbonics	northeast of Mosquero	liquid CO_2, dry ice	140 tons/day; maximum of 270 tons/day, depending on supply of feedstock
Amoco Production Co.	southeast compressor station	southwest of Clayton	CO_2 gas, delivered by pipeline to Permian Basin for use in enhanced oil recovery.	

and Bachman, 1965). Johnson (1983) has pointed out that geochemists have tended to support a juvenile magmatic origin because of the isotopic analyses of the noble gases.

The petroleum industry has generally supported the hypothesis that the CO_2 was derived from the chemical breakdown of carbonate rocks by adjacent igneous intrusions. Lang (1959) studied the C^{12}/C^{13} carbon-isotope ratios of the CO_2 gases. He concluded that the carbon in the CO_2 gases was isotopically heavy and was derived from marine limestones. Support for this hypothesis is given by Johnson (1983); a bed of limestone contains sufficient CO_2 in the form of carbonate to form the quantity of CO_2 found in the Bravo dome area. There are three principal geologic arguments against the hypothesis of an igneous-carbonate rock origin. First, there has been limited volcanic activity in the Bravo dome area. Second, although the thermal decomposition of carbonates by magmatic intrusions is a well-known process, that decomposition could be expected to occur only in the vicinity of the intrusion and would not occur over the entire areal extent of a carbonate bed. Third, very few carbonate beds occur within or beneath the principal CO_2 reservoirs, the Abo Formation and the Tubb sandstone. The only stratigraphic units in the Bravo dome area that contain significant amounts of carbonate are the upper part of the Yeso Formation and the San Andres Formation. A similar stratigraphic distribution of carbonate occurs on the Sierra Grande uplift.

Lang's (1959) isotope studies can also be used to support the hypothesis of ground-water solution of carbonate rocks. However, a strong geologic argument against that hypothesis is the paucity of carbonate rocks within or beneath the principal CO_2 reservoir units at Bravo dome.

The hypothesis that the CO_2 originated by bacterial or thermal decomposition of organic matter has largely been discounted. Paleozoic strata on the Bravo dome and Sierra Grande uplift are mostly red beds, evaporites or evaporitic carbonates, and thus have a low content of sedimentary organic matter. Some Paleozoic strata in the Tucumcari and Dalhart basins have a fairly high content of organic matter, but those strata appear to have generated mostly hydrocarbon gases and only a minimal amount of CO_2.

PROCESSING FACILITIES

Five plants presently exist that are capable of processing CO_2 in Union and Harding Counties (Table 4). The Amoco plant near Clayton receives gas from the Bravo Dome field, compresses it and injects it into the Bravo pipeline, which carries it to enhanced recovery projects in the Permian Basin. The other four plants process gas that is produced from the Bueyeros CO_2 field. Those four plants produce liquid CO_2 and dry ice, which are shipped by truck to their markets. The plant of the Liquid Carbonics Company at the Des Moines field has been dismantled. No processing facilities presently exist at the Des Moines field.

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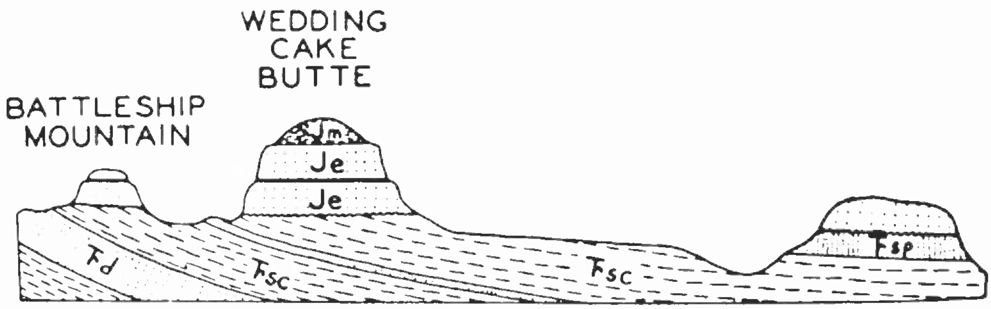

FIG. 3.—Diagrammatic cross section in Union County, New Mexico, showing the angular unconformity between the Jurassic and the Triassic formations: typical Dockum "red beds," *Tr d;* Sloan Canyon formation, *Tr sc;* Sheep Pen Canyon formation, *Tr sp;* Exeter sandstone, *Je;* and Morrison formation, *Jm*.

E-W geological cross section in the vicinity of Wedding Cake Butte, Union County, New Mexico published by Stovall during the 1930's. Note that the cross section is incorrect inasmuch as strata identified as "typical Dockum 'red beds'" underlie the Entrada along the western edge of Wedding Cake Butte.