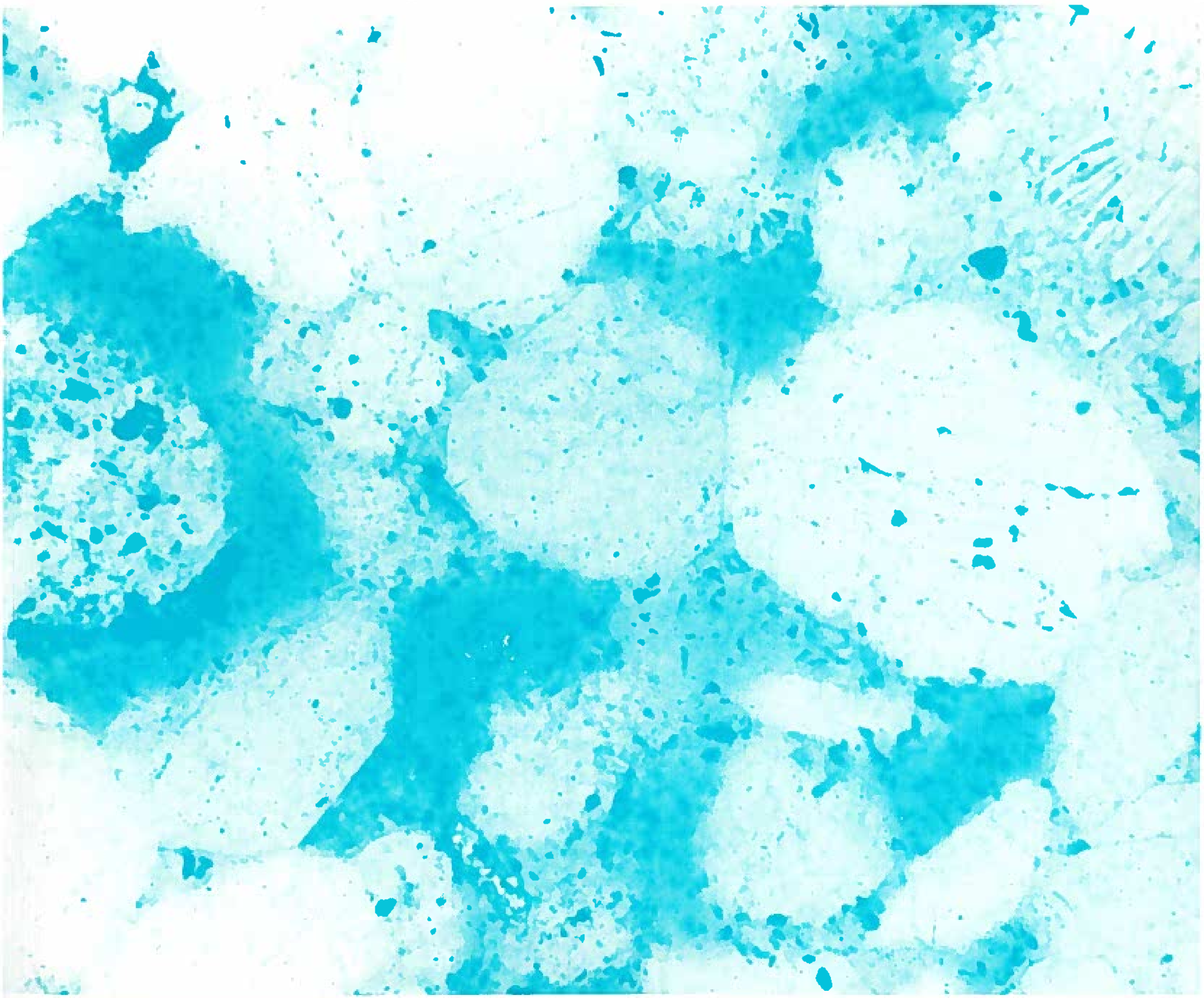
Subsurface petroleum geology of Santa Rosa Sandstone (Triassic), northeast New Mexico

by Ronald F. Broadhead



CIRCULAR 193 New Mexico Bureau of Mines & Mineral Resources 1984

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COVER—Well-developed primary porosity in Santa Rosa sandstone, 800-810 ft, Husky Oil Co. and General Crude Oil Co. No. 1 Hanchett State, Sec. 16, T. 8 N., R. 24 E., Guadalupe County, New Mexico.

Circular 193

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Contents

Figures

Tables

Abstract

The Santa Rosa Sandstone (Triassic) occurs at depths of less than 2,000 ft over most of northeast New Mexico. Although the Santa Rosa Sandstone is currently not producing, two major petroleum accumulations are known to exist in it. One accumulation is located approximately 6 mi north of Santa Rosa, where oil-impregnated Santa Rosa Sandstone crops out; these outcrops of oil-impregnated sandstone are known as the Santa Rosa tar sands. The oil in the tar sands is viscous and heavy. The Santa Rosa tar sands were mined in the 1930's for road-surfacing material, but presently are not being worked. The other known petroleum accumulation in the Santa Rosa Sandstone is a pool of heavy oil that occurs at depths of 400-800 ft in northeast Guadalupe County. Attempts are being made to recover the heavy oil with steamflooding in two small pilot fields, the O'Connell Ranch field and the T-4 Ranch field. In northeast New Mexico the Santa Rosa Sandstone is 67-350 ft thick. It rests on the Artesia Group (Permian) with angular unconformity and is subdivided into three regionally recognizable units: a lower sandstone unit 18-140 ft thick, a middle mudstone unit 0144 ft thick, and an upper sandstone unit 7-150 ft thick. The lower and upper sandstone units are blanket deposits composed mostly of fine- to medium-grained porous sandstones and minor red siliciclastic mudstones. The middle mudstone unit is a blanket deposit composed chiefly of red siliciclastic mudstones and minor lenticular sandstones. The lower and upper sandstone units were deposited by braided streams that flowed southeast toward a large Santa Rosa—age lake that was centered in west-central Texas. The middle mudstone unit is of lacustrine origin and was deposited during a high stand of the lake. Structures on the Santa Rosa Sandstone are mostly gentle northwest-to northeast-trending folds. The heavy oil in the tar-sand deposit at Santa Rosa Lake and the heavy oil near Newkirk both occur in the upper sandstone unit. Shows of asphaltic hydrocarbons have been encountered in the lower unit. Stratigraphic and petrographic studies indicate that good reservoirs are widespread in the lower and upper sandstone units in northeast New Mexico. The blanket geometry of the lower and upper sandstone units indicates that structure probably plays an important or even dominant role in the trapping of any undiscovered hydrocarbons in the Santa Rosa. Oil proximal to the outcrop belt of the Santa Rosa Sandstone has probably been flushed by recently recharged, fresh ground water. Although the source of the oil in Santa Rosa Sandstone is not definitely known, geochemical studies point to the San Andres Formation (Permian) or possibly Pennsylvanian rocks.

Introduction

This study was undertaken because little is available in print on the subsurface geology of the Santa Rosa Sandstone in northeast New Mexico. Interest in the Santa Rosa Sandstone as a potential oil-producing unit has risen with recent plans to reopen the abandoned tar-sand quarry at Santa Rosa Lake and the current attempt to steamflood the heavy-oil accumulation at the O'Connell Ranch field and the T-4 Ranch field near Newkirk. The Santa Rosa is a shallow formation, occurring at depths of less than 2,000 ft over much of northeast New Mexico (Figs. 1, 2). The tar-sand deposit is a classic example of an oil seep that indicates the possible presence of commercial oil accumulations in the shallow subsurface. The purpose of this report is to investigate the regional subsurface stratigraphy and structure of the Santa Rosa Sandstone in northeast New Mexico. Emphasis has been placed on the relationship of stratigraphy and petrography to the regional development of petroleum reservoirs.

Acknowledgments—Frank E. Kottlowski, Director of the New Mexico Bureau of Mines and Mineral Resources, suggested this study. Robert M. North helped take the thin-section photographs. George L. Scott, Jr. and David W. Love reviewed the manuscript. George L. Scott, Jr. provided the author with free access to his personal files and well records. Lynne McNeil typed the manuscript.

Methods of investigation

Drill cuttings from 16 wells (Table 1) were analyzed in 10-ft intervals in order to establish contacts of lithostratigraphic units on gamma-ray logs and also to describe and analyze lithology. Emphasis was placed on description of reservoir units. Primary analysis of drill cuttings was done with a Bausch & Lomb Stereozoom Binocular Microscope that has a magnification range of 7 x to 30 x . Cuttings were placed in a small dish and covered with water during analysis. Immersion in water minimizes light refraction and also removes dust which accumulates on samples during storage, thus bringing out details not generally observed during analysis of dry cuttings. Also, colors of wet rocks are generally more varied and distinctive than colors of dry rocks. Percentage of rock type was determined with a standard visual comparator chart (Swanson, 1981, fig. 12.1) and estimated to the nearest 10%; if a rock type was judged to be less than 10% of a sample, it was assigned a trace percentage. Color was described using the GSA Rock-color Chart (Goddard et al., 1980). Grain size was determined with a visual comparator obtained from the American/Canadian Stratigraphic Corp. Sorting was determined with a comparator chart (Compton, 1962, p. 214) and so was roundness (Powers, 1953, p. 118). The presence of calcite in a sample was deter-

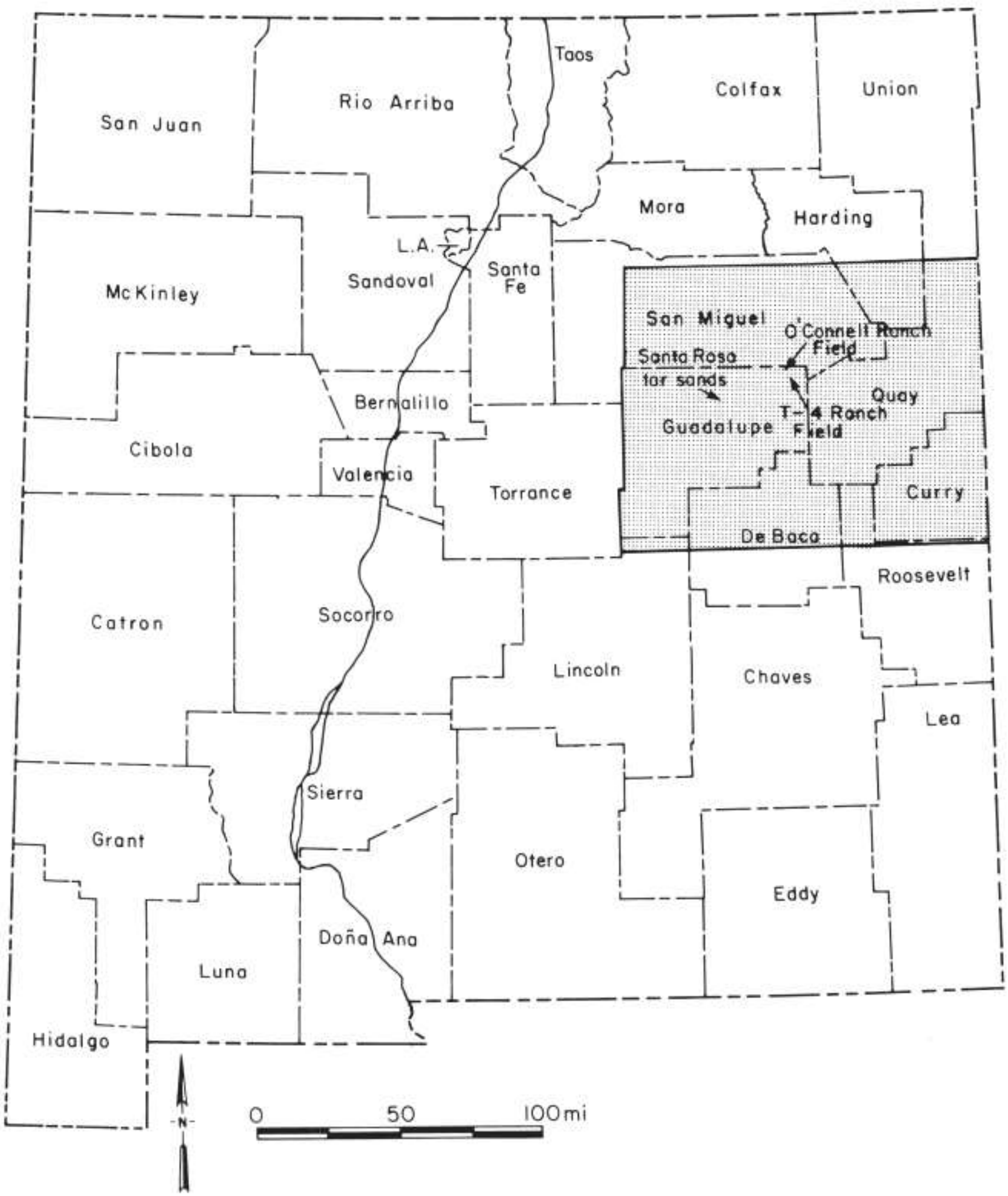


FIGURE 1—Study area (shaded) and locations of the tar-sand deposit at Santa Rosa Lake and the O'Connell Ranch and T-4 Ranch oil fields.

TABLE 1—Wells used in study. GL = ground level, DF = derrick floor, KB = kelly bushing, L = geophysical logs, C = analysis of cuttings with binocular microscope, TS = analysis of cuttings in thin section, A = core analyses (obtained from Martin, 1983).

Operator, well number, and lease	Location (section–township–range, county)	Completion date (month/year)	Elevation (ft)	Total depth (ft)	Data
Pair Oil Co. No. 1 Overton Federal	20–2N–22E, De Baca	4/59	4,887 DF	5,427	L
Twentieth Century Oil Corp. No. 1 Myrick	18–2N–25E, De Baca	12/57	4,405 GL	1,547	L
F. R. Jackson No. 1 A. W. Skarda	3–2N–32E, Curry	9/49	4,426	3,314	L
General Crude Oil Co. No. 1–B Federal "055571"	25–3N–23E, De Baca	11/59	4,588 GL	1,547	L
General Crude Oil Co. No. 1–A Federal "055570"	6–3N–24E, De Baca	11/59	4,577 GL	1,536	L
General Crude Oil Co. No. 1 Olive Henry	20–3N–24E, De Baca	12/59	4,538 DF	1,585	L
Pure Oil Co. No. 1 Pure Federal	31–3N–28E, De Baca	9/46	4,135 DF	6,469	L
Shell Oil Co. No. 1 Stephenson	2–3N–32E, Curry	2/64	4,568 GL	7,012	L
Capitan Drlg. Co. No. 3 DeBaca Core Test	18–4N–27E, De Baca	6/66	4,543 GL	2,340	L
Cities Service Oil Co. No. 1 Widner	17–4N–31E, Curry	4/54	4,557	7,348	L
Continental Oil Co. No. 1 Williams Federal	31–5N–24E, De Baca	11/71	4,408 GL	1,376	L
Abercrombie & Hawkins No. 1 Nappier	22–5N–26E, De Baca	10/49	4,518	5,560	L; C
Marathon Oil Co. No. 1 State "16"	16–5N–31E, Curry	4/73	4,638 DF	6,575	L
Franklin, Aston, & Fair, Inc. No. 1 Green Estate	10–5N–32E, Curry	6/61	4,700 GL	8,180	L; C; TS
Texas Gulf Prod. Co. No. 1 Garrett	34–5N–34E, Curry	12/62	4,568 GL	7,538	L; C; TS
Slick Moorman No. 1 Dougherty	4–5N–35E, Curry	11/50	4,426	6,860	L
Humble Oil & Refining Co. No. 6–22–5 Core Test	5–6N–25E, De Baca	7/66	4,542 GL	1,030	L
United Western Mineral Co. No. 1 Joe Killough Federal	11–6N–25E, De Baca	8/57	4,634 DF	2,608	L
Amoco Production Co. No. 1 State "GM"	16–6N–29E, Quay	9/79	4,845 GL	6,400	L
Exxon Corp. No. 1 Evelyn G. Brown	35–6N–34E, Curry	11/74	4,423 GL	7,067	L
Lonnie Kemper No. 1 "17" Federal	17–7N–21E, Guadalupe	6/68	5,052 GL	745	L
Sunray Oil Corp. No. 1 N. Mex. Federal	3–8N–18E, Guadalupe	2/55	5,525 DF	4,653	L
Sunray Mid-Continent Oil Co. No. 1 R. Padilla	4–8N–19E, Guadalupe	9/55	5,364	3,800	L
Sunray Oil Co. No. 1 N.M. Federal 'A'	5–8N–19E, Guadalupe	4/55	5,425	3,728	L
Trans-Pecos Resources No. 1 Fluitt	1–8N–22E, Guadalupe	5/70	4,836 KB	1,438	L
General Crude Oil Co. No. 1–1 State	2–8N–23E, Guadalupe	2/58	4,998 GL	7,103	L
Husky Oil Co. & General Crude Oil Co. No. 1 Hanchett State	16–8N–24E, Guadalupe	3/56	5,027	7,244	L; C; TS
Henderson & Erickson No. 1 Redondo Mesa	30–8N–31E, Quay	5/75	4,379 KB	2,628	L
A. G. Hill Co. No. 1 Federal "A"	27–9N–19E, Guadalupe	12/52	5,558	4,932	L
Trans-Pecos Resources No. 1 Latigo Ranch Blk "A"	2–9N–23E, Guadalupe	7/82	4,887 KB	7,702	L
Shell Oil Co. No. ST–34–69 Shell Strat	13–9N–27E, Quay	1/70	4,436 KB	2,640	L
Shell Oil Co. No. ST–5–69 Shell Strat	22–9N–28E, Quay	5/69	4,384 KB	2,739	L
Amoco Production Co. No. 1 Baker	29–9N–30E, Quay	3/74	4,208 KB	8,330	L
General Crude Oil Co. No. 1 R. L. Spires	22–10N–22E, Guadalupe	6/56	4,959	7,661	L; C
General Crude Oil Co. No. 1 Simpson	21–10N–23E, Guadalupe	7/55	4,664	9,151	L
General Crude Oil Co. No. 1 A. S. Wilke "14"	14–10N–24E, Guadalupe	11/58	4,790 DF	6,980	L; C; TS
Kenneth Hankins No. 1 Virginia Branch	9–10N–25E, Guadalupe	7/68	—	1,295	L; C
Humble Oil & Refining Co. No. 6–44–30 Federal	30–10N–26E, Guadalupe	5/66	4,582 GL	1,428	L
Miami Petroleum Co. Inc. No. 1 Hoover Ranch "A"	2–10N–27E, Quay	6/59	4,259 GL	6,415	L; C; TS
Sunray Mid-Continent Oil Co. No. 1 Ira J. Briscoe	31–10N–30E, Quay	1/59	4,243 DF	9,069	L; C
Shell Oil Co. No. 1 North Pueblo	23–10N–31E, Quay	4/70	4,104 GL	5,629	L
Shell Oil Co. No. 2 North Pueblo	25–10N–31E, Quay	5/70	4,127 KB	7,867	L
Burk Royalty Co. No. 1 Elder Dennis	27–10N–31E, Quay	10/58	—	2,710	L; C
Humble Oil & Refining Co. No. 6–43–25 Core Test	25–11N–24E, Guadalupe	5/66	4,820 GL	1,310	L
Sam D. Ares No. 1 Beth State	4–11N–25E, Guadalupe	3/66	—	1,221	C
Corona Oil Co. No. 1 O'Connell Ranch Unit	10–11N–25E, Guadalupe	—	4,518 GL	443	A
Humble Oil & Refining Co. No. 6–11–13 Core Test	13–11N–25E, Guadalupe	5/66	4,830 GL	1,160	L
Corona Oil Co. No. 10 O'Connell Ranch Unit	15–11N–25E, Guadalupe	10/81	4,582 GL	515	A
Corona Oil Co. No. 11 O'Connell Ranch Unit	15–11N–25E, Guadalupe	10/81	4,578 GL	478	A
Corona Oil Co. No. 12 O'Connell Ranch Unit	15–11N–25E, Guadalupe	—	—	—	A
Rio Petro Ltd. No. 16 State	15–11N–25E, Guadalupe	12/83	4,589 KB	1,186	C; L
Humble Oil & Refining Co. No. 1 W. R. Moore, Jr.	23–11N–25E, Guadalupe	10/63	4,932 DF	3,915	L
Humble Oil & Refining Co. No. 1 Neafus Core Test	24–11N–25E, Guadalupe	10/65	4,896 GL	1,268	L
H. C. McCulloch No. 1 Higgins	28–11N–25E, Guadalupe	3/68	4,575 GL	1,012	L
Humble Oil & Refining Co. No. 6–33–8 Core Test	8–11N–26E, Guadalupe	10/66	4,756 GL	900	L
Humble Oil & Refining Co. No. 6–21–25 Core Test	25–12N–23E, San Miguel	5/66	4,732 GL	824	L
Humble Oil & Refining Co. No. 6–13–27 Core Test	27–12N–24E, San Miguel	5/66	4,404 GL	860	L
Humble Oil & Refining Co. No. 2 Neafus Core Test	34–12N–25E, San Miguel	12/65	4,460 GL	1,259	L
Humble Oil & Refining Co. No. 6–41–34 Core Test	34–12N–26E, San Miguel	—/66	5,326 GL	2,071	L
Puretex Oil No. 1 Frank Chappell, Jr.	13–12N–29E, San Miguel	12/71	4,103 KB	4,932	L
Miami Petroleum Co. No. 2 Hoover Ranch	18–12N–29E, San Miguel	9/58	4,119 DF	7,075	L

TABLE 1 (continued).

Operator, well number, and lease	Location (section–township–range, county)	Completion date (month/year)	Elevation (ft)	Total depth (ft)	Data
Puretex Oil No. 2 Frank Chappell, Jr.	17–12N–30E, San Miguel	11/71	4,163 KB	5,006	L
O. L. Ledgerwood No. 1 Kimes	11–12N–32E, Quay	9/49	4,035	6,505	L
N. G. Penrose No. 1 Tippins	35–12N–34E, Quay	10/51	4,065	5,615	L; C; TS
Humble Oil & Refining Co. No. 6–41–12 Core Test	12–13N–23E, San Miguel	9/66	4,648 GL	945	L
Miami Petroleum Co. No. 3 Hoover Ranch	25–13N–26E, San Miguel	4/59	4,158 DF	6,670	L; C
Miami Petroleum Co. No. 2 Bell Ranch	12–14N–27E, San Miguel	9/58	4,274 GL	3,202	L
Sunray Mid-Continent Oil Corp. No. 1 State "N"	16–24N–32E, Harding	10/58	3,925 DF	2,850	L
Marian B. Edmonds & Arthur A. Deeters No. 2 Cain	22–15N–33E, Harding	9/68	4,140 GL	1,430	L; C; TS
Powers Wire Products, Inc. No. 1–28 State	28–15N–34E, Quay	12/69	4,051 KB	2,540	L; C
Powers Wire Products, Inc. No. 2–28 State	28–15N–34E, Quay	3/70	4,076 KB	2,747	L
Continental Oil Co. No. 1 Leatherwood–Reed	15–16N–17E, San Miguel	9/54	6,740	3,911	L
Aladdin Petroleum Corp. No. 1 Waggoner Estate Tract 2	2–16N–26E, San Miguel	12/67	4,338	2,961	L
Humble Oil & Refining Co. No. 1 State "CP"	36–16N–36E, Quay	11/71	4,025 GL	1,159	L
D. W. St. Clair No. 1 Sedberry	25–17N–16E, San Miguel	2/68	6,631 GL	4,813	L
Silver Monument Minerals, Inc. No. 1 Iva Sedberry	25–17N–16E, San Miguel	5/74	6,584 KB	4,811	L
Monument Energy Corp. No. 2 Sedberry "B"	25–17N–16E, San Miguel	7/74	6,586 KB	4,718	L
Monument Energy Corp. No. 1 Sue Ann	19–17N–17E, San Miguel	6/74	6,665 KB	5,030	L
Humble Oil & Refining Co. No. 1 State "CO"	28–17N–36E, Quay	11/71	4,291 GL	1,400	L; C; TS

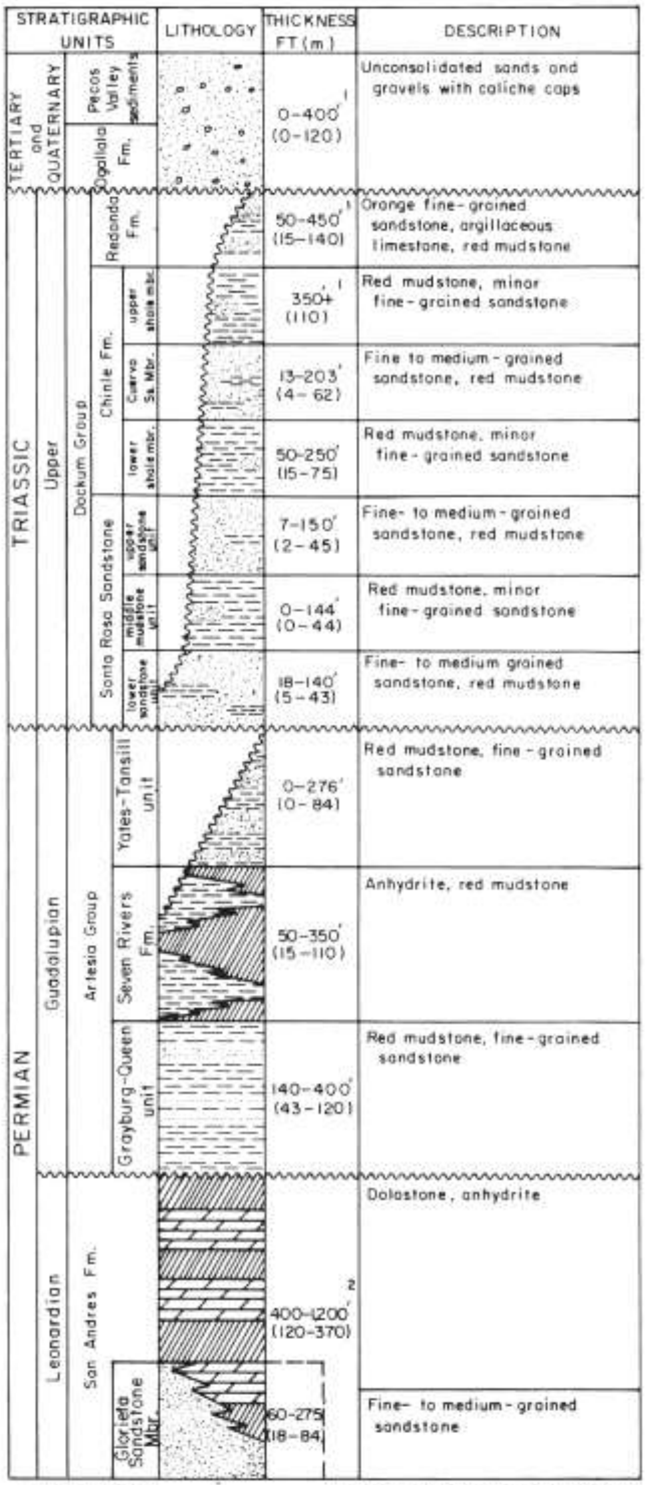
mined by strong effervescence in a 10% dilute HCl solution; the presence of dolomite in a sample was determined by weak effervescence in a 10% dilute HCl solution. All drill cuttings were examined for fluorescence under ultraviolet light. Samples with suspected hydrocarbons were immersed in cigarette lighter fluid in order to obtain a cut of soluble hydrocarbons.

Reservoir geology was further characterized by analysis of thin sections of drill cuttings. Thin sections were made of cuttings of the Santa Rosa Sandstone from eight wells. Cuttings of only the most porous sandstones from the upper and lower units of the Santa Rosa were picked so that the best reservoirs were analyzed. Thin sections were made with blue epoxy in order to enhance pore study. Percent composition was estimated using visual comparator charts (Bacelle and Bosellini, 1965).

Gamma-ray borehole logs from 73 wells were used to correlate lithostratigraphic tops and to interpret lithology (Figs. 3-5 in pocket). Only logs that were judged to be of good quality were used. With wells for which cuttings were examined, tops were correlated to the nearest foot with gamma-ray logs after they had been identified by analysis of cuttings. The Artesia—Santa Rosa contact was identified in the subsurface by analysis of cuttings and by correlation of reference outcrops of the Santa Rosa Sandstone and the Artesia Group into the subsurface (Fig. 5 in pocket, Fig. 6); a gamma-ray profile of the outcrop section was made with a hand-held scintillometer and correlated with the gamma-ray log of a nearby well (Fig. 6) according to the method of Ettensohn et al. (1979). Gamma-ray logs were also used to determine net thickness of sandstone in the upper and lower sandstone units of the Santa Rosa Sandstone and in the Cuervo Member of the Chinle Formation. Analysis of drill cuttings revealed that a "shale" base line could be drawn through gamma-ray logs of Chinle mud-stone, because the mudstone is more radioactive than the sandstone. Deflections to the left of the "shale" base line indicate sandstone and deflections to the right of it indicate mudstone. Examination of drill cuttings revealed that deflections to the left of the base line may rarely be caused by limestone. This method was also used by McGowen et al. (1979) to construct regional subsurface facies maps of the lower part of the Dockum Group. For this study, the log-derived data were used to construct sandstone isolith maps of the lower and upper units of the Santa Rosa Sandstone and the Cuervo Member of the Chinle Formation (Figs. 8-10 in pocket). Sandstone isolith maps show the total thickness of sandstone. Sandstone isolith maps were constructed rather than isopach maps or sandstone percentage maps because it was felt that the sandstone isolith maps best evaluate the potential pay thickness of a reservoir unit. The isopach maps show total thickness of all lithologies in the Santa Rosa and Cuervo Sandstone, whereas the sandstone percentage map will show only the percent thickness of the Santa Rosa or Cuervo that is sandstone and not how much sandstone is present.

Stratigraphy

The regional stratigraphy of the Santa Rosa Sandstone is discussed below in order to put the reservoir analyses in a meaningful stratigraphic framework. The stratigraphy of rock units underlying and overlying the Santa Rosa is discussed in lesser detail. The stratigraphy of the Santa Rosa, other Triassic, and Upper Permian units is summarized in Fig. 2.



[1] Kelley (1972)
[2] Foster and others (1972, fig. 4)
3. Bernal Formation west of Vaughn and north of Santa Rosa (see text)

FIGURE 2—Stratigraphic chart of Upper Permian and Triassic rocks in northeast New Mexico.

San Andres Formation (Permian: Leonardian)

In northeast New Mexico, the San Andres Formation is composed of interbedded dolostone, limestone, anhydrite, salt, mudstone, and sandstone. A basal sandstone-rich unit is the Glorieta Sandstone Member. Foster et al. (1972, fig. 4) indicate that the San Andres Formation varies in thickness from 400 to 1,200 ft in the area covered by this report. For more detailed information on the stratigraphy of the San Andres in northeast and east-central New Mexico, readers are referred to Kelley (1972, pp. 9-13), Foster et al. (1972, pp. 9-11), and Pitt and Scott (1981).

Artesia Group (Permian: Guadalupian)

The Artesia Group was named by Tait et al. (1962) to embrace five formations which had already been defined in southeast and east-central New Mexico. In ascending order, the five formations are: Grayburg Formation, Queen Formation, Seven Rivers Formation, Yates Formation, and Tansill Formation. The Artesia Group has been correlated by many workers with the Whitehorse Group of Oklahoma and the Chalk Bluff Formation of southeast New Mexico (Tait et al., 1962, pp. 505-511). In his mapping of the 8,000 mil Fort Sumner 1° x 2° sheet of east-central New Mexico, Kelley (1972, pp. 13-18) subdivided the Artesia Group into three lithologic and surface-mappable rock units that are correlative with the five formations constituting the Artesia Group in southeast New Mexico. Kelley's three units are (ascending): the GrayburgQueen unit (comprising the undivided Grayburg and Queen Formations), the Seven Rivers Formation, and the Yates—Tansill unit (comprising the undivided Yates and Tansill Formations). Kelley's threefold subdivision of the Artesia has been extended into the subsurface for this study (Fig. 2, Figs. 3-5 in pocket). The Artesia Group varies in thickness from 134 to 918 ft in the subsurface of the study area (Fig. 7 in pocket). Although some of the thickness variation appears to be due to a northwestward depositional thinning, most of the thinning is caused by an erosional angular unconformity between the Artesia and the overlying Dockum Group (Triassic). The Artesia dips regionally southeast, and the Yates—Tansill, Seven Rivers, and Grayburg—Queen all are erosionally truncated in a northwest direction by the overlying Dockum Group. The lower contact of the Artesia Group (with the San Andres Formation) is sharp and is thought to be unconformable with a "mild erosion surface" (Kelley, 1972, p. 16).

Grayburg-Queen unit

The Grayburg and Queen Formations have been correlated into northeast New Mexico in the subsurface by Tait et al. (1962, fig. 3) and on the surface as the undivided Grayburg—Queen unit by Kelley (1972, pp. 14-15). A dashed contact between the Grayburg and the Queen was drawn by Tait et al. (1962, fig. 3), indicating a belief on their part that the contact between these two units is uncertain in the subsurface of northeast New Mexico. In the area covered by this report, the Grayburg—Queen unit is 140-400 ft thick. It thins to the north and west; the thinning is depositional and results from onlapping onto Permian-age paleohighlands.

In the area covered by this report, the Grayburg-Queen unit is composed chiefly of interbedded mudstones and sandstones with minor anhydrite, dolostone, and halite. The mudstones are pale reddish brown (10R5/4) to moderate reddish orange (10R616) and silty to argillaceous. A few mudstones are various shades of greenish gray. Sandstones are light gray (N7) to very light gray (N8) and very fine-grained. Dolostone is pink to white and microcrystalline. Anhydrite is white (N9) to very light gray (N8) and microcrystalline. Percentage of anhydrite and halite decreases northward.

Seven Rivers Formation

The Seven Rivers Formation was correlated into the subsurface of northeast New Mexico from southeast New Mexico by Tait et al. (1962, fig. 3). Kelley (1972, pp. 16-18) correlated the Seven Rivers into northeast New Mexico from southeast New Mexico on surface mapping. In the area covered by this report, the Seven Rivers Formation is 50-350 ft thick. It thins to the north and west. As with the Grayburg—Queen unit, thinning is mostly depositional and results from stratigraphic onlapping of Permian-age paleohighlands. Where the overlying Yates—Tansill unit has been removed by post-Artesia but pre-Dockum erosion, thinning of the Seven Rivers is accentuated. The Seven Rivers rests sharply and conformably on the Grayburg—Queen unit.

The Seven Rivers Formation is composed of interbedded anhydrite, mudstone, and sandstone, and minor halite. Anhydrite is dominant in the east and southeast parts of the study area, where halite is also present. As the Seven Rivers thins to the north and west, it grades into a clastic facies of interbedded mudstone, sandstone, and minor anhydrite. Anhydrite in the Seven Rivers is white (N9) to very light gray (N8), microcrystalline, and generally dolomitic. Mudstone is moderate reddish brown (10R416) to moderate reddish orange (10R616), silty to argillaceous, and calcareous. Sandstone is pale reddish brown (10R5/4) to moderate reddish brown (10R4/6) or yellowish gray (5Y8/1) to white (N9) and fine- to very fine-grained; some sandstone is cemented by dolomite.

Yates—Tansill unit

The Yates and Tansill Formations were correlated into the subsurface of northeast New Mexico from southeast New Mexico by Tait et al. (1962, fig. 3). Kelley (1972, p. 18) mapped the Yates—Tansill unit on the surface in east-central New Mexico, where it rests sharply and conformably on the Seven Rivers Formation. In the area covered by this report, the Yates-Tansill unit is 0-276 ft thick. Major thinning is due to erosional truncation by the Dockum Group and is to the north and west. The maps of Kelley (1972) indicate that in east-central New Mexico post-Artesia erosion has left several erosional "outliers of Yates scattered across a terrain of Seven Rivers" (Kelley, 1972, p. 18), implying the existence of a paleodrainage system developed on top of the Artesia Group. Certainly the coincidence of several thin areas of the Artesia with sandstone thicks in the overlying Lower Santa Rosa (Figs. 7, 8 in pocket) suggests, but does not prove, the presence of such a paleodrainage system. The outliers of Seven Rivers may also be explained by the peneplanation of a folded Artesia surface, with thicker Yates—Tansill unit preserved in the synclines. A lack of areally persistent and depositionally horizontal marker beds in the overlying Dockum Group makes paleodrainage mapping, as suggested by Busch (1974, pp. 87-92), difficult. Undoubtedly, both paleostructure and paleotopography are responsible for the location of Yates—Tansill outliers.

The Yates—Tansill unit is composed primarily of mudstone and sandstone, with only minor dolostone and limestone. Mudstone is moderate reddish orange (10R6/6) to grayish red (10R4/2) or various shades of greenish gray; it is silty to argillaceous. Sandstone in the Yates—Tansill unit is very light gray (N8) to light gray (N7) or pale reddish brown (10R5/4) and fine- to very fine-grained. Limestone is white (N9) to very light gray (N8), microcrystalline lime mudstone with a chalky texture. Dolostone is pink to light gray and microcrystalline.

Bernal Formation (Permian: Guadalupian)

The term Bernal Formation was first used by Kelley (1949, fig. 2) and later by Bachman (1953) for brownish-red siltstone and minor fine-grained sandstone that crop out near Bernal Butte, T. 13 N., R. 16 E., San Miguel County, New Mexico. The Bernal is stratigraphically sandwiched between the San Andres Formation and the Dockum Group. It thins northward and is generally absent north of Ocate in northwest Mora County; in the Ocate area of northwest Mora County the Bernal lies unconformably on the Glorieta Sandstone Member of the San Andres Formation (Bachman, 1953).

The stratigraphic superposition of the Bernal implies an equivalence to the Artesia Group. Tait et al. (1962, fig. 3, p. 515) correlated the Bernal with the Grayburg, Queen, and lower part of the Seven Rivers Formations. Kelley (1972, pp. 13-16, 21) implied a correlation of the Bernal with the Grayburg and Queen Formations and suggested that the name Bernal be retained north of the latitude of Santa Rosa and west of the longitude of Vaughn. Red fine-grained sandstones of the upper Bernal exposed just south of Santa Rosa were examined during this study and were correlated into the subsurface as the northwestern clastic fades of the Seven Rivers Formation (Fig. 6). There-

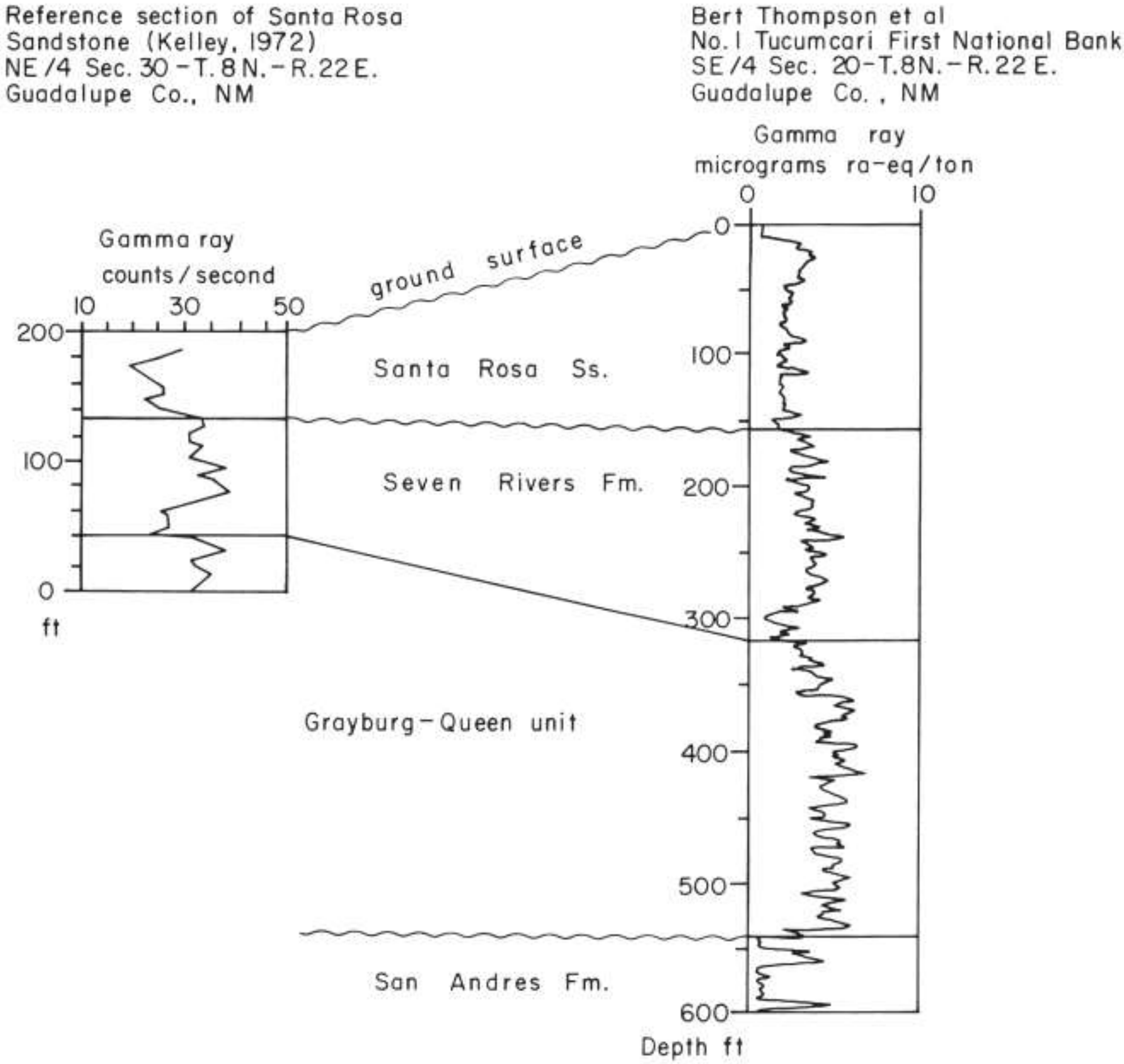


FIGURE 6—Gamma-ray profile of reference section of Santa Rosa Sandstone (Kelley, 1972, p. 22) correlated into the subsurface.

fore, the Bernal is equivalent to the Grayburg, Queen, and Seven Rivers Formations, in agreement with Tait et al. (1962, fig. 3, p. 515).

Dockum Group (Triassic)

The Triassic System is represented by the Dockum Group in northeast New Mexico. The Dockum is Late Triassic in age (Colbert and Gregory, 1957). Lower and Middle Triassic rocks are absent, and the Dockum rests with angular unconformity on Permian rocks, as discussed previously. In northeast New Mexico the Dockum Group is divided into three formations, in ascending order the Santa Rosa Sandstone, the Chinle Formation, and the Redonda Formation. A sandstone-rich unit in the Chinle has been named the Cuervo Sandstone Member (Kelley, 1972, pp. 23-25).

Santa Rosa Sandstone

The Santa Rosa Sandstone was named by Dar ton (1922, p. 183) for medium- to coarse-grained, white to buff sandstone that crops out in the vicinity of Santa Rosa, Guadalupe County, New Mexico. Kelley (1972, pp. 21-23) designated a type section and two reference sections. The Santa Rosa Sandstone is a blanket deposit that forms the base of the Dockum Group in northeast New Mexico. In the area covered by this report the Santa Rosa Sandstone is 67-350 ft thick.

Several workers have stratigraphically subdivided the Santa Rosa Sandstone into members on the basis of surface geology. All such subdivisions were applicable to studies of local areal extent. Read et al. (in Kelley, 1972, p. 23) subdivided the Santa Rosa into a lower sandstone unit, a middle sandstone unit, and an upper sandstone unit in the Guadalupe mining district, Sec. 6, T. 7 N., R. 20 E., Guadalupe County, New Mexico. Aggregate thickness of the three units is 140-160 ft, but the top of the section has been eroded. Gorman and Robeck (1946) and Finch and Wright (1975) subdivided the Santa Rosa into four members in the vicinity of the Santa Rosa tar-sand deposit at Santa Rosa Lake, T. 10-11 N., R. 22-23 E., Guadalupe County, New Mexico. In ascending order, the four members are: lower sandstone member, middle sandstone member, shale member, and upper sandstone member. Kelley (1972, pp. 21-23) subdivided the Santa Rosa into a lower member composed of sandstones and an upper member composed of sandstones.

Subsurface stratigraphic investigations carried out as part of this study indicate that the Santa Rosa Sandstone is divisible into three widespread and recognizable stratigraphic units in northeast New Mexico (Fig. 2, Figs. 3-5 in pocket). These units are: lower sandstone unit, middle mudstone unit, and upper sandstone unit. These units are laterally traceable in the subsurface using gamma-ray borehole logs. My lower sandstone unit is equivalent to the lower and middle sandstone members of Gorman and Robeck (1946); my middle mudstone unit is equivalent to the shale member of Gorman and Robeck; and my upper sandstone unit is equivalent to the upper sandstone member of Gorman and Robeck.

The contact between the Santa Rosa Sandstone and the Artesia Group is often correlated incorrectly in the subsurface of northeast New Mexico. Many workers correlate the Artesia top at the first (highest) anhydrite encountered in the section. This anhydrite is marked by a negative kick on gamma-ray borehole logs. The first anhydrite generally marks the top of the Seven Rivers Formation and is internal to the Artesia Group. Therefore, the red mudstones and fine-grained sandstones of the Yates-Tansill unit are included by many in the Dockum, increasing the measured thickness of the Dockum by 0-300 ft and decreasing the measured thickness of the Artesia by 0-300 ft. The base of the Dockum was correlated in this study at the base of the lowest sandstone bed in the Santa Rosa Sandstone (Figs. 3-5 in pocket). Although quite possibly some Dockum mudstone locally underlies the lowest sandstone bed, that mudstone is probably thin, and the pick at the base of the lowest sandstone will not result in any significant error in correlation. Southeast of the study area, where more lacustrine conditions prevailed during Dockum deposition (McGowen et al., 1979, 1983), it is conceivable that the Artesia-Dockum contact coincides with the contact of two mudstone beds.

At the eastern end of cross section A-A' (Fig. 3 in pocket) in the Sunray Mid-Continent No. 1 Ira J. Briscoe, the Shell Oil No. 2 North Pueblo, and the N. G. Penrose No. 1 Tippins, approximately 100 ft of red mudstone is present beneath the Santa Rosa that does not crop out in northeast or east-central New Mexico. That mudstone is probably part of the Yates-Tansill unit and was mapped that way because of lithologic similarity to the Yates-Tansill unit. That mudstone could possibly be an erosional outlier of the post-Artesia Quartermaster Formation (Permian) of the Texas panhandle or an equivalent of the pre-Santa Rosa Tecovas Formation (Triassic) of west Texas. Definite correlation of that mudstone is not possible without paleontologic study.

Lower sandstone unit—The lower sandstone unit is a blanket deposit 18-140 ft thick in the area covered by this report. It is predominantly sandstone, but some red mudstone beds are present. Net thickness of sandstone, as determined by analysis of gamma-ray logs, ranges from 14 to 127 ft (Fig. 8 in pocket). Percent sandstone ranges from 15 to 100% and is more than 70% in most wells studied.

Sandstones in the lower unit are light gray (N8) to light brown (5YR5/6), fine- to very coarse-grained, and moderately to well sorted. Some are conglomeratic. They are composed predominantly of angular to subrounded quartz and are cemented by intergranular calcite. Mudstones in the lower unit are red to maroon and are generally similar to mudstones found in the overlying Chinle Formation. In one well, the N. G. Penrose No. 1 Tippins located in Sec. 35, T. 12 N., R. 34 E., Quay County, the lower sandstone unit contains a large amount of white (N9) to very light gray (N8) microcrystalline limestone.

Middle mudstone unit—The middle mudstone unit is 0-144 ft thick in the study area. The surface studies by Gorman and Robeck (1946) and Kelley (1972, pp. 20-21) indicate that it is locally absent. It was present in **all but one** well examined during the course of this study. The middle unit conformably overlies the lower sandstone unit, is sharply and unconformably overlain by the upper sandstone unit, and is thinnest where the upper unit has eroded down into it. The unconformity between the middle and upper units probably represents only a short duration of time.

The middle unit is composed predominantly of moderate reddish-brown (10R4/6) to moderate reddish-orange (10R6/6), silty to argillaceous mudstones which are similar to the mudstones found in the overlying Chinle Formation. Casts of plant stems are common in the mudstones. The middle unit contains minor amounts of gray to greenish-gray mudstone, fine-grained sandstone, and white to light-gray microcrystalline limestone.

Upper sandstone unit—The upper sandstone unit is a blanket deposit 7-150 ft thick in the study area. It is composed chiefly of sandstone, with minor mud-stone, limestone, and coal. Net thickness of sandstone ranges from 0 to 138 ft (Fig. 9 in pocket). Percent sandstone in the upper unit ranges from 0 to 100% and is greater than 60% in most wells studied.

Sandstones in the upper unit are very light gray (N8) to light greenish gray (5GY8/1), fine- to very coarse-grained, and moderately to well sorted. They are composed primarily of angular to subrounded quartz and are cemented by intergranular calcite. Mudstones in the upper unit are red to maroon and are generally similar to the mudstones found in the overlying Chinle Formation. Limestones are white to light-gray and microcrystalline. In some wells the upper unit comprises an upward-fining sequence with both percentage of sandstone and grain size of sandstone decreasing upward; this upward-fining trend is not evident in most wells. Analyses of drill cuttings indicate that a few thin and discontinuous coal beds are present near the top of the upper unit.

Chinle Formation

The Chinle Formation conformably overlies the Santa Rosa Sandstone. The contact with the Santa Rosa appears to be somewhat gradational, but can be picked consistently with gamma-ray borehole logs. The Chinle is composed of red to brown mudstone with minor interbedded sandstone. Kelley (1972, pp. 23-25) subdivided the Chinle in east-central New Mexico into lower shale member, Cuervo Sandstone Member, and upper shale member.

Lower shale member—The lower shale member is approximately 50-250 ft thick in the area covered by this report. It is composed primarily of moderate reddish-brown (10R416) to moderate reddish-orange (10R6/ 6), argillaceous, calcareous mudstone. It also contains minor amounts of greenish-gray to bluish-gray mud-stone and some laterally discontinuous beds of fine-to very fine-grained sandstone. Casts of plant stems are common in the red mudstones.

Cuervo Sandstone Member—The Cuervo Sandstone Member is 13-203 ft thick in the area covered by this report. It is composed mostly of sandstone and contains lesser amounts of mudstone and trace amounts of coal. Net thickness of sandstone ranges from 4 to 201 ft (Fig. 10 in pocket) and lateral facies changes from sandstone to mudstone are common. Percentage of sandstone ranges from 4 to 100% and is greater than 50% in most wells studied. Subsurface correlations made with gamma-ray logs and descriptions of drill cuttings indicate that the Cuervo is a laterally traceable unit that is present throughout the study area (Figs. 3-5 in pocket), although it is dominantly mudstone in some places. The lower contact with the lower shale member of the Chinle is laterally traceable with gamma-ray logs; it is sharp and apparently erosional in most wells (Figs. 3-5 in pocket), but gradational in a few wells. Although it has not been mapped by most workers as a separate unit on the surface, the regional outcrop distribution of the Chinle (Dane and Bachman, 1965) suggests that the Cuervo Member crops out over a large part of the study area.

Sandstone in the Cuervo is light gray (N7) to medium gray (N5) or pale red (10R6/2) to pale reddish brown (10R514). It is fine- to very fine-grained and well sorted. Calcite cement is common. Cuervo sandstone is generally finer-grained than Santa Rosa sandstone. The Cuervo is generally composed of two units of sandstone separated by a unit of mudstone; the mudstone unit or either of the sandstone units are locally absent. Gamma-ray logs indicate that each of the sandstone units forms an upward-fining sequence in some wells.

Upper shale member—The upper shale member is at least 350 ft thick in northeast New Mexico (Kelley, 1972, p. 25). It crops out over approximately 50% of the area covered by this report. It is chiefly mudstone with only minor, lenticular sandstone beds. Mud-stones in the upper shale member are mostly moderate reddish brown (10R4/6) to moderate reddish orange (10R6/6) to grayish red (10R4/2) and commonly contain casts of plant stems. A trace amount of mud-stones is very light gray (N8) to light gray (N7). The mudstones are silty to argillaceous and most are calcareous. Sandstones are moderate reddish orange (10R6/6) to grayish red (10R412) to moderate reddish brown (10R4/6), fine- to very fine-grained, silty, moderately to well sorted, and generally somewhat calcareous. Some sandstones in the upper shale member are white (N9) to light gray (N7), but are otherwise similar to the red sandstones.

Redonda Formation

The Redonda Formation is the uppermost stratigraphic unit of the Dockum Group in northeast New Mexico. Its occurrence in northeast New Mexico is limited, however, because of extensive pre-Cretaceous and Cenozoic erosion. It was first named by Dobrovolny et al. (1946) for exposures at Mesa Redonda, Quay County, New Mexico. The Redonda was not encountered in the subsurface during this study, but Kelley (1972, pp. 25, 28) reported that it is approximately 50-450 ft thick in northeast New Mexico. It is composed of evenly bedded orange-red sandstone and mudstone. The contact with the underlying Chinle Formation is apparently a disconformity (McGowen et al., 1983, p. 32); however, Griggs and Read (1959, p. 2005) considered the contact conformable. The Redonda Formation is unconformably overlain by the Exeter Sandstone (Jurassic) except in places where the latter has been eroded.

Dockum sedimentology

The Dockum Group of east New Mexico and west Texas was deposited in a continental basin (McGowen et al., 1983). The central part of the basin is located in west-central Texas and contains mostly lacustrine deposits that are ringed by fluvial and deltaic deposits around the edges of the basin (McGowen et al., 1983). Dockum sediments in northeast New Mexico and west Texas were deposited by fluvial, deltaic, and lacustrine systems. Sedimentation was cyclic; the cyclicity resulted from alternating low and high stands of the Dockum lake. The northwest part of the Dockum basin was located in northeast New Mexico.

The lower sandstone unit of the Santa Rosa Sandstone was deposited as two distinct depositional systems. McGowen et al. (1979, pp. 8-9) concluded that the lower part of the lower unit (their Lower Sandstone Member) was deposited as an alluvial fan or a fan delta. The upper part of the lower unit (their Middle Sandstone Member) was interpreted as the deposit of a coarse-grained, meandering alluvial system. Lupe (1977) stated that the Santa Rosa Sandstone in the vicinity of Santa Rosa was deposited as a complex of braided streams, floodplains, and lakes. Sediment-transport directions were to the east and south

(McGowen et al., 1979, p. 43), an interpretation supported by the sandstone isolith map of the lower sandstone unit (Fig. 8 in pocket) that shows east- and southeast-trending sandstone bodies separated by east- and southeast-trending muddy areas. The east to southeast trends indicate a generally southeast paleoflow, toward the large Dockum lake in west Texas and east-central New Mexico that was described by McGowen et al. (1979, 1983). The muddy areas separating areas of high sandstone content were the loci of interfluvial and possibly lacustrine deposition. The microcrystalline limestones encountered in the N. G. Penrose No. 1 Tippins, located in Sec. 35, T. 12 N., R. 34 E., Quay County, are lacustrine deposits. The coincidence of thick-sandstone trends in the north and west parts of the study area with underlying thin areas in the Artesia Group suggests that there may have been some paleotopographic control on sedimentation; fluvial Dockum sandstones may have been preferentially deposited in broad valleys eroded into the Artesia Group. Deltas were probably formed where Santa Rosa streams emptied into the Dockum lake, but the fairly uniform sheetlike nature of the lower unit of the Santa Rosa Sandstone indicates that the bulk of it is probably an alluvial-plain deposit which was dominated by braided streams.

The middle mudstone unit of the Santa Rosa Sandstone was interpreted by McGowen et al. (1979, pp. 8-9) as a lacustrine to prodelta deposit. Its widespread distribution over northeast New Mexico (Figs. 3-5 in pocket) suggests that it was deposited after a lacustrine transgression resulting from a high stand of the Dockum lake. It can generally be interpreted as a blanket of lacustrine mud containing deltaic and lacustrine sands of local areal extent.

The upper sandstone unit of the Santa Rosa Sandstone was interpreted as a fan-delta deposit by McGowen et al. (1979, pp. 8-9) that prograded southeast over the lacustrine deposits of the middle mud-stone unit. The sandstone isolith map (Fig. 9 in pocket) shows east- and southeast-trending sandstone bodies that indicate a general south to southeast paleoflow along trends that are generally coincident with depositional trends of the lower sandstone unit. The upward-fining grain size observed in a few wells drilled through the upper unit indicates that the rivers may have been locally meandering, but they were probably mostly braided. A core from the upper unit in the O'Connell Ranch field (Fig. 11) is composed almost entirely of sandstone which is planar-laminated and medium-scale cross-laminated, features that are certainly suggestive of braided-stream deposition. Although deltas were doubtless formed where braided streams of the upper unit emptied into the Dockum lake, most of the upper unit appears to have been deposited as an alluvial sheet sand dominated by braided streams. Muddy areas located between major sandstone trends (Fig. 9 in pocket) were probably the loci of floodplains and small alluvial-plain lakes and ponds.

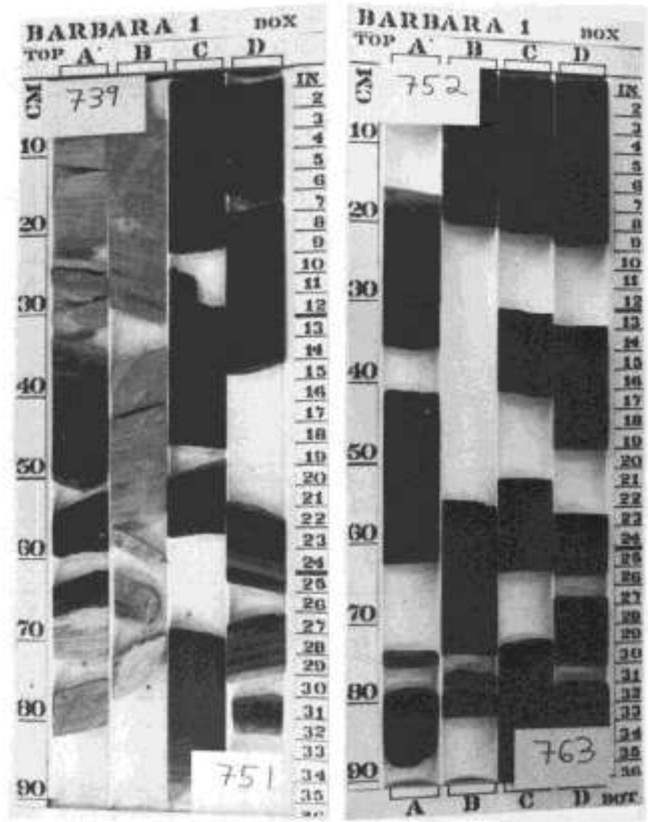


FIGURE 11—Upper sandstone unit of Santa Rosa Sandstone, Public Lands Exploration Co. No. 1 Barbara, Sec. 17, T. 11 N., R. 26 E., Guadalupe County, New Mexico. Oil-saturated, fine-grained sandstone (dark-colored) intercalated with unsaturated, fine-grained sandstone (light-colored). Calcite cement controls zones of oil impregnation. Note cross laminations and planar horizontal laminations.

Sediments of the Chinle Formation are mostly mudstone with discontinuous and minor sandstone lenses. It would therefore seem likely that they were deposited in lacustrine and possibly deltaic environments. The major exception to this is the Cuervo Sandstone Member. The Cuervo is a sheet deposit of a braided fluvial system (Jacka *in* Phillips, 1973, p. 43). The sandstone isolith map of the Cuervo Member (Fig. 10 in pocket), unlike the sandstone isolith maps of the Santa Rosa Sandstone, does not indicate clearly defined depositional trends or sediment-dispersal patterns. It does, however, show a general decrease in sandstone thickness to the southeast, indicating a general southeast paleoflow coincident with paleoflow in the Santa Rosa Sandstone.

The Redonda Formation is a lacustrine deposit (Granata et al., 1983, p. 32). Granata et al. interpreted Redonda sandstones as lacustrine shoreface deposits; Redonda mudstones were also interpreted as lacustrine and were presumably deposited in lower-shoreface and basinal environments.

Structure

Detailed surface structure of the entire study area has not been reported in the literature, and the paucity of subsurface data makes detailed mapping of subsurface structure difficult. Few faults or folds have been mapped on the surface. Perhaps this is due to the difficulty of identifying structurally mappable horizons in the Dockum Group, which crops out over most of the study area. The few structures that have been mapped on the surface (Dobrovolny et al., 1946; Dane and Bachman, 1965) have a northeast strike, although Wanek (1962) mapped some northwest-trending, gentle folds in northeast San Miguel County. Gorman and Robeck (1946) mapped several gentle, north-trending folds in north-central Guadalupe County. In west San Miguel County, west of the major outcrop belt of Santa Rosa Sandstone, Dane and Bachman (1965) mapped several north-trending faults that are roughly parallel to the east edge of the Sangre de Cristo Mountains.

Foster et al. (1972, fig. 10) mapped the structure of the Precambrian surface in east-central New Mexico. In the study area they show a regional southeast dip on the Precambrian. The regional dip is interrupted by eight high-angle, northwest- to north-trending faults and three high-angle, east- to northeast-trending faults. Fault displacements are as great as 4,500 ft. Earlier structure maps on the Precambrian surface (Harley, 1940; Foster and Stipp, 1961) show the same regional southeast dip, but were contoured without the faults. All of these maps depicted two major low areas that interrupt the regional dip. One low area was an enclosed basinal depression near Cuervo, approximately 15 mi northeast of Santa Rosa; it has been referred to as the Cuervo basin. The second low area is an enclosed basinal depression approximately 5 mi south of Tucumcari; it is referred to as the Tucumcari basin. The northeast-trending Sierra Grande arch is noticeable on both maps as is a positive area in northern Quay County which is the south flank of the Bravo dome.

For this study, a structure map was contoured on the San Andres Formation (Fig. 12 in pocket). The San Andres Formation was chosen for three reasons. First, the top of the San Andres is a good geophysical log marker that is readily recognized, even on logs of poor quality. Second, it is present throughout most of the study area, even where the stratigraphically higher Santa Rosa Sandstone has been thinned or removed by Cenozoic erosion. Third, the structure of the Santa Rosa Sandstone was found to be similar to the structure of the San Andres.

San Andres structures generally strike northeast—southwest. The dominant structure is the southeast-dipping regional slope off the Sierra Grande uplift to the north and the Pedernal uplift to the west. Three northeast-trending, high-angle faults are superimposed on the regional slope and form northeast-trending horsts and grabens. Also apparent are northeast-trending anticlines and synclines.

Generally, San Andres structures follow the outlines of the major Pennsylvanian to Wolfcampian-age structural elements in northeast New Mexico, the Sierra Grande arch, the Bravo dome, and the Pedernal uplift. Apparently, the Sierra Grande and Pedernal uplifts were reactivated after San Andres deposition. Thick areas in the Artesia Group (Fig. 7 in pocket) generally correspond to structural lows on the San Andres surface (Fig. 12 in pocket), indicating that the top of the Artesia was partially planed off prior to Dockum deposition, leaving thicker areas of Artesia uneroded in the San Andres synclines. Because structure on the Santa Rosa is similar to structure on the San Andres, it appears that structures were again reactivated after deposition of the Santa Rosa. The locations of major folds and basinal depressions in the San Andres and the Santa Rosa may be controlled by basement faults over which Permian and Triassic rocks have been draped.

Petroleum occurrences

The two documented accumulations of petroleum in the Santa Rosa Sandstone are at Santa Rosa Lake in T. 10 N., R. 21 E., Guadalupe County, and at the O'Connell and T-4 Ranch fields, T. 11 N., R. 25-26 E., Guadalupe County. The accumulation at Santa Rosa Lake is also known as the "Santa Rosa tar sands" and is a surface exposure of oil-impregnated sandstone. The geology of the Santa Rosa tar sands was first reported by Gorman and Robeck (1946) and later by Budding (1979, 1980). McDowell (1972, p. 178) and Gorman and Robeck (1946) indicate that the oil occurs in the upper sandstone unit. The petroleum has a gravity of 11.9° API and a viscosity of 30,000 centipoise at 60°F, which classifies it as a heavy oil (Budding, 1980, pp. 4, 5). The sandstone has porosities of 1013% and an average permeability of 100-200 millidarcies (Budding, 1980, p. 5). The Santa Rosa tar sands contain an estimated 90.9 million bbl of oil in place (Budding, 1979, p. 9; 1980, p. 5).

The Santa Rosa tar sands were mined between 1930 and 1939 by the New Mexico Construction Company. The oil-impregnated sandstone was used for road surfacing in New Mexico, Colorado, Oklahoma, and Texas. Total production was 153,000 tons (Gorman and Robeck, 1946). Interest in the Santa Rosa deposit was revived during the late 1970's. Plans were made by Solv-Ex Corporation to mine the tar sands and recover oil from them with a solvent extraction process. These plans were abandoned in 1983 because of unfavorable economics and the encroachment of Santa Rosa Lake onto the tar-sand outcrops. The subsurface areal extent of oil-impregnated sandstone at Santa Rosa Lake has not been determined.

The O'Connell Ranch field and the T-4 Ranch field were discovered by the Humble Oil and Refining Company in the early 1960's. Although Humble drilled several cores of oil-impregnated sandstone, no attempt was made to produce oil at that time. In 1981, Public Lands Exploration Company (later called Corona Oil Company and now called Rio Petro Limited) initiated two pilot steam-flood projects, the O'Connell Ranch pilot and the T-4 Ranch pilot, to recover heavy oil from the Santa Rosa Sandstone. The O'Connell Ranch pilot is located in Sec. 10, T. 11 N., R. 25 E., Guadalupe County, and the T-4 Ranch pilot is located in Sec. 17, T. 11 N., R. 26 E., Guadalupe County. The oil in the O'Connell Ranch and T-4 Ranch fields occurs in the upper sandstone unit of the Santa Rosa Sandstone, but some gilsonite occurs in the lower sandstone unit (George L. Scott, Jr., pers. comm. 1983).

Gravity of the oil at the O'Connell Ranch field is 15-17° API and its viscosity is 1,367 centipoise at 70°F (Martin, 1983a, table 2). Average porosity of the reservoir sand is 20.8%, ranging from an average of 19.2 to 22.5% for individual wells; average permeability is 218 millidarcies, ranging from an average of 195 to 272 millidarcies for individual wells (Martin, 1983a, table 12). Average oil saturation is 58.1%, ranging from 51.8 to 63.3% for individual wells (Martin, 1983a, table 12). The oil is trapped within the upper unit of the Santa Rosa Sandstone (Fig. 3 in pocket, Rio Petro Ltd. No. 16 State). Depth to oil-saturated sandstone is approximately 400 ft at the O'Connell Ranch field and 800 ft at the T-4 Ranch field. The trap is a combined structural—stratigraphic trap. The primary trapping is caused by the large east-trending Newkirk anticline, which is visible at the surface. Lateral facies changes of the reservoir to mudstone also limit and define the field (Martin, 1983, fig. 3). Oil saturation within the reservoir is uneven, caused by unevenly distributed calcite cement.

The O'Connell Ranch pilot steamflood has been unsuccessful thus far, but this is probably due to repeated mechanical failure of the steam generators. From August 2, 1981 until January 1, 1983, only 70 bbl of oil were recovered, while approximately 25,000 bbl of water were converted to steam and injected (Scott and Joy, 1983). Since mechanical problems associated with steam injection have been resolved, field response and oil production have increased (Martin, 1983b), and the outlook for commercial recovery of oil has improved. It is estimated that almost 7 million bbl of oil are in place at the O'Connell Ranch field, 1.9 million bbls of which are potentially recoverable by steam flooding under the most favorable conditions (Martin, 1983a, p. 12).

Steam injection began in October 1982 in the T-4 Ranch field (Martin, 1983b). Although no oil had been produced by October 1983, there does appear to be a good reservoir response to steam injection (Martin, 1983b). The outlook for commercial oil production from the T-4 Ranch field is promising.

No other potentially commercial accumulations of oil are known in the Santa Rosa Sandstone of northeast New Mexico, but several wells have encountered either oil shows or dead oil (Fig. 13 in pocket, Table 2). The occurrences of oil shows and dead oil listed in Table 2 were obtained by examination of scout cards, driller's logs, and drill cuttings on file at the New Mexico Bureau of Mines and Mineral Resources. Dead oil is defined as oil that does not fluoresce under ultraviolet light and does not cut when immersed in a petroleum solvent. No attempt was made to distinguish between dead oil and a bona fide oil show because most scout cards and driller's logs only report "show of oil" without data on volume, gravity, viscosity, fluorescent properties, or drill-stem tests (if any). My examination of drill cuttings revealed only traces of dead oil without fluorescence or cut. Most cuttings examined were several years old, however, and probably would not fluoresce anymore, although they may have in the past. The occurrences of dead oil probably indicate that liquid hydrocarbons were once widespread in the Santa Rosa Sandstone, but have since migrated. No record was found of oil shows in the Cuervo Sandstone Member of the Chinle Formation, but gilsonite was recovered in the Cuervo from shallow water wells drilled near the O'Connell Ranch field (George L. Scott, Jr., pers. comm. 1983).

TABLE 2—Wells in study area with reported hydrocarbon shows or dead oil in the Santa Rosa Sandstone. Does not include wells from the O'Connell Ranch field or shallow cores taken in the tar sands at Santa Rosa Lake.

Operator, well number, and lease	Location (section–township–range, county)	Completion date (month/year)	Total depth (ft)	Type of hydrocarbon occurrence	Source of information
Sam D. Ares No. 1 Beth State	4–11N–25E, Guadalupe	3/66	1,221	dead oil	cuttings
Frio Oil No. 2 Saunders	11–5N–35E, Curry	3/29	1,312	oil show	driller's log, scout card
James D. Ward No. 1 Ward	25–8N–32E, Quay	12/39	710	oil show	scout card
H. T. McGee No. 1 Mrs. Chapman	9–9N–35E, Quay	6/38	1,123	oil show	scout card
Quay County Development Company No. 1 Hut Wallace	19–9N–33E, Quay	3/36	1,322	oil show	scout card
Jensen Oil Co. No. 2 First National Bank	27–10N–31E, Quay	12/49	2,660	dead oil	driller's log, scout card
Triton Oil & Gas Corp. No. 1 Purcell	14–11N–33E, Quay	2/83	1,000	flared gas for 7 minutes	scout card

Petrography and reservoir geology

Reservoir properties of the two major reservoir units discussed in this report, the lower and upper sandstone units of the Santa Rosa Sandstone, were studied using drill cuttings, sample logs, thin sections of drill cuttings (Fig. 14; Table 3), geophysical logs, cores, and core analyses. Reservoir properties of the Cuervo Member were examined to a lesser extent and using only geophysical logs, sample logs, and descriptions of drill cuttings made with a binocular microscope. Porosity was determined from three types of geophysical logs: formation density, neutron porosity, and sonic; chiefly formation density logs were used. Only geophysical logs judged to be of good quality were analyzed for porosity. The core analyses were obtained from Martin (1983a).

Lower sandstone unit of Santa Rosa Sandstone

Reservoirs in the lower sandstone unit are fine- to medium-grained, poorly to well-sorted, angular to subangular quartzose sandstones. They are classified as the sublitharenites and lithic arenites of Dott (1964). Sandstone cuttings from seven wells were studied in thin sections (Fig. 14D; Table 3).

Quartz is the most abundant component in sandstones of the lower unit; it averages 60% and ranges from 50 to 70%. The quartz is silt size to very coarse sand size and generally monocrystalline, but some grains are polycrystalline. Syntaxial quartz overgrowths are common on the quartz grains. The overgrowths project into open pore spaces or abut one another along planar contacts. They show no evidence of mechanical abrasion and are a cement precipitated in situ within the Santa Rosa.

Calcite is the next most abundant component in sandstones of the lower unit. It averages 20% and ranges from 0 to 40%. The calcite forms intergranular blocky to poikilotopic cement that replaces framework grains and quartz overgrowths (Fig. 14D).

Rock fragments are the next most abundant component. They average 10% and range from 0 to 30%. Rock fragments are altered volcanics, granite, microcrystalline limestone, and siliciclastic mudstone. The granitic fragments are composed of quartz, potash feldspar, and plagioclase feldspar; the granitic fragments often have a micropegmatite texture. The volcanic fragments are composed of microcrystalline masses of zeolites, clay minerals, quartz, and feldspar. Individual quartz and feldspar crystals are generally less than 10 microns in diameter. The clays have first-order gray to bluish-gray interference colors, indicating that they are possibly kaolinite. Some volcanic-rock fragments are squashed and conform to the boundaries of nonlabile grains (e.g. quartz), indicating that they were fairly soft during compaction. Other volcanic fragments are extensively fractured, indicating that they were rigid during compaction. Micro-crystalline limestone fragments are lime mudstones according to the classification of Dunham (1964). Some of the microcrystalline limestones may be intraclastic, having formed in Dockum lakes; others perhaps formed as a result of pedogenesis.

Feldspars are present in most sandstones of the lower unit. They average a trace percent and range from 0% to a trace. Both plagioclase and potash feldspar are present. They are generally fresh or only slightly altered to clay.

Other constituents are present in amounts ranging from 0% to a trace. They are detrital clays (rarely as much as 20%), detrital micas, and hematite.

TABLE 3—Petrographic data obtained from thin-section study. DO = dead oil, H = hematite, P = pyrite, T = trace; [1]present in trace amounts; [2]classification of Dott (1964).

Operator, well number, and lease	Location (section-township-range, county)	Sample depth (ft)	Stratigraphic unit	Quartz	Feldspar	Rock fragments	Clay	Mica	Calcite	Pore Space	Other[1]	Sandstone[2] subtype	Mean grain size	Sorting	Reservoir quality
Franklin, Aston, & Fair No. 1 Green Estate	10-5N-32E, Curry	1,380–1,390	lower Santa Rosa	70	T	10	0	T	20	T		sublitharenite	fine sand	moderate-good	poor-fair
Texas Gulf Production Co. No. 1 Garrett	34-5N-34E, Curry	1,550–1,560	upper Santa Rosa	50	10	10	0	T	30	0		sublitharenite	fine sand	moderate	poor
Texas Gulf Production Co. No. 1 Garrett	34-5N-34E, Curry	1,760–1,770	lower Santa Rosa	50	T	20	0	0	30	0		lithic arenite	medium sand	poor-good	poor
Husky Oil Co. & General Crude Oil Co. No. 1 Hanchett State	16-8N-24E, Guadalupe	800–810	upper Santa Rosa	70	T	10	T	T	T	20		sublitharenite	medium sand	moderate	good
Husky Oil Co. & General Crude Oil Co. No. 1 Hanchett State	16-8N-24E, Guadalupe	910–920	lower Santa Rosa	60	0	T	20	T	20	T		quartz arenite, quartz wacke	medium sand	poor-moderate	poor
General Crude Oil Co. No. 1 A. S. Wilkie "14"	14-10N-24E, Guadalupe	790–800	upper Santa Rosa	70	T	10	0	T	20	T		sublitharenite	fine sand	good	poor
General Crude Oil Co. No. 1 A. S. Wilkie "14"	14-10N-24E, Guadalupe	940–950	lower Santa Rosa	60	T	30	0	T	0	T		lithic arenite	fine sand	good	poor
Miami Petroleum Co. No. 1 'A' Hoover Ranch	2-10N-27E, Quay	1,340–1,350	lower Santa Rosa	70	T	20	0	0	10	T	H, DO	sublitharenite	fine sand	good	fair
N. G. Penrose No. 1 Tippins	35-12N-34E, Quay	550–560	upper Santa Rosa	70	T	10	0	T	10	10		sublitharenite	fine sand	good	good
Edmonds & Peters No. 2 Cain	22-15N-33E, Harding	610–620	upper Santa Rosa	40	T	0	50	T	10	0		quartz wacke	fine sand	very poor	none
Edmonds & Peters No. 2 Cain	22-15N-33E, Harding	700–710	lower Santa Rosa	50	T	10	0	T	40	0	H, P	sublitharenite	very fine sand	good	none
Humble Oil & Refining Co. No. 1 'CO' State	28-17N-36E, Quay	570–580	upper Santa Rosa	40	0	20	0	0	40	T	DO	lithic arenite	medium sand	poor-good	poor-fair
Humble Oil & Refining Co. No. 1 'CO' State	28-17N-36E, Quay	640–650	lower Santa Rosa	70	T	10	0	T	10	10		sublitharenite	fine sand	good	poor

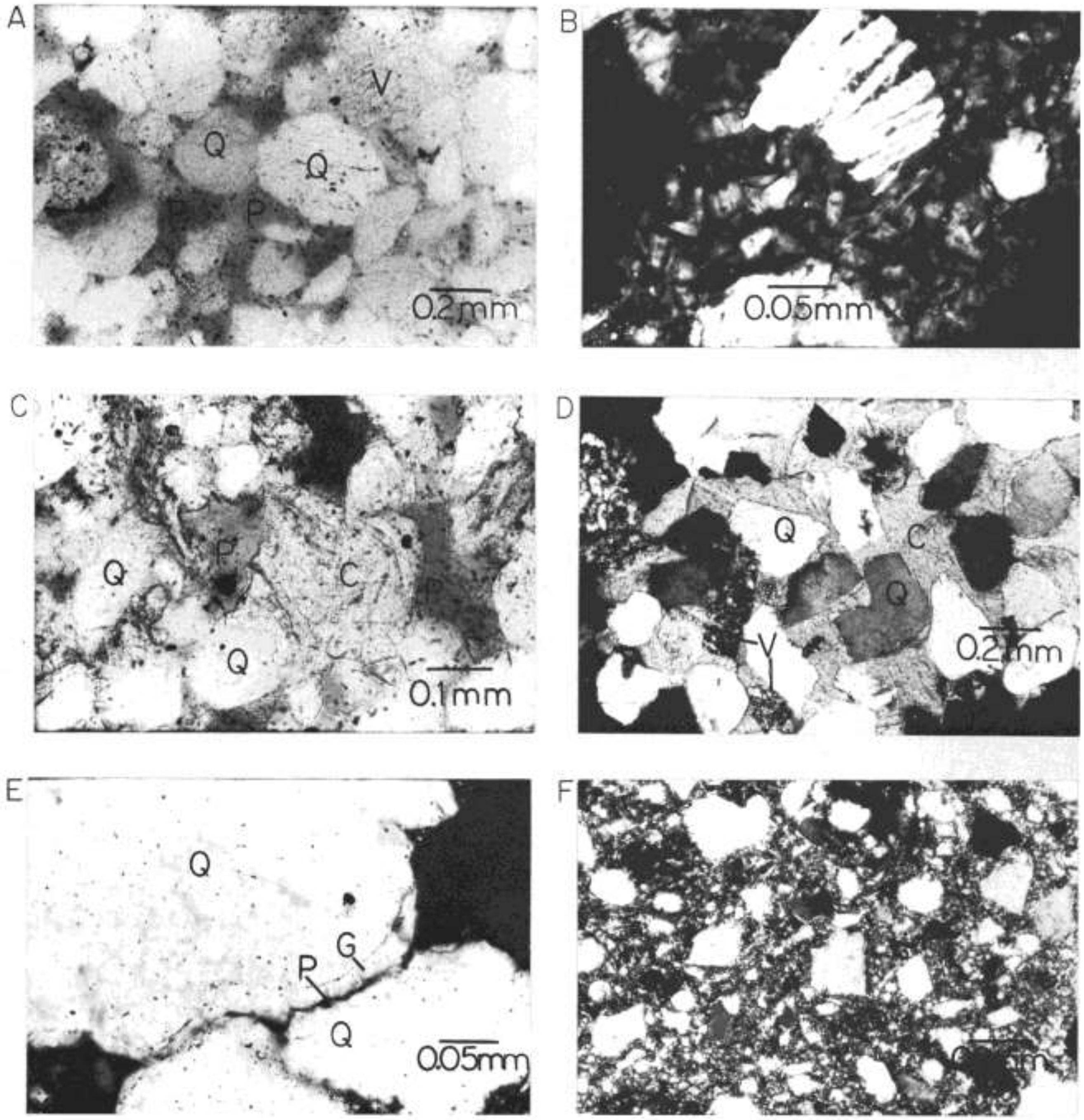


FIGURE 14—**A,** Sublitharenite with well-developed primary intergranular porosity. Note rounded quartz grains (Q), pore space (P), and altered volcanic fragment (V). Upper sandstone unit of Santa Rosa Sandstone, 800–810 ft, Husky Oil Co. and General Crude Oil Co. No. 1 Hanchett State, Sec. 16, T. 8 N., R. 24 E., Guadalupe County, New Mexico. Plane light. **B,** Altered volcanic-rock fragment of Fig. 14A, composed of finely intermixed zeolites, clay minerals, and quartz. Crossed nicols. **C,** Calcite cement (C) partially filling pore space (P) and replacing quartz framework grains (Q). Sublitharenite. Upper sandstone unit of Santa Rosa Sandstone, 550–560 ft, N.G. Penrose No. 1 Tippins, Sec. 35, T. 12 N., R. 34 E., Quay County, New Mexico. Plane light. **D,** Calcite cement (C) completely filling primary pores and replacing quartz framework grains (Q) in lithic arenite. Note altered volcanic rock fragments (V). Lower sandstone unit of Santa Rosa Sandstone, 1,760–1,770 ft, Texas Gulf Production Co. No. 1 Garrett, Sec. 34, T. 5 N., R. 34 E., Curry County, New Mexico. Crossed nicols. **E,** Authigenic syntaxial quartz overgrowths (G) filling pore space (P) between detrital quartz grains (Q) in sublitharenite. Upper sandstone unit of Santa Rosa Sandstone, 800–810 ft, Husky Oil Co. and General Crude Oil Co. No. 1 Hanchett State, Sec. 16, T. 8 N., R. 24 E., Guadalupe County, New Mexico. Crossed nicols. **F,** Detrital quartz grains floating in detrital clay matrix in a quartz wacke. Upper sandstone unit of Santa Rosa Sandstone, 610–620 ft, Edmonds and Peters No. 2 Cain, Sec. 22, T. 15 N., R. 33 E., Harding County, New Mexico. Crossed nicols.

Visual porosity averages only a trace amount and ranges from 0 to 10%. Geophysical logs indicate maximum porosities of 15-36% for individual wells in the lower unit; maximum porosity averages 26%. The most porous sandstones were not available for thin-section study because they are poorly cemented and disaggregate into individual grains during drilling. Micro-porosity is present in the volcanic-rock fragments. It appears to occur as secondary-matrix porosity within the zeolites and, rarely, as open fractures with widths less than 10 microns. Most of the porosity in the lower Santa Rosa is primary intergranular, one that has been reduced by cementation with quartz overgrowths and later with calcite. In some cuttings as much as 50% of the porosity is present as secondary micropores within the volcanic-rock fragments. Grain-to-grain contacts are mostly point, indicating that early cementation stopped compaction. Pores generally form an interconnected network. A trace of porosity is secondary, resulting from both fracturing and dissolution of calcite cement.

The reservoir quality of the sandstones in the lower unit is good. The sandstones have well-developed primary pores that have not been destroyed by compaction or occluded to any significant extent by silica and calcite cements. Good permeability is indicated by the well-developed network of interconnected pores. The blanket geometry of the lower unit indicates that good-quality reservoir rock is widespread in northeast New Mexico, although the net thickness of sandstone reservoir varies (Fig. 8 in pocket).

Upper sandstone unit of Santa Rosa Sandstone

Reservoirs in the upper unit are fine- to medium-grained, poorly to well-sorted, angular to subrounded quartzose sandstones (Fig. 14A). Composition is similar to the composition of sandstones in the lower unit. Most sandstones can be classified as sublitharenites of Dott (1964). Sandstone cuttings from six wells were studied in thin sections (Fig. 14A—C, E, F; Table 3).

Quartz is the most abundant constituent in sandstones of the upper unit. It averages 60% and ranges from 40 to 70%. The quartz is silt size to very coarse sand size and generally monocrystalline, but some grains are polycrystalline. As in the lower unit, syntaxial quartz overgrowths are common (Fig. 14E). The overgrowths project into open pore spaces or abut one another along planar contacts. They show no evidence of mechanical abrasion; they are a cement precipitated in situ within the Santa Rosa.

Calcite is the next most abundant component in sandstones of the upper unit. It averages 20% and ranges from a trace to 40%. The calcite is an intergranular, blocky to poikilotopic cement that replaces framework grains and the syntaxial quartz overgrowths (Fig. 14C).

Rock fragments average 10% of sandstones in the upper unit. They range from 0 to 20%. The most abundant rock fragments are altered volcanics (Fig. 14A, B), granite, and microcrystalline limestone. They are similar to rock fragments in the lower Santa Rosa.

Feldspars compose only a trace amount of sandstones in the upper unit. They range from 0 to 10%. Both plagioclase and potash feldspar occur. The feldspars are fresh or only slightly altered to clays.

Other components in sandstones of the upper unit are clay minerals (rarely as much as 50%; Fig. 14F), mica, and hematite. They are present in amounts ranging from 0% to a trace.

Visual porosity averages 10% of sandstones in the upper unit and ranges from 0 to 20%. Maximum porosity determined from geophysical logs averages 25%, ranging from 15 to 36% for individual wells. Maximum porosity determined by analysis of cores from four wells in the O'Connell Ranch field averages 26.4% and ranges from 24.9 to 27.5% for individual wells (Martin, 1983a, tables 8-12). The average porosity of sandstone in the O'Connell Ranch field is 20.8%, ranging from an average of 19.2 to 22.5% for individual wells (Martin, 1983a, table 12). Average permeability in the O'Connell Ranch field is 218 millidarcies, with a maximum permeability of 750 millidarcies in a single one-ft interval of core. As with the lower unit, it is unlikely that the most porous and permeable sandstones of the upper unit were analyzed in thin sections because cuttings of these rocks have been disaggregated into individual sand grains during drilling. Most of the porosity is primary and intergranular, but in some cuttings it may be secondary microporosity that is present within altered volcanic-rock fragments. Porosity has been reduced by cementation with quartz overgrowths and later with calcite. Grain-to-grain contacts are mostly point, indicating that early cementation stopped compaction. Pores generally form an interconnected network. A trace amount of porosity is secondary, resulting from fracturing and dissolution of calcite cement.

The reservoir quality of sandstones in the upper unit of the Santa Rosa Sandstone is generally good, a statement certainly supported by the presence of heavy oil in the O'Connell and T-4 Ranch fields and at Santa Rosa Lake. As with the lower unit, sandstones in the upper unit have well-developed primary pores that form an interconnected network, indicating good permeability. The blanket geometry of the upper unit indicates that good-quality reservoir rock should be widespread in northeast New Mexico, although the net thickness of sandstone varies (Fig. 9 in pocket). Reservoir quality and net sandstone thickness appear to be more variable than in the lower unit; a facies change from sandstone to mudstone is a partial trapping mechanism in the O'Connell and T-4 Ranch fields.

Cuervo Member of Chinle Formation

Potential reservoirs in the Cuervo Member of the Chinle Formation are very fine- to medium-grained, moderately to well-sorted, calcareous-cement quartzose sandstones. Although no thin sections were studied, cuttings of Cuervo sandstones were analyzed with a low-power binocular microscope. The maximum porosity of Cuervo sandstones, as determined from geophysical logs, ranges from 14 to 33% in individual wells and averages 25% . Most Cuervo sandstones are well cemented by calcite. Analysis of cuttings with a binocular microscope indicates that they are generally less porous than the Santa Rosa sandstones. The sandstone isolith map (Fig. 10 in pocket) shows the Cuervo has thicker sandstone reservoirs to the north and west; the unit is mostly mudstone in the southeast part of the study area.

Petroleum source rocks

The source rock of the petroleum in the Santa Rosa Sandstone appears to be the San Andres Formation (Gorman and Robeck, 1946; Budding, 1979, p. 10; 1980, p. 5). Budding (1979, 1980) geochemically analyzed the heavy oil from the tar-sand deposit at Santa Rosa Lake in order to determine the source rock, and concluded that the oil is biodegraded because it has a low content of alkanes (1.5-2.2%) in the C_{15+} paraffinnaphthene fraction. It is reasonable to conclude that the oil is biodegraded because its exposure to air and oxygenated fresh water at the surface and in the shallow subsurface allows ample opportunity for attack by aerobic bacteria.

The Santa Rosa oil has a preponderance of C_{25}-C_{28} molecules in the cycloalkane fraction, indicating thermal immaturity (Budding, 1980). The low gravity of the oil (11.9°API) may be explained by its thermal immaturity and/or bacterial degradation of long-chain paraffins.

The correlation of the Santa Rosa oil with a San Andres source is based on ratios of stable carbon isotopes. Budding (1980) used the type curve of Stahl (1978) to calculate that the original bituminous matter from which the Santa Rosa oil was derived had a delta ^{13}C equal to, or larger than, — 26.6%0. This value is approximately equal to values reported for Permian oil of the northwest shelf of the Permian Basin, but is lighter than Pennsylvanian and older oils of the Permian Basin.

The San Andres Formation is the most likely oil source among Permian-age rock units on the northwest shelf. Other Permian-age rock units are the Artesia Group, the Yeso Formation, the Abo Formation, and the Hueco Formation. The Artesia Group is composed mostly of anhydrite, sandstone, and red beds, unlikely source rocks. The San Andres contains a high percentage of limestone, which could possibly be a source rock. The Yeso Formation is similar to the Artesia Group in gross lithology and therefore is an unlikely source. The Abo can probably be eliminated as a possible source because it consists of red beds. The Hueco Formation also consists mostly of red beds in Guadalupe, Quay, Curry, and San Miguel Counties, and can probably be eliminated as a possible source.

Deeper Pennsylvanian-age rocks could be the source rocks of the Santa Rosa oil. Limestones and mudstones are abundant in the Pennsylvanian section of the Tucumcari basin and could be source rocks of oil. Oil may have migrated upward from the Pennsylvanian System through Pennsylvanian-age faults. As previously mentioned, however, carbon-isotope data support a Permian source for the oil.

It is unlikely that sediments of the Dockum Group were a source for the Santa Rosa oil. The Dockum is composed of red beds which owe their color to oxidation during either deposition or diagenesis. Oxidation destroys most organic matter that might generate petroleum. The few thin coals in the Dockum are composed of terrestrial plants, which would be more likely to generate gas than oil (Barker, 1979, pp. 125-129). Also, Budding used the Carbon Preference Index and pristane-to-phytane ratios to show that the Santa Rosa oil was derived from a marine source; as previously discussed, the Dockum is a nonmarine deposit.

Further study is needed to positively identify the source rock of the Santa Rosa oil. First, oil from the O'Connell Ranch Field and T-4 Ranch field should be analyzed geochemically because, unlike the oil in the Santa Rosa tar-sand deposit, it has not been subject to extensive bacterial degradation at the surface, although it may have been biodegraded in the subsurface. All potential source rocks from the Dockum down to Precambrian basement would need to be analyzed for thermal maturity and stable carbon isotopes. The thermal-maturation study would indicate which rock units have been buried deeply enough to generate petroleum. The isotope study would be used to correlate thermally mature sources with the oil from the O'Connell and T-4 Ranch fields.

Petroleum potential of Santa Rosa Sandstone and Cuervo Member of Chinle Formation

Santa Rosa Sandstone

The tar-sand deposit at Santa Rosa lake is a classic example of an oil seep that indicates the possible presence of large petroleum accumulations. The occurrence of oil is documented by the accumulation at the O'Connell Ranch field and T-4 Ranch field and by reports of dead oil and oil shows in several wells (Table 2).

The blanket geometry of the upper and lower sandstone units of the Santa Rosa Sandstone indicates that the Santa Rosa makes a good reservoir throughout the study area. There may be local facies changes that create local permeability barriers, but analyses of drill cuttings with a binocular microscope, thin sections of drill cuttings, and geophysical logs indicate that good Santa Rosa reservoirs are widespread (Figs. 8, 9 in pocket).

The numerous reports of dead oil indicate that much oil had once accumulated in the Santa Rosa, but has since migrated or has been flushed by ground water. Areas in the subsurface that are proximal to Santa Rosa outcrops receive recharge of influent precipitation and surface water (see Dinwiddie and Clebsch, 1973). Most of the Santa Rosa that is proximal to the outcrop belt of Santa Rosa Sandstone has probably been flushed by recently recharged, fresh ground water. Therefore, it would seem that there is better potential for petroleum accumulations in the Santa Rosa toward the south and east parts of the study area where outcrops of the Santa Rosa are not present and the effects of recharge have been less. In areas closer to the outcrop, structural traps or stratigraphic barriers may have locally protected oil accumulations from groundwater movement; this is more likely to have occurred in the upper sandstone unit than in the lower sandstone unit because of the greater stratigraphic variability in the upper unit. Not to be overlooked is the possibility that ground-water movement has hydrodynamically trapped oil in structurally low areas. The blanket geometry of both the upper and lower sandstone units suggests that structure plays an important or even dominant role in the trapping of hydrocarbons in the Santa Rosa in northeast New Mexico.

Cuervo Member of Chinle Formation

Although the Cuervo Member of the Chinle Formation is similar lithologically to the upper and lower units of the Santa Rosa Sandstone, it is less likely to contain significant petroleum accumulations for three reasons. First, much of the Cuervo has probably been flushed by influent surface water because it crops out over a large part of the study area. Second, there are no reported major oil occurrences in the Cuervo, although there are some oil shows. Third, Cuervo reservoirs are generally thinner than Santa Rosa reservoirs because there is generally less sandstone in the Cuervo than in the Santa Rosa.

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Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, µm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}

TO CONVERT	MULTIPLY BY	TO OBTAIN
Pressure, stress		
lb in^{-2} (= lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (= kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0° C)
inches of Hg (at 0° C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	l sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	m^2 sec^{-1}
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	l sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units, BTU	2.52×10^{-1}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F − 32	5/9	°C (Celsius)

Divide by the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929.

Editor: Jiri Zidek
Drafter: James Brannan

Type face: Palatino

Presswork: Miehle Single Color Offset
Harris Single Color Offset

Binding: Saddlestitched with softbound cover

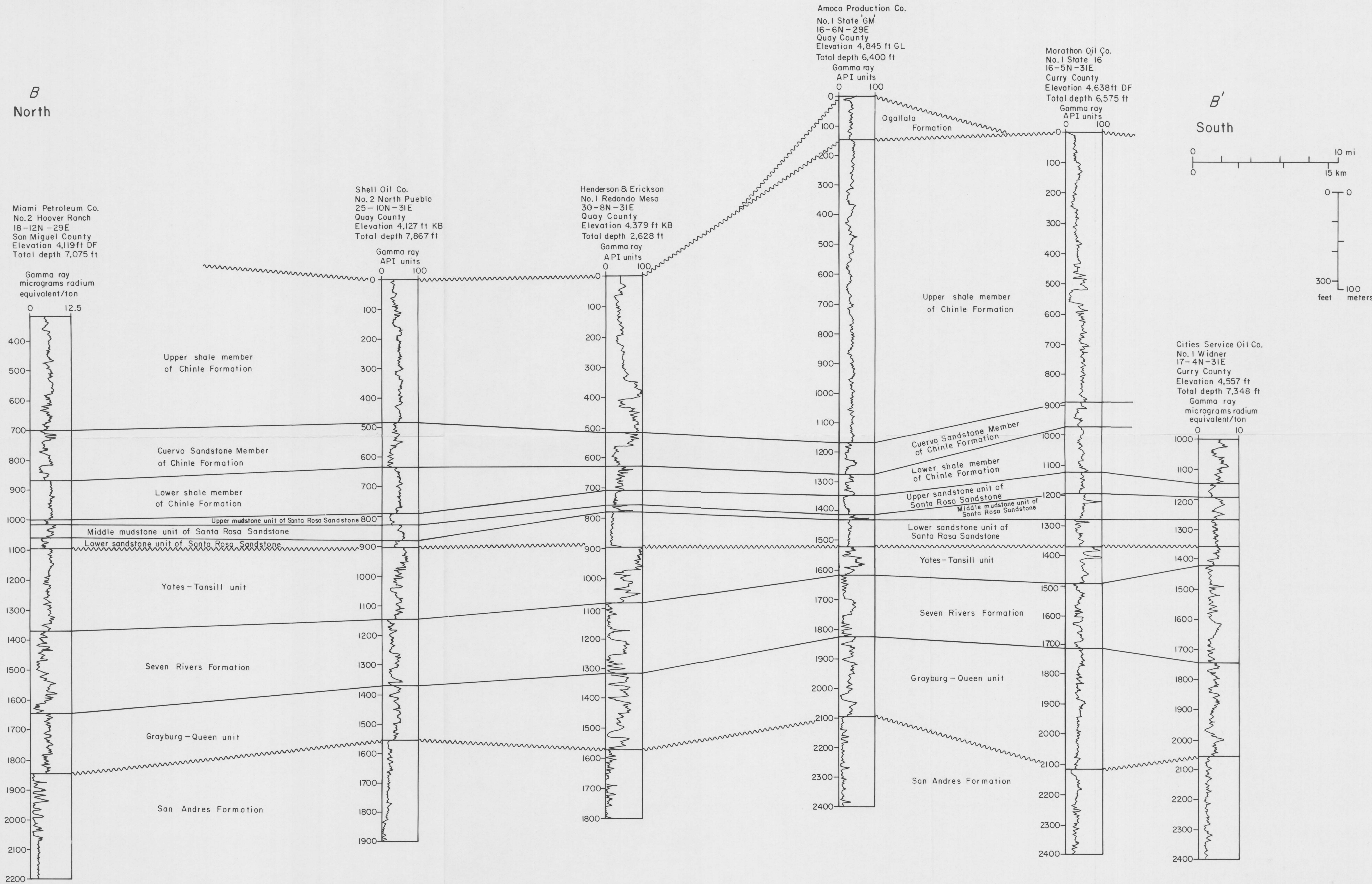
Paper: Cover on 12-pt. Kivar
Text on 70-lb White Matte

Ink: Cover—PMS 320
Text—Black

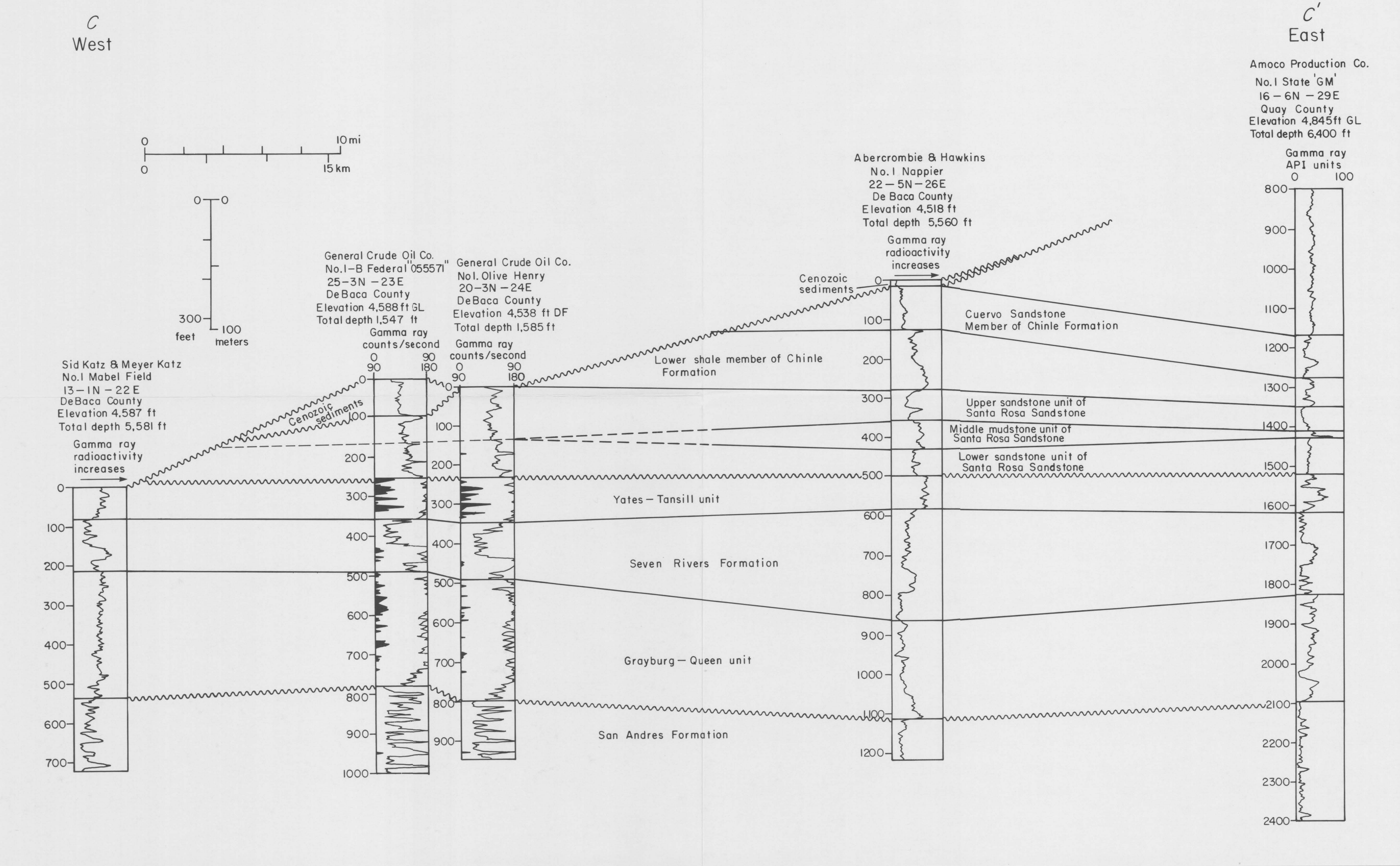
Quantity: 900

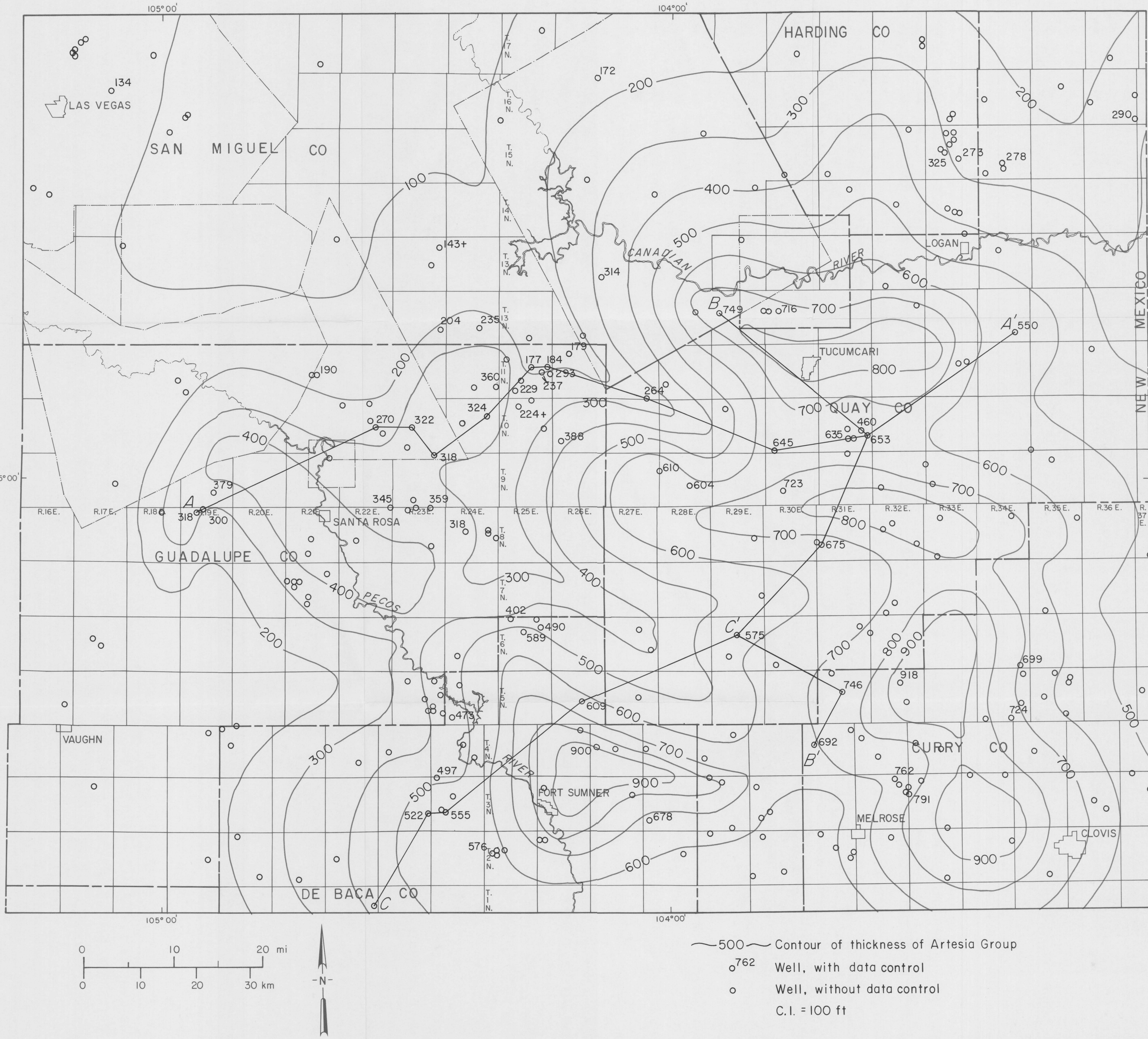
Contents of pocket

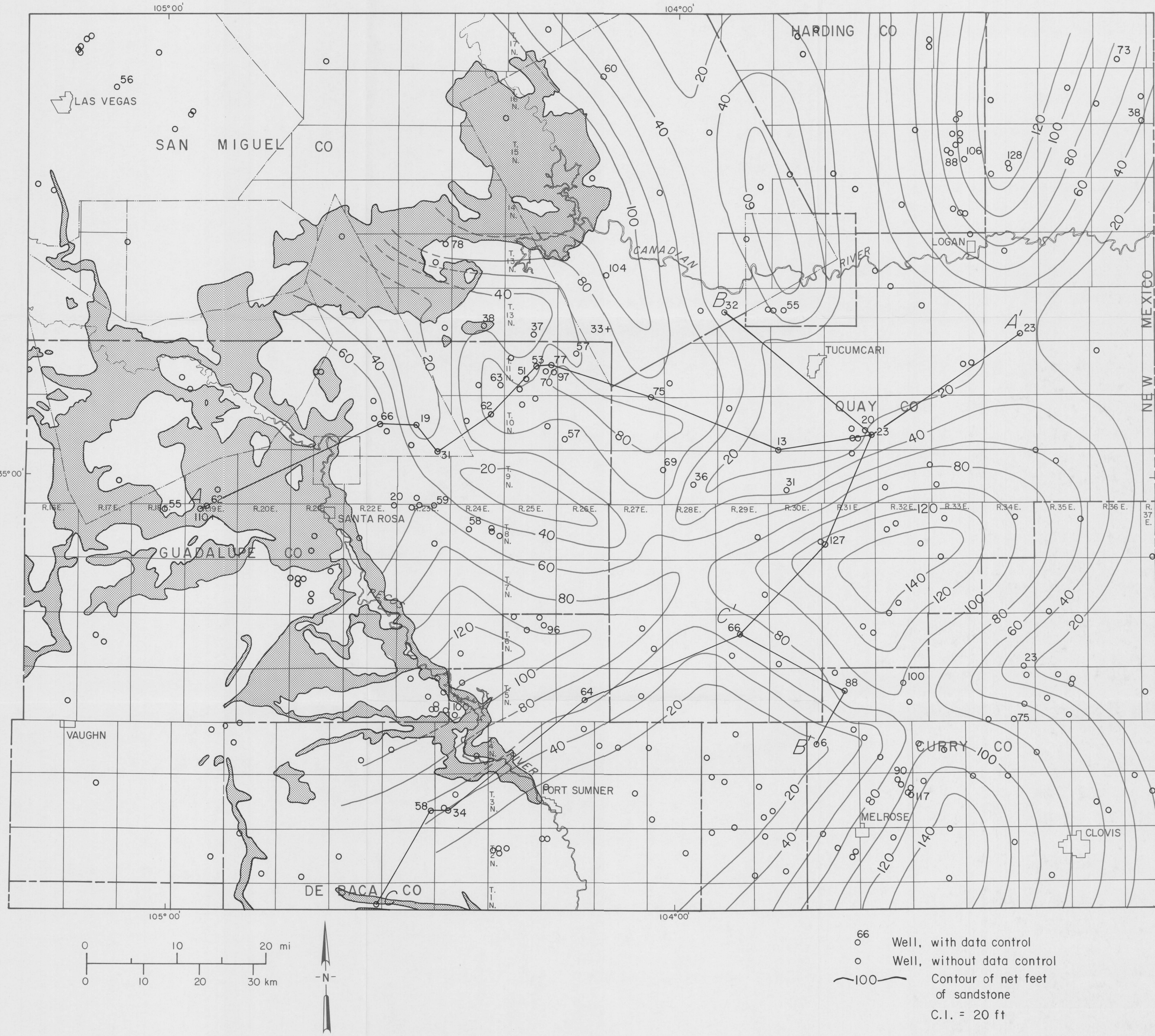
NMBM&MR Circular 193, Figure 3

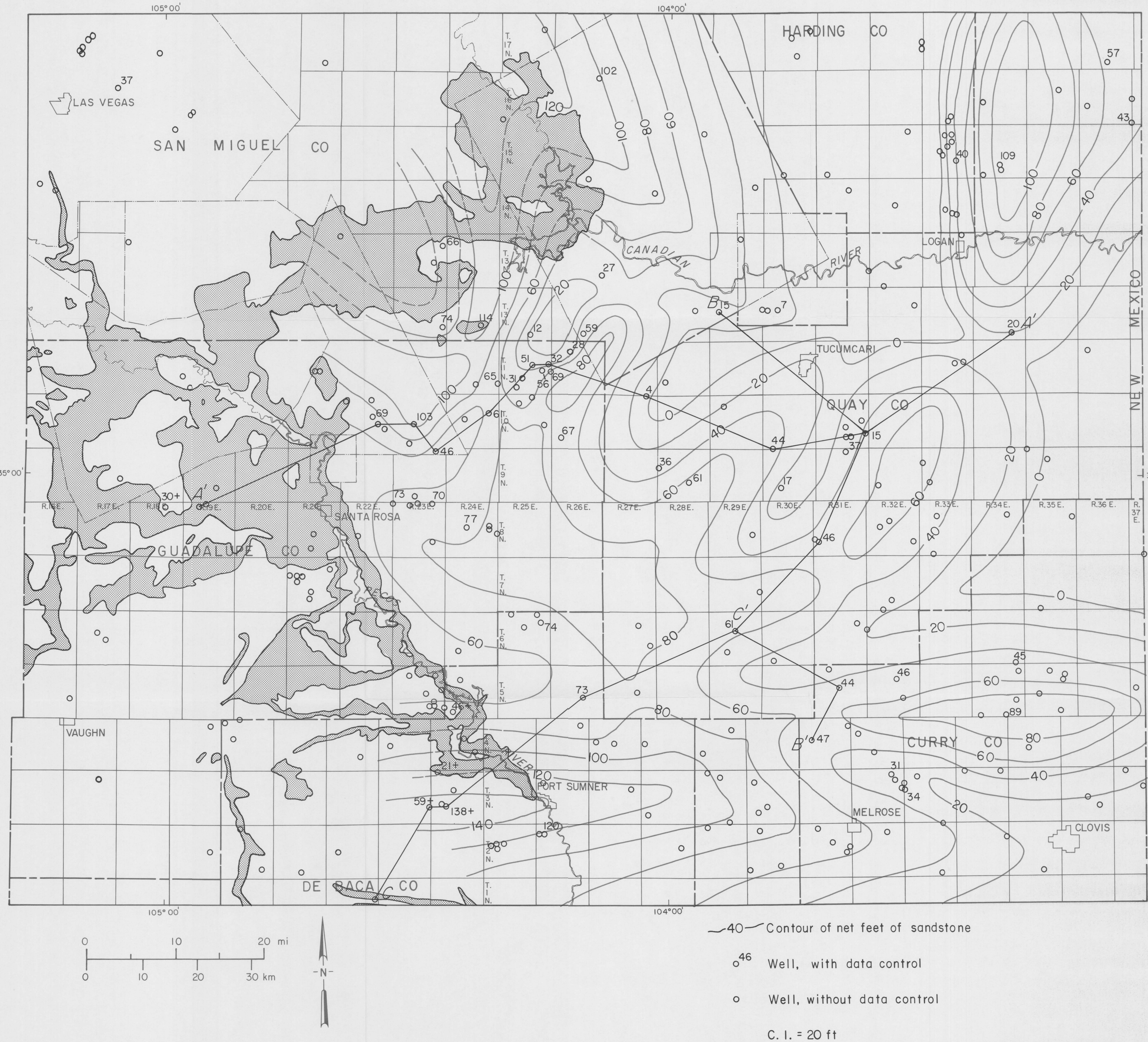

B
North
B'
South
Miami Petroleum Co.
No. 2 Hoover Ranch
18-12N-29E
San Miguel County
Elevation 4,119 ft DF
Total depth 7,075 ft
Gamma ray micrograms radium equivalent/ton
Shell Oil Co.
No. 2 North Pueblo
25-10N-31E
Quay County
Elevation 4,127 ft KB
Total depth 7,867 ft
Gamma ray API units
Henderson & Erickson
No. 1 Redondo Mesa
30-8N-31E
Quay County
Elevation 4,379 ft KB
Total depth 2,628 ft
Gamma ray API units
Amoco Production Co.
No. 1 State 'GM'
16-6N-29E
Quay County
Elevation 4,845 ft GL
Total depth 6,400 ft
Gamma ray API units
Marathon Oil Co.
No. 1 State 16
16-5N-31E
Curry County
Elevation 4,638 ft DF
Total depth 6,575 ft
Gamma ray API units
Cities Service Oil Co.
No. 1 Widner
17-4N-31E
Curry County
Elevation 4,557 ft
Total depth 7,348 ft
Gamma ray micrograms radium equivalent/ton
Ogallala Formation
Upper shale member of Chinle Formation
Cuervo Sandstone Member of Chinle Formation
Lower shale member of Chinle Formation
Upper mudstone unit of Santa Rosa Sandstone
Middle mudstone unit of Santa Rosa Sandstone
Lower sandstone unit of Santa Rosa Sandstone
Upper sandstone unit of Santa Rosa Sandstone
Yates-Tansill unit
Seven Rivers Formation
Grayburg-Queen unit
San Andres Formation
0 10 mi
0 15 km
feet meters

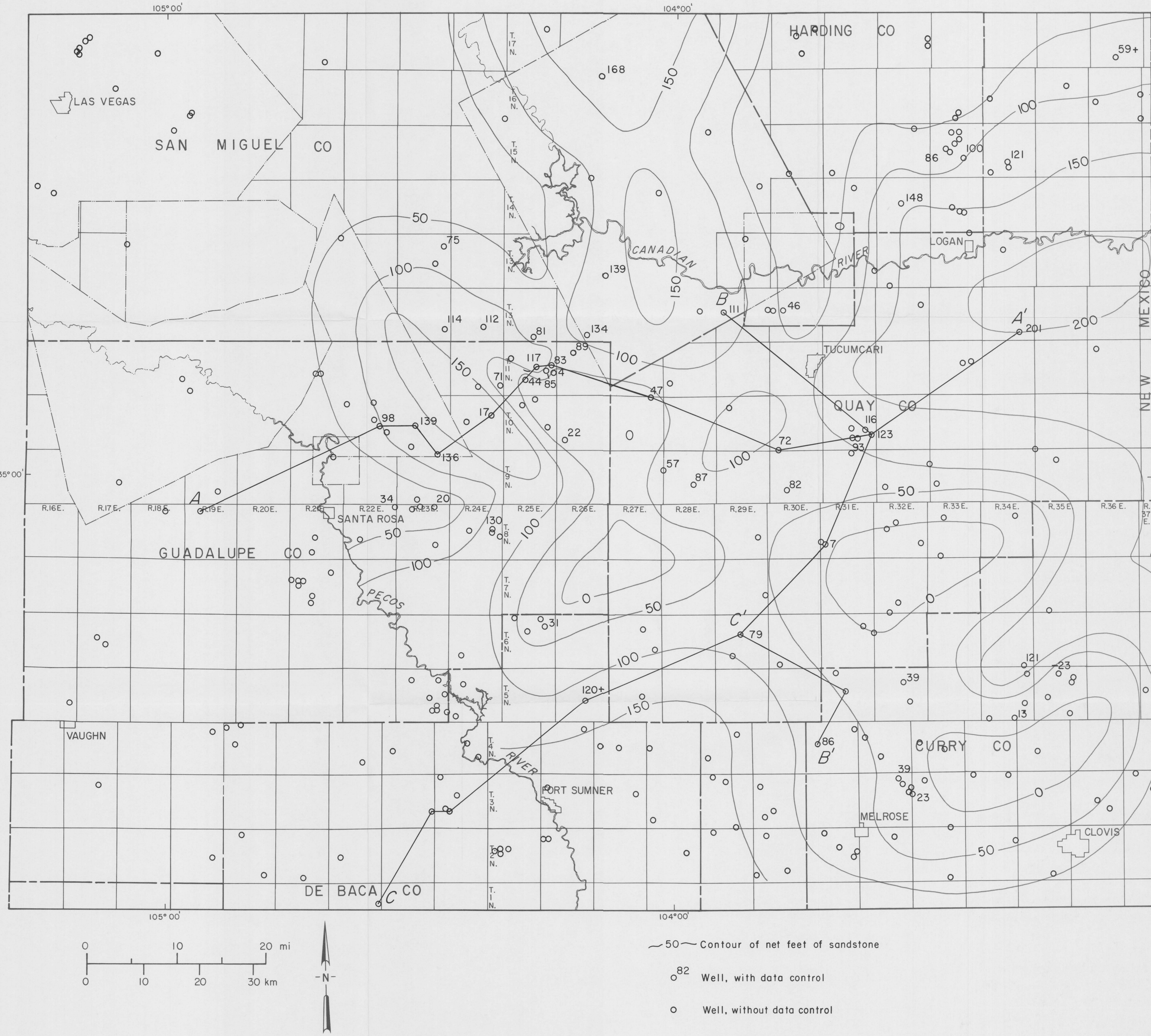
NMBM&MR Circular 193, Figure 5

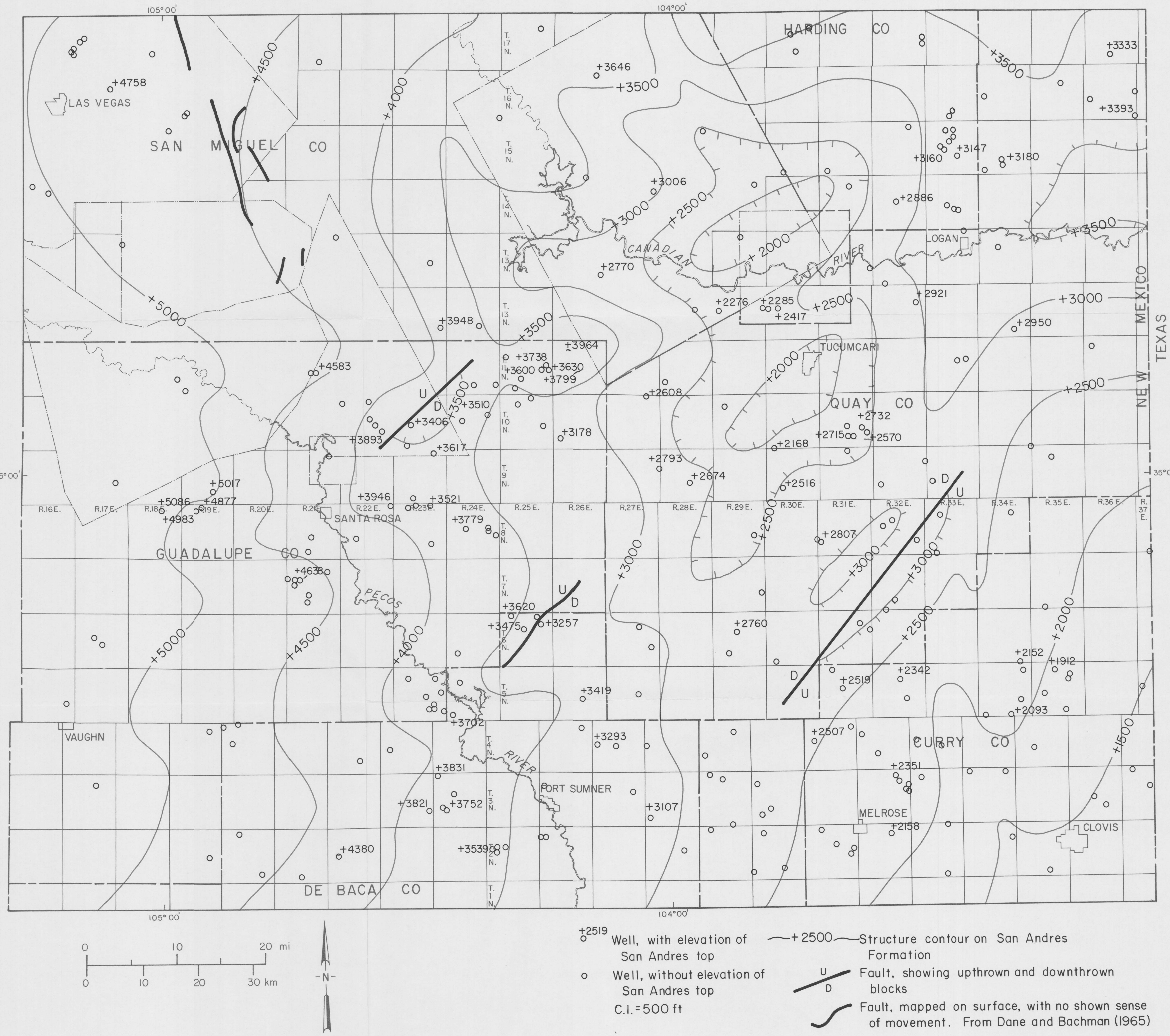


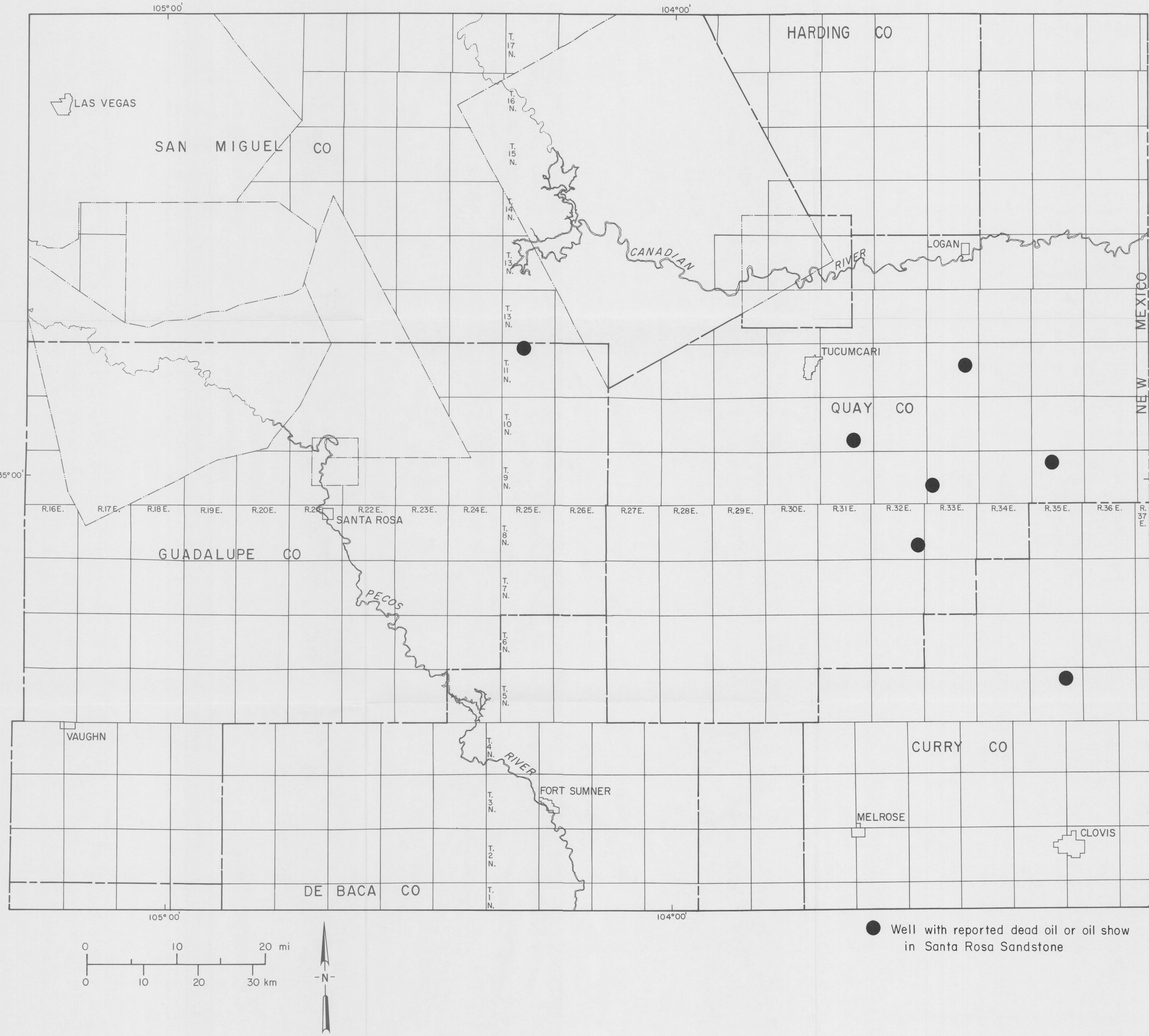

105°00'
104°00'
35°00'
HARDING CO
SAN MIGUEL CO
LAS VEGAS
GUADALUPE CO
SANTA ROSA
QUAY CO
TUCUMCARI
LOGAN
CANADIAN RIVER
PECOS RIVER
NEW MEXICO
TEXAS
VAUGHN
DE BACA CO
FORT SUMNER
MELROSE
CURRY CO
CLOVIS
R.16E. R.17E. R.18E. R.19E. R.20E. R.21E. R.22E. R.23E. R.24E. R.25E. R.26E. R.27E. R.28E. R.29E. R.30E. R.31E. R.32E. R.33E. R.34E. R.35E. R.36E. R.37E.
T.17N. T.16N. T.15N. T.14N. T.13N. T.12N. T.11N. T.10N. T.9N. T.8N. T.7N. T.6N. T.5N. T.4N. T.3N. T.2N. T.1N.
A A' B B' C C'
0 10 20 mi
0 10 20 30 km
N
500 Contour of thickness of Artesia Group
762 Well, with data control
Well, without data control
C.I. = 100 ft


105°00'
104°00'
35°00'
HARDING CO
SAN MIGUEL CO
LAS VEGAS
LOGAN
CANADIAN RIVER
TUCUMCARI
QUAY CO
NEW MEXICO
TEXAS
GUADALUPE CO
SANTA ROSA
PECOS RIVER
VAUGHN
FORT SUMNER
CURRY CO
MELROSE
CLOVIS
DE BACA CO
R.16E. R.17E. R.18E. R.19E. R.20E. R.21E. R.22E. R.23E. R.24E. R.25E. R.26E. R.27E. R.28E. R.29E. R.30E. R.31E. R.32E. R.33E. R.34E. R.35E. R.36E. R.37E.
T.17N. T.16N. T.15N. T.14N. T.13N. T.12N. T.11N. T.10N. T.9N. T.8N. T.7N. T.6N. T.5N. T.3N. T.2N. T.1N.
A
A'
B
B'
C
C'
0 10 20 mi
0 10 20 30 km
N
66
Well, with data control
Well, without data control
—100— Contour of net feet of sandstone
C.I. = 20 ft


HARDING CO
SAN MIGUEL CO
LAS VEGAS
GUADALUPE CO
SANTA ROSA
QUAY CO
TUCUMCARI
LOGAN
CANADIAN RIVER
CURRY CO
CLOVIS
MELROSE
FORT SUMNER
VAUGHN
DE BACA CO
NEW MEXICO
TEXAS
105°00'
104°00'
35°00'
0 10 20 mi
0 10 20 30 km
N
40 Contour of net feet of sandstone
46 Well, with data control
Well, without data control
C. I. = 20 ft


105°00'
104°00'
35°00'
HARDING CO
SAN MIGUEL CO
LAS VEGAS
QUAY CO
TUCUMCARI
LOGAN
GUADALUPE CO
SANTA ROSA
DE BACA CO
FORT SUMNER
VAUGHN
CURRY CO
MELROSE
CLOVIS
NEW MEXICO
TEXAS
CANADIAN RIVER
PECOS RIVER
A
A'
B
B'
C
C'
R.16E. R.17E. R.18E. R.19E. R.20E. R.21E. R.22E. R.23E. R.24E. R.25E. R.26E. R.27E. R.28E. R.29E. R.30E. R.31E. R.32E. R.33E. R.34E. R.35E. R.36E. R.37E.
T.17N. T.16N. T.15N. T.14N. T.13N. T.12N. T.11N. T.10N. T.9N. T.8N. T.7N. T.6N. T.5N. T.4N. T.3N. T.2N. T.1N.
0 10 20 mi
0 10 20 30 km
N
50 Contour of net feet of sandstone
82 Well, with data control
Well, without data control
C.I. = 50 ft.


HARDING CO
SAN MIGUEL CO
LAS VEGAS
GUADALUPE CO
SANTA ROSA
QUAY CO
TUCUMCARI
LOGAN
CURRY CO
MELROSE
CLOVIS
DE BACA CO
FORT SUMNER
VAUGHN
NEW MEXICO
TEXAS
CANADIAN RIVER
PECOS RIVER
105°00'
104°00'
35°00'
0 10 20 mi
0 10 20 30 km
N
+2519 Well, with elevation of San Andres top
○ Well, without elevation of San Andres top
C.I.=500 ft
+2500 Structure contour on San Andres Formation
U D Fault, showing upthrown and downthrown blocks
Fault, mapped on surface, with no shown sense of movement. From Dane and Bachman (1965)


105°00'
104°00'
HARDING CO
LAS VEGAS
SAN MIGUEL CO
T. 17 N.
T. 16 N.
T. 15 N.
T. 14 N.
T. 13 N.
T. 13 N.
T. 11 N.
T. 10 N.
T. 9 N.
T. 8 N.
T. 7 N.
T. 6 N.
T. 5 N.
T. 4 N.
T. 3 N.
T. 2 N.
T. 1 N.
CANADIAN
RIVER
LOGAN
TUCUMCARI
QUAY CO
NEW MEXICO
TEXAS
35°00'
35°00'
R.16E.
R.17E.
R.18E.
R.19E.
R.20E.
R.21E.
R.22E.
R.23E.
R.24E.
R.25E.
R.26E.
R.27E.
R.28E.
R.29E.
R.30E.
R.31E.
R.32E.
R.33E.
R.34E.
R.35E.
R.36E.
R. 37 E.
SANTA ROSA
GUADALUPE CO
PECOS
RIVER
VAUGHN
CURRY CO
FORT SUMNER
MELROSE
CLOVIS
DE BACA CO
105°00'
104°00'
0 10 20 mi
0 10 20 30 km
N
Well with reported dead oil or oil show in Santa Rosa Sandstone