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# Regional Sand Distribution of the Frio Formation, South Texas— A Preliminary Step in Prospecting for Geothermal Energy

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## INTRODUCTION

### General

Many prospective oil wells have penetrated the geopressured zone in Tertiary sediments along the Texas Gulf Coast. However, because few oil or gas wells produce from this area, the regional sand distribution within these zones is not well known. Limited data indicate that the pore spaces within the sand in the geopressured zone are filled with water that has a high temperature and a relatively low dissolved-solids content and that is saturated with methane gas. This water is believed to be an important source of thermal energy and methane gas. For more information concerning the origin of the geopressured zone see Dorfman and Kehle (1974) and Jones (1970).

The first step in appraising the Gulf Coast geothermal resources entails a detailed geologic study of the main sand trends. Of these, the Frio and Wilcox formations appear to be the thickest (fig. 1). This report deals largely with the Frio formation. The Wilcox formation has been studied by Fisher and McGowen (1967). Other parts of the Tertiary that have been studied in detail are the

| AGE | SERIES | GROUP/FORMATION |
|---|---|---|
| Quaternary | Recent | Undifferentiated |
| | Pleistocene | Houston |
| Tertiary | Pliocene | Goliad |
| | Miocene | Fleming |
| | | Anahuac |
| | ?——? | |
| | Oligocene | Frio |
| | | Vicksburg |
| | Eocene | Jackson |
| | | Claiborne |
| | | Wilcox |
| | | Midway |

Figure 1. Tertiary formations of the Gulf Coast of Texas. Of prime interest in this report is the Frio and upper part of the Vicksburg (darker shaded area); other formations already studied and summarized in Bureau of Economic Geology (The University of Texas at Austin) reports are shown in the lighter shaded area.

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Queen City formation (Claiborne), which was reported on by Guevara and Garcia (1972), and the Jackson formation, reported on by Fisher and others (1970).

The United States Atomic Energy Commission, through the Lawrence Livermore Laboratory, and the Center for Energy Studies, The University of Texas at Austin, supported this preliminary study of the geothermal resources of the Frio sands in South Texas. The South Texas area (immediately north of Corpus Christi and south to the Rio Grande, fig. 2) was selected because the geopressured zone is known to occur there at relatively shallow depths (Jones, 1970) and because of the abundance of oil-well records for the area. The study includes a sand-facies analysis and an integration of the facies data with existing information relative to temperatures and pressures. This paper is modified from a circular published earlier by Bebout, Dorfman, and Agagu (1975).

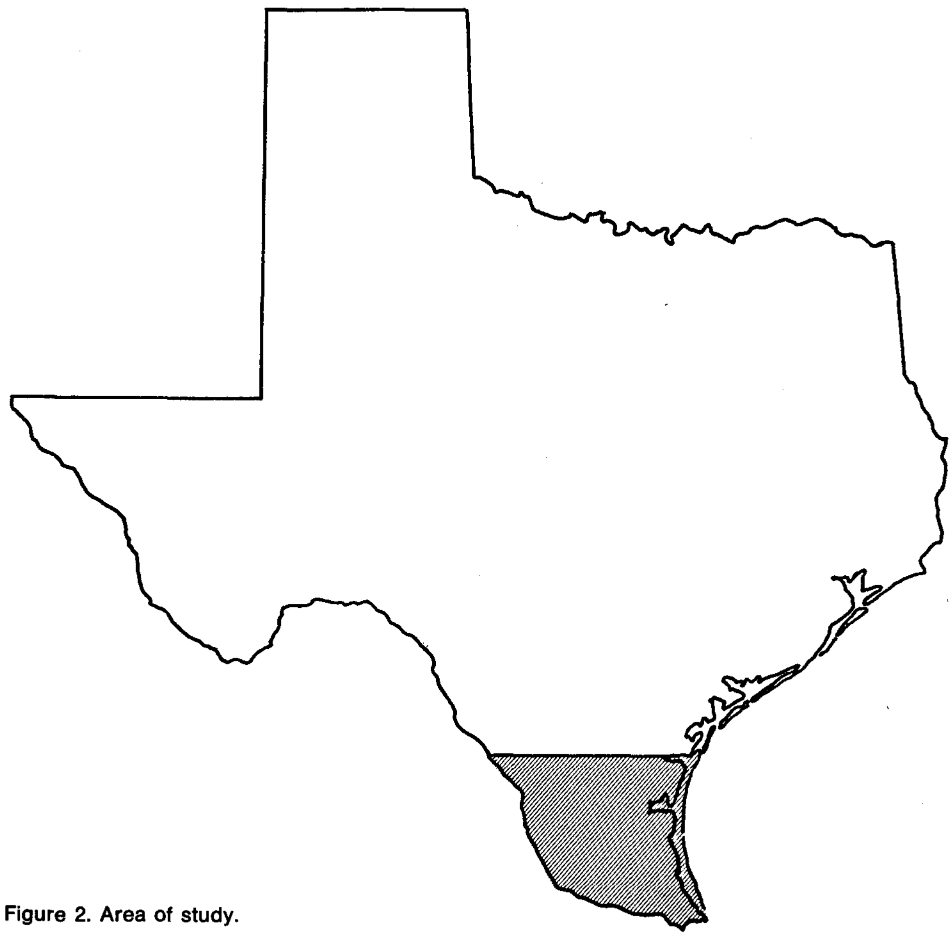

Figure 2. Area of study.

## Regional Framework

The Tertiary of the Gulf Coast is made up of a number of sand-shale packages that dip steeply into the Gulf of Mexico (fig. 3). Each of these packages also thickens considerably in the same direction (fig. 4), forming a wedge-shaped body (fig. 5). The wedges are dominantly shale with scattered, discontinuous sand bodies at the thin, landward end; thick sand with thin shales in the central portion; and thick shale with thin, relatively continuous sands at the downdip portion of the wedge. In general, each younger wedge is displaced gulfward from the preceding wedge.

Because this Tertiary section is too thick and areally extensive to study as a single unit, it has been necessary to subdivide it into genetic units. This subdivision is difficult to accomplish on the basis of lithology alone because of the

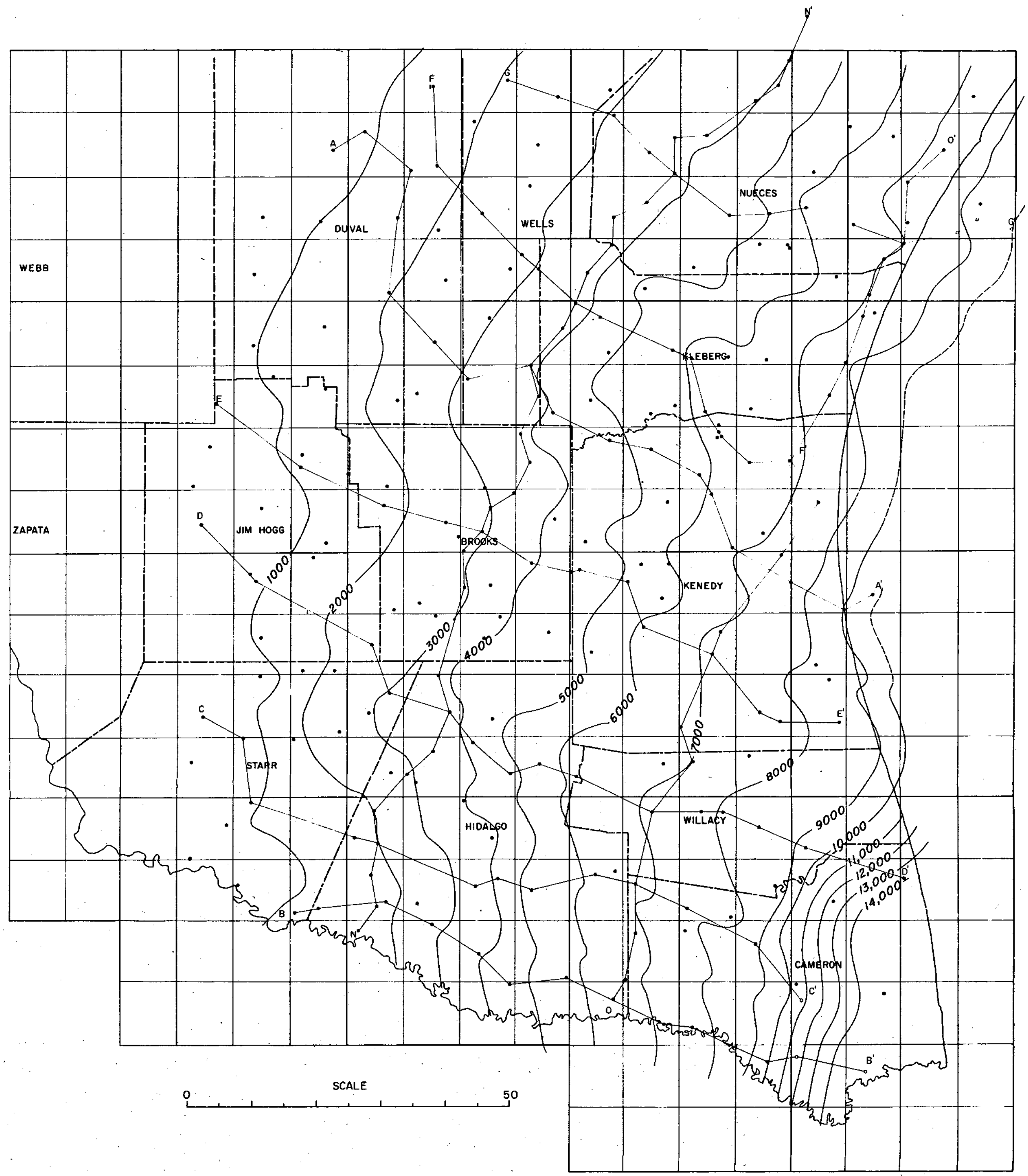


Figure 3. Structure on top of the Frio formation.

repetitiveness of sand-shale occurrence and the lack of recognizable physical breaks. Thus, organizations exploring for oil and gas in marine portions of the wedges use evolutionary change within foraminiferal groups to subdivide grossly the Tertiary section. Major foraminiferal zones significant to this study are shown in figure 6.

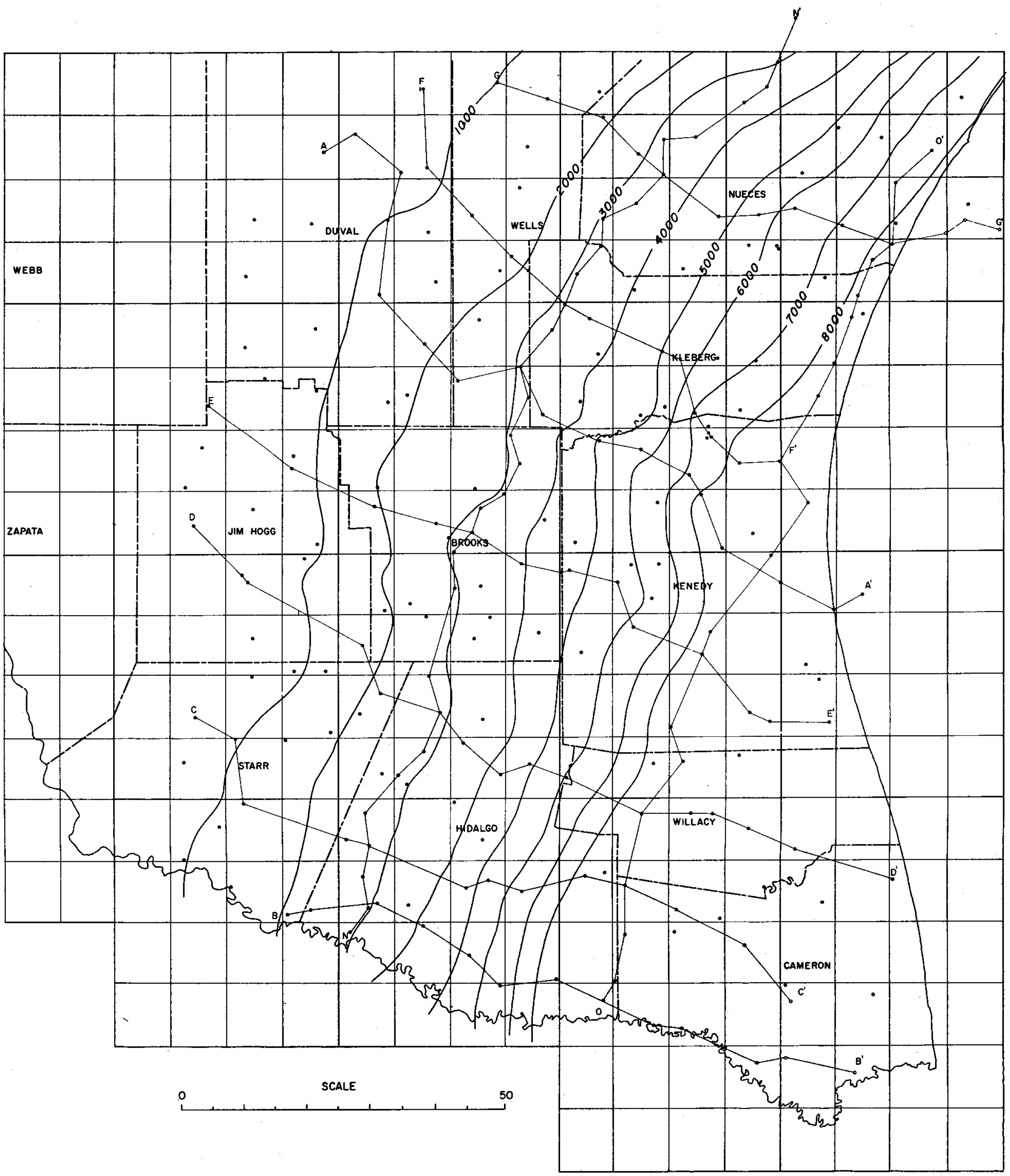


Figure 4. Total thickness of Frio formation, South Texas.

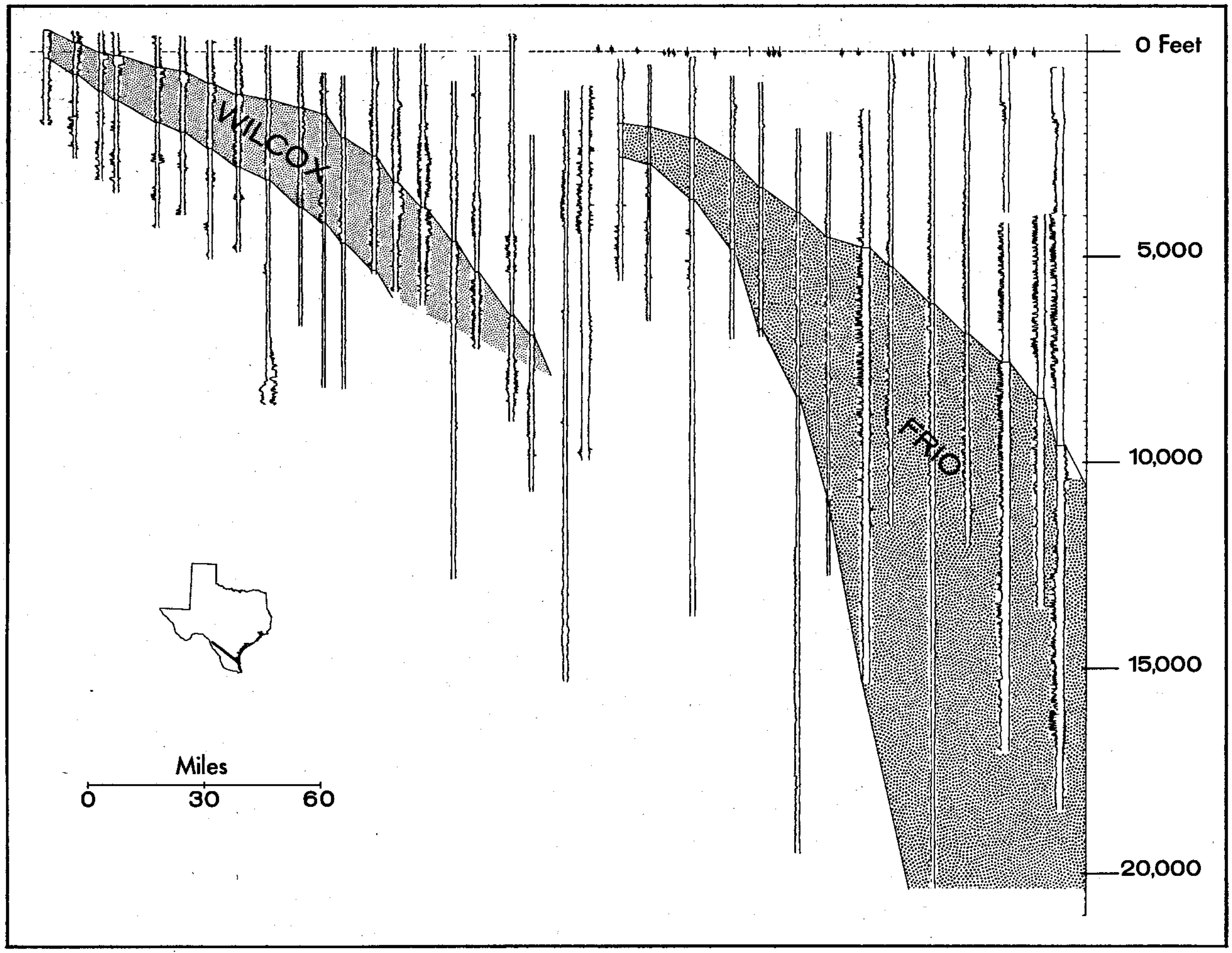


Figure 5. Regional cross section on a sea-level datum showing the pattern of sand-shale packages offlapping toward the coast.

| SERIES | GROUP/FORMATION | |
|---|---|---|
| Miocene | Anahuac | Discorbis nomada<br>Heterostegina texana* |
| Oligocene | Frio | Marginulina vaginata*<br>Cibicides hazzardi<br>Nonion struma<br>Nodosaria blanpiedi*<br>Textularia mississippiensis<br>Anomalia bilateralis |
| | Vicksburg | Textularia warreni* |

Figure 6. Foraminifer zonation, Texas Gulf Coast Miocene and Oligocene.

## Growth Faults

Much of the thickening, which is manifest regionally as thick sand-shale wedges, is believed to have been caused by contemporaneous growth faults (fig. 7). Because the faults are active while sedimentation is taking place, considerable thickening of the sedimentary units involved occurs on the gulfward, or down, side of the fault. A regional, or structural, cross section (fig. 8) shows the cumulative effect of crossing several growth faults; the uniform thickening shown on the regional facies sections actually represents an averaging of the effects of these faults.

Because of the complexity of the faulting in South Texas (figs. 7, 8, 9), it is impossible to portray these faults on the regional sections. The displacement is quite variable along most of the faults, and for many it is only a few hundred feet. Because of this complexity and small displacement, it was considered preferable to study the sand distribution regionally, at first without regard to the

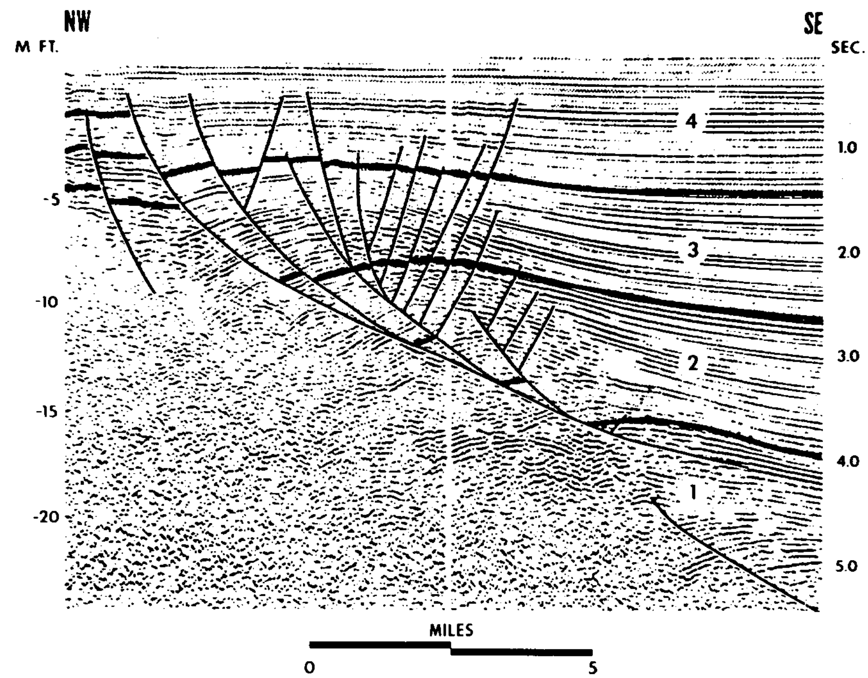


Figure 7. Depositional thickening as a result of contemporaneous growth faulting (from Bruce, 1973).

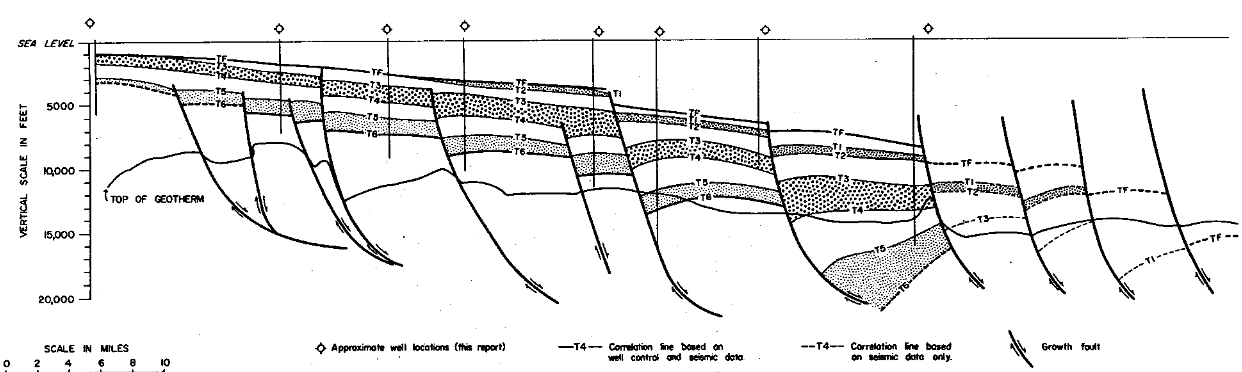


Figure 8. Diagrammatic regional cross section adapted from a seismic section and from electrical log and paleontological control. This section parallels the B-B′ section near the Rio Grande; the *T* markers from the B-B′ section have been projected into this section to show the relationship of the depositional patterns (interpreted from electrical logs) to the growth faults (interpreted from the seismic sections).

faults, though acknowledging that growth faulting is common and is the normal mechanism for providing space to thicken the section rapidly downdip. The faults are not believed to have affected the depositional patterns appreciably except for significantly increasing thickening. The location of growth faults, confirmed by seismic sections of a regional and local nature, will be of critical importance later, when attention is focused on the selection of local prospective areas.

As a result of growth faulting, porous sand reservoirs once in contact with time-equivalent extensive sand units updip may be displaced downward on the coast side of the fault to then be in contact, across the fault, with impermeable shale. Thus, extensive oil and gas reservoirs and potential geothermal reservoirs develop as a result of sedimentary processes and contemporaneous structure.

## CORRELATIONS

Reliable resource assessment is based on a thorough understanding of the sand distribution and geometry. In a sand-shale section, this type of regional information is commonly obtained through the construction of a grid of dip and

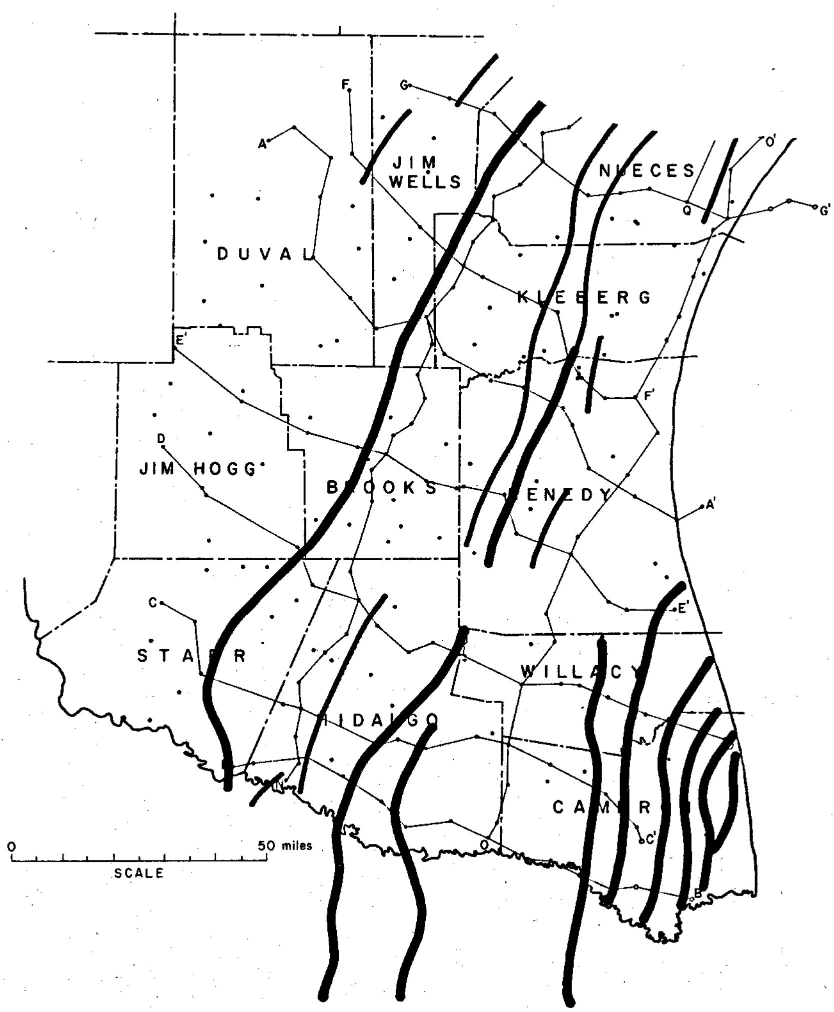


Figure 9. Generalized location of growth faults in South Texas.

strike electrical-log cross sections. On these cross sections, detailed correlations lead to the subdivision of the section into smaller, more meaningful, and more easily handled units.

For the Frio study, 232 electrical logs were obtained from wells spaced approximately 5 to 10 miles apart throughout the South Texas area (fig. 10). Only

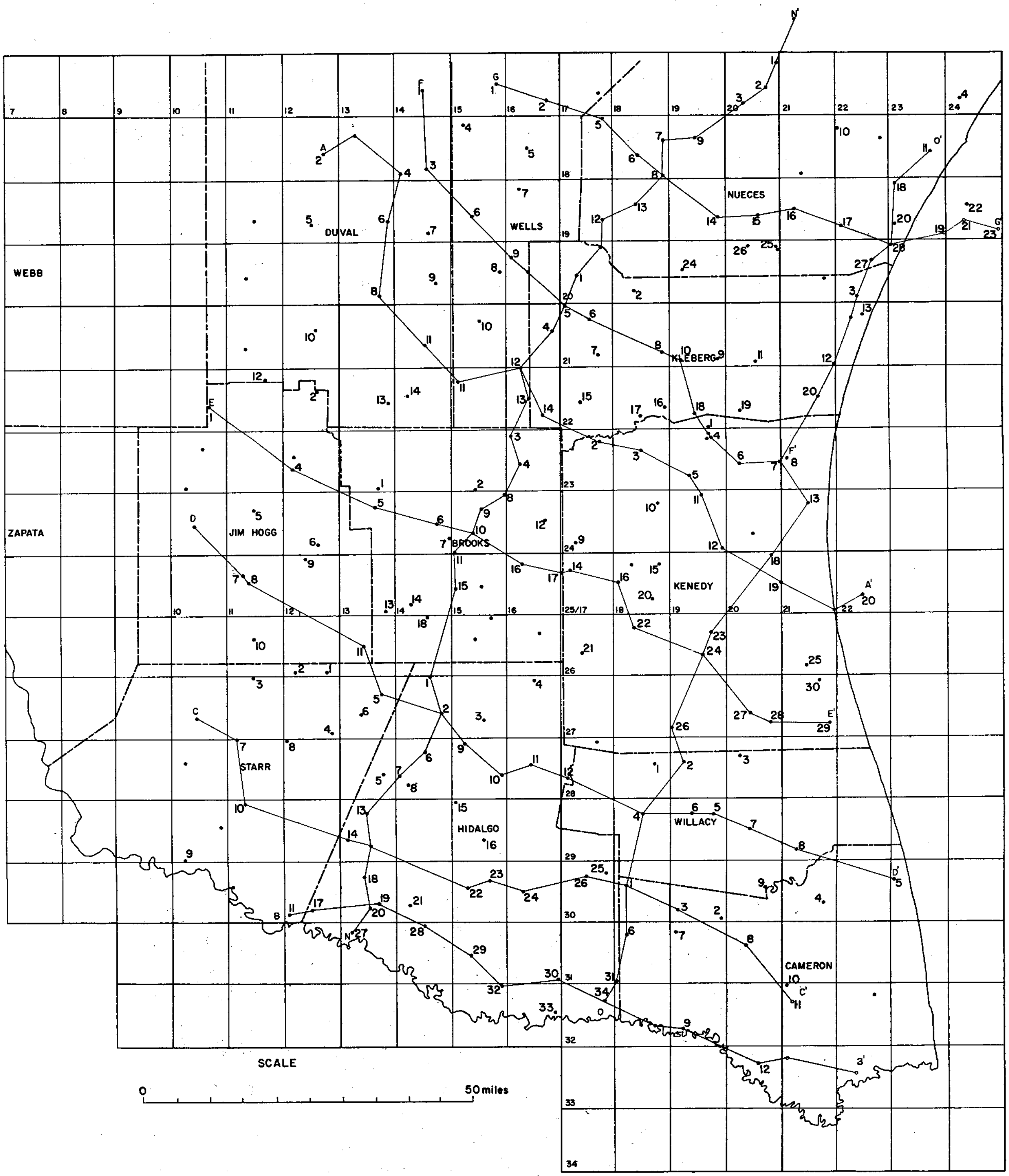


Figure 10. Well-log control and cross sections constructed for the Frio study.

LIST OF WELLS

Brooks County

| | | |
|---|---|---|
| 1. | City Products Corp. | G. S. Saunders et al. #1 |
| 2. | Shell Oil Co. | J. L. Cage #C-1 |
| 3. | General Crude Oil Co. | R. G. Garza #1 |
| 4. | Gunther, Warren & Gulf Oil Corp. | Miller et al. #1 |
| 5. | Russell McGuire | Saunders #1 |
| 6. | NOR-MAC-Burns | J. L. Cage #1 |
| 7. | Humble Oil & Rfg. Co. | C. F. Hooper #7 |
| 8. | Carrl Oil, General Crude, Pan Am. | R. G. Cage et al. #1 |
| 9. | Forest Oil Co. | Cage Ranch #1 |
| 10. | Forest Oil Co. | Ed Rachal Foundation #1 |
| 11. | Humble Oil & Rfg. Co. | C. F. Hopper #5 |
| 12. | Humble Oil & Rfg. Co. | D. J. Sullivan "B" #28 |
| 13. | Humble Oil & Rfg. Co. | Mestena Oil & Gas Co. #G-5 |
| 14. | Humble Oil & Rfg. Co. | Mestena Oil & Gas Co. #G-3 |
| 15. | Humble Oil & Rfg. Co. | B. A. Skipper, Jr. #11 |
| 16. | Humble Oil & Rfg. Co. | R. J. Kleberg, Jr., Trustee, Los Muertos Pasture #7 |
| 17. | Humble Oil & Rfg. Co. | J. Kleberg, Jr., Trustee, Sacahuista Pasture #2 |
| 18. | Standard Oil of Texas | Braulia de Garcia #1-14 |

Cameron County

| | | |
|---|---|---|
| 1. | Texaco, Inc. (proprietary) | C. A. Johnson #1 |
| 2. | Amerada Petr. Corp. | W. O. Huff #1 |
| 3. | Gulf Oil Corp. | J. H. McDaniel #1 |
| 4. | Shell Oil Co. | Continental Fee #1 |
| 5. | Magnolia Petr. Co. | G. Kerlin #1 |
| 6. | Hydrocarbon Prod. Co. | J. R. Bevers et al. #1 |
| 7. | Harkins & Co. & R. Mosbacher | L. Rohman #1 |
| 8. | Aluminum Co. of America | Old Colony Trust Est. #1 |
| 9. | Brazos Oil | State Tract 215 #1 |
| 10. | Holmes Drlg. Co. | T. Sweeney et al. #1 |
| 11. | Dow Chemical | Conoco Mineral Fee #1 |
| 12. | Humble Oil & Rfg. Co. | Cameron County Water Control & Improvement District 6 #1 |

Duval County

| | | |
|---|---|---|
| 1. | C. C. Winn | Salinas Est. #2 |
| 2. | Shell Oil Co. | Stegall #A-1 |
| 3. | Humble Oil & Rfg. Co. | E. Garcia #1 |
| 4. | Taylor Rfg. Co. | Parr #T-2 |
| 5. | Pyramid Drlg. Co. | J. M. Luby Est. #1 |
| 6. | The Texas Co. | Gravis #1-A |
| 7. | Humble Oil & Rfg. Co. | W. W. Garcia #1 |
| 8. | Hiawatha Oil & Gas Co. | Parr #D-1 |
| 9. | Quintana Petr. Corp. | Frank & Clyde Allen #1 |
| 10. | Hillcrest Oil Co. | K. Shaffer #1 |
| 11. | Hunt Oil Co. | Dechampa #1 |
| 12. | Arco Oil Corp. | Laura McBryde #1 |
| 13. | Texaco, Inc. | Canales #1 |
| 14. | Continental Oil Co. | Glasscock et al. #1 |

Hidalgo County

| | | |
|---|---|---|
| 1. | Humble Oil & Rfg. Co. | McGill Bros. #416 |
| 2. | Shell Oil Co. | A. A. McAllen #9 |
| 3. | Shell Oil Co. et al. | Goldston Est. #1 |
| 4. | Humble Oil & Rfg. Co. | Santa Fe - Mula #7 |
| 5. | Pontiac Rfg. | Arrowhead Ranch #1 |
| 6. | Shell Oil Co. | A. A. McAllen et al. #1 |
| 7. | Shell Oil Co. | G. Coates-Newmont Oil Co. #1 |
| 8. | Taylor Oil & Gas Co. | K. J. Alexander #1 |
| 9. | Shell Oil Co. | A. W. Beaurline #1 |
| 10. | Magnolia Petr. Co. | G. Doughty #1 |
| 11. | Magnolia Petr. Co. | R. Garcia #1 |
| 12. | N. E. Hanson | S. Dobbins #1 |
| 13. | P. H. Welder | W. J. Davis #1 |
| 14. | Coastal States | G. H. Coates et al. #1 |
| 15. | Austral Oil Co., Inc. | R. Vela et al. #1 |
| 16. | Humble Oil & Rfg. Co. | B. Hanks #1 |
| 17. | Phillips Oil | Flores #1 |
| 18. | Sinclair Prairie Oil Co. | S. Geininger #1 |
| 19. | Humble Oil & Rfg. Co. | Texan Dev. Co. #1 |
| 20. | Coastal States | T. E. Murchison #1 |
| 21. | Houston Oil Co. of Texas | Hidalgo-Willacy #A-1 |
| 22. | Mokeen Oil Co. | J. T. Atwood #1 |
| 23. | Amerada Petr. Corp. | T. & N. O. RR. Co. #1 |
| 24. | Union Prod. Co. | Wysong Unit #2 |
| 25. | Continental Oil Co. | E. E. Johnson #1 |
| 26. | Standard Oil Co. of Texas | Rio Farms Inc. #1 |
| 27. | Houston Oil Co. | Hidalgo-Willacy Oil Co. |
| 28. | Conoco | M. L. Talbot #1 |
| 29. | Tenneco Oil | McAllen Field Wide Unit #36 |
| 30. | LaGloria Corp. | South Weslaco Gas Unit #1 |
| 31. | Shell Oil Co. | H. W. Drawe #1 |
| 32. | Sinclair Oil | Houston Unit #2 |
| 33. | LaGloria Corp. | South Weslaco Gas Unit #11 |
| 34. | Bettis & Shepard | Schwartz #1 |

Jim Hogg County

| | | |
|---|---|---|
| 1. | British American Oil Prod. Co. | Adams #1 |
| 2. | Humble Oil & Rfg. Co. | Mestena Oil & Gas Co. #C-2 |
| 3. | Cox Hamon | Armstrong #1 |
| 4. | W. Young | Mestina #3 |
| 5. | P. L. Davidson | Well Bros. #1 |
| 6. | G. C. Ayres | Mestena Oil & Gas Co. #4 |
| 7. | The Texas Co. | A. K. East #6 |
| 8. | Burns Trust #2 | East #1 |
| 9. | E. R. Thomas | Holbein #1 |
| 10. | Sun Oil Co. | A. C. Jones #63 |
| 11. | Humble Oil & Rfg. Co. | A. M. Bass #30 |

Jim Wells County

| | | |
|---|---|---|
| 1. | Carrl Oil et al. | Shaeffer Ranch #V-1 |
| 2. | O. Maclain | Rehmet #4-A |
| 3. | Texas Southern Oil & Gas Co. | E. Monse #2 |
| 4. | Gulf Coast Minerals, Inc. | Robles Heirs #1 |
| 5. | W. E. Rowe | W. Meyer #2 |
| 6. | Sunray-Mid-Continental Oil Co. | C. Muil #1 |
| 7. | Appell Drlg. Co. | H. H. Chiles #1 |
| 8. | Carrl Oil & Shore Expl. Co. | A. C. Skinner #2 |
| 9. | Sid Katz Expl. | J. E. Morgan #1 |
| 10. | H. R. Smith | C. Driscoll Est. #1 |
| 11. | G. E. Chapman | Howell et al. Unit #1 |
| 12. | Sun Oil Co. | Canales #117 |
| 13. | Sun Oil Co. | A. T. Canales #43 |

## Kenedy County

| | | |
|---|---|---|
| 1. | Humble Oil & Rfg. Co. | S. K. East #B-18 |
| 2. | Gulf Oil Corp. | McGill Est. #2 |
| 3. | Humble Oil & Rfg. Co. | H. F. McGill #1 |
| 4. | Humble Oil & Rfg. Co. | S. K. East #B-15 |
| 5. | Humble Oil & Rfg. Co. | J. G. Kenedy, Jr. #"J"-2 |
| 6. | Humble Oil & Rfg. Co. | J. G. Kenedy, Jr. #G-1 |
| 7. | Pan Am. | Kenedy #1 |
| 8. | LaGloria Corp. | Kenedy Ranch #B-1 |
| 9. | Humble Oil & Rfg. Co. | R. J. Kleberg, Jr., Trustee, Patricio Pasture #10 |
| 10. | Humble Oil & Rfg. Co. | J. G. Kenedy, Jr. #C-2 |
| 11. | Humble Oil & Rfg. Co. | Kenedy #J-4 |
| 12. | Humble Oil & Rfg. Co. | S. K. East #D-1 |
| 13. | Humble Oil & Rfg. Co. | State Tract 249 #1 |
| 14. | Humble Oil & Rfg. Co. | R. J. Kleberg, Sacahuista Pasture #2 |
| 15. | Humble Oil & Rfg. Co. | S. K. East #41 |
| 16. | Humble Oil & Rfg. Co. | S. K. East #17 |
| 17. | Humble Oil & Rfg. Co. | C. M. Armstrong #20 |
| 18. | Humble Oil & Rfg. Co. | S. K. East #C-1 |
| 19. | Mobil Oil Corp. | State Tract 309 #1 |
| 20. | Mobil Oil Corp. | Texas Gulf 59202 State Tract 961L |
| 21. | Humble Oil & Rfg. Co. | Santa Fe Ranch Julian Pasture #1 |
| 22. | Humble Oil & Rfg. Co. | C. M. Armstrong #22 |
| 23. | Humble Oil & Rfg. Co. | S. K. East "G" #1 |
| 24. | Humble Oil & Rfg. Co. | King Ranch-Saltillo #2 |
| 25. | Humble Oil & Rfg. Co. | State Tract 384 #1 |
| 26. | Texaco, Inc. | Yturria L and L A NCT - 2 #1 |
| 27. | Humble Oil & Rfg. Co. | King Ranch #2 |
| 28. | Humble Oil & Rfg. Co. | King Ranch - Tio Moya #1 |
| 29. | Gulf Oil Corp. | State Tract 427 #1 |
| 30. | Continental Oil Co. | State Tract 393 #1 |
| 31. | Humble Oil & Rfg. Co. | R. J. Kleberg, Jr., Frustel Stillman #7 |

## Kleberg County

| | | |
|---|---|---|
| 1. | Humble Oil & Rfg. Co. | King Ranch - Stratton #T-1 |
| 2. | Golden Trend Oil & Gas Corp. | Marshall-Michele #1 |
| 3. | Pure Oil Co. | State Tract 168 #A-1 |
| 4. | Humble Oil & Rfg. Co. | King Ranch - Seeligson #E-45 |
| 5. | Humble Oil & Rfg. Co. | King Ranch - Borregos #262 |
| 6. | Humble Oil & Rfg. Co. | King Ranch - Borregos #ME-5 |
| 7. | Meeker & Hass Bros. | O'Conner #1 |
| 8. | Lone Star Oil Co. | Mull #1 |
| 9. | Humble Oil & Rfg. Co. | King Ranch - Visnaga #8 |
| 10. | Mokeen Oil Co. | H. A. M. #A-1 |
| 11. | Humble Oil & Rfg. Co. | King Ranch - Alazan #3 |
| 12. | Humble Oil & Rfg. Co. | State Tract 197 #1 |
| 13. | Kelly Bell | State Tract 184 #1 |
| 14. | Humble Oil & Rfg. Co. | King Ranch - Laguna Larga #10 |
| 15. | Humble Oil & Rfg. Co. | King Ranch - Canelo #17 |
| 16. | Cities Service Petr. | R. B. Poteet #1 |
| 17. | Mokeen Oil Co. et al. | Yeargen #1 |
| 18. | Sun Oil Co. | Laguna Olmos Gas Unit 372 #1 |
| 19. | Humble Oil & Rfg. Co. | Baffin Bay State Tract 57 #1 |
| 20. | Shell Oil Co. | State Tract 206 #1 |

## Nueces County

| | | |
|---|---|---|
| 1. | Getty Oil Co. | Wilkerson #1 |
| 2. | Spartan Drlg. Co. | E. H. Granberry #1 |
| 3. | Southern Minerals Corp. | M. H. Griffith #1 |
| 4. | Getty Oil Co. | State Tract 275 #1 |
| 5. | Kirkpatrick Oil & Gas Co. & Natol Petr. | A. P. Regmund #1 |
| 6. | Gillring Oil | Winfield #8 |
| 7. | Southern Minerals Corp. | B. Sterns #1 |
| 8. | Glasscock Bros. & Puenticitas Oil Co. | La Rochelle #1 |
| 9. | Richardson Petr. | F. Nemec #1 |
| 10. | Forest Oil Corp. & Mobil Oil Co. | State Tract 786 #7 |
| 11. | Shell Oil Co. | State Tract 346 #1 |
| 12. | Champlin Oil & Rfg. Co. | B. Woffard #C-2 |
| 13. | Puenticitas Oil Co. | Simmons & Perry "B" #60 |
| 14. | The Atlantic Rfg. Co. | J. S. Womack |
| 15. | Newman Bros. | W. W. Walton #1 |
| 16. | Coastal States | P. Kraft #1 |
| 17. | J. P. Driscoll et al. | F. D. Smith et al. #1 |
| 18. | Atlantic Richfield Co. & Tidewater Co. | St. 45-47 Unit, Tr. #470, #3 |
| 19. | Cities Service | State Tract 773L #1 |
| 20. | Humble Oil & Rfg. Co. | Laguna Madre State Tract 52 #1 |
| 21. | Gulf Oil Co., Humble Oil & Rfg. Co. | State Tract 772 #B-1 |
| 22. | Humble Oil & Rfg. Co. | State Tract 772 #1 |
| 23. | Union Oil of Calif. | State Tract 775-L #1 |
| 24. | G. N. Graham | Al. Dorsogna #1 |
| 25. | The Chicago Corp. | Chapman Ranch #3 |
| 26. | A. O. Morgan & Southern Minerals Corp. | Chapman Heirs #43-1 |
| 27. | Humble Oil & Rfg. Co. | State Tract 173 #1 |
| 28. | Cherryville Corp. | B. Dunn et al. #1 |

## Starr County

| | | |
|---|---|---|
| 1. | Richardson Petr. Enterprise | E. Yzaguirre #B-1 |
| 2. | Oil Operations, Inc. | Margo Est. #A-1 |
| 3. | Sun Oil Co. | A. C. Jones #55 |
| 4. | Sun Oil Co. | J. F. Hall-State #1-A |
| 5. | Humble Oil & Rfg. Co. | D. Olivarez #1 |
| 6. | Magnolia Petr. Co. | F. B. Guerra #5 |
| 7. | Sun Oil Co. | O. B. Simpson State #1 |
| 8. | Sun Oil Co. | G. H. Coates State #A-4 |
| 9. | Owen & Moss | W. S. Parks #4 |
| 10. | Lockhart Oil Co. of Texas | J. D. Brock #2 |
| 11. | Sun Oil Co. | Reilly #A-1 |

## Willacy County

| | | |
|---|---|---|
| 1. | Humble Oil & Rfg. Co. | M. F. Garcia #2 |
| 2. | Texaco Inc. | Hurria L & L Co. #A-10 |
| 3. | Humble Oil & Rfg. Co. | Sauz-Ranch-Jardin #1 |
| 4. | Pan Am. | Coleman #1 |
| 5. | Sun Oil Co. | Scott #1 |
| 6. | Shoreline Petr. Corp. | Lorena Walker #1 |
| 7. | Humble Oil & Rfg. Co. | Williamar Unit #1 |
| 8. | Humble Oil & Rfg. Co. | Sauz-Ranch-Nopal #2 |
| 9. | Phillips Petr. Co. | Livingston #1 |

those wells that penetrated the entire Frio were selected except in the downdip areas along the coast, where no wells penetrated the entire Frio section. The top and base of the section were located with the aid of micropaleontology—*Heterostegina* and *Marginulina* are near the top of the Frio, and *Textularia warreni* is near the base. Where these markers are lacking, structure and major shale breaks were used.

Seven dip sections and two strike sections were constructed for the Frio section, using the top of the formation as a datum. These sections illustrate the Frio as a wedge of sediment less than 1,000 feet thick on the updip end of the section and more than 10,000 feet thick on the downdip end.

In order to subdivide the Frio wedge into more manageable units, correlation points within the Frio had to be established. This was accomlished on the basis of several assumptions: (1) the entire Frio thickens significantly downdip and, therefore, each genetic unit within the Frio also thickens; (2) major shale breaks represent longer periods of deposition than the intervening sand and will carry for greater distances with some reliability; (3) each genetic unit is transported slightly seaward of the previous, or older, unit; and (4) each unit consists of a dominantly shale section with thin, discontinuous sands on the updip portion, with thick, extensive sands in the central portion, and with shale dominant on the downdip portion.

The pattern thus obtained consists of a series of sand-shale packages (figs. 11 and 12) that thicken toward the Gulf; sand percentages increase to near the present coast, where shale deposition then becomes dominant. The updip limit of each package occurs nearer the Gulf than the preceding package (fig. 13A), a pattern that parallels very closely the updip limits of foraminiferal markers (fig. 13B).

## DEPOSITIONAL ENVIRONMENTS

Sand-percentage maps were made for each unit (*T*0-*T*1, *T*1-*T*2, *T*2-*T*3, *T*3-*T*4, *T*4-*T*5, and *T*5-*T*6); data for these maps were obtained from the interpretation of the spontaneous potential curve of electric logs on the cross section and from infill wells between sections. The total sand thickness for each unit was calculated for each well; net sand and sand percentages were plotted on maps and contoured to depict sand distribution for each unit (figs. 14-19).

Depositional systems recorded by these sands and shales were interpreted with the use of sand-percentage and net-sand maps, in addition to cross sections and characteristic log patterns, thickness relationships of the associated sands and shales, and core data. Core control was sparse and contributed only to a very minor extent.

The depositional systems identified here include fluvial, high-constructive delta, and strandplain. The variations in the sand-shale ratio and distribution and in the geometry of the sand bodies that lead to the identification of the depositional systems are shown on a cross section of the T4-*T*5 zone (fig, 20).

FLUVIAL SYSTEM. Sand is distributed in narrow, somewhat sinuous bands perpendicular to the coastline along the updip portion of the area. The sand bodies are commonly thin and are discontinuous laterally along strike. Individual sand bodies range in thickness from approximately 10 to 50 feet. The log patterns between and enclosing these fluvial channels indicate extensive areas very poor in sand. These areas, which are dominantly clay with very thin lignites, represent overbank and swamp or marsh environments.

HIGH-CONSTRUCTIVE DELTA SYSTEM. Along the Rio Grande in Hidalgo and Cameron Counties, thick sand bodies are oriented in a dip direction. The sand bodies are 100 to 600 feet thick, and commonly are represented by a log

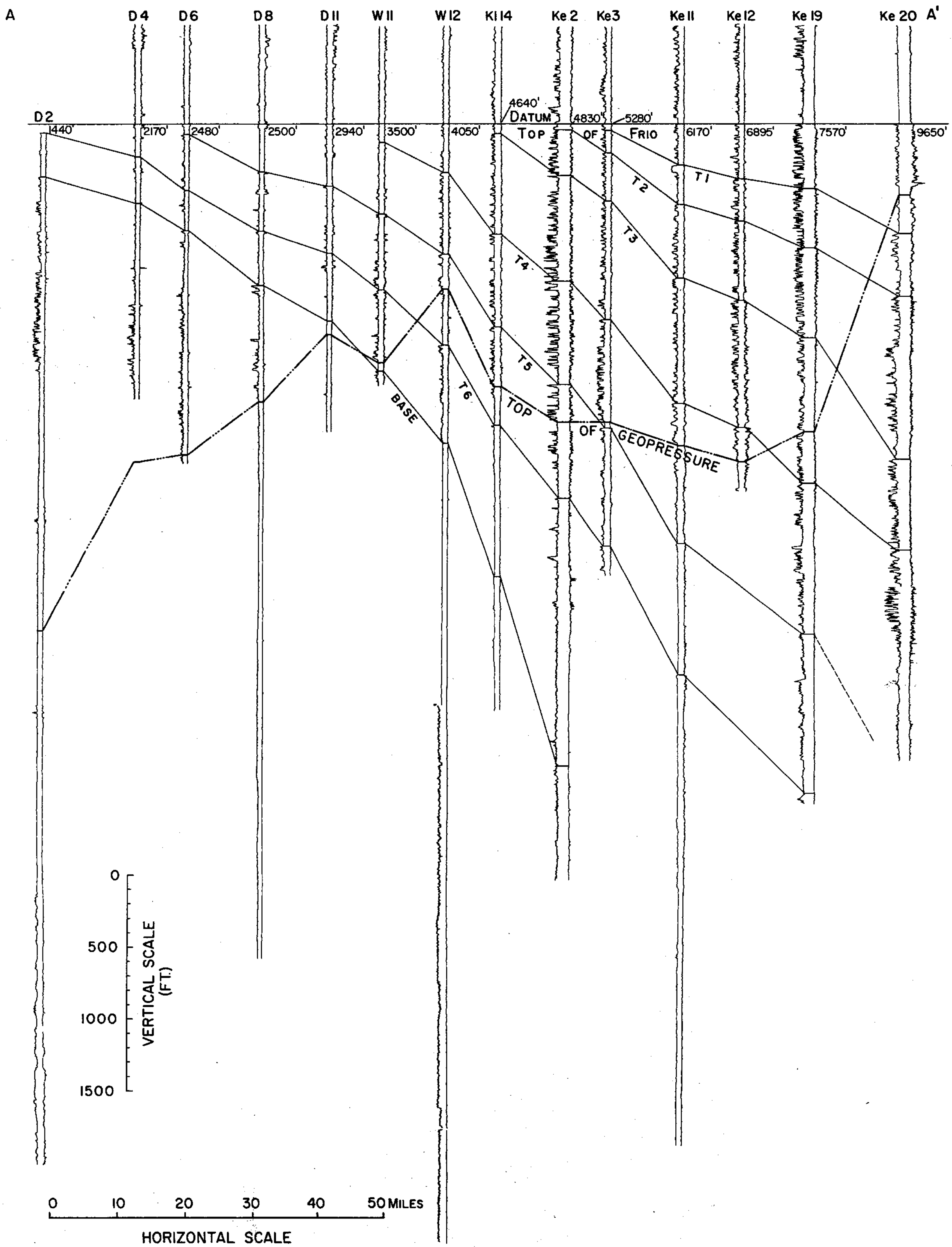


Figure 11. Sand-facies distribution along section A-A′, datum on top of the Frio. *T* markers indicate correlation points interpreted by using major shale beds and foraminifer zones. The top of the geopressured zone is indicated by the broken line.

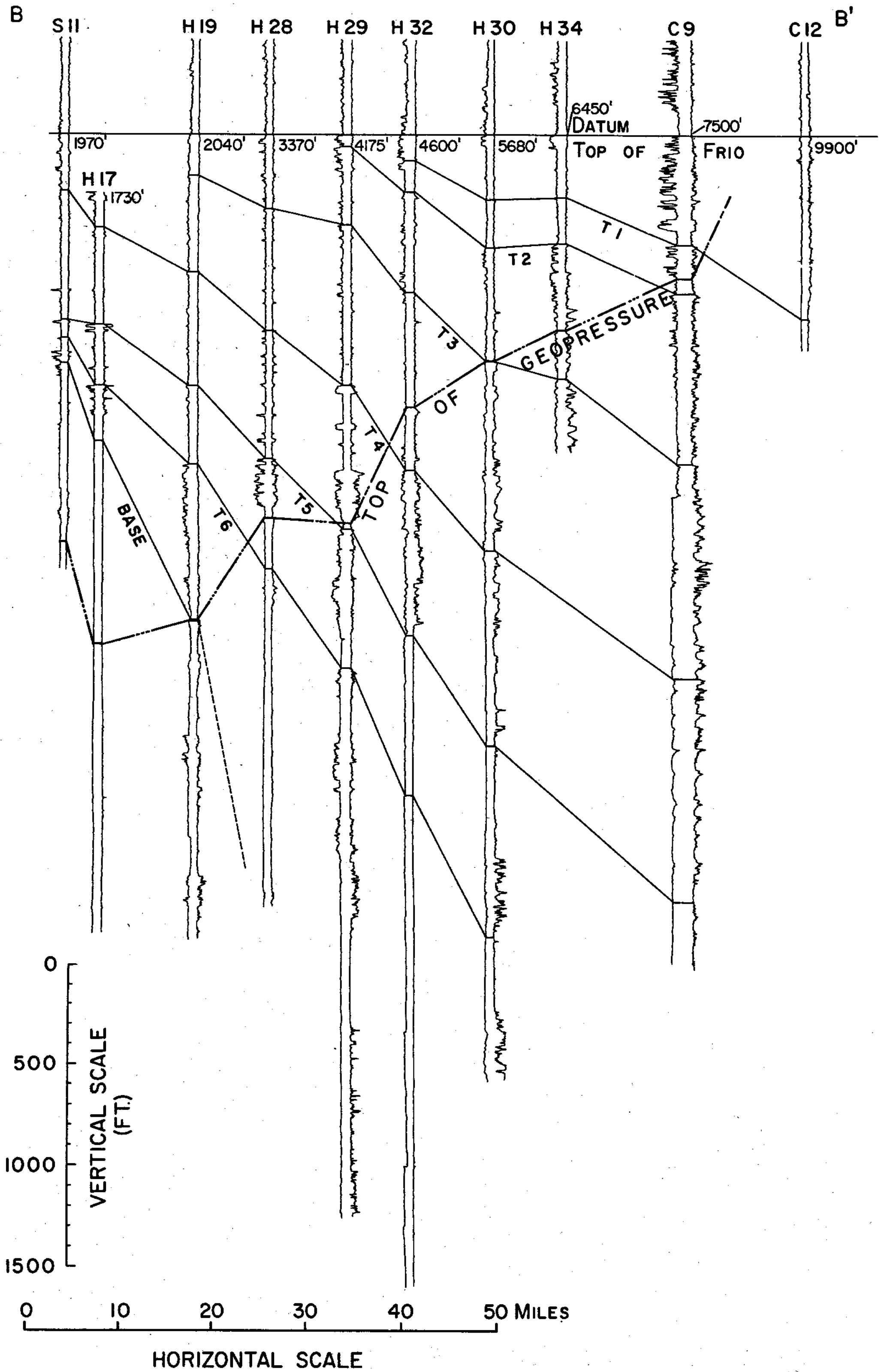


Figure 12. Sand-facies distribution along section B-B′, datum on top of the Frio. *T* markers indicate correlation points interpreted by using major shale beds and foraminifer zones. The top of the geopressured zone is indicated by the broken line.

pattern that indicates a gradational base and coarsening upward of the grain size.

Few wells penetrate the Frio section seaward of the area of thick sand accumulation. Those that show a dominantly shale section are interpreted as prodelta clay. The few sands in the prodelta environment are relatively thin (from 10 to 75 feet thick), become thinner gulfward, and are probably sheetlike in distribution.

STRANDPLAIN SYSTEMS. Strandplain sands are by far the most dominant type of sand body in the South Texas Frio. These sand bodies are mapped as narrow bands parallel to strike and deposited by wave action and longshore currents into beach ridges and offshore bars. Complexes of these ridges and bars accumulate to form a broad belt 5 to 10 miles wide and 30 miles to hundreds of miles long. Individual sand bodies are from 10 to several hundred feet thick and are separated by shale units a few feet thick to more than 100 feet thick.

## GEOTHERMAL POTENTIAL

A geopressured zone is commonly defined as one in which the subsurface fluid pressure significantly exceeds that of normal hydrostatic pressure, or approximately 0.464 psi for each foot of water column (Jones, 1969). An increase in the temperature and reduction of the salinity of the water in the sand reservoirs in the geopressured zone accompany this increase in pressure. The occurrence of geopressure (considered in this report to be 0.7 psi per foot) is identified primarily on the basis of well-log data. The criteria used to identify this zone are (1) gradual reduction in the negative self-potential deflection; (2) increase in weight of drilling mud used to control geopressure; (3) location of the point of setting of intermediate casing, which is usually close to the top of the transition zone; and (4) reduction of density and resistivity of shale.

The presence of a broad band of geopressured sediments parallel to the Texas Coast has been well known for years (Jones, 1970). Where the geopressured zone crosses the Frio, it defines an irregular surface that varies

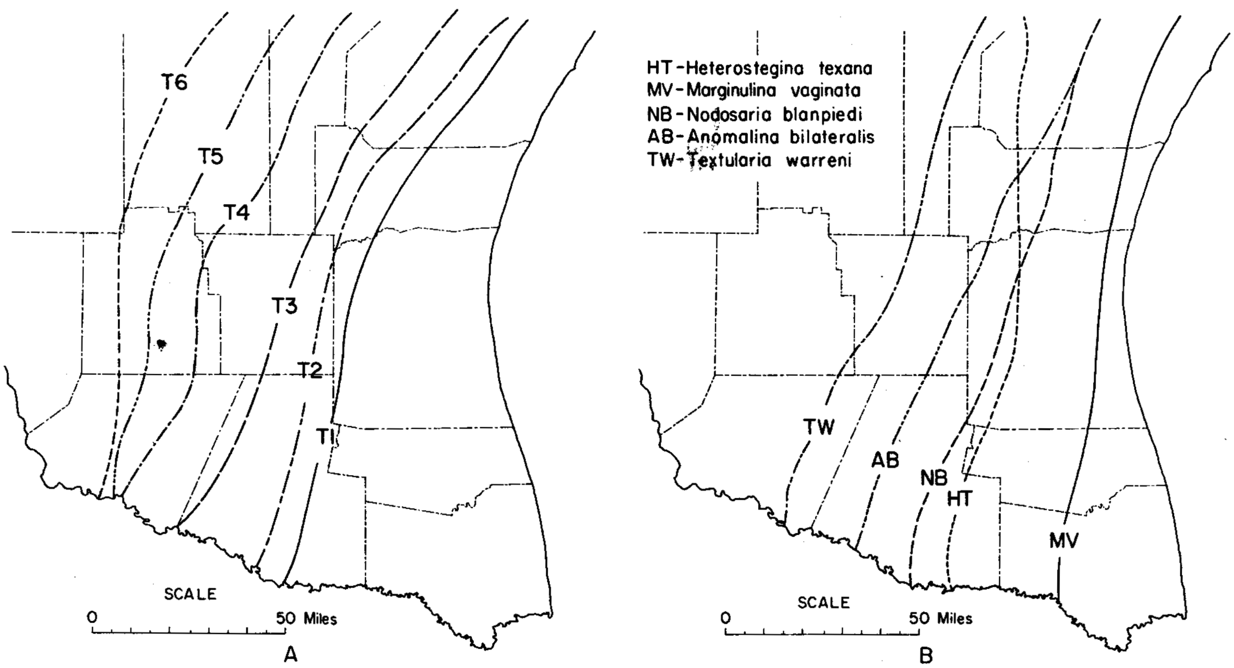


Figure 13. (*A*) Updip limits of *T* markers, and (*B*) updip limits of foraminifer markers (after Holcomb, 1964.)

in depth from 8,000 to 12,000 feet below sea level (fig. 21). The depth to the geopressured zone relates not only to the depth of the sediments below sea level but also to the amount of fluid leakage around growth faults, which displaces the zone downward (fig. 7) and to the nature of the sand-shale section. High-sand areas made up of relatively thin sand bodies separated by thin

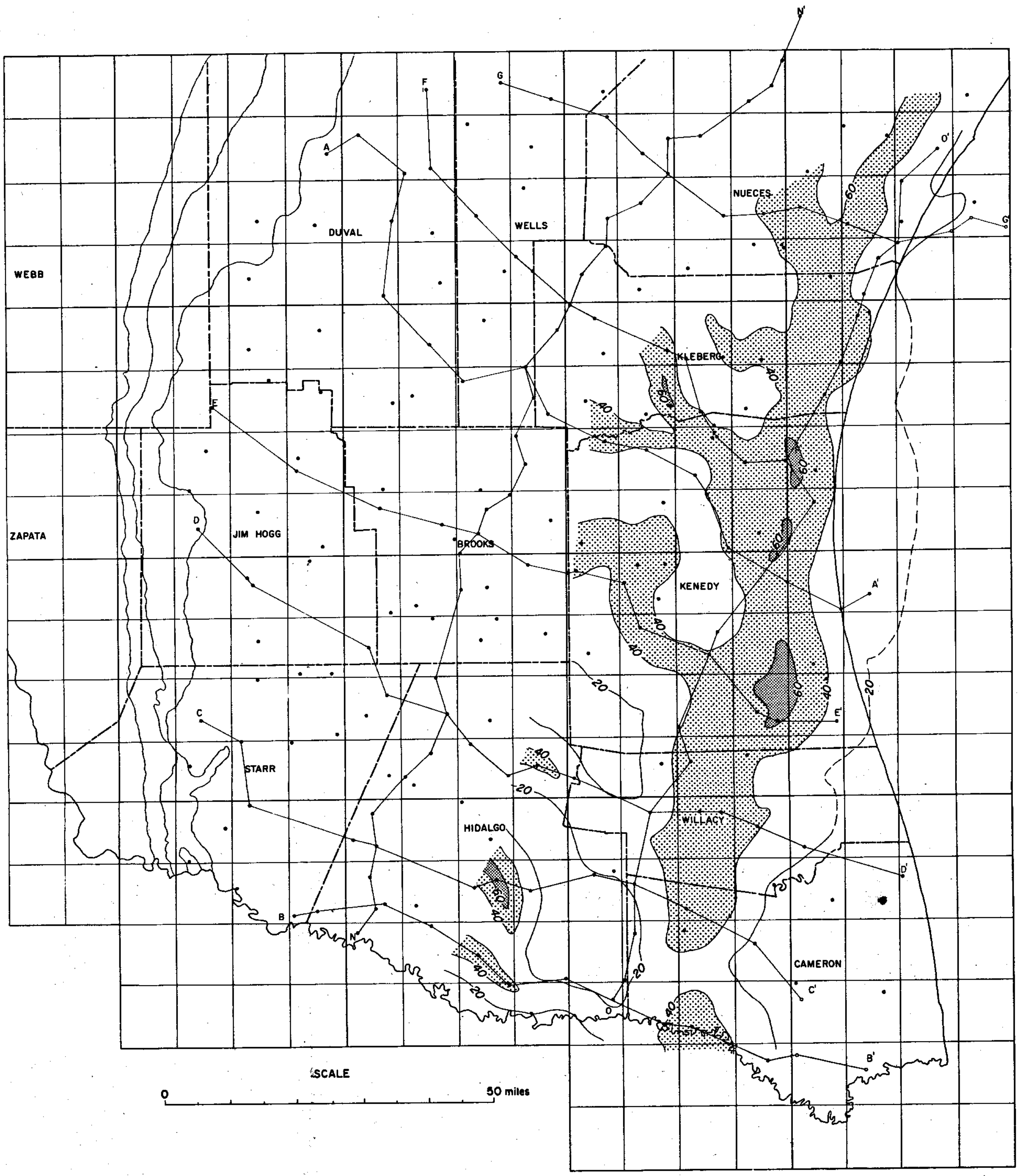


Figure 14. Sand percentage in zone T1–T2.

shales, typical of strandplain sediments, characteristically have depressed or deeper geopressured zones (fig. 11); high-sand areas containing thick deltaic sand bodies separated by thick shales are geopressured at shallower depths (fig. 12). This relationship reflects the effectiveness of the thick shales separating the deltaic sands in sealing the reservoir and the probability of considerable leakage through the thin shales of the strandplain sediments.

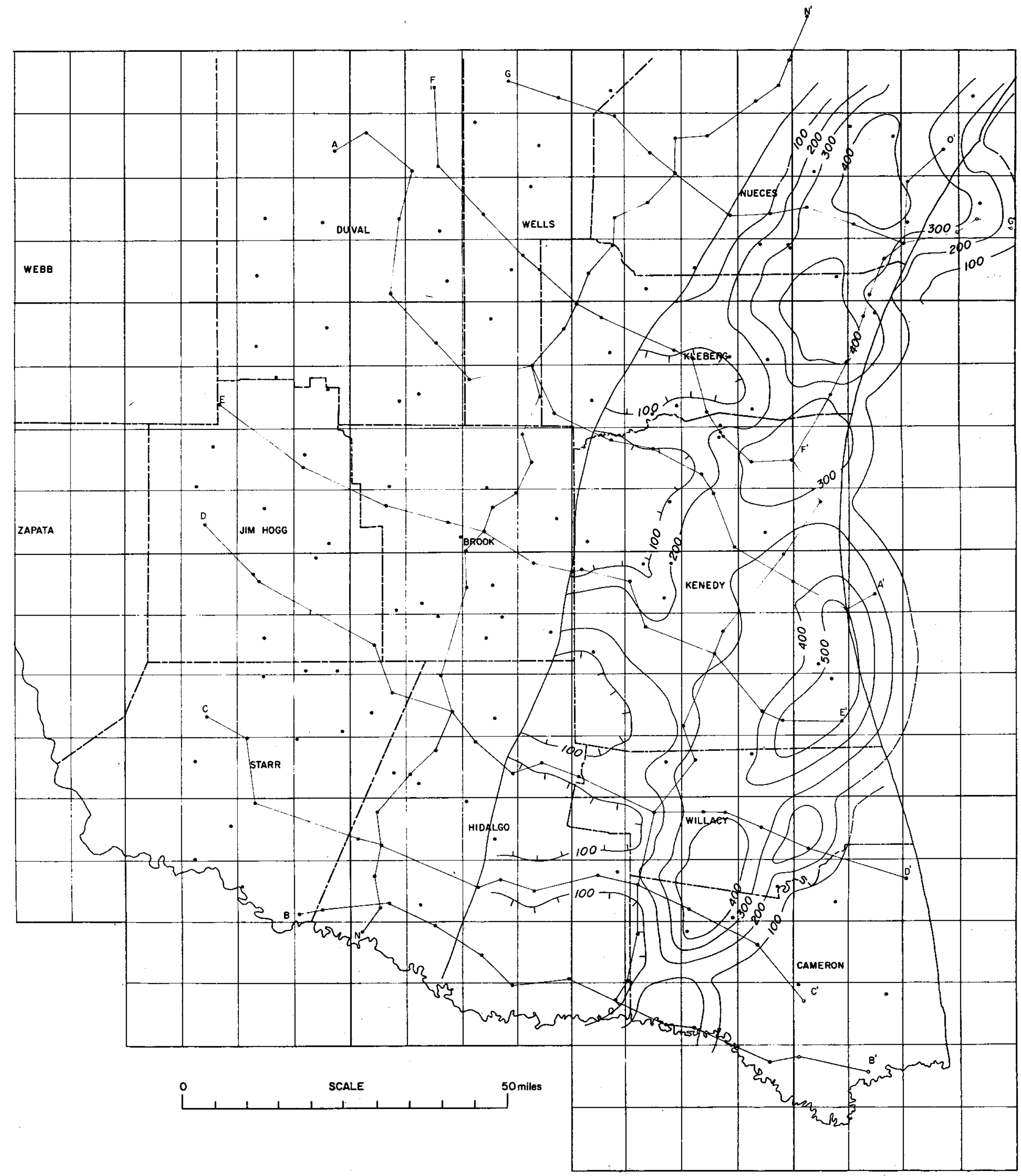


Figure 15. Net sand in zone T1-T2.

Isothermal maps have been constructed for correlation points *T3–T4*, *T4–T5*, and *T5–T6* (figs. 22, 23, and 24) based on uncorrected well-log bottom-hole temperatures. Ramey (1962) has shown that stabilized temperature readings require extensive effort and commonly result in corrected temperatures only about 10% higher than the routine readings. Because each of the wells used

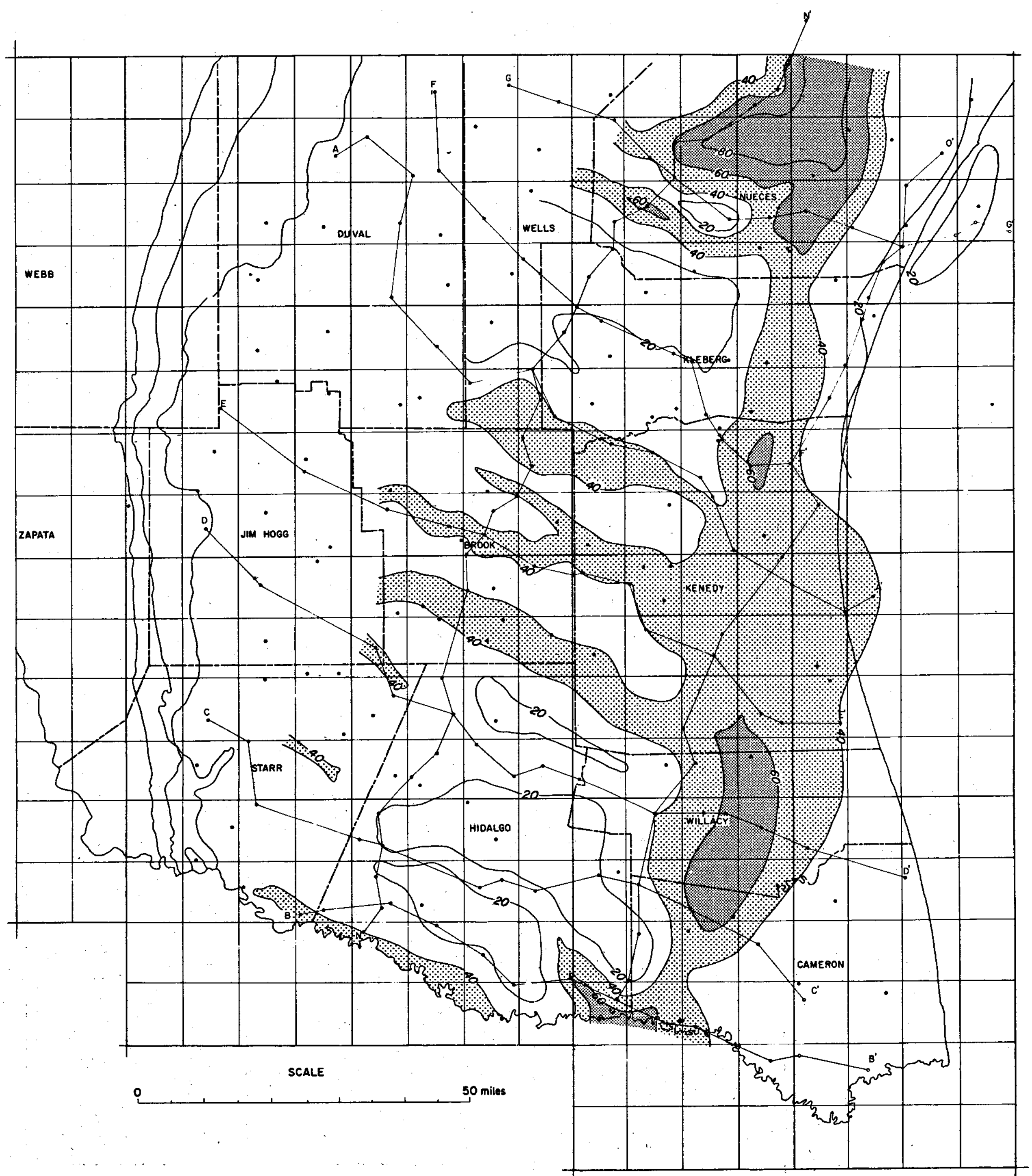


Figure 16. Sand percentage in zone *T3–T4*.

here has only one temperature reading in the Frio interval, the density of the data used for these maps is approximately one-third that used in the preparation of the other maps.

Two observations can be made on the basis of these very general isothermal maps. First, steepening of dip occurs in each interval approximately at the

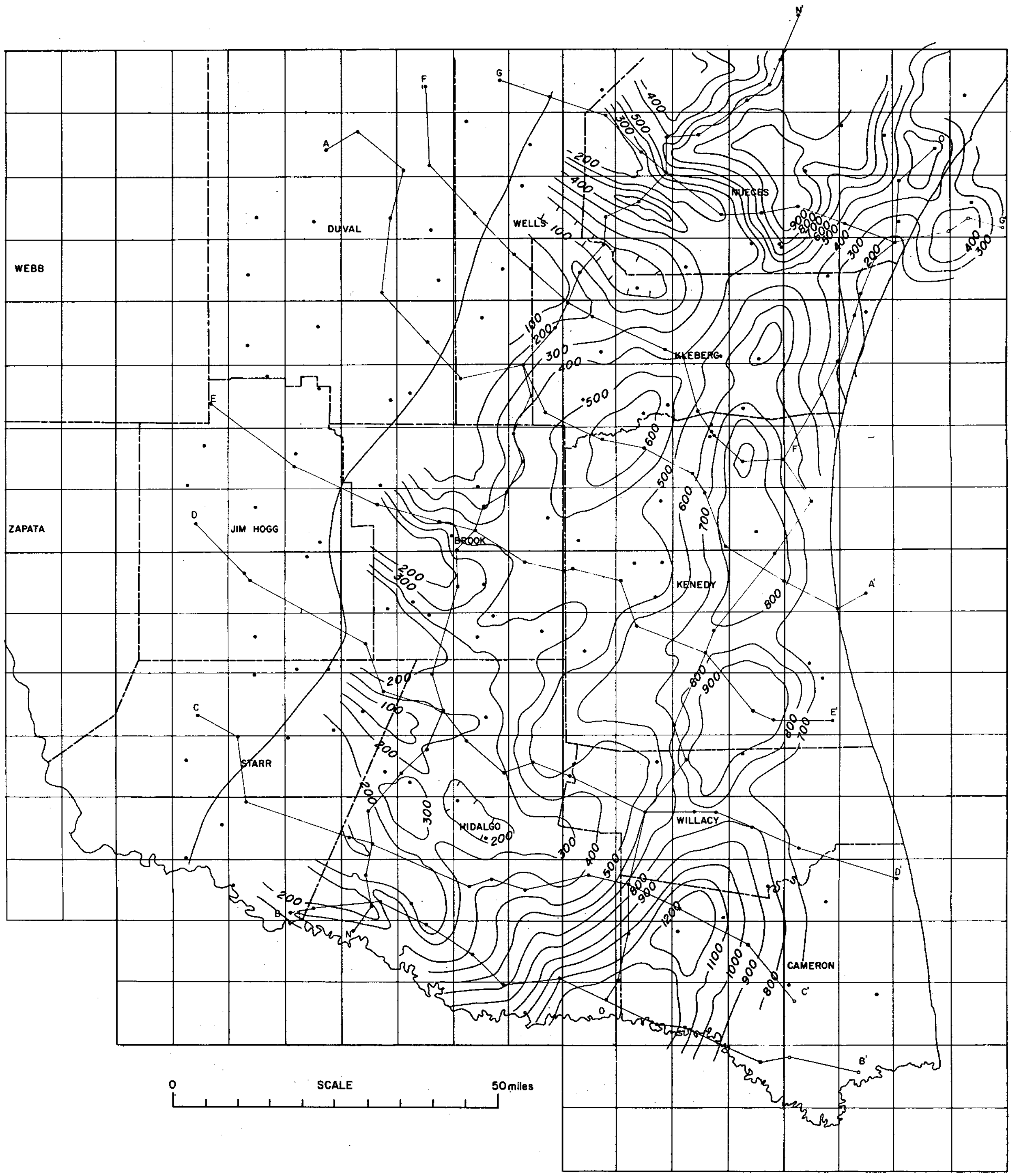


Figure 17. Net sand in zone T3-T4.

225°F isothermal line. Second, lower temperatures seem to occur in areas of maximum sand deposition because the geopressured zone is displaced deeper in these areas.

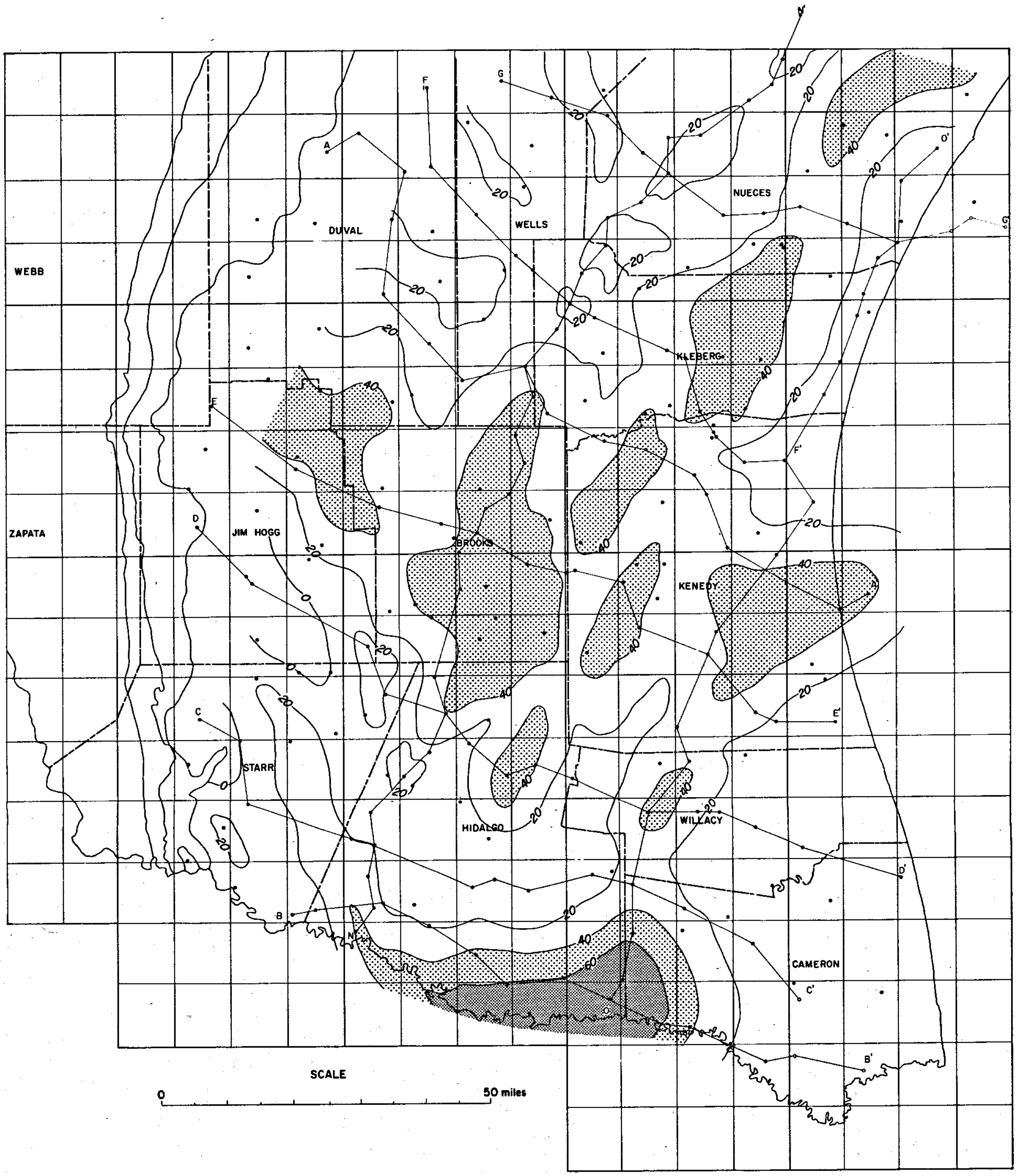


Figure 18. Sand percentage in zone *T4–T5*.

## CONCLUSIONS AND POTENTIAL GEOTHERMAL FAIRWAYS

Three major Frio sand depocenters have been delineated:

1. Southeastern Hidalgo, western Willacy, and western Cameron Counties. The highest sand ratios occur in the lower Frio in thick sand bodies (100 to 600 feet thick) that are primarily dip oriented. These sand bodies were deposited as high-destructive deltas.


Figure 19. Net sand in zone *T4–T5*.

2. Eastern Kenedy and Kleberg Counties. A high-sand area occures in the upper Frio, where sand bodies 10 to 100 feet thick are separated by thin shale intervals. These sand bodies are oriented in strike direction and accumulated mainly as strandplain deposits.

3. North-central Nueces County. In the middle Frio (*T*3–*T*4) a high ratio of sand occurs at the northern part of the study area. Preliminary work farther north indicates that these sand bodies thicken considerably in that direction.

Temperatures of 250°F and greater occur at depths of 10,000 feet or deeper. For the Frio formation, this includes parts of the lower three correlation units (*T*3–*T*4, *T*4–*T*5, and *T*5–*T*6). In order to delineate prospective areas, the 250°F and 300°F isotherms have been added to their respective sand-percentage maps for the above three units (figs. 25, 26, and 27). This combination has resulted in the recognition of several prospective areas (fig. 28) in Hidalgo, Cameron, Willacy, and Kenedy Counties for which more detailed, local studies must be made. Not taken into consideration at this stage are other critical factors such as areal distribution and thickness of individual sand bodies, porosity, and permeability.

## ACKNOWLEDGMENTS

Sincere appreciation is expressed to Dr. Paul Jones, Water Resources Division, U.S. Geological Survey, for providing four regional correlation sections of the Tertiary of South Texas, which served as a guide for the construction of additional cross sections and for more detailed subdivision of the Frio interval.

Thanks are also extended to Exxon Company, USA, Mobil Oil Corporation, and Tenneco Oil for providing some basic data used in this report.

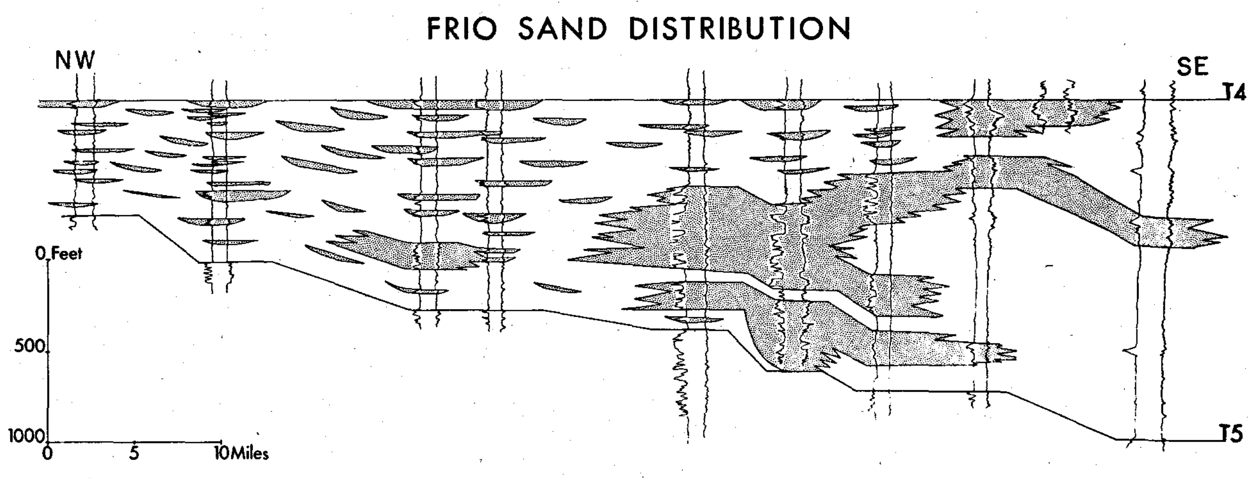


Fig. 20. Sand distribution between *T*4 and *T*5 along section *F-F'*.

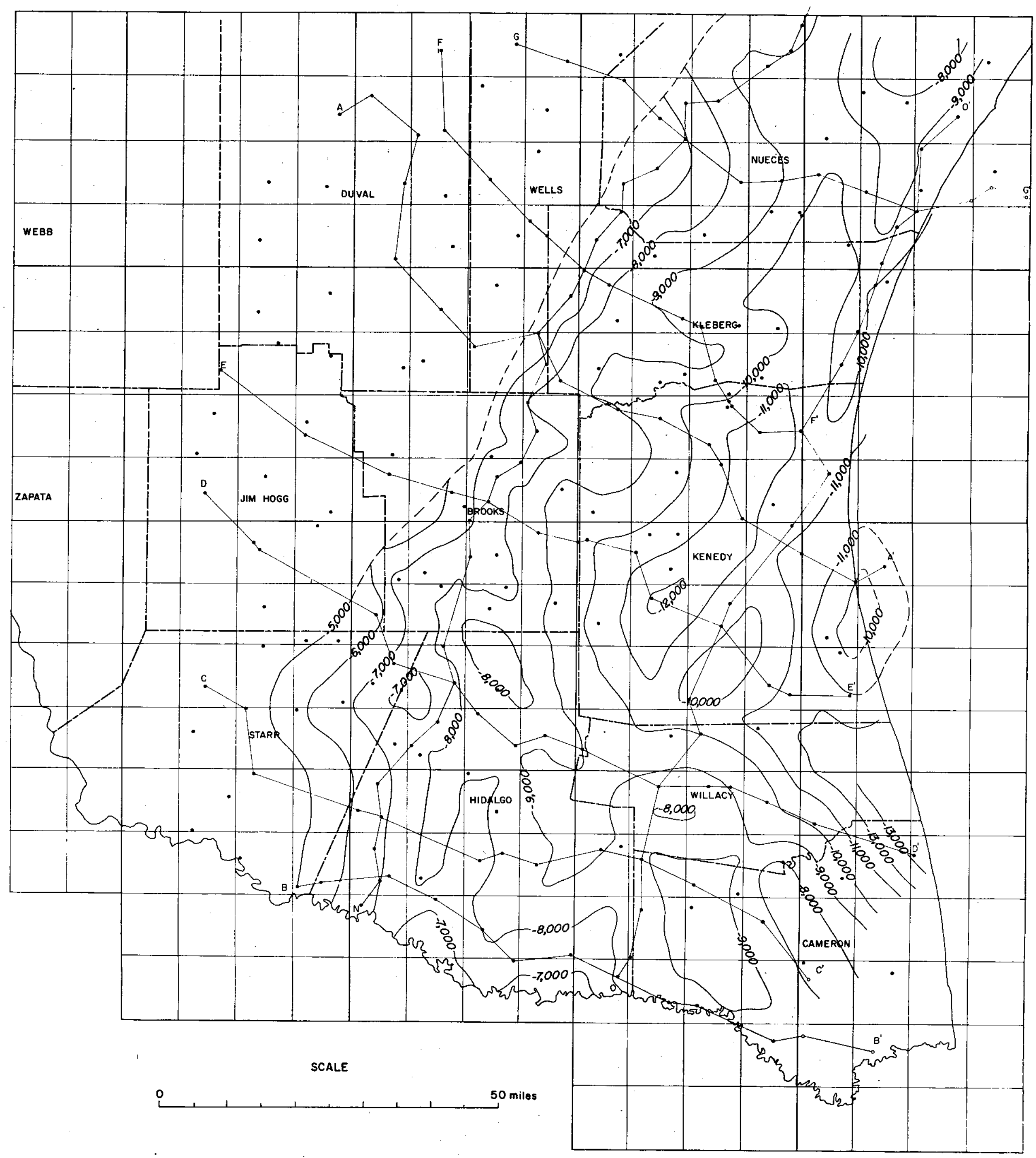


Figure 21. Top of the geopressured zone, South Texas.

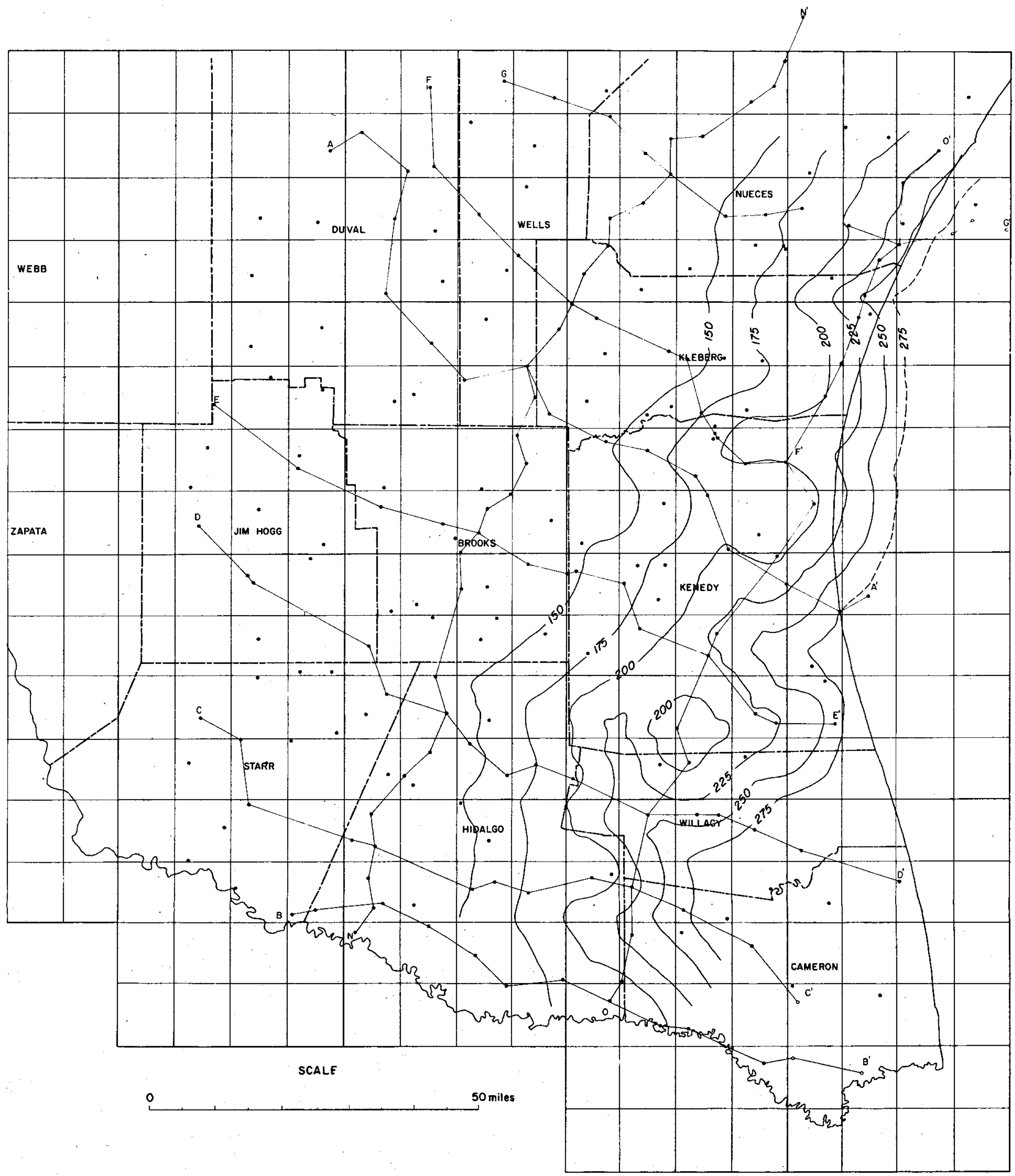


Figure 22. Isothermal map of *T3–T4*.

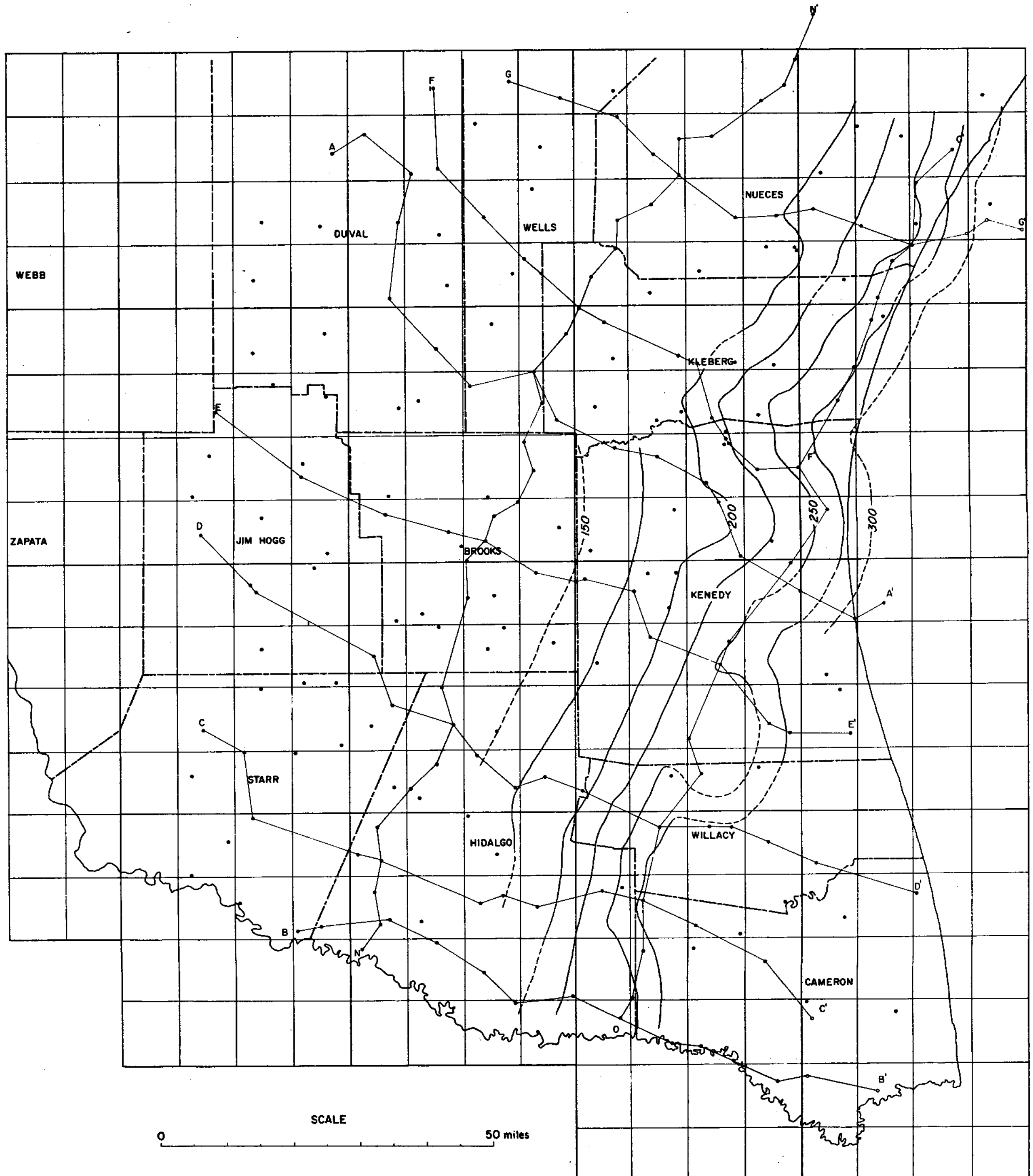


Figure 23. Isothermal map of T4–T5.

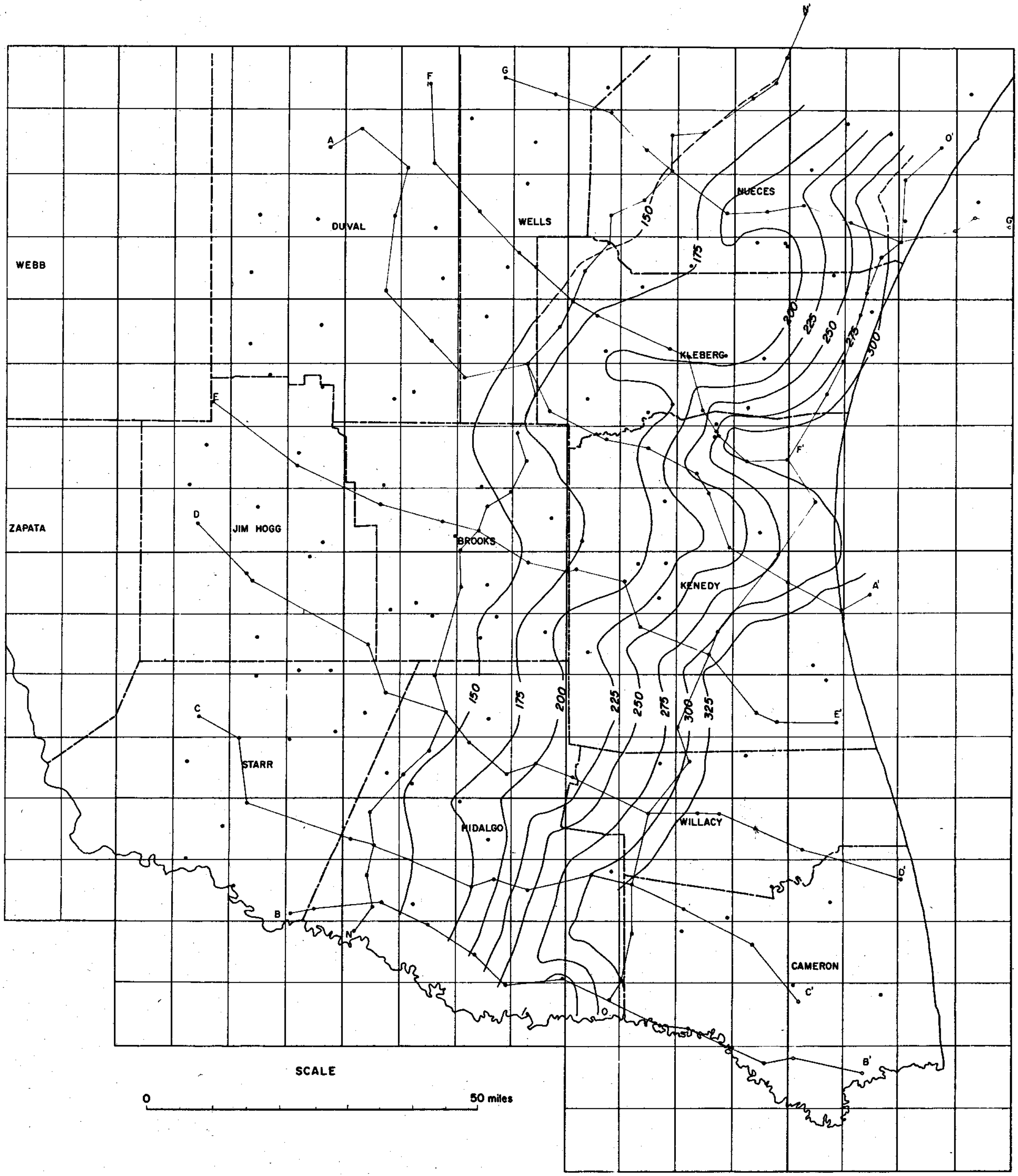


Figure 24. Isothermal map of *T5–T6*.

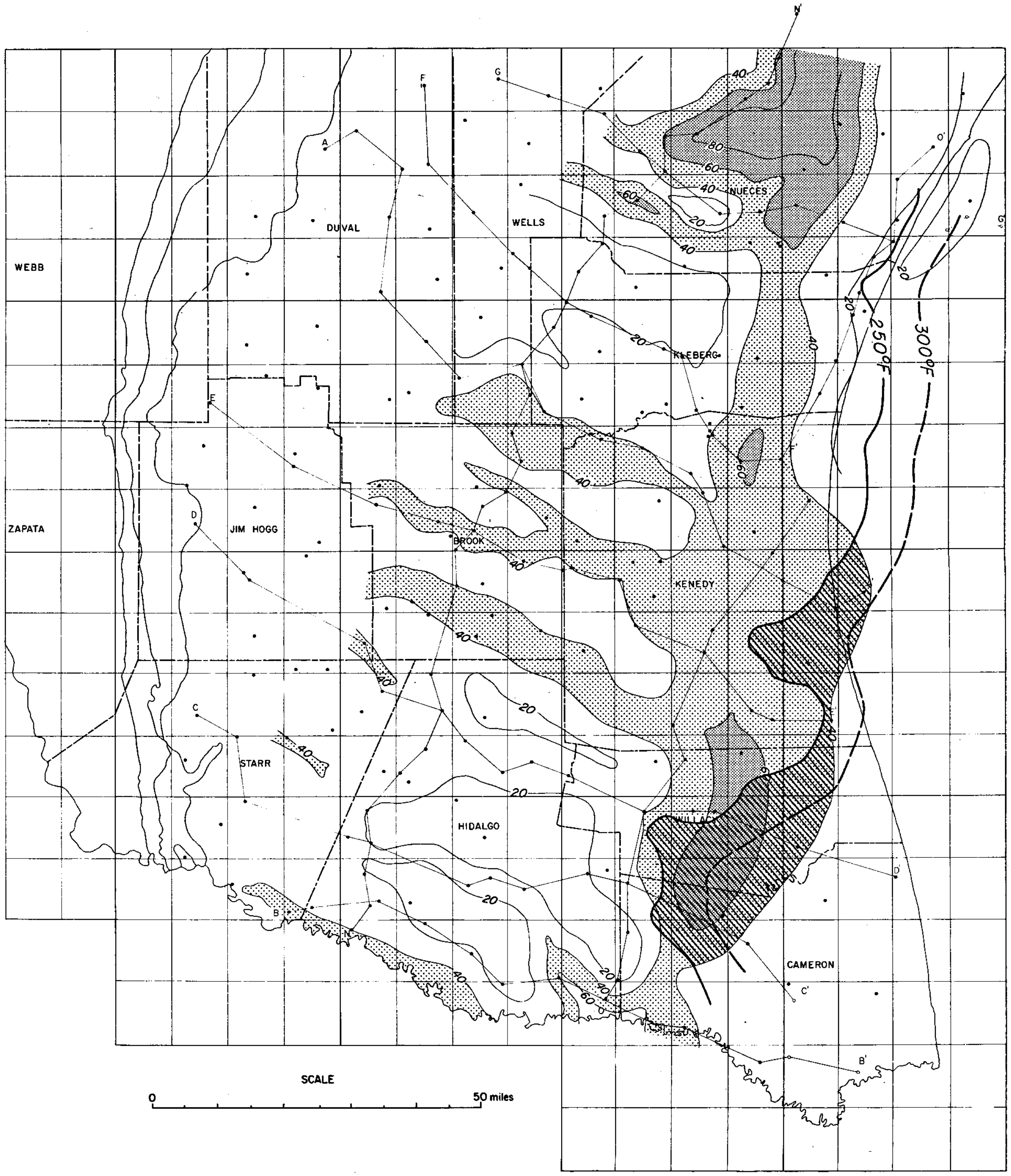


Figure 25. *T3-T4* isothermal lines (250° and 300°F) superimposed on sand-percentage map to outline gross prospective areas (heavy shading).

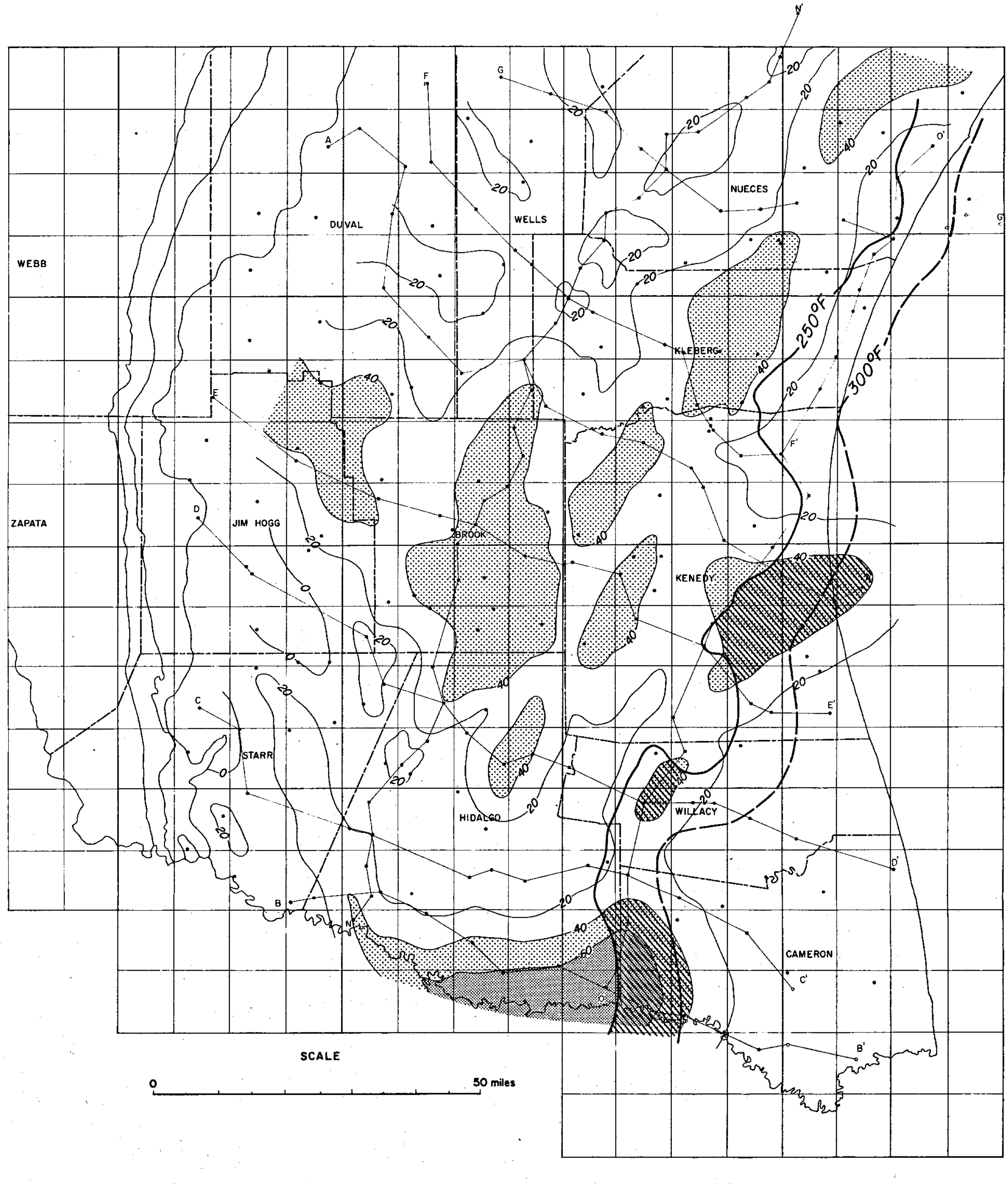


Figure 26. T4–T5 isothermal lines (250° and 300°F) superimposed on sand-percentage map to outline gross prospective areas (heavy shading).

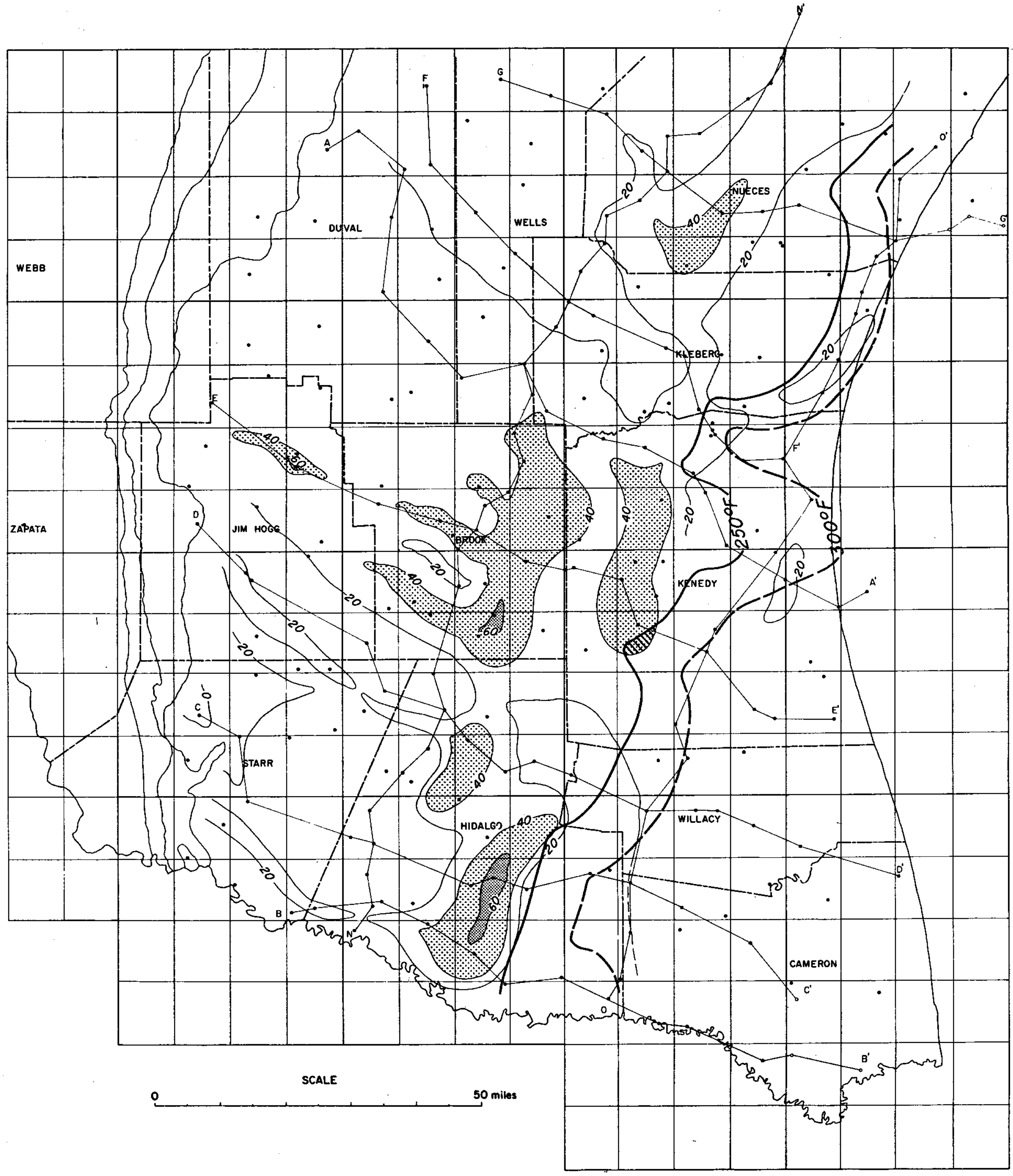


Figure 27. T5-T6 isothermal lines (250° and 300°F) superimposed on sand-percentage map to outline gross prospective areas (heavy shading).

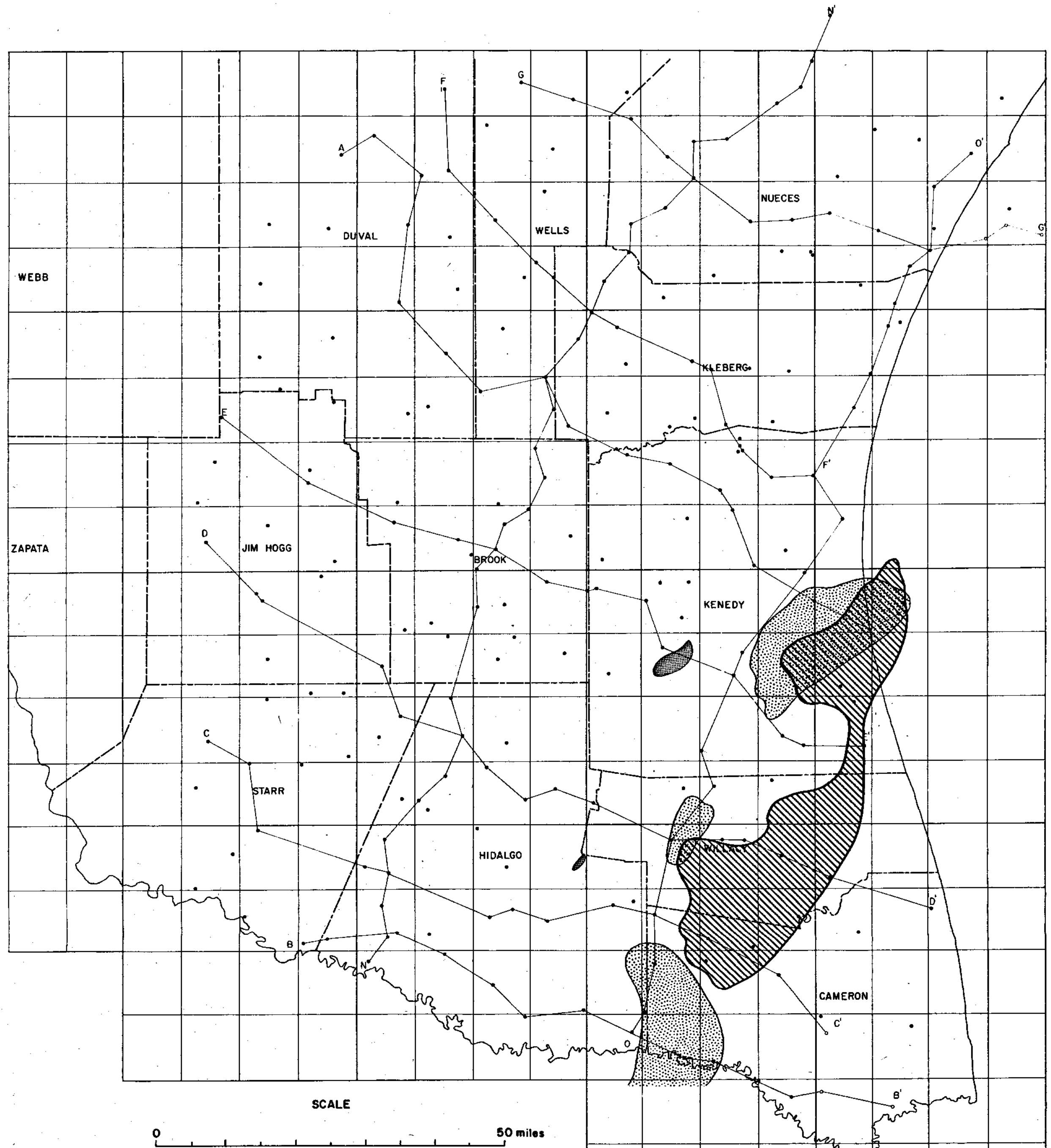


Figure 28. Potential geothermal fairways, Frio formation, South Texas—a composite of figures 25, 26, and 27.

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# Discussion

**Butler**
**Chevron Oil Co.**

On your composite sand map, you showed sand distribution where you corresponded the temperature to show the favorable areas. I guess the little dots that you had on there were your control points.

My question is this, is there a lot of well control? You had a pretty good blob of sand drawn there. How many wells was that area controlled by, or did you have access to seismic data which would indicate that the sand covered that area?

**Bebout**

No, no seismic data. Moderate well control in most places and not so good in others. A little bit of imagination here and there and some geological reasoning with the idea that we understand depositional systems and what the sand bodies ought to look like if we know the depositional environment. So we're projecting some, and that's why we wouldn't go with this alone. We want to go back in and get seismic data over the fields since we have obtained all of the well control that there is now. It wasn't all on the slide. We've gone back and gotten all the wells, but still, it's sparse.

**Groat**

To emphasize what Don just has said, the fairway approach has used this depositional systems technique because the well control is sparse in places. So you do extrapolation and the need for detail is obvious, and it will be brought in.

**Eubank**
**Delta Drilling Co.**

You did sidestep the porosity and permeability question of the Frio. Do you have enough information to give us some data on that?

**Bebout**

We're just going into that now. In fact, we're preparing to go to Corpus Monday and get a large number of core plugs which have been run on some of these old wells. We've had a discouraging experience trying to obtain a full-diameter core bacause most of it has been discarded for one reason or another. We did find out that the core lab saves all these plugs, so we're going down and getting plugs from many of these old wells and we have someone who's going to start a project on that within days.

Also, in all these wells the porosity and permeability has also been released. This is through Exxon and Atlantic-Richfield, Chevron, Amoco, and other oil companies which have contributed greatly to what we're doing.

**Hise**
**Louisiana State University**

I was just wondering, you seem to be a man who has spent a good bit of time looking around in this business. How many of these sands are you finding that meet the general parameter? Are we talking about the fingers of one hand or are we talking about 100 or are we talking about 500 or 10,000?

This is one of the things we've missed so much in the past. Nobody has really taken a good 6 or 8 month's look at anything. Now, I realize that you have a lot of other trends to study and a lot more area than that, but could you give us any preliminary information about what you're seeing, about something that would fit the necessary requirements?

**Bebout**

That's a bad question. We're having a little trouble in the Frio meeting the standards that I set up, 500 feet thick and 300 square miles and 300 degrees, 20 percent porosity—well, the porosity we don't know. We're having trouble meeting all those, but we think maybe we're overestimating what we need, too. These are sort of ball-park figures, so we're looking at it with the idea that we will describe everything using much more restrictive prerequisites, with the idea that maybe our engineer friends will come down a little in size. We wouldn't find anything to fit those right now in Frio, but we do find some very attractive looking areas to us. We're in maybe a one-hand category.

**Groat** That's one of the nice things about having a lot of section left to look at; it's down the road a ways.

**Bebout** Yes, it always looks better farther on. We are encouraged by what we're finding.

**Groat** I think we'll wrap up the questions for now and defer any further questions until the general discussion period at the end of this session.