EMD 2-66-3306

NEW MEXICO BUREAU OF MINES & MINERAL RESOURCES

OPEN-FILE REPORT 153

ANALYSES OF PETROLEUM SOURCE AND RESERVOIR ROCKS IN SOUTHWESTERN NEW MEXICO

Petroleum Source Rocks in Exploration Wells Drilled to Paleozoic or Mesozoic Units, Hidalgo and Grant Counties, New Mexico

Sam Thompson III

September 1981

New Mexico Energy Research and Development Institute

NOTICE

The New Mexico Energy Research and Development Program is funded by the New Mexico Energy and Minerals Department, P.O. Box 2770, Santa Fe, NM 87501.

Research projects are administered by the New Mexico Energy Research and Development Institute.

EMD 2-66-3306

ANALYSES OF PETROLEUM SOURCE AND RESERVOIR ROCKS IN SOUTHWESTERN NEW MEXICO

Petroleum Source Rocks in Exploration Wells Drilled to Paleozoic or Mesozoic Units, Hidalgo and Grant Counties, New Mexico

Final Report

(1/1/78 - 8/31/81)

Principal Investigator:

Sam Thompson III
New Mexico Bureau of Mines
and Mineral Resources
Socorro, New Mexico 87801

September 1981

The work from which this material is drawn was conducted with the support of the New Mexico Energy and Minerals Department, the New Mexico Energy Institute at the New Mexico Institute of Mining and Technology, and the New Mexico Bureau of Mines and Mineral Resources. However, the author remains soley responsible for the content of this material.

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO.

2. PUBLICATION DATE

3. PERFORMING ORGAN. REPORT NO.
NMBMMR Open-file rept. no. OF-153

4. TITLE AND SUBTITLE - ANALYSES OF PETROLEUM SOURCE AND RESERVOIR ROCKS IN SOUTHWESTERN NEW MEXICO: Petroleum source rocks in exploration wells drilled to Paleozoic or Mesozoic units, Hidalgo and Grant Counties, New Mexico

5. EMD PROJECT NUMBER
2-66-3306

6. AUTHOR(S)
Sam Thompson III

7. TYPE OF REPORT & PERIOD
Final Report
Grant Period: 1/78-8/81

8. PERFORMING ORGANIZATION NAME AND ADDRESS
New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS

New Mexico Energy and Minerals Department
P.O. Box 2770
Santa Fe, NM 87501

New Mexico Energy Institute
New Mexico Institute of Mining & Tech.
Socorro, NM 87801

10. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention here)

Main objective of this geologic study was to identify and evaluate petroleum-source rocks in 7 key exploration wells drilled in the frontier area of southwesternmost New Mexico. Samples of drill cuttings were selected from Paleozoic-Mesozoic units. At GeoChem Laboratories, Inc., analyses were made of organic-carbon percentage, kerogen type and thermal-alteration index, vitrinite reflectance, $C_{15}+$ hydrocarbons, and Rock-Eval pyrolysis. Results indicate fair-good oil- and/or gas-source units in dolostones, limestones, or mudstones of the El Paso-Montoya (Ordovician), Escabrosa-Paradise (Mississippian), Horquilla (Pennsylvanian-Permian), Colina-Epitaph (Permian), and U-Bar-Mojado (Lower Cretaceous). In other formations, only poor source units are indicated with present control. Petroleum-source maps show organic-richness and kerogen variations apparently related to depositional/diagenetic trends. At normal depths of burial, Mesozoic-Paleozoic units are thermally mature; older Paleozoic units are overmature in the southern part of the area. In the central part, Lower Cretaceous units are overmature because of deep burial in the lower plate of a major thrust; underlying Paleozoic units may be thermally metamorphosed. Trends of favorable source units may be used to increase the probability of discovering commercial petroleum accumulations in future exploration wells.

11. KEY WORDS (6 to 12 entries, alphabetical order capitalize only the first letter of the first key word unless a proper name; separated by semicolons)
Exploration wells; Hidalgo and Grant Counties, New Mexico; Paleozoic-Mesozoic stratigraphic units; petroleum source rocks.

12. AVAILABILITY

13. NUMBER OF PAGES
126

14. PRICE

SUMMARY

In the southwestern part of New Mexico, several petroleum-exploration wells have been drilled. Although encouraging shows of oil and gas have been reported, no commercial production has been established yet. Many prospective areas remain untested. Mining, farming, ranching, and other industries, as well as the population centers, have created a demand for energy that currently is being supplied by fossil fuels produced outside the region.

The most basic question in the exploration of such a frontier area is whether petroleum-source rocks are present and whether their quality and quantity are sufficient to have generated commercial volumes of oil or gas. Recent developments in the discipline of petroleum geochemistry have made the identification and evaluation of source rocks more precise and more operational.

Percentages of organic carbon indicate the basic parameter of richness. Amorphous, algal, and degraded herbaceous kerogens generate oil; herbaceous kerogens generate oil and gas; woody kerogens generate gas; inertinite (coaly) kerogens generate only trace amounts of methane. Colors of the kerogens are used to determine thermal maturity. If the organic matter is too immature, only gas will be generated. At maturity, oil will be generated from the appropriate kerogens. If overmature, oil will tend to be thermally degraded to gas. At extreme temperatures of thermal metamorphism, gas will not be preserved.

In this study, samples were selected from 7 exploration wells drilled to Paleozoic or Mesozoic rocks in the southern parts of Hidalgo and Grant Counties. Analyses were run by GeoChem Laboratories, Inc. of Houston, Texas. Results are encouraging for future exploration.

Of the 14 Paleozoic-Mesozoic formations recognized in this area, 9 contain favorable source units of oil or gas. Fair to good source units are identified in dolostones, limestones, or mudstones of the El Paso-Montoya (Ordovician), Escabrosa-Paradise (Mississippian), Horquilla (Pennsylvanian-Permian), Colina-Epitaph (Permian), and U-Bar-Mojado (Lower Cretaceous). In other formations, only poor source units are indicated with present control.

Petroleum-source maps constructed for each formation show variations in organic richness and kerogen type that appear to be related to depositional and/or diagenetic trends. At normal depths of burial, the Mesozoic-Paleozoic units are thermally mature; older Paleozoic units are overmature in the southern part of the area. In the central part, Lower Cretaceous units are overmature because of deep burial in the lower plate of a major thrust fault; underlying Paleozoic units may be thermally metamorphosed.

With these maps, trends of favorable source units may be used to increase the probability of discovering commercial petroleum accumulations in future exploration wells. With improvements in the stratigraphic/sedimentologic framework of the wells and outcrop sections, and an increase in the geochemical control, more precise boundaries of the source units can be drawn, and more accurate projections can be made to the subsurface prospects.

CONTENTS

Page

Introduction 1

Geologic Setting 4

Exploration Wells 9

Identification and Evaluation of Petroleum-Source Rocks 14

- Basic Concepts and Methods 14
- Applications and Results 18
- Discussions of Individual Wells 37

Distribution of Petroleum-Source Units 57

Conclusions and Recommendations 78

Acknowledgments 84

References 86

Tables 1-10 91

Figures 1-17 103

INTRODUCTION

Does southwestern New Mexico contain significant petroleum resources? This question can be answered only after industry drills a sufficient number of thorough exploration wells at strategic locations. Although several wildcats have been drilled since the 1940's, and encouraging shows of oil and gas have been encountered, no commercial production has been established yet. Many prospective areas remain untested. Mining, farming, ranching, and other industries, as well as the population centers, have created a demand for energy that currently is being supplied by fossil fuels produced outside of the region.

Exploration has been based mainly on the fact that the southwestern one-quarter of the state is underlain by a Paleozoic stratigraphic section similar to that of the productive Permian Basin in southeastern New Mexico (Greenwood and others, 1977). The southeastern part has an estimated ultimate recovery of 4.31 billion barrels of oil and 26.5 trillion cubic feet of gas from Paleozoic reservoirs (Kottlowski and Thompson, 1980, p. 62, 64). A gross estimate of the ultimate recovery in the southwestern part is about one-quarter to one-half that of the southeastern part, considering some stratigraphic differences in the Paleozoic section and a more complex Mesozoic-Cenozoic history.

As a first step toward a more accurate resource estimate, we began a research program at the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) in late 1974 to identify and evaluate petroleum source rocks and related reservoir rocks in southwestern

New Mexico. Such basic information guides operators to prospective areas and helps both industry and government assess the petroleum potential of the region.

The Pedregosa Basin in the southwesternmost corner of New Mexico was selected as the first geologic province to study in the program. This area in Hidalgo and Grant Counties is judged to have the greatest petroleum potential in the region, based on preliminary knowledge of the surface stratigraphic sections and the several exploration wells which have been drilled. To assist in the evaluation of the surface and subsurface sections, Geo Chem Laboratories, Inc. of Houston, Texas, was contacted to run organic geochemical analyses on the source rocks and Core Laboratories, Inc. of Dallas, Texas, to run porosity/permeability analyses on the reservoir rocks. Alonzo D. Jacka of Texas Tech University was contacted for petrographic analyses of depositional and diagenetic features which are useful in evaluation of both the source and reservoir rocks.

To finance the work done outside of NMBMMR, grants were obtained from the State of New Mexico. During 1975-1977, minor funding was provided by the Energy Resources Board (Grants 74-104, 75-109, and 76-350) for co-investigation with Wolfgang E. Elston of the University of New Mexico in his project: "Application of volcanology to petroleum exploration in southwestern New Mexico". Results of source and reservoir analyses were presented in NMBMMR Circular 152 (Thompson and others, 1977) and Open-File Reports OF-96, 97 (Cernock 1976, 1977). During 1978-1981, major funding was provided from the present grant through the Energy and Minerals

Department and New Mexico Energy Institute. Results were presented in NMBMMR Circular 176 (Thompson and Jacka, 1981) and Open File Reports OF-140, 149, and 151 (Tybor, 1981a, b, and c). NMBMMR funded the analyses presented in OF-152 (Tybor, 1981d).

In this final report on the present grant, work funded by the previous grants and some nonfunded research at NMBMMR (such as Thompson and others, 1978) have been included to provide a comprehensive summary of the source-rock analyses on samples from exploration wells drilled in the area. Other studies in progress on reservoir rocks and the stratigraphic/sedimentologic framework of surface and subsurface sections will be discussed briefly here; documentation will be presented in future NMBMMR publications.

GEOLOGIC SETTING

Figure 1 is a generalized geologic map of the southern parts of Hidalgo and Grant Counties, New Mexico, the subject area of this report. Surface stratigraphic sections of Paleozoic and Mesozoic (Lower Cretaceous) rocks are exposed in the Big Hatchet, Sierra Rica, Little Hatchet, Animas, and Peloncillo Mountains. Of the 25 exploration wells drilled in this area, 11 have encountered Paleozoic or Lower Cretaceous rocks in the subsurface; results are discussed in the following chapter. Information from these surface/subsurface stratigraphic sections and others in the region indicates that the Paleozoic-Mesozoic units generally have been preserved and are missing only locally as a result of faulting or erosion.

Table 1 is a stratigraphic summary of Paleozoic-Mesozoic (Lower Cretaceous) units exposed in the Big Hatchet Mountains. The classic work by Zeller (1965) established the stratigraphic framework for this area. The Paleozoic section is about 11,500 ft thick and consists mostly of limestones, dolostones, mudstones, and sandstones deposited mainly under shallow-marine, stable-shelf conditions. Deep-marine deposits are indicated in the lower part of the Percha Shale (Devonian) and the upper part of the Horquilla Formation (Pennsylvanian-Permian). The Lower Cretaceous section is about 10,000 ft thick and consists of conglomerates and redbeds, shallow-marine limestones with rudist buildups in the upper part, and shallow-marine to deltaic sandstones and mudstones.

Based on reconnaissance studies of Zeller's sections in the Big Hatchet Mountains, some reservoir units are indicated in El

Paso dolostones, Montoya dolostones, Epitaph dolostones, and Mojado sandstones; petroleum-source units are inferred in Percha mudstones, Escabrosa limestones, Horquilla shelf limestones and basin mudstones, Colina limestones, Concha limestones, U-Bar limestones, and Mojado mudstones. Redescription of Zeller's sections is in progress; this work will include documentation of the source and reservoir units exposed in these sections.

In the Big Hatchet Peak section (not measured by Zeller), dolostone reservoirs in the upper Horquilla have a net thickness of 484 ft,and associated limestones are shown to be fair source units (Thompson and Jacka, 1981). The porous dolostones lie along the shelf margin of the Alamo Hueco Basin, a deep-marine basin expressed by deposition of dark mudstones and limestones in the upper Horquilla south of Big Hatchet Peak (Zeller, 1965, p. 42). The Alamo Hueco Basin lies within the more regional Pedregosa Basin, a general area of subsidence in Pennsylvanian time (Greenwood and others, 1977, p. 1449).

Tectonic and igneous complexities in Cenozoic time probably had both positive and negative effects on petroleum accumulations in the Paleozoic and Lower Cretaceous rocks (Thompson, 1976). Laramide deformation in late Cretaceous to early Tertiary time produced many thrust faults and compressional folds which could have formed traps for oil and gas.

A major thrust zone with Precambrian or Paleozoic rocks thrust northeastward over Lower Cretaceous rocks trends northwest-southeast through the central part of the area (fig. 1). Exposed segments of the thrust zone were mapped by Zeller (1958, 1970, 1975) in the northern end of the Animas Mountains, the southern end of the Little Hatchet Mountains, and the southwestern end of the Sierra Rica. Drewes and Thorman (1978, p. 292, fig. 1) join the thrust zone they mapped in the central part of the Peloncillo Mountains with the segment of the main thrust in the northern part of the Animas Mountains. However, their thrusts appear to be of a different structural style,and the stratigraphic displacements only involve Paleozoic rocks (Drewes and Thorman, 1980). From the northern Animas area, the main thrust zone may continue northwestward (through the complex Pratt area) and connect with the Hidalgo thrust exposed at the northern end of the Chiricahua Mountains in southeastern Arizona, where Precambrian or Paleozoic rocks again are seen to be thrust northeastward over Lower Cretaceous rocks (Drewes, 1980).

Much recent exploration has been prompted by projection of the Cordilleran overthrust belt through southeastern Arizona and southwestern New Mexico (Drewes, 1978). However, many differences are noted between the productive Wyoming-Utah part and the Arizona-New Mexico part, where Jurassic reservoirs and Upper Cretaceous source rocks are absent, and where post-Laramide volcanism and block faulting probably have destroyed some of the thrust-belt traps (Woodward and DuChene, 1981). A more fundamental difference may be indicated by an alternate interpretation of the thrusting itself. In the Wyoming-Utah area, low-dipping, continuous overthrusts are documented with many tens to perhaps hundreds of miles of displacement. In Arizona-New Mexico, several thrusts appear to have formed as a result of branching upward and outward from wrench zones (Thompson, 1980, p. 210; see also Drewes, 1980, and Drewes and Thorman, 1978, 1980). Because of the indicated abundance of wrench (strike-slip) faults in the areas of thrusting, this alternative explanation should be given some consideration in exploration programs.

As a result of broad tectonic uplift in Laramide time, marine conditions disappeared from the region. Thus, the nonmarine deposits of the Cenozoic section are not expected to contain petroleum source rocks similar to those of the Paleozoic-Mesozoic. Lake deposits may contain source material, but none has been recognized in the Cenozoic of this area.

Much of the nonmarine section here is composed of volcanic rocks. Cretaceous volcanic rocks are generally andesitic and are recognized only in the Pyramid and Little Hatchet Mountains. Tertiary volcanic rocks generally are rhyolitic, are more widespread, and range up to 8,000 ft in thickness in the Animas Mountains as shown by Elston and others (1979). Their several ash-flow tuff cauldrons of Oligocene age are shown on fig. 1. Within these volcanic centers, intensive heat probably drove off any accumulations of oil or gas. However, stratigraphic sections located only a few thousand feet away from the cauldrons show no thermal metamorphism.

Basin and Range faulting in Miocene time and later produced relative uplift of the mountains and downdropping of the intermontane valleys. Displacements on some bounding faults are 5,000 ft or more. This episode of extensional faulting was probably the most negative event with respect to the preservation of petroleum accumulations. Subsurface fluid systems no doubt were disrupted. Flushing by fresh water is evident in reservoirs that were exposed or tapped by fractures in the uplifted areas. In the deep subsurface beneath the intermontane valleys, flushing is less likely and the structure may be less complicated.

During and after the Basin and Range faulting, the valleys tended to be filled with alluvial conglomerates, sandstones, and mudstones of the Gila Formation, which is Tertiary to Quaternary (Pliocene to Pleistocene) in age. Because much of the detrital material in the Gila was eroded from Tertiary volcanic rocks, the differentiation of the two is difficult to determine in drill cuttings. Nevertheless, the thickness of the Gila in some wells is estimated to be over 2,000 ft. Younger Quaternary (Pleistocene to Holocene) sediments are rarely over 200 ft thick.

Within this complex geologic setting, the best exploration strategy is to: 1) determine the most favorable petroleum source and reservoir units based on available control, 2) project these objectives along stratigraphic trends into the subsurface of the graben valleys where preservation of oil or gas is more likely, and avoid volcanic cauldrons or other negative complexities, and 3) within the source/reservoir trends, locate drillable prospects on individual structures beneath the valleys by geophysical surveys with guidance from surface and subsurface geology.

EXPLORATION WELLS

In the map area of fig. 1, covering about 3,500 square miles (9,200 square kilometers), a total of 25 wells have been drilled to date in exploration for oil and gas. Three shallow wells were omitted from that map because they are too near other wells to be shown at that scale. In 6 of the wells, shows of oil and gas were found.

Figure 2 shows the 11 wells in this same area that have been drilled to Precambrian, Paleozoic, or Mesozoic (Lower Cretaceous) rocks. Of this total, 6 have been drilled to Precambrian or lower Paleozoic rocks, thereby penetrating practically all of the sedimentary column at those localities. Two wells have been drilled only to upper Paleozoic rocks, and the remaining 3 have been drilled only to Lower Cretaceous rocks. In spite of this meager subsurface control, several petroleum source and reservoir units can be evaluated with data from the wells. When control from the surface sections is added, the evaluation will be more comprehensive.

Table 2 lists basic data on these 11 wells in geographic order (by township, range, and section). Data on 7 of them are modified from a previous paper on wells drilled to Precambrian or Paleozoic rocks in the Pedregosa Basin area (Thompson and others, 1978). Locations, names, and completion dates were taken from scout tickets in the NMBMMR Library of Subsurface Data supervised by R. A. Bieberman. Elevations are of the kelly-bushing (KB) or derrick-floor (DF) datum from which wire-line logs were measured; only ground-level (GL) elevations are available for the two wells on which no wire-line logs were run.

Determinations of formation tops should be considered preliminary because detailed stratigraphic work on these wells has not been completed. The most thoroughly studied well is the KCM No. 1 Forest Federal (Thompson and others, 1977), but important petrographic analyses of the Horquilla Formation are pending. A detailed lithologic study of the Cockrell No. 1 Playas State is nearing completion, with petrographic and other analyses to follow. Tops in the Humble (Exxon) No. 1 State BA are the most accurately determined (Thompson in Zeller, 1965, p. 116) because of the excellent set of drill cuttings and wire-line logs available on that well; more detailed lithologic and petrographic analyses are planned.

Tops in 5 wells were determined tentatively from a general examination of drill cuttings mounted on strip logs (in the Subsurface Library) in combination with study of the wire-line logs. Those in the Hachita Dome No. 1 Tidball-Berry Federal were modified from Zeller (1965, p. 119). Those in the three other Cockrell wells, the No. 1 Pyramid Federal, the No. 1 Coyote State, and the No. 1 State-1225 were modified from notes by R. W. Foster (written communication, 1976). Those in the KCM No. 1 Cochise State A were modified from a description by R. F. Broadhead (written communication, 1977).

Tops in the remaining 3 wells were determined from reported information. Those in the Graham No. 1 Hatchet Federal, the most recently drilled well, were modified from the lithologic log of Permian Basin Sample Laboratory (Midland, Texas). The Graham well was drilled at a location only 1,500 ft northwest of the Hachita Dome well. The differences in depths of the formation tops indicate local structural or stratigrahic complexities; however, more detailed study of the Graham well may resolve the differences. Tops in the Powers No. 1 State were modified slightly from a description by C. H. Thorman (written communication, 1976). Tops in the Wininger and Berry No. 1 State are the most uncertain. They were based on the driller's log and the map of the surface geology by Zeller (1970); no cuttings or wire-line logs are available. At the reported location, Cretaceous rocks are exposed and the depth to Permian rocks is estimated conservatively to be over 12,000 ft. Previous reports of Mississippian rocks at the surface and Ordovician rocks at the shallow total depth of 1,500 ft are judged to be erroneous.

Where possible, the total depths of the wells in table 2 are taken from the maximum depths measured by wire-line logs. Designations of formations at total depth are based on the best information available. Instead of questionable Mojado at the bottom of the Wininger and Berry well, the formation may be Ringbone (Upper Cretaceous) or U-Bar (Lower Cretaceous). Cuttings are available only down to a depth of 7,030 ft in the Cockrell No. 1 Playas, so the reported Precambrian rocks cannot be checked with lithologic/ petrographic or radiometric analysis. Previous reports of "granite", implying Precambrian basement in two wells, are in error. The KCM No. 1 Forest Federal bottomed in a Tertiary intrusive rock dated radiometrically at about 27 million years (Deal and others, 1978, table 1, sample no. 8). The porphyritic granodiorite at the bottom of the Powers No. 1 State is considered by Thorman to be the same as the Tertiary dike rock he mapped on the surface a few miles to the east. Mississippian rocks reported previously as lying beneath a thrust fault at the bottom of the Humble No. 1 State BA (Thompson in Zeller, 1965, p. 116) are now considered to be unfaulted El Paso based on observations of other geologists who have studied the cuttings.

Shows of oil and gas encountered while drilling are taken from several sources including scout tickets, hydrocarbon logs (mudlogger's reports), and driller's logs. Additional checking will be done during studies of individual wells. All are judged to be minor, noncommercial shows. Gas from the Wininger and Berry No. 1 State was reported to be combustible, but after bailing a hole nearly full of water, no gas was detected. Combustible gas was reported to have flowed from the Hachita Dome well, but the flow died within a few days. Absence of shows in the nearby Graham No. 1 Hatchet Federal indicates that those reported in the Hachita Dome well are not extensive. A minor gas flow at a rate of 10,000 cubic feet per day was measured on a drill-stem test of Epitaph dolostones in the Humble No. 1 State BA. M. T. Hall cleaned out the abandoned hole, perforated and acidized the zone from 4,172-4,261 ft, but swabbed and flowed at a rate of only 86,000 cubic feet of gas per day. Small amounts of oil and gas have been extracted from cuttings during geochemical analyses, and although these have been excluded from table 2 because they were not found during the drilling operations, they will be discussed in the next chapter.

IDENTIFICATION AND EVALUATION OF PETROLEUM SOURCE ROCKS

Basic Concepts and Methods

Accumulation of petroleum in commercial quantities is dependent upon the favorable relationship in space and time of four general factors: 1) generation of petroleum from source rocks, 2) migration along reservoir rocks or fractures, 3) entrapment in structural or stratigraphic traps enclosing effectively sealed reservoirs which have adequate water- or gas-drive mechanisms, and 4) preservation from effects of thermo-, hydro-, or biodegradation and other negative processes. All these factors are critical, but unless a source is present, no petroleum can be generated. Moreover, the composition of the source material (and the degree of thermal maturation) will determine whether petroleum occurs as natural gas, crude oil, or asphalt.

After many centuries of speculation about the source of oil and gas, the most widely accepted concept is that petroleum is generated from vegetal organic matter which was: 1) deposited in a marine or lacustrine environment under reducing conditions, 2) enclosed in relatively impermeable mudstones or carbonate rocks, and 3) buried deep enough and long enough to cause thermal alteration of organic matter and the formation of hydrocarbons. In support of this concept, observations by petroleum geologists indicate that nearly all producing reservoirs are closely associated with organically rich mudstones or limestones in marine or lacustrine sedimentary sections that have been buried several thousands of feet for several millions of years.

More rigorous evidence concerning the source of petroleum is provided by the rapidly developing discipline of petroleum geochemistry, a hybrid of petroleum geology and organic chemistry. Laboratory experiments are performed to document the transformation of organic matter into hydrocarbons. Laboratory analyses are used to determine source-rock characteristics and relate them to oil and gas occurrences. An indication that petroleum geochemistry has finally reached maturity is that the first textbooks on the subject were prepared recently by Tissot and Welte (1978) and Hunt (1979).

Methods of identifying and evaluating source rocks by petroleum geochemistry have become more precise and more operational in recent years. Previously, exploration geologists working in frontier areas usually could only make inferences about source rocks based on correlation with similar stratigraphic sections in producing areas. Early analyses by organic chemists provided some insight, but limited results were available for only a few areas, analyses took too long to be used routinely in wildcat drilling, and predictions for exploration were not successful enough to sustain credibility among operators. Advances in techniques of the major discipline of organic chemistry have helped the subdiscipline of organic geochemistry to increase the scope and precision of analyses of source rocks and to permit faster and wider applications of the results.

By the late 1960's, as a routine operation on exploration wells, some major oil companies began to collect cuttings preserved in cans to be shipped to their own research laboratories. Such preservation allows for qualitative and quantitative determinations of hydrocarbon gases and light oils which otherwise would escape. Measurements of organic-carbon percentage and chromatographic analyses of heavy oils were also made, although cuttings need not be canned. Palynologists made a significant contribution with their observations that source rocks containing mostly land-plant kerogens tended to generate gas and those containing mostly marine-algal or sapropelic kerogens tended to generate oil, and that the progressively darker color of kerogens was an indicator of increasing thermal alteration, an important factor in the maturation and preservation of petroleum. Other studies, such as mass-spectographic analyses, were made in special cases.

In the early 1970's, G.S. Bayliss and D.G. Van Delinder, former employees of Exxon, formed Geo Chem Laboratories, Inc. in Houston, Texas. It became the first service company to offer a full range of petroleum-geochemical analyses. Geo Chem has done jobs for all of the major oil companies, several small companies and independents, federal and state geological surveys, and research organizations. It remains the leader in the field although several competitors have started business in the last few years. An excellent guide to basic concepts, analytical methods, and interpretation procedures used by Geo Chem was prepared recently by Smith and Bayliss (1980).

In the late 1970's, workers at the Institut Francais du Petrole developed a new instrument of pyrolysis called Rock-Eval which may provide a major breakthrough in source-rock analyses

(Tissot and Welte, 1978, p. 443-447; Hunt, 1979, p. 458-462). Long known as a laboratory technique, pyrolysis is the heating of the kerogen in a source-rock sample (in the absence of oxygen) to yield hydrocarbons; it thus is a method of measuring the petroleum-generating capacity of a source rock. In the new, rapid, and less-expensive method which can be used at the well site, a sample of about 100 milligrams of pulverized rock is put into the Rock-Eval device and heated progressively up to 550°C in an inert atmosphere. At a moderate temperature, the free hydrocarbons are volatilized and recorded on the flame-ionization detector as the first peak. At a higher temperature, pyrolysis of kerogen yields hydrocarbons which are recorded as the second peak. During cooling, the carbon-dioxide resulting from pyrolysis is passed through a thermal-conductivity detector and recorded as the third peak.

Sums and ratios of these peaks are used to determine the amount of hydrocarbons that could have been generated from the source rock, the chemical types of kerogen which indicate whether oil or gas is more likely to have been generated, and the stage of maturation. Rock-Eval has been tested in a variety of sedimentary basins during the world-wide increase of drilling activity in the last few years. Although results generally are held confidential by operators, the overall reaction from industry appears to be favorable. Cautious operators are continuing to use previous geochemical methods while they judge the effectiveness of the Rock-Eval instrument.

A basic assumption in pyrolysis and other geochemical methods is that a present rock sample is representative of a petroleum source throughout its history. This assumption is supported by the inference that petroleum generation is a slow, inefficient process. Some consideration should be given to the possibility that Paleozoic or even Mesozoic rocks may contain source characteristics now that are much different from those they contained in the past when they may have been actively generating hydrocarbons.

Future advances in petroleum geochemistry may resolve these and other problems. However, no matter how precisely source rocks may be identified and evaluated, they are but one consideration in the exploration for petroleum. The whole space-time spectrum of generation-migration-entrapment-preservation should be analyzed within the geologic framework of each prospective area.

Applications and Results

To apply the modern concepts and methods of petroleum geochemistry to New Mexico, and to begin publication of such results in the state, this research program was initiated in late 1974. GeoChem Laboratories, Inc. was contacted then to run source-rock analyses on samples from selected wells (and outcrop sections) in this pilot study on southwestern New Mexico. Their advice and cooperation have contributed greatly to the planning and implementation of the study.

Selection of wells. Figure 3 shows the 7 exploration wells in the map area that were selected here for petroleum-geochemical analyses at GeoChem. Selections were made for best possible coverage of the geographic area and the Paleozoic-Mesozoic stratigraphic units. The first two wells to be selected were the KCM No. 1 Forest Federal and the KCM No. 1 Cochise State A; they were drilled in the early part of the research program and the operator agreed to collect canned cuttings. Of the previously drilled wells, the Humble No. 1 State BA was the most thorough exploration test of the Paleozoic section. The Hachita Dome No. 1 Tidball-Berry Federal was selected because it had several reported shows of oil and gas in the pre-Pennsylvanian section. Of the many wells drilled by Cockrell, the No. 1 Coyote State penetrated a complete Lower Cretaceous section and all of the Lower Paleozoic preserved at that location, the No. 1 Playas State penetrated a complete pre-Permian section, and the No. 1 Pyramid Federal penetrated all of the Paleozoic preserved there.

Additional selections for future analyses may include the Powers No. 1 State because it drilled a thick section of Lower Cretaceous rocks, and the Cockrell No. 1 State-1125 because it drilled some Permian rocks. The Graham No. 1 Hatchet Federal may be selected although it is so close to the Hachita Dome well that it may not add significant control, and the cuttings reportedly are poor. No cuttings are available on the Wininger well.

Selection of samples. After selection of each well, the next consideration was the selection of samples to be analyzed. For the two wildcats that were actively drilling, the KCM No. 1 Forest Federal and the No. 1 Cochise State A, canned cuttings were collected empirically at arbitrary, even 100-ft depths. Although the opportunity to measure the amounts of hydrocarbon gases and light oils was a great advantage, the inability to select depths rationally with most favorable rock types was a disadvantage. However, for the other 5 wells which were drilled previously, specific samples were chosen to represent dark-colored mudstones and carbonate rocks that appeared to be good or fair petroleum sources. Some light-colored ones, inferred to represent poor source rocks, were included to determine the boundaries of source units and to test the selection procedure. For general depth coverage, one sample was chosen per 100 ft or so of marine-sedimentary section; more were included in good source units. Where possible, a specific 10-ft sample was chosen to represent a source unit 50 ft thick or more. For stratigraphic coverage, at least one sample per Paleozoic or Mesozoic formation was included.

As a departure from the usual practice of making a composite sample for a 100-ft interval, a request was made to run analyses on specific 10-ft intervals so petroleum-geochemical results could be compared directly with those of lithologic, petrographic, and other analyses. Additional control can be filled in later if warranted. In some cases where sufficient amounts of cuttings were not available in a single 10-ft interval, similar rock types from intervals above or below were combined into a composite sample.

Drill cuttings may not provide completely reliable samples for analyses. Depth intervals of samples from rotary-drilled wells may not be accurate if lag is determined incorrectly; lag is the time it takes for cuttings after leaving the drill bit to be transported through the drilling mud and reach the surface. Even if the lag is correct, rock types in a sample may not be representative of the drilled interval. Mixing of extraneous rock types may be caused by caving, recirculation, or elutriation (variable transport of cuttings with different sizes or specific gravities). Mixing of indigenous rock types can also occur if different types are thinly interbedded. Any mixture tends to complicate the analytical results. To minimize these problems, selections were made where possible from samples with one dominant rock type which appeared correlative with responses at equivalent depths on wire-line logs. More accurate results could be obtained if more cores were available.

Selection of analyses. The analytical program for the samples selected from each well was discussed with GeoChem and generally was left to their best judgment. Following the usual practice, the percentage of organic carbon was to be measured on each sample as a first-step screen to determine which ones indicated sufficient organic richness to warrant additional analyses.

Microscopic examination of kerogen was requested on each formation to determine relative amounts of algal/amorphous (oil-prone) or land-plant (gas-prone) source material and to determine the degree of thermal alteration for an estimate of maturation. At least one determination of vitrinite reflectance per well was requested; some workers believe that it is a better indicator of maturation than kerogen.

For samples with fair to good organic richness, the heavy oils were to be extracted and analyzed by chromatography. The amounts and kinds of compounds give clues to the generation-capacity of the source rock, the composition of oils generated, and the maturation history. Pyrolysis determinations were requested after the Rock-Eval instrument was set up at GeoChem. These data also provide information on generation capacity, chemical types of kerogen, and maturation history.

Tabulation of data. Tables 3-9 list the petroleum-geochemical data on the 7 exploration wells. Data on each well are shown in a separate table, and the tables are presented in the same geographic order established in table 2. Items in the first 3 columns of each table generally were determined prior to the analyses: depth interval, rock type, and color. Analytical results from GeoChem are tabulated in the next 7 columns. Only selected parameters are shown; additional results may be found in the referenced reports by GeoChem on individual wells. In the last column, a summary evaluation is made of organic richness, tendency for oil or gas generation, and the stage of maturation.

In the following paragraphs, the type of information in each column is explained as to the notations used and significance of the results.

Depth interval (column 1). Depth of each sample-interval analyzed is given in feet (ft). Most intervals of individual samples are 10 ft thick. Those greater than 10 ft generally indicate that GeoChem needed more material, expanded the interval chosen for analyses, and prepared composite samples. Because 10-ft samples were selected to represent source units 50 ft or more thick in most cases, lumping of the same rock type into composite samples normally should have caused no problems.

Data from each major stratigraphic unit (table 1) are blocked together under the heading of the formation name. This arrangement allows for ready comparison of data within each unit, between other units in the same well, and within the same unit in other wells. Because of lag, depths of sample intervals listed under a formation may differ slightly from the tops determined on wire-line logs (table 2).

Rock type (column 2). Abbreviations of basic rock types are: Ds = dolostone, Ls = limestone, and Ms = mudstone (claystone, siltstone, shale), and Ss = sandstone. Modifiers include: calc = calcareous, chty = cherty, dolic = dolomitic, mdy = muddy (argillaceous, silty, shaly), sdy = sandy. Lithologic determinations were made with a 10x binocular microscope; some have been confirmed by petrographic analyses, but most should be considered preliminary. In a few cases, the original determination was modified in accordance with the description by GeoChem, especially where composite samples were prepared.

Different rock types are evaluated with different scales of source-rock parameters. For example, carbonate rocks (limestones and dolostones) may be considered as organically rich as mudstones even if the carbonates have lower percentages of organic carbon. With more detailed lithologic and petrographic study of drill cuttings and outcrop samples in this area, more accurate evaluations of the petroleum-source characteristics can be made.

Color notation (column 3). Standard color notations, based on the Geological Society of America color chart of Goddard and others (1951), were determined with a 10x binocular microscope and a white-light illuminator while cuttings were wet. These notations, which are taken from the Munsell system, indicate hue (number and letter), lightness value (number before slant), and chroma or degree of saturation (last number). For example, 5YR4/1 is the notation for brownish gray with a hue of 5YR (brown), a lightness value of 4 (medium dark gray, range is from 1-black to 9-white), and a chroma of 1 (least vivid, with a range to most vivid at 6). Most of the hues of the rocks described are 5YR-brown, 10YR-yellowish brown, or 5Y-olive. Where no hue is discernible, the lightness value of neutral tones is used; for example, N1-black or N9-white. Although this semi-quantitative system is the only one available for general use by geologists, many rock colors fall between those of the standard chips. Thus the actual determinations are only best approximations; they may vary from geologist to geologist, or even within a stratigraphic section being described by one geologist.

In general, darker rocks (with lower lightness values) tend to be richer in organic carbon than lighter-colored ones (Hunt, 1979, p. 265). On this basis, samples were selected for analyses. In this area, rocks with lightness values of 5 or higher (lighter) generally contain very poor amounts of organic carbon. Some with values less than 5 (darker) also have been found to be very lean, so lightness is not an infallible indicator of organic richness.

Hosterman and Whitlow (1981), in a study of Devonian mudstones of the Appalacian Basin, found that percentages of organic carbon decrease exponentially with respect to increasing lightness values. They prepared pressed-powder wafers from drill cuttings and cores and examined them dry. At 0.6 percent organic carbon, determined to be the minimum for a gas source in that area, the noncalcareous mudstones have a lightness value of about 6.0 (4.0 when wet) compared to 5.5 for the calcareous mudstones (containing 5 percent or more calcite). They do not state whether the 5 percent of calcite is a threshold, or whether increasing percentages show a relationship to decreasing lightness values at the same percentages of organic carbon. If the latter is true, a mudstone may tend to be richer in organic carbon than a limestone with the same lightness value.

GeoChem workers describe dry cuttings, so their lightness values tend to be higher than those determined here. In some cases, they describe a mix of hues or values which may indicate that the selected rock types with a specified color could not be picked completely from the cuttings within practical time limits. Such mixing may explain some apparent descrepancies between color determinations and percentages of organic carbon.

Percentage of organic carbon (column 4). GeoChem's measurements of total organic carbon (TOC) by combustion with a Leco Carbon Analyzer, are placed in this column. A repeat measurement is run on every tenth sample as an analytical check; differences seldom exceed 0.03 percent. The repeat determinations were not listed here unless they were the values of samples submitted for other analyses.

As an interpretation aid, GeoChem presents the following scales of organic richness based on percentage of organic carbon (Smith and Bayliss, 1980, p. D-1). For mudstones (shales), 0.00 to 0.50 = poor, 0.50 to 1.00 = fair, 1.00 to 2.00 = good, 2.00 to 4.00 =

very good, and greater than 4.00 = excellent. For carbonate rocks (limestones and dolostones), 0.00 to 0.12 = poor, 0.12 to 0.25 = fair, 0.25 to 0.50 = good, 0.50 to 1.00 = very good, and greater than 1.00 = excellent.

Hunt (1979, p. 270) stated that many geochemists believe the minimum amount of organic carbon needed to generate sufficient oil for a commercial accumulation is 0.40 to 1.00 percent in mudstones and about 0.30 percent in carbonate rocks. However, in some cases the organic-carbon content may exceed 1.00 percent and the oil-generating capacity may be low, as determined by pyrolysis (Hunt, 1979, p. 464).

In southwestern New Mexico, many of the Paleozoic and Mesozoic mudstones are calcareous or dolomitic. Measurements of carbonate percentages may permit interpolation between the organic-richness classes for end-member mudstones and pure carbonate rocks.

Kerogen (column 5). Kerogen is defined chemically as the organic material in rocks that is insoluble in carbon disulfide (or other solvents). This material can be analyzed visually to determine the palynological types and amounts. Samples are prepared for microscopic examination by acidizing the inorganic rock material, concentrating the finely disseminated organic material, and mounting these plant remains on slides.

Types and symbols of kerogen determined by GeoChem (Smith and Bayliss, 1980, p. B-7) are: 1) Al = algal; 2) Am = amorphous-sapropelic, which is structureless material produced by bacterial degradation of algal or herbaceous plant remains; 3) H = herbaceous, from the softer parts of plants such as leaves or grasses; 4) W =

woody; 5) I = inertinite, which is herbaceous or woody material that has been altered to black, opaque particles (in earlier reports, the term "C = coaly" was used); and 6) U = unidentified material. Algal, amorphous, and degraded herbaceous (H*) kerogens tend to generate oil, herbaceous types generate both oil and gas, woody types generate gas, and inertinite types generate only traces of methane (Hunt, 1979, p. 274, fig. 7-5).

Amounts of kerogen are determined semi-quantitatively by GeoChem (Smith and Bayliss, 1980, p. D-4): 1) P = predominant population, 60 to 100% of kerogen; 2) S = secondary population, 20 to 40%; and 3) T = trace population, 1 to 20%. As an example, the notation Am;H;W indicates a predominant population of amorphous kerogen, a secondary population of herbaceous, and a trace population of woody. A notation such as H-W;Am;Al indicates a mixture of herbaceous and woody forming the predominant population. A notation such as Am;-;- indicates no clearly defined secondary or trace population.

Thermal-alteration index (column 6). At GeoCehm (Smith and Bayliss, 1980, p. B-14), the color of cuticle (or spore-pollen) fragments in herbaceous kerogen is used to determine thermal alteration. The color range from yellowish green to black indicates increasing thermal alteration on a scale from 1 to 5.

In general terms, the ranges of thermal-alteration indices indicate the maturation stage of organic matter in the source rock: 1 to 2 = immature, biogenic generation of gas; 2 to 3 = mature, generation of oil; 3+ to 4 = overmature, thermal cracking of oil to generate gas; and 5 = metamorphosed, dry gas or barren (modified from Hunt, 1979, p. 324, table 7-10). A more detailed classification is used by GeoChem (Smith and Bayliss, 1980, p. D-5).

Vitrinite reflectance (column 7). Vitrinite is a coal maceral composed of humic material. Its reflectance, the ratio of reflected/incident light, is less than that of inertinite and greater than that of exinite. Vitrinite particles are selected from the kerogen, mounted in epoxy, polished, and placed under a reflecting microscope with oil-immersion lenses. Vitrinite reflectance in oil, Ro, is measured as a percentage (Smith and Bayliss, 1980, p. B-11-13; Hunt, 1979, p. 328-339).

According to GeoChem (Smith and Bayliss, 1980, p. D-5), the values of vitrinite reflectance corresponding to the general stages of maturation (discussed with the thermal-alteration index) are: less than 0.6 percent = immature, 0.6 to 1.5 = mature, 1.5 to 4.0 = overmature, greater than 4.0 = metamorphosed. According to Hunt (1979, p. 332 and fig. 7-49), vitrinite reflectance is 0.45 to 2.0 percent in the oil-generation range; with 0.6 to 1.0 being the range where oil-generation is dominant. From 1.0 to 2.0 percent the gas/oil ratio increases; from 2.0 to 3.5 only gas is generated.

Because pre-Silurian rocks contain no vitrinite, this method cannot be used to determine maturation in the Bliss, El Paso, or Montoya. Because vitrinite tends to be rare in carbonate rocks, the method is of limited use in much of the remaining Paleozoic and Mesozoic section of southwestern New Mexico. Thus kerogen analyses are preferred for general coverage in this area, and they give important information or oil- or gas-prone kerogens as well as the thermal-alteration index. Nevertheless, at least one determination of vitrinite reflectance was requested for the better source units in each well to provide a check on the thermal-alteration index.

C_{15+} extraction (column 8). The notation C_{15+} indicates hydrocarbon and nonhydrocarbon compounds with 15 or more carbon atoms. Such compounds with large molecules form heavy oils which tend to remain in the source rock after the gases and light oils have migrated. At GeoChem, these bitumens are removed from source rocks by means of an organic solvent in a ballmill or a Soxhlet extractor (Smith and Bayliss, 1980, p. B-5). After measuring the total C_{15+} bitumen in parts per million (ppm), and removing the asphaltenes, the pentane-soluble fraction is separated further by liquid chromatography into paraffin-naphthene (P-N) hydrocarbons, aromatic (Arom) hydrocarbons, and the nonhydrocarbon compounds of nitrogen-sulfur-oxygen (NSO).

In column 8, the total C_{15+} bitumen, P-N, and Arom amounts are plotted. The total C_{15+} hydrocarbons may be calculated by adding P-N and Arom; the total C_{15+} nonhydrocarbons (asphaltanes and NSO's) may be calculated by subtracting the total hydrocarbons from the total bitumen. All these data and other information are tabulated in the GeoChem reports.

As a measure of hydrocarbon richness, GeoChem uses the following scale of total C_{15+} bitumen (Smith and Bayliss, 1980, p. D-2 - 3): 0 to 250 ppm = very poor; 250 to 500 = poor; 500 to 1,000 = fair; 1,000 to 2,000 = good; 2,000 to 4,000 = very good; over 4,000 = excellent. Another measure is the scale of total C_{15+} hydrocarbons (P-N plus Arom): 0 to 50 ppm = very poor; 50 to 100 =

poor; 100 to 200 = fair; 200 to 400 = good; 400 to 800 = very good; over 800 = excellent (see also Hunt, 1979, p. 263, table 7-1). According to Hunt (1979, p. 266-267, fig. 7-1), the minimum amount of C_{15+} hydrocarbons in oil-source rocks is about 70 ppm; where the amount exceeds 20 percent of the total organic carbon, the C_{15+} hydrocarbons normally are in reservoir rocks rather than in source rocks.

An immature source is indicated if the P-N hydrocarbons make up less than about 10 percent of the total C_{15+} bitumen, or if the P-N/Arom ratio is less than 1 (Smith and Bayliss, 1980, p. D-7). Other ratios of hydrocarbon compounds may be used as indicators of maturation (Hunt, 1979, p. 377).

Although C_{15+} extractions of samples offer direct evidence of heavy oil in a source rock, the amounts and types of compounds may not represent the source conditions exactly. Some amounts or types may have migrated in or out of the source prior to drilling, and some may have been lost during drilling operations.

Carbon-preference index and pristane/phytane ratio (column 9). For additional analysis of the C_{15+} hydrocarbons, the paraffin-naphthene (P-N) fraction is separated by gas chromatography to show separate peaks of normal paraffins in the C_{15} to C_{35} range, separate peaks of the isoprenoids (branched paraffins) pristane (ipC_{19}) and phytane (ipC_{20}), and an envelope of naphthenes below (Smith and Bayliss, 1980, p. B-18). Areas under the peaks are proportional to the relative abundance of the normal paraffins and isoprenoids.

In a given sample, the carbon-preference index, C.P.I., is the ratio determined by adding the areas under each peak for odd numbers of carbon atoms in normal-paraffin compounds and dividing by the total of peak areas for even numbers. In column 8, the B index (C.P.I.-B) is plotted; it is determined in the carbon-number range from C_{24} to C_{32}. Indices normally range from 5 in modern sediments, to 1-3 in ancient mudstones, to 1 in crude oil (Hunt, 1979, p. 302). A mature source rock may be expected to have an index of 0.9-1.3. However, carbonate rocks may have indices less than 1, marine scurce material will have an index near 1 regardless of maturity, and large quantities of land plants can increase the index up to 20.

The pristane/phytane ratio, ip19/ip20, is determined by dividing the peak areas of these isoprenoid hydrocarbons. If less than 1, the ratio indicates kerogen derived from marine or lacustrine plants; if greater than 3, it indicates kerogen derived from land plants (Hunt, 1979, p. 280, table 7-5). Pristane tends to be produced in an oxidizing environment and phytane tends to be produced in a reducing environment (Tissot and Welte, 1978, p. 112, fig. II.3.14). Because phytane tends to break down with increasing thermal maturation, an index greater than 3 may indicate an overmature source, provided that the original rock did not contain excessive phytane and other conditions are normal (L.P. Tybor, personal communication, 1981).

Pyrolysis (column 10). As explained previously, pyrolysis is heating of the kerogen in a source-rock sample to yield hydrocarbons. Using the new Rock-Eval instrument, the sample is heated progressively (Smith and Bayliss, 1980, p. B-4-5). Free hydrocarbons are volatilized and recorded on peak S_1. Pyrolysis of kerogen yields hydrocarbons which are recorded on peak S_2.

Carbon dioxide is recorded on peak S_3. Amounts are given in milligrams/gram, mg/g. The temperature recorded at the peak of S_2 is designated by GeoChem as T°C Max; note that it is not an estimate of maximum paleotemperature.

Tissot and Welte (1978, p. 447-448) designate the sum of $S_1 + S_2$ as the genetic potential of the source rock. They assume that S_1 represents the amount of hydrocarbons that have been generated so far, and that S_2 represents the amount remaining to be generated. They classify source rocks according to this sum as follows: less than 2 mg of hydrocarbons/g of rock (2 kg/metric ton) = poor source, 2 to 6 mg/g = fair source, and more than 6 mg/g = good source. Some oil shales run as high as 100 or 200 mg/g.

Although their empirical classification may be useful in some cases, the basic assumption that S_1 represents the amount of generated hydrocarbons may be fallacious. If any hydrocarbons have migrated out of the source rock, as at least some should have done if the source is in a favorable relationship with a reservoir, then the S_1 value would be less than the total. If hydrocarbons have migrated from another source into the one sampled, the S_1 value would tend to be greater than the amount generated. In partial support of their assumption is the observation by Hunt (1979, p. 22) that only 0.4 to 10% of the oil generated in source rocks migrates to reservoirs; however, an unknown amount could have been dissipated.

Hunt (1979, p. 464) warns that differences in the inorganic rock matrix may affect hydrocarbon yields during pyrolysis (S_2), and that small samples of 50-100 mg may not be representative of a source unit.

Tissot and Welte (1978, p. 191) define the transformation ratio as the ratio of petroleum generated from a source rock to the total that could be generated. They (p. 453) suggest that the ratio $S_1/(S_1 + S_2)$ is a close approximation of the transformation ratio, provided no migration has taken place. They (p. 506) indicate that the ratio begins at 0 when a source is most immature and increases progressively to a maximum of 1 when all the hydrocarbons have been generated and only a carbonaceous residue is left in the matrix.

Smith and Bayliss (1980, p. D-9c) present a GeoChem chart in which $S_1/(S_1 + S_2)$ is plotted with respect to T°C Max. They show that the range of oil generation lies between a ratio of 0.1 to 0.4 and a T°C Max of 435 to 460.

Tissot and Welte (1978, p. 142-146) recognize three chemical types of kerogen based on atomic-ratio plots of hydrogen/carbon, H/C, versus oxygen/carbon, O/C. At shallow depths of burial, the designated Type I is recognized by a high H/C of 1.5 or more and a low O/C of 0.1 or less. Type II has intermediate ratios. Type III has a low H/C less than 1.0 and a high O/C of 0.2 or more. With increasing depths of burial, and thus increasing maturity, plots of the three types converge and come together where kerogen approaches 100% carbon. Determinations of the ratios, or hydrogen and oxygen indices, are approximated with respective values of S_2 and S_3, each divided by the amount of organic carbon. Type I kerogen normally is rich in algal or amorphous organic material deposited in lacustrine environments. Type II normally is derived from plankton and bacteria deposited in a reducing marine environment. Type III normally is derived from land plants which may have been oxidized and deposited in either a nonmarine or marine environment. Type I and II kerogens tend to generate oil and Type III kerogen tends to generate gas.

In recent laboratory experiments, Katz (1981 and personal communication) found that Rock-Eval results are questionable. The peaks S_2 and S_3, and the resulting determinations of the hydrogen and oxygen indices, are strongly affected by the mineral composition of the matrix, particularly clays versus carbonates. He also found wide differences between samples with rich versus lean amounts of organic carbon. He has called for a better device to evaluate pyrolysis data.

In the GeoChem reports, all of the standard parameters and ratios derived from Rock-Eval pyrolysis are tabulated. L.P. Tybor (personal communication, 1981) finds that the value of S_1 may be useful in an approximate evaluation of oil-source richness. For values of S_1, less than 0.2 = poor, 0.2 to 0.4 = fair, 0.4 to 0.8 = good, 0.8 to 1.6 = very good, and over 1.6 = excellent. This scale does not work well for samples with abundant gas-prone kerogen because S_1 values tend to be low. For values of S_2, less than 1.0 = poor, 1.0 to 2.0 = fair, and 2.0 to 4.0 = good. This scale works best for samples with abundant amorphous kerogen.

Basic evaluation (column 11). This last column offers a summary evaluation of three basic source-rock parameters: organic richness (Org), tendency for oil or gas generation at maturity (O/G), and the stage of thermal maturation (Mat). For most samples, only the first parameter can be determined. Where multiple analyses were run, the second and third parameters can be determined. In this basic evaluation the parameters are determined with single criteria, but others are listed for comparison. No known system is available to weight all the criteria that could be used to determine each parameter, especially for this area. Some specific comparisons will be made in the discussions of individual wells.

Organic richess is determined from the percentage of organic carbon in column 4. Using the scales for mudstones and limestones discussed under that heading, the notations are P = poor, F = fair, G = good, VG = very good, and E = excellent. Comparisons may be made with total C_{15+} bitumens and total C_{15+} hydrocarbons (P-N plus Arom) in column 8 and the sum of $S_1 + S_2$ in column 10.

Tendency for oil or gas generation at maturity is based on the kerogen analyses in column 5. The symbol O designates a tendency for oil generation and is used where algal, amorphous, or degraded herbaceous kerogen form the predominant population and no secondary population is indicated. The symbol G designates gas generation and is used where woody kerogen forms the predominant population. The symbol O,G designates a greater tendency for oil generation than gas generation and is used where algal and/or amorphous kerogens form the predominant population and herbaceous and/or woody kerogens form the secondary population. The symbol G,O is used for the reverse. A dash (-) designates neither oil nor gas generation and is used where inertinite forms the predominant population. Trace populations are neglected in this basic evaluation.

For comparison, several GeoChem charts can be used to check oil or gas generation (Smith and Bayliss, 1980, figs. 30-35). Plots of organic-carbon percentage (column 4) versus total C_{15+} bitumens or hydrocarbons (column 8) can be used for this purpose and for a quantitative estimate of the volume of oil in barrels per acre-foot (figs. 30, 30-A, and 30-B). A plot of T°C Max versus $S_1/(S_I + S_2)$ from column 10 can be used to see if a sample falls in the oil-generation range. Pyrolysis data may also be used to make plots of hydrogen and oxygen indices to determine the Type I or II kerogens that are oil-prone and Type III kerogen that is gas-prone (Tissot and Welte, 1978, p. 143, fig. II.4.11).

Maturation of organic matter is determined from the thermal-alteration index in column 6. Using the scale discussed under that heading, I = immature (1 to 2), M = mature (2 to 3), O = overmature (3+ to 4), and T = thermally metamorphosed (5). Note that a source indicated to generate oil at maturity may generate only gas at immature or overmature stages.

Several indicators of thermal maturation can be used in comparison. Vitrinite reflectance, column 7, provides the most direct comparison; some problems were discussed under that heading. The ratio of P-N/Arom and other C_{15+} data from column 8 can be used to distinguish immature versus mature sources. The carbon-preference index and the pristane/phytane ratio from column 9 should also be compared, but these values tend to vary with the types of rock or organic material as discussed previously. From pyrolysis data in column 10, the values of S_1 and S_2 can be used to approximate oil-source richness according to Tybor's scales, the transformation ratio of $S_1/(S_1 + S_2)$ can be calculated to determine the stage of maturation between 0 and 1, and the hydrogen and oxygen indices can be plotted to determine the stage of maturation for Type I, II, or III kerogen.

Discussions of Individual Wells

In the remainder of this chapter, each individual well is discussed as to significant observations or specific problems concerning the data or basic evaluations given in tables 3-9. These source-rock analyses will be re-examined when more complete studies are made including lithologic, petrographic, and other analyses.

Cockrell No. 1 Pyramid Federal (table 3). Depth intervals, rock types, and color notations were determined during the current project using the mounted-cuttings strip log. Geochemical data were taken from Tybor (1981d).

This well was drilled on the northwest side of the volcanic cauldron mapped in the southern part of the Pyramid Mountains (fig. 1). At the unconformity between the Tertiary volcanic rocks and the Escabrosa (Mississippian), over 6,000 ft of younger Paleozoic and Lower Cretaceous rocks are absent by erosion or nondeposition. Most of the missing section probably was deposited and removed by erosion in medial Wolfcampian, Late Permian-Early Cretaceous or Late Cretaceous-Early Tertiary time. All of the preserved Escabrosa-Bliss units are cut by Tertiary intrusive rocks. Nevertheless, this well provides important control for the source rocks in the lower Paleozoic section. No shows of oil or gas were reported by the United Core mudlogger.

Escabrosa limestones contain generally poor amounts of organic carbon. The one sample with a fair amount (5,990-6,000 ft) contains mixed rock types and may not be reliable. Oil-generating kerogens are more abundant than gas-generating types. Thermal alteration is generally mature, but some kerogens have reached the overmature stage. Apparently, the Tertiary intrusions into the Escabrosa (and each of the older Paleozoic units in this well) produced no significant thermal metamorphism of the organic matter.

Percha mudstones generally contain poor amounts of organic carbon. Gas-generating kerogens are more abundant than oil-generating types. This is the only section of Percha in which amorphous kerogens are described; a more oil-prone facies may be present in this part of the area. Thermal alteration again is generally mature with some overmature.

As in other sections, the basal Percha (6,840-6,850 ft) is the richest part, here containing a fair amount of organic carbon. Vitrinite reflectance is in lower part of the overmature range, indicating slightly higher thermal alteration than the index based on kerogen color. A very poor amount (264 ppm) of C_{15+} bitumen was extracted, including a poor amount (69 ppm) of hydrocarbons. The carbon-preference index (C.P.I.-B) and the pristane/phytane ratio (ip 19/ip 20) indicate a mature source. Pyrolysis determinations indicate poor oil-source richness.

Montoya dolostones have poor amounts of organic carbon, oil-generating kerogen, and a mature to partially overmature aspect of thermal alteration. El Paso dolostones also have poor amounts of organic carbon and oil-generating kerogen; however, thermal alteration is more evenly distributed between the mature and overmature range, probably a result of greater depth of burial. Because land plants did not appear until Silurian time, amorphous-algal kerogens are the only types expected in the Montoya-El Paso. No carbonate rocks or mudstones were observed in the Bliss, so no analyses were attempted.

Cockrell No. 1 Coyote State (table 4). Depth intervals, rock types, and color notations were determined during the current project using the mounted-cuttings strip log. Geochemical data were taken from Tybor (1981b).

This well drilled the thickest section of Mojado in the area. Because the samples are of generally good quality, a thorough evaluation can be made. No shows of gas were reported by the United Core mudlogger, and only a trace of oil fluorescence and cut was described in Mojado sandstones (4,140-4,150 ft). Overall, the Mojado here has a range of organic richness from poor to excellent, gas-and oil-generating kerogen, and a mature stage of alteration. According to the pyrolysis data, the genetic potential is poor, but gas generation is indicated. Samples in the upper part of the Mojado (1,950-4,110 ft) are organically lean, but richness in the darker mudstones of the lower Mojado (4,300-6,080 ft) is generally fair to good.

The sample at 5,620-5,630 ft has excellent richness, 9.98 percent, and also has a high vitrinite reflectance, 3.49-4.81 percent. The latter normally indicates overmaturity or metamorphism; however, kerogen control above and below documents a mature stage of alteration. The high vitrinite reflectance may be due to a large amount of reworked, thermally-altered, land-plant material. Although kerogen types were not determined in this sample, those above and below are predominantly highly altered inertinites that are inferred to be reworked (only indigenous kerogen is listed in table 4).

C_{15+} data from the two composite samples in the lower Mojado support the evidence of maturity. C_{15+} hydrocarbon content of 176 ppm in the upper sample (5,100-5,230 ft, plotted on the data line for sample 5,160-5,170 ft) suggests a fair oil source, and that of 63 ppm in the lower sample (5,650-5,900 ft) suggests a poor oil source. However, these minor amounts of heavy oil could have been generated along with gas from the herbaceous kerogens.

This well drilled a relatively thin section of U-Bar, but it appears to be unfaulted. It is the only complete subsurface section of U-Bar in the area. Limestones in the upper part (6,400-6,500 ft) have good organic richness, gas-and oil-generating kerogen, and a mature stage of alteration. C_{15+} and pyrolysis data support the basic evaluation. Limestones and mudstones in the lower U-Bar (6,810-7,090 ft) are organically lean. Red mudstones of the Hell-to-finish are also lean.

At the unconformity between the Hell-to-finish (Lower Cretaceous) and the Montoya (Ordovician), up to 10,000 ft of younger Paleozoic rocks are absent by erosion or nondeposition. Much of the missing section probably was deposited and removed by erosion in Late Permian-Early Cretaceous time. However, even the oldest Paleozoic rocks contain mature organic matter, so great depths of burial appear unlikely.

Dolostones and limestones of the Montoya and El Paso are very lean. Amorphous and algal kerogens indicate oil generation at maturity, but amounts are too small to constitute a significant source.

<u>KCM No. 1 Cochise State A (table 5).</u> Canned cuttings were collected by the mudlogger at arbitrary depths 100 to 500 ft apart.

Rock types and color notations were taken from a lithologic-petrographic description by R.F. Broadhead. Geochemical data, including measurements of hydrocarbon gases and gasolines that are not shown in table 5, were taken from Cernock (1976).

This well drilled a thick section of inferred Mojado. Unfortunately, it was abandoned before reaching the U-Bar, so the correlation remains in doubt. No datable palynomorphs were found.

Black mudstones in the upper part of the section (2,390-3,700 ft) may belong to the Ringbone Formation, a nonmarine unit inferred to be Upper Cretaceous in age which is exposed in the Little Hatchet Mountains (Zeller, 1970). However, they tentatively are correlated with the dark mudstones of the lower Mojado seen in the Cockrell No. 1 Coyote State. Organic richness ranges from poor to fair. Kerogens are gas-and oil-prone. Alteration indices are in the overmature range. Although presently at shallow depths, this section probably was buried to great depths in the lower plate of the main thrust zone (fig. 1). The inferred overburden was removed by erosion prior to deposition of the Tertiary volcanic rocks. As an alternative explanation, the overmature rating may have been determined from reworked, highly altered kerogens. Inertinites (coaly kerogens) are listed in the predominant population of this well but were considered reworked in the Cockrell No. 1 Coyote State.

While the black mudstone section was being drilled, minor amounts of methane and ethane gas were detected in the drilling fluid by the Simco mudlogger. Analyses of hydrocarbon gases and gasolines in the canned cuttings, as determined at the GeoChem laboratory, were moderately rich to rich amounts (688-35,360 ppm) of methane (C_1), lean amounts (62-144 ppm) of ethane-butane (C_2-C_4), and no pentane-heptane (C_5-C_7) (ratings from Smith and Bayliss, 1980, p. D-1-2). C_{15+} bitumen extractions are very poor (70-193 ppm). In most samples the amounts of P-N and Arom were too small to measure. In sample 3,190-3,200 ft, the total of C_{15+} hydrocarbons is only 37 ppm. In that sample, no carbon-preference index could be determined. Note in the three samples from 3,490 to 4,200 ft that the B index was indeterminate, so the A index was listed in column 9 of table 5. These C_1-C_7 and C_{15+} data confirm the evaluation of this black-mudstone section as a fair gas source and a poor oil source.

White to gray, quartzose-feldspathic sandstones in the lower part of the section (3,890-5,300 ft) are probably Mojado. Preliminary reports of igneous rocks from this interval apparently are in error. They probably resulted from identification with a binocular microscope of feldspars in the small cuttings; however, Broadhead's petrographic evidence shows that these are detrital grains.

Organic richness in the sandstones is expectably very poor. The dominant amorphous kerogens would indicate oil generation given sufficient richness and maturity; however, only small amounts of organic matter were seen on the kerogen slides in these two samples (4,190-4,200 ft and 4,990-5,000 ft), and they may be caved from the black-mudstone unit.

Minor amounts of methane and ethane gas were detected in the sandstone unit by the mudlogger; no oil fluorescence or cut was reported. Analyses of hydrocarbon gases and gasolines in the canned cuttings determined lean to moderately rich amounts (293-1,095 ppm) of methane (C_1), very lean to lean amounts (26-541 ppm) of ethane-butane (C_2-C_4), and very lean to lean amounts (0-479 ppm) of pentane-heptane (C_5-C_7). Because most of the C_1, nearly all of the C_2-C_4, and all of the C_5-C_7 hydrocarbons were measured in the air space at the tops of the cans, the gases and gasolines are probably not indigenous to the sandstones. Amounts of C_{15+} bitumen are very poor (61-100 ppm), and the amounts of C_{15+} hydrocarbons were too small to measure. Gases, gasolines, and heavy oils may have migrated from the U-Bar limestones below, or from the black-mudstones above, but probably were thermally degraded when temperatures reached the overmature range.

Hachita Dome No. 1 Tidball-Berry Federal (table 6). Depth intervals, rock types, and color notations were determined during the current project using the mounted-cuttings strip log. Geochemical data were taken from Tybor (1981a).

This well was drilled on the upper plate of the main thrust zone (fig. 1). Zeller (1975) shows the structural position of this well in relationship to the thrust mapped in the Sierra Rica. After Laramide thrusting, about 18,000 ft of upper Paleozoic and Lower Cretaceous have been removed by erosion. This well provides important control for source rocks in the lower Paleozoic. Some shows of oil and gas were reported by the operator (table 2).

All of 10 samples of the Escabrosa limestones contained poor amounts of organic carbon. In the one sample analyzed for kerogen, the amorphous type is predominant and would indicate oil generation if organic richness were sufficient. A mature stage of thermal alteration was determined.

In the black Percha mudstones, organic richness is generally poor but is fair at the base. Gas-generation is indicated by the dominant woody kerogen. Thermal alteration is mature to overmature. At the base, a fair amount (740 ppm) of C_{15+} bitumen was extracted, including a very good portion (407 ppm) of hydrocarbons. The relatively high aromatic content indicates that heavy oil was generated from the generally gas-prone woody material or from the minor amorphous kerogens. High percentages of vitrinite reflectance were determined on reworked material; no indigenous populations were recognized. According to pyrolysis data the genetic potential is poor in the Percha and older units.

Montoya dolostones contain very poor amounts of organic carbon. Kerogens indicate oil generation and a mature stage of alteration. El Paso limestones contain poor to fair amounts of organic carbon and oil generation is indicated; however, thermal alteration has reached the overmature stage, probably as a result of the great overburden prior to Tertiary erosion. In the black mudstone of the basal El Paso, which is transitional with the Bliss lithology, organic content is very good and oil prone, but also overmature.

Cockrell No. 1 Playas State (table 7). Depth intervals, rock types, and color notations down to 5,600 ft were determined in a detailed lithologic analysis that was in progress during the current project; the remainder were determined with the mounted-cuttings strip log. Geochemical data were taken from Tybor (1981c).

This well was drilled on a structural high within the Playas Valley (fig. 1). Probably after Laramide time, about 14,000 ft of Permian and Lower Cretaceous rocks were removed by erosion. This well provides important control for source rocks in the middle and lower Paleozoic. Unfortunately, cuttings are poor or absent as a result of lost circulation in parts of the Horquilla, Paradise, and Escabrosa. No gas, oil fluorescence or cut were reported by the United Core mudlogger.

Horquilla limestones generally contain poor to marginally fair amounts of organic carbon. The dominant amorphous and degraded-herbaceous kerogens indicates oil generation. Thermal alteration has reached the mature stage as determined by color of the kerogens and by one determination of vitrinite reflectance. From the richest sample at 3,250-2,260 ft, a poor amount (371 ppm) of C_{15+} bitumen was extracted, including a poor amount (95 ppm) of hydrocarbons. Pyrolysis data indicate a poor genetic potential.

Paradise limestones generally contain good to very good amounts of organic carbon. Kerogens are gas-and oil-prone, and thermal alteration is in the mature to overmature range. Vitrinite-reflectance percentages are in the overmature range. In the richest sample at 4,000-4,010 ft, extraction of C_{15+} bitumen was poor (347 ppm), including a fair amount (175 ppm) of hydrocarbons, which may have been generated from trace to secondary populations of herbaceous or amorphous kerogen. Pyrolysis data on that sample indicate a poor genetic potential. As in this case, where no S_2 peak was obtained, GeoChem designates the indeterminate T°C Max as 0. One dark mudstone at 4,050-4,060 ft has poor organic richness.

At the top of the Escabrosa, a light brownish gray limestone in the sample at 4,130-4,140 ft was selected for analysis. The organic-carbon percentage (0.36) indicates good richness, but may have been determined on caved material from the overlying Paradise. In this part of the well, cuttings are so small that they are difficult to pick selectively. Types of kerogen and thermal-alteration indices are similar to those in the Paradise. The wide range of vitrinite-reflectance determinations indicates a mixing of cuttings; the modal range is listed in column 7. C_{15+} bitumen extraction was poor. P-N and Arom amounts were too small to measure. The total C_{15+} hydrocarbons may be estimated as 63 ppm by taking one-half the difference between amounts of total bitumen and nonhydrocarbons. Pyrolysis data indicate a poor genetic potential. The rest of the samples of Escabrosa limestones have more normal organic richness in the poor to fair range. Both oil- and gas-generating kerogens are present, and thermal alteration is mature to overmature.

Percha mudstones generally have poor organic richness. Inertinite kerogens predominate, and there are no secondary populations, so neither oil nor gas is likely to have been generated. Thermal alteration is mature to overmature. The basal part at 5,560-5,570 ft is the richest with a fair percentage (0.83) of organic carbon. A good amount (1,163 ppm) of C_{15+} bitumen was extracted, but P-N and Arom amounts were too small to measure. The high percentage of nonhydrocarbons may indicate that an asphaltic residue has formed along the Percha/Montoya unconformity. Pyrolysis data indicate a poor genetic potential.

Montoya dolostones contain fair to good percentages of organic carbon. Amorphous-algal kerogens would have generated oil, but it would have been thermally degraded during the overmature stage of alteration. A good amount (1,382 ppm) of C_{15+} bitumen was extracted, but P-N and Arom amounts were too small to measure. Here also an asphaltic residue is indicated. The United Core mudlogger reported a show of dead oil around 5,780 ft.

El Paso limestones and dolostones generally contain poor amounts of organic carbon. Dominant amorphous-algal kerogens may have generated oil, but the poor richness and overmature kerogens make that doubtful. In the sample at 6,630-6,640 ft the organic richness is good on the dolostone scale. However, the GeoChem description mentions some mudstone which also was analyzed; that amount (0.36 percent) is poor on the mudstone scale.

A sandy dolostone in the Bliss has fair organic richness. Although inertinite kerogens are dominant, the secondary amorphous types may have generated some oil. At the overmature stage of alteration, the oil probably was thermally cracked to form gas and condensate.

KCM No. 1 Forest Federal (table 8). Canned cuttings were collected by the mudlogger at arbitrary depths 100 to 300 ft apart from 1,300 to 4,400 ft. Afterward, additional samples were selected from 70 to 1,210 ft. Rock types and color notations were determined in a detailed lithologic study (Thompson, 1977). Geochemical data, including measurements of hydrocarbon gases and gasolines not shown in table 8, were taken from Cernock and Bayliss (1977), a supplementary report by Cernock dated October 6, 1977, and a revision of the kerogen data by A.B. Reaugh dated September 16, 1981.

This well was drilled on the Winkler Anticline, an inlier of Paleozoic and Mesozoic rocks surrounded by Tertiary volcanic rocks in the central part of the Animas Mountains (fig. 1). It spudded in the basal part of the Earp Formation and drilled a fairly complete section of Horquilla. However, from 2,255 to 4,464 ft (total depth) was an igneous-metamorphic complex of Tertiary intrusive rocks and metamorphosed Horquilla. Documentation of the metamorphism and the position of the well in a volcanic-cauldron complex is presented in the series of papers by Thompson and others (1977). Renault (1980a, b) analyzed carbonate thermoluminescence and crystallite-size variation in cherts to make more precise estimates of the paleotemperature profile. Although it condemned the Winkler Anticline as a petroleum prospect, this KCM well provided important data concerning the effects of thermal metamorphism on the source rocks of this area. No shows of oil or gas were reported by the Simco mudlogger.

In the Big Hatchet Mountains, the Earp Formation consists of red mudstones, sandstones, and conglomerates. In this area, it is in a limestone facies. Only the lower 255 ft of Earp were evaluated in this well. The one sample analyzed, from 70-80 ft, shows that the limestone contains only a marginally fair amount of organic carbon. Kerogens are oil and gas prone. Thermal alteration has reached the mature stage probably as a result of burial long before Tertiary intrusion. More than 3,000 ft of younger Permian rocks overlying the Earp were removed from the crest of the anticline by erosion between Late Permian and Early Cretaceous time. About 7,600 ft of Lower Cretaceous rocks and possibly 1,000 ft of Upper Cretaceous-Lower Tertiary conglomerates exposed on the flanks of the anticline were eroded from the crest prior to Tertiary volcanism (Zeller and Alper, 1965).

Shallow-marine, shelf limestones of the uppermost Horquilla (260-760 ft) contain poor to very good amounts of organic carbon. Kerogens indicate both gas and oil generation. Thermal alteration is in the mature to overmature range.

Deep-marine, dark basin mudstones in the middle part of the upper Horquilla can be divided into two source units. The upper one (790-1,210 ft) has generally fair amounts of organic carbon, gas- and oil-generating kerogens, and an overmature aspect indicated by thermal-alteration indices and vitrinite reflectance. C_{15+} bitumen was extracted from dried cuttings in fair amounts (554-1,070 ppm), but hydrocarbon amounts were too small to measure. The B carbon-preference index was indeterminate, so the A index is given in column 9.

The lower source unit in the mudstone section (1,300-1,500 ft) has generally poor amounts of organic carbon, dominantly gas-generating kerogens, and again an overmature aspect indicated by thermal alteration indices and vitrinite reflectance. In the samples of canned cuttings, analyses of hydrocarbon gases and gasolines determined lean to rich amounts (424-1,005 ppm) of methane (C_1), very lean amounts (25-42 ppm) of ethane-butane (C_2-C_4), and very lean amounts (5-13 ppm) of pentane-heptane (C_5-C_7). C_{15+} bitumen was extracted from canned cuttings in poor to fair amounts (343-912 ppm), including very poor to good amounts (25-278 ppm), of hydrocarbons.

These C_{15+} hydrocarbons may have been generated from the trace populations of degraded herbaceous kerogen in the lower unit. If so, then why are no C_{15+} hydrocarbons present in the upper unit which has some secondary populations of degraded herbaceous kerogen? This question may be explained by a difference in sample preservation. Analyses of the lower unit were made on canned cuttings; those of the upper unit were made nearly two years later with dried cuttings. However, L.P. Tybor (personal communication, 1981) states that in GeoChem's experience, such drying has no significant effect on the C_{15+} results. A more likely explanation is that these hydrocarbons have migrated from another source. In both the upper and lower mudstone units, organic matter has reached the overmature stage and any indigenous C_{15+} hydrocarbons should have been thermally degraded.

In previous reports on this well, thermal-alteration indices were less, and an unusual relationship was shown at the boundary between the upper and lower mudstone units. The indices above were determined to be in the overmature range, and those below were determined to be in the mature range. The previous worker had made these determinations in two separate studies. For this project, A.B. Reaugh was asked to restudy the kerogen slides;

she found that the entire section from 310-2,000 ft is overmature.

On the electrical log, the upper mudstone unit has a greater deflection on the spontaneous-potential curve (-100 mv) and a generally lower resistivity on the induction curve (more than 200 ohm-meters) than the lower unit. Because both units appear the same on the gamma ray-sonic log, the upper unit was considered to be a washout zone produced during drilling (Thompson, 1977, p. 11). In the current project, the rock types were checked again using a mounted-cuttings strip log, and both units appear to be dark calcareous mudstones as described previously. No oil fluorescence or cut was detected and no bitumen could be extracted with naphtha from selected samples. Nevertheless, A.D. Jacka found dolomite and dead oil in a preliminary study of the thin sections. When he makes a more detailed petrographic analysis, some key questions may be resolved concerning the source aspects of the basin mudstones and the relationship with the dolostone-reservoir facies at the shelf margin.

Beneath the mudstones are deep-marine limestones in the lower (main) part of the upper Horquilla. The highest interval in this unit (1,590-1,800 ft) has good amounts of organic carbon. The sample at the top (1,590-1,600 ft) has secondary amounts of degraded herbaceous kerogen, which may have generated some oil. However, gas-generating kerogens are dominant, including a newly designated, relict amorphous (Am*) type (A.B. Reaugh, personal communication, 1981). Analyses of gases and gasolines determined lean to rich amounts (259-7,336 ppm) of methane, very lean amounts (16-25 ppm) of ethane-butane, and very lean amounts (2-4 ppm) of pentane-heptane. C_{15+} bitumen was extracted in poor amounts (222-381 ppm), including very poor amounts (24-39 ppm) of hydrocarbons.

The next interval in this limestone unit (1,890-2,200 ft) has fair amounts of organic carbon. Kerogens indicate only gas generation; however, the amounts of kerogen were so small that the analyses are considered unreliable. Amounts of methane decreased markedly to lean (498-740 ppm). Lean amounts of ethane-butane (101-337 ppm) and pentane-heptane (24-54 ppm) show a marked increase from the overlying unit, but most of these hydrocarbons came from the air space in the tops of the cans, indicating that they may not be indigenous. These limestones show some recrystallization that is transitional with the metamorphism below.

All of the remaining samples analyzed (2,290-4,400 ft) are from the igneous-metamorphic complex of Tertiary quartz monzonite and Horquilla marble and hornfels. Because it is unlikely that quartz monzonites and white marbles would contain 0.13-0.14 percent organic carbon, all of these determinations probably were made on the caved limestones and mudstones in the samples. Such misleading results were excluded from table 8.

The Tertiary intrusives metamorphosed the Horquilla up to 2,000 ft above the main quartz-monzonite body encountered in the bottom of the well. The next 300 ft of limestones above were recrystallized. However, the overlying 1,800 ft of limestones and mudstones appear to have escaped the metamorphic effects and the source-rock parameters do not appear to have been disturbed significantly. If this one example is representative of vertical and lateral relationships, petroleum-source rocks lying more than a few thousand feet away from the Tertiary intrusive complexes, may not be affected.

Humble No. 1 State BA (table 9). Depth intervals, rock types, and color notations were determined during the current project using the mounted-cuttings strip log; however, it only goes down to 11,000 ft. Below that depth, general intervals were selected from the description of Zeller (1965, p. 116-117), and specific intervals were chosen at GeoChem.

Geochemical data are taken from Cernock (1977) and a supplementary report by Cernock dated July 3, 1978. The latter contains only the kerogen and thermal-alteration index determinations for sample 460-470 ft and those between 4,160 and 4,220 ft. These palynological determinations were made by A.B. Reaugh, who recognized degraded herbaceous kerogen (H*) and assigned slightly lower thermal-alteration indices than those given in the previous report. Composite samples were prepared for some kerogen and C_{15+} analyses. They are shown by gross intervals in columns 5-6. For example, the first such composite is 4,350-4,390 ft and the data are plotted along the line for 4,350-4,360 ft.

This well was drilled on a prominent surface anticline in the U-Bar Formation located southwest of the Big Hatchet Mountains. A nearly complete Paleozoic section was drilled down to the total depth of 14,585 ft, which is the record so far in Hidalgo County. Part of the Epitaph Formation was repeated by a reverse fault. Beneath the fault, a minor amount of gas was recovered on a drill-stem test of Epitaph dolostones. Older formations are in normal stratigraphic succession down to the botttom of the well where another reverse fault may be present. Cuttings are generally good and free of cavings, so source-rock evaluations in this key well are considered reliable. The Tex-Mex mudlogging report was not available at this writing.

One sample of limestone in the lower part of the U-Bar Formation has a good amount of organic carbon, oil-generating kerogen, and a mature aspect of thermal alteration. Maturity probably was reached prior to deposition of the Tertiary volcanic rocks, which unconformably overlie the lower U-Bar in the Alamo Hueco Mountains to the south, because over 8,000 ft of younger U-Bar and Mojado have been removed from this location by pre-Tertiary erosion. Hell-to-finish has poor organic richness as would be expected in such red mudstones.

Because of lost-circulation while drilling into cavernous limestones at the top of the Concha, no samples are available for most of that unit. The one near the base with poor organic richness may not be representative of the entire formation.

In the Epitaph, light-colored dolostones contain poor amounts of organic carbon. Darker ones generally have fair amounts, oil- and/or gas-generating kerogens, and a mature stage of thermal alteration. Consecutive samples in the 4,160-4,220 ft interval were selected to evaluate the dark-dolostone zone from which a minor amount of gas (10,000 cubic ft) was recorded on a drill-stem test. The zone has good to very good amounts of organic carbon, oil- and gas-generating kerogens, and a mature aspect. The lowest sample in the Epitaph at 4,350-4,360 ft has a good amount of organic carbon, gas-and oil-generating kerogen, and a mature aspect. A very poor amount (59 ppm) of C_{15+} bitumen was extracted from this sample, and no measureable C_{15+} hydrocarbons were detected.

Dark Colina limestones have fair amounts of organic carbon, gas- and oil-generating kerogens, and a mature aspect. Red mudstones and limestones (probably conglomerates) in the Earp have only poor amounts of organic carbon as expected.

Dark, deep-marine mudstones and limestones of the Horquilla Formation have poor to good amounts of organic carbon, gas-and oil-generating kerogens, a mature to overmature aspect in the upper part, and an overmature aspect in the lower part of the section (below 8,790 ft). The overmature stage of thermal alteration is confirmed by the determination of vitrinite reflectance at 10,050-10,060 ft. All determinations of thermal alteration in formations below are also in the overmature range. Only poor amounts (89-172 ppm) of C_{15+} bitumen were extracted from the Horquilla samples, and amounts of C_{15+} hydrocarbons were too small to measure. Because some normal paraffins in the nC_{30}-nC_{32} range were absent, the A carbon-preference index was listed in column 9 for these samples and others below.

Paradise mudstones and limestones contain poor to fair amounts of organic carbon. However, if all the organic material is predominantly inertinite as in the sample at 11,100-11,110 ft, the hydrocarbon-generation capacity would be lower than the percentage of organic carbon indicates. Secondary and trace populations of woody and herbaceous kerogen may have generated gas. A poor amount (126 ppm) of C_{15+} bitumen was extracted, and no hydrocarbons were measureable. Escabrosa limestones contain only poor to marginally fair amounts of organic carbon.

Percha mudstones have poor to fair (at base) amounts of organic carbon. Inertinite kerogens predominate, but some gas or oil may have been generated from secondary to trace populations of herbaceous and woody types. C_{15+} bitumens were extracted in very poor amounts (106-190 ppm). The poor amount (50 ppm) of C_{15+} hydrocarbons determined in the sample at the base may have been derived from the herbaceous or amorphous kerogens in the Percha, or may have migrated along the Percha/Montoya unconformity.

Montoya dolostones have poor to marginally fair amounts of organic carbon. Most of the El Paso limestones (13,300-14,060 ft) contain poor amounts of organic carbon. The predominant amorphous kerogens may have generated oil; the secondary herbaceous material probably is caved because no land-plants were present before Silurian time. The secondary population of herbaceous kerogen in the lowest sample (14,400-14,440 ft) may also be caved; however, the predominant woody material probably is not caved in such good cuttings. This evidence may be used in support of a previous interpretation that this interval is middle or lower Escabrosa lying beneath the El Paso with the reverse-fault contact at 14,120 ft. Nevertheless, this basal interval will be left tentatively in the El Paso until micropaleontological or other definitive evidence is available.

DISTRIBUTION OF PETROLEUM-SOURCE UNITS

Table 10 is a summary of the basic evaluations from tables 3-9. It represents the general vertical distribution of petroleum-source units from the youngest formation at the top (Mojado) to the oldest at the base (Bliss). Evaluations of individual samples have been grouped by formation to show the ranges of organic-carbon richness, dominance of oil-or gas-generating kerogens at maturity, and the stages of maturation based on thermal-alteration indices. It also represents the general horizonal distribution of source units from the Cockrell No. 1 Pyramid Federal well on the northwest (left) to the Humble No. 1 State BA well on the southeast (right). Supporting or nonsupporting lines of evidence from other geochemical data for these basic evaluations were given in the discussions of individual wells in the previous chapter.

Figures 4-17 show the basic-evaluation symbols from table 10 spotted by the wells in a series of petroleum-source maps for each formation. The order from youngest to oldest presents the normal succession of units as they would be encountered during drilling. The reverse order shows the distribution of source units through time.

Near each key well, the current-evaluation range of source units in the given formation is also spotted (and written out in capital letters). The current evaluation considers the probability of oil or gas generation at the presently determined, thermal-maturation stage of a given source unit. None of the source units in this study was determined to be immature. If a source unit is mature, the same phase of oil or gas generation designated in the basic evaluation may be used in the current one. If a unit is overmature, the current phase will be gas (including possibly some condensate) even if oil is the only phase designated in the basic evaluation. Nevertheless, the possibility of oil generation at a lesser depth in an adjacent area, or in the same area at a previous time, should be considered in any comprehensive assessment.

Subjective judgement was used in rational determination of current evaluations (in contrast to the objective use of standard scales in empirical determination of basic evaluations). The poor-fair-good classification corresponds generally to the basic evalutation of organic richness; however, an estimated modal range of richness is used and marginal or aberrant values are discounted. Also, the amount of inertinite kerogen, which generates only a trace of gas, is subtracted from the total by 60 percent where that type constitutes the predominant population (or by 30 percent if two types constitute the predominent population). Kerogen evidence is believed to be generally reliable in determinations of oil or gas generation at maturity and of thermal-alteration stages; however, other geochemical or geologic evidence may be considered in the current evaluations.

On these maps, major changes of depositional facies are indicated. Limestone facies may be better source areas than mudstone facies with the same organic richness.

The present eroded edge of the main thrust zone (black triangles on upper plate) is taken from fig. 1. The inferred maximum extent of this major Laramide structure is plotted a few miles to the northeast (open triangles on upper plate). Prior to erosion in Late Cretaceous-Early Tertiary time, the overburden of Precambrian, Paleozoic, and Mesozoic rocks may have reached a total of over 20,000 ft on the upper plate. Such great depths of burial produced overmature thermal alteration of the Lower Cretaceous and older rocks in the lower plate.

Localities where the formations are absent by erosion or nondeposition are indicated as accurately as present control permits. Many units are absent on the Burro Uplift, the southern part of which extends into the northern part of the map area. Probably all of the Paleozoic formations were deposited over this region. Horquilla and older units may have been removed from parts of the Burro Uplift by mid-Wolfcampian erosion. However, between Late Permian and Early Cretaceous time, most of the Paleozoic section was eroded from the uplift. Lower Cretaceous rocks may have onlapped this positive element, but they also were removed by erosion on the Laramide expression of the uplift between Late Cretaceous and Early Tertiary time.

On the northeast-southwest trending Winkler Anticline, where the KCM No. 1 Forest Federal well was drilled, Concha (and Scherrer), Epitaph, and much Colina were eroded between Late Permian and Early Cretaceous time (Zeller and Alper, 1965). Around several wells, local erosion between Late Cretaceous and Early Tertiary time is inferred on Laramide anticlines or other highs with axes generally trending northwest-southeast.

To avoid congestion on these small-scale maps, some post-Laramide features were omitted, but they should be checked on fig. 1 when evaluating petroleum prospects. Local metamorphism is indicated within the Tertiary volcanic cauldrons and in other areas with Tertiary intrusive rocks, including the central Peloncillo Mountains (25S, 21 W), northern Pyramid Mountains (23S, 19W), and southern Little Hatchet Mountains (28-29S, 16W). Local erosion of a unit, at least by Quaternary time, is indicated where older rocks are exposed on the surface.

These petroleum-source maps provide a reasonably complete summary of the available subsurface data in southern Hidalgo and Grant Counties. They will be improved with more detailed stratigraphic-sedimentologic studies of the wells and outcrop sections, and with added geochemical control from outcrop samples. They will become more useful with a companion set of maps showing petroleum-reservoir evaluations.

In the remainder of this chapter, the petroleum-source map of each formation is discussed. Selected information on individual wells is reviewed as a background for discussions of the current evaluations, especially those which differ significantly from the basic evaluations. Some observations are recorded about source characteristics of outcrop sections; most are preliminary because geochemical evaluations have not been made yet.

Mojado (fig. 4). Mudstones of the Mojado Formation generally constitute a poor to fair gas and oil source in the area. Sandstones in the lower part are the most closely associated reservoirs.

In the Cockrell No. 1 Coyote State well (25S, 16 W), the basic evaluation indicates poor to excellent organic richness, gas-and oil-generating kerogen, and a mature stage of thermal alteration. However, inertinites are the predominant kerogens in the richer samples (Tybor, 1981b, table V, summary column), including probably the one sample with excellent richness at 5,620-5,630 ft. For the current-evaluation range, the adjusted richness is poor-fair. C_{15+} data indicate some heavy-oil generation. A mature stage of thermal alteration is documented for the entire Mesozoic-Paleozoic section in this well. The mudlogger reported a slight show of oil in Mojado sandstone, but fresh water (chloride content 120-150 ppm) was recovered on two drill-stem tests.

Similar source characteristics may be expected in the Powers No. 1 State well (26S, 17W) and in the Brockman Hills exposures (25S, 16W). Reported shows of oil and gas in the Wininger and Berry No. 1 State well (27S, 16W) are inferred to be in the Mojado.

If the mudstones in this area onlap the Burro uplift to the northeast, stratigraphic traps may be present in the underlying sandstones. However, it appears more likely that the Mojado and older units were eroded from the uplift, and that fresh water entering from the exposed area migrated downdip into the sandstones.

In the KCM No. 1 Cochise State A well (28S, 17W), the current evaluation shows that the Mojado here constitutes a poor to fair gas source. Adjustments of the percentages of organic carbon for the predominant co-populations of inertinite (and woody kerogen) do not change the poor-fair range of richness. Analyses of canned cuttings demonstrate that the mudstones generated dry gas with minor amounts of wet gas and gasolines. Only very minor amounts of heavy oil (C_{15+} hydrocarbons) were extracted. Although amorphous kerogens occur in trace to secondary populations, their appearance here may indicate a more favorable oil-prone facies toward the southwest in a depositional environment farther offshore. Minor dry gas shows were reported by the mudlogger. The overmature stage of thermal alteration is considered to be the result of deep burial in the lower plate of the main thrust zone.

Because of local erosion around the wells, no subsurface sections of Mojado could be evaluated on the upper plate of the main thrust zone and the area to the southwest. A mature stage of alteration is inferred for this area based on determinations in older units.

At the key surface section south of the Big Hatchet Mountains (32S, 15W), dark mudstones may lie in the covered intervals between the sandstones. In this more offshore direction, the mudstones may contain a higher percentage of amorphous or algal, oil-prone kerogens. Sandstones in this section have the best reservoir quality of any seen in the Mojado of this region.

U-Bar (fig. 5). Limestones of the U-Bar constitute a poor to fair gas and oil source in the northern part and a poor (?) to good oil (and gas?) source in the southern part of the map area. Sandstones in the overlying Mojado may be the most closely associated reservoirs. No effective porosity has been observed in the rudist buildups in the upper U-Bar (or in the equivalent massive limestones of the Mural in southeastern Arizona).

In the Cockrell No. 1 Coyote State, the reduction of organic-carbon percentages for inertinites results in a poor-fair range of richness. Although the KCM No. 1 Cochise State A was not drilled to the U-Bar, any source units probably are overmature, judging by the ones in the Mojado.

In the Humble No. 1 State BA well (32S, 16W), only the basal part of the U-Bar was drilled. The one sample analyzed has good organic richness, predominantly degraded herbaceous kerogen which should generate oil, and a mature aspect of thermal alteration. In the surface section to the northeast, some parts of the U-Bar are judged to have poor organic richness, but the entire section should be documented. Some gas-prone kerogens probably will be found.

Hell-to-finish (fig. 6). Red mudstones of the Hell-to-finish are judged to be very poor sources of petroleum. The poor organic richness shown in the basic evaluation of the Cockrell No. 1 Coyote State would be reduced by the predominant co-population of inertinite. Woody kerogens may have generated some gas. The amount of organic carbon is very low (0.05 percent) in the sample from the Humble well.

Concha (fig. 7). Limestones of the Concha may constitute a poor to fair source of petroleum based on preliminary observations in the Big Hatchet Mountains and in other sections in the region. In the Humble well, the only sample analyzed contains very poor amounts of organic carbon, but it may not be representative of the entire formation. According to evidence in the Cockrell No. 1

Coyote State, the Concha and older Paleozoic rocks down to the Montoya were eroded from a broad area of the Burro Uplift prior to the deposition of the Hell-to-finish.

Epitaph (fig. 8). As documented in the Humble well, light-colored dolostones in the upper part of the Epitaph contain poor amounts of organic carbon. Dark-colored dolostones in the lower part generally contain fair amounts of organic carbon and only trace populations of inertinite. In a dark-colored zone about 60 ft thick, which lies below a major reverse fault, organic richness is good to very good, and degraded herbaceous kerogens are dominant. However, only a small amount of gas was recovered on a drill-stem test of this zone. These herbaceous kerogens may not have been degraded sufficiently to become oil prone. In the current evaluation of the entire Epitaph, gas generation is judged to be quantitatively more important than oil generation. Additional control may be obtained in the Big Hatchet Mountains and in the Cockrell No. 1 State 1125 (31S, 17W). Minor porosity has been observed in the Epitaph of this region.

A mature stage of thermal alteration is inferred over the southern part of the area up to the eroded edge of the main thrust zone. In the overmature area beneath the restored part of the thrust, any oil generated probably has been degraded thermally to gas (and possibly condensate). In the inferred mature area northeast of the major thrusting, oil could have been preserved if that facies contained sufficient richness of oil-generating kerogens.

Colina (fig. 9). Dark limestones of the Colina probably constitute a fair gas source wherever present in the area. All six samples in the Humble well contain fair amounts of organic carbon. Kerogens are mainly woody and herbaceous with only trace populations of inertinite. Similar source characteristics may be documented in the Big Hatchet Mountains and in the Cockrell No. 1 State-1125 well.

Earp (fig. 10). In the Humble well, red mudstones and limestone conglomerates of the Earp contain very poor amounts of organic carbon. This facies is exposed in the Big Hatchet Mountains and appears to extend over much of the region. The limestone facies observed in the Winkler Anticline area is areally restricted, at least on the north and east sides. This limestone has a nonmarine aspect and may be a coastal-lagoon or lake deposit. The lower part of that section was drilled by the KCM No. 1 Forest Federal well (31S, 18W). The only sample analyzed contains marginally fair amounts of organic carbon. Kerogens are predominantly amorphous with secondary amounts of woody and inertinite types. Thermal alteration has barely reached the mature stage. A poor oil and gas source is designated for the current evaluaton of this minor limestone facies.

Horquilla (fig. 11). Outcrop samples from selected dark Horquilla limestones in the Big Hatchet Peak section (31S, 15W) contain fair to very good amounts of organic carbon (Thompson and Jacka, 1981, p. 70, table 2). Kerogens are predominantly of the degraded herbaceous type; secondary populations are woody with minor inertinite. Over most of this 3,200-ft section, thermal-alteration indices are in the mature range (2+ to 3+, generally 3);

the basal part is overmature (3+ to 4-). For the current evaluation, a fair-good oil and gas source is designated. In the upper part of the Horquilla, several porous dolostones are described; their net thickness is 484 ft. This reservoir facies is projected as a relatively narrow band around the margin between the shallow-marine shelf and the deep-marine basin facies of the upper Horquilla.

In the Cockrell No. 1 Playas State well (30S, 17W), the Horquilla is only 1,356 ft thick, possibly as a result of depositional thinning northward from the shelf margin, Tertiary normal faulting, and Tertiary-Quaternary erosion of the uppermost part. No dolostones were recognized in the lithologic study. The limestones contain poor to marginally fair amounts of organic carbon, discounting inertinite. Amorphous kerogens are predominant in the upper part, indicating a more oil-prone facies than that of the Big Hatchet Peak section. Degraded herbaceous, woody, and inertinite kerogens predominate in the lower part, indicating oil and gas generation. All thermal-alteration indices are in the mature range. A poor oil and gas source is designated for the current evaluation.

In the KCM No. 1 Forest Federal well (31S, 18W), the Horquilla is at least 3,500 ft thick. In the upper part, shelf limestones with predominant co-populations of woody and inertinite kerogen contain poor to very good amounts of organic carbon, which after subtraction of inertinites are poor to good. Secondary populations of degraded herbaceous kerogen may have generated some oil. Basin mudstones contain poor to fair amounts of organic carbon, (even after adjustments for inertinite), predominant co-populations of woody-inertinite kerogens, and secondary to trace populations of degraded herbaceous types. Basin limestones contain good amounts of organic carbon, and predominant populations of relict amorphous or woody-intertinite kerogens, all of which are gas prone. Analyses of canned cuttings show abundant methane and lean amounts of other gases, gasolines, and heavy oil (C_{15+}). Although the organic matter in the uppermost part of the Horquilla is mature, that in most of the upper Horquilla is overmature, so any oil that was generated has probably been thermally degraded to gas. The thermal alteration may be a result of normal burial and/or local excessive heating. The lower part of the Horquilla here has been thermally metamorphosed to marble and hornfels by Tertiary quartz-monzonite intrusives. For the current evaluation, a poor-good, gas source is interpreted in the upper Horquilla.

In the Humble No. 1 State BA well (32S, 16W), the Horquilla is over 4,700 ft thick. Basin mudstones and limestones in the upper part, and shelf limestones in the lower part, contain poor to good amounts of organic carbon. Kerogens are predominantly woody with secondary amounts of herbaceous or inertinite types. Amounts of C_{15+} hydrocarbons were too small to measure. With depth, thermal alteration increases from mature to overmature. A poor-good gas and oil source is interpreted for both the basic and current evaluations.

Because the porous dolostones in the upper Horquilla constitute the best reservoir objective in the area, the associated source facies should be studied in more detail, especially in the Big Hatchet Mountains. Organic richness appears to be best near the shelf-basin margin. Amorphous kerogens appear to be limited to the northwest side. Algal kerogens were expected to be abundant, especially in the algal-rich shelf limestones. However, the vegetative parts may have been selectively devoured or oxidized in the depositional or diagenetic environment (Thompson and Jacka, 1981, p. 70).

At normal depths of burial, the lower part of the Horquilla tends to reach an overmature stage of thermal alteration. In the deeper parts of graben valleys, where chances are best for preservation of petroleum in commercial quantities, the upper Horquilla source rocks may be overmature and any oil generated may be thermally degraded. However, the probability of gas generation and preservation is excellent.

Paradise (fig. 12). In the Cockrell No. 1 Playas State, Paradise limestones and mudstones contain poor to very good amounts of organic carbon even after subtraction of predominant co-populations of inertinite. Woody kerogens constitute the other predominant co-populations, and herbaceous types are secondary. The fair amount of C_{15+} hydrocarbons may have been generated by the secondary to trace populations of herbaceous and amorphous kerogens. Thermal-alteration indices are in the mature-overmature range; vitrinite-reflectance indicates overmature. An overall fair to good gas and oil source is interpreted for the current evaluation of this section.

In the Humble well, the basic evaluation indicates poor to fair amounts of organic carbon. However, subtraction of predominant inertinite indicates only poor richness. Moderate amounts of gas may have been generated from the secondary and trace populations of woody and herbaceous kerogen. Thermal alteration has reached the overmature stage. A poor gas source is indicated.

Escabrosa (fig. 13). In the Cockrell No. 1 Pyramid Federal well (24S, 19W), Escabrosa limestones contain poor to marginally fair amounts of organic carbon, predominantly degraded herbaceous-woody and amorphous kerogens. Thermal alteration is mature to partially overmature. Tertiary intrusives apparently did not metamorphose the organic matter. For the current evaluation, a poor oil and gas source is indicated.

In the Hachita Dome No. 1 Tidball-Berry Federal well (30S, 15W), the limestones contain only poor amounts of organic carbon. In the one sample analyzed for kerogen, amorphous is the only type present, and the thermal-alteration index is mature. A poor oil source is indicated.

In the Cockrell No. 1 Playas State, the one good rating of organic richness is reduced to fair by subtraction of inertinite. Both gas- and oil-prone kerogens are present, and thermal alteration is mature to overmature. A poor-fair, gas and oil source is indicated.

In the Humble well, organic-carbon content is poor to marginally fair. A poor source is indicated.

Dark limestones seen in the middle part of the Escabrosa in the Big Hatchet Mountains may be organically rich. Some beds in the lower part may be moderately rich. Massive, white, crinoidal limestones in the upper part are probably poor source units.

Percha (fig. 14). In the Pyramid well, dark Percha mudstones contain generally poor amounts of organic carbon. One sample at the base contains a fair amount, subtraction of inertinite decreases it to poor. Secondary populations of amorphous-herbaceous kerogens may have generated some oil. Thermal alteration is mature to partially overmature. A poor gas and oil source is indicated for the current evaluation.

To the west in the Peloncillo Mountains (25S, 21W), the Percha has been metamorphosed by Tertiary intrusions. Other Paleozoic and Mesozoic units have been affected to varying degrees.

In the Hachita Dome well, the mudstones again contain generally poor amounts of organic carbon. The one sample at the base with a fair amount, according to the basic evaluation, contains a poor amount when the predominant co-population of inertinite is subtracted. Woody kerogens are also predominant. Thermal alteration is mature to overmature. Aromatic C_{15+} hydrocarbons extracted from the basal sample may have been derived from woody material or from trace populations of amorphous-herbaceous kerogens. A poor gas and oil source is indicated.

In the Playas well, mudstones again contain generally poor amounts of organic carbon. The basal samples is fair (0.83 percent), but when the predominant inertinite is subtracted (estimated to be 80 percent or more because there are no secondary populations), the result is poor (0.17 percent). The good amount of C_{15+} bitumen, with no measureable hydrocarbons, may be an asphaltic residue that was formed along the Percha/Montoya unconformity. Thermal alteration is mature to overmature. A poor source is indicated, and neither oil nor gas are likely to have been generated.

In the Humble well, mudstones again contain generally poor amounts of organic carbon. The fair basal part becomes poor when the predominant inertinite is subtracted. Secondary populations of woody and herbaceous kerogens may have generated gas and some oil. The poor amounts of C_{15+} hydrocarbons may have been derived from trace populations of amorphous material. Thermal alteration is overmature. A poor gas source is indicated.

Higher percentages of organic carbon at the base of the Percha may be the result of a higher influx of detrital inertinite. After the inferred rapid rise of sea level in early Percha time, organic material should have been preserved with anoxic conditions in the deeper marine environment. During shallowing in late Percha time, more oxic conditions would have permitted biodegradation of organic material.

Bitumens extracted from the basal Percha may not have been generated from an indigenous source. The basal mudstones probably served as a seal for petroleum migrating up through fractures in the older Paleozoic carbonate rocks. Asphaltic residues may indicate later thermal- or hydro-degradation.

Because the equivalent Woodford is judged to be a good source unit in the Permian Basin area, the Percha was expected to be at least fair in Pedregosa Basin area. However, these results indicate a poor gas source at best and possibly a nonsource in some sections.

Montoya (fig. 15). Montoya and older Paleozoic rocks have been eroded from a smaller area on the Burro Uplift than the younger rocks. Previous information indicated that the Montoya was eroded between Late Ordovician and Late Devonian time in southeastern Arizona and adjacent parts of southwestern New Mexico.

However, recent control indicates that the Montoya probably is present in the western part of the map area.

The Fusselman Formation (Silurian) contains porous dolostones and is a major reservoir objective in Luna County (to the east). In southern Hidalgo and Grant Counties, the Fusselman appears to be absent by erosion between Late Silurian and Late Devonian time.

In the Pyramid well, Montoya dolostones contain very poor amounts of organic carbon. Because land-plants did not appear until Silurian time, only amorphous-algal kerogens are present in the Montoya (and older Paleozoic units). Thermal alteration is mature to partially overmature. A poor oil source is designated for the current evaluation.

In the Coyote well, the dolostones again contain very poor amounts of organic carbon. Amorphous kerogen is the only type present. Thermal alteration has only reached the mature stage in the Montoya and older units in this well. A poor oil source is designated. Younger Paleozoic units between this well and the restored edge of the main thrust (figs. 7-14) are inferred to be mature also.

In the Hachita Dome well, the dolostones again contain very poor amounts of organic carbon. Amorphous (algal-derived) kerogen is the only type present. Thermal-alteration is shown by the one kerogen determination to be mature; however, those above are mature to overmature, and those below are overmature. A poor oil source is designated for the current evaluation. If additional evidence shows this section to be overmature, the designation should be changed to a poor gas source.

In the Playas well, the dolostones contain fair to marginally good amounts of organic carbon. Amorphous (algal) kerogens are predominant. Inertinite is present as a secondary population and is indicated to be an indigenous kerogen. It probably was produced by thermal alteration or oxidation of the amorphous (algal) kerogen. Unfortunately, thermal alteration is overmature, so any oil generated from this rich facies probably has been thermally degraded to gas. The lack of measurable C_{15+} hydrocarbons within the good amount of C_{15+} bitumen, and the mudlogger report of dead oil, confirm the overmature interpretation. A fair gas source is designated for the current evaluation.

In the Humble well, the dolostones contain poor to marginally fair amounts of organic carbon. Kerogens were not analyzed. Thermal alteration is probably overmature, judging by the indices in units above and below. A poor gas source is designated.

In the Big Hatchet Mountains, some of the dark dolostones may contain sufficient organic matter to be classified as a fair to good source for basic evaluation as in the Playas well. This outcrop section lies between the thermally mature section in the Hachita Dome well and the overmature one in the Humble well. Minor porosity has been observed. Additional documentation may show the Montoya to be an important petroleum objective in the Playas and Hachita Valleys.

El Paso (fig. 16). In the Pyramid well, El Paso dolostones contain very poor amounts of organic carbon and amorphous kerogen. Thermal alteration is mature to overmature. Depending upon the stage of maturation, poor oil or gas source is designated for the current evaluation.

In the Coyote well, dolostones and limestones have very poor amounts of organic carbon, amorphous (algal) kerogens, and a mature aspect of thermal alteration. A poor oil source is designated.

In the Hachita Dome well, limestones contain poor to fair amounts of organic carbon and amorphous (algal) kerogens. Thermal alteration is overmature. The operator reported one gas show at a depth in the lower Montoya, and two gas shows at depths in El Paso limestones. The lowest sample in the El Paso (2,558-2,560 ft) is in a black, silty mudstone; this lithology is transitional with the underlying Bliss. The mudstone has very good amounts of organic carbon, amorphous kerogen, and an overmature thermal alteration. The only oil show reported by the operator was immediately below this interval. A current evaluation of poor-good gas source is designated for the combined limestone (poor-fair) and mudstone (good) units.

In the Playas well, limestones and dolostones contain generally very poor amounts of organic carbon. Amorphous and amorphous (algal) kerogens are described; inertinite is present in only trace amounts. Thermal alteration is overmature. In the lower part, one sample (6,630-6,640 ft) contains good amounts of organic carbon on the dolostone scale. Some mudstone is also present; on that scale, the amount of organic carbon would be poor. This mudstone may be correlative with that in the Hachita Dome well; however, it is about half as rich and the kerogen is predominantly amorphous with secondary amounts of inertinite. A poor-fair gas source is designated for the current evaluation of the combined rock types.

In the Humble well, definite El Paso limestones contain poor amounts of organic carbon. Kerogens are predominantly amorphous, with secondary co-populations of inertinite and herbaceous types; the latter probably is caved from the Percha or a younger unit. Thermal alteration is overmature. Limestones at the base of the section contain poor to fair amounts of organic carbon, and the kerogens are predominantly woody. The latter should not be present in an Ordovician unit. This basal section may be Escabrosa beneath a reverse fault, or the organic material may be caved. In either case, the data would not be representative of the El Paso. For the current evaluation, excluding the basal section, a poor gas source is designated.

In the Big Hatchet Mountains, several dark limestones and dolostones are present and may contain significant amounts of organic carbon. Dark mudstones in the lower part may be equivalent to those described in the subsurface sections.

Because all the El Paso kerogen is overmature in the three southern wells, the entire southern area up to the eroded edge of the main thrust is designated as overmature. (The same may be true of the overlying Montoya if additional analyses in the Hachita Dome well show that section to be overmature.) The area designated as overmature between the eroded and restored edges of the main thrust may actually be metamorphosed at such great depths, and the temperature limit of gas preservation may have been surpassed.

Bliss Formation (fig. 17). At many localities in the region, the boundary between the El Paso limestones/dolostones and

Bliss sandstones has been selected arbitrarily in a zone of transition. With detailed sedimentologic studies, a more reliable boundary can be chosen. Such work is beginning in the Big Hatchet Mountains, but has not been extended to other sections as yet.

Reconnaissance work at several exposures and in preliminary studies of the cuttings indicate that the normal sandstone facies of the Bliss extends over the northern part of the map area. No carbonate or mudstone units were seen in the cuttings that appeared worthy of petroleum geochemical analyses.

In the Cockrell No. 1 Playas well, a sandy dolostone was sampled and found to contain a marginally fair amount of organic carbon in the basic evaluation. However, inertinite is the predominant kerogen. Amorphous types constitute the secondary population. Thermal alteration is overmature. For the current evaluation, a poor gas source is designated. In this well and in the Hachita Dome well, mudstones in the El Paso-Bliss transition contain higher percentages of organic carbon than the carbonate rocks. After detailed study, one or both of these mudstone units may be placed in the Bliss.

In the Big Hatchet Mountains (Mescal Canyon section of Zeller, 1965), the Bliss contains several dark dolostones which may have significant amounts of organic carbon. However, if the kerogens are dominantly inertinite as in the Playas well, the generation capacity may be low. Any oil generated by amorphous kerogens probably was thermally degraded to gas when temperatures reached the overmature stage. This dolostone and sandstone facies of the Bliss may cover much of the area to the south and extend westward into Arizona. If the volume is large enough, the dolostone part could be an important gas source.

No effective porosity has been observed in the Bliss sandstones (or carbonate rocks) of this area. Quartzose sandstones are tightly cemented with silica. Feldspathic-arkosic sandstones found in channels eroded into Precambrian granite contain clay matrix as well as silica cement.

CONCLUSIONS AND RECOMMENDATIONS

Based on the current evaluations shown on the series of petroleum-source maps (figs. 4-17), the Paleozoic and Mesozoic formations of southern Hidalgo and Grant Counties, New Mexico appear to have a total generation capacity for abundant gas and moderate amounts of oil. At maturity, more oil was generated from several of the older units, but as temperatures reached the overmature range, that oil was thermally degraded to gas.

In the southern part of the area, fair to very good source units for gas have been identified in: El Paso limestones and dolostones (Ordovician), Montoya dolostones (Ordovician), Escabrosa limestones (Mississippian), Paradise limestones and mudstones (Mississippian), Horquilla limestones and mudstones (Pennsylvanian-Permian), Colina limestones and Epitaph dolostones (Permian). Fair to good source units for oil have been identified in the Escabrosa, Paradise, Horquilla, Colina, Epitaph, and U-Bar limestones (Lower Cretaceous). Mojado mudstones (Lower Cretaceous) have not been drilled in this area, but fair to good source units may be found in outcrop sections. Only poor source units are identified in Bliss dolostones (Cambrian-Ordovician), Percha mudstones (Devonian), Earp red mudstones (Permian), Concha limestones (Permian), and Hell-to-finish red mudstones (Lower Cretaceous).

Organic richness and types of kerogen appear to be highly variable over short distances of a few miles in some units, reflecting depositional/diagenetic changes. With additional control, other facies of the Bliss, Earp (limestone), and Concha may be found to contain at least fair source units. Because the Percha consists of dark marine mudstones similar to the equivalent Woodford, it was expected to contain fair to good source units; however, only the basal part has sufficient organic richness and the kerogens are dominantly inertinite. Nonmarine red mudstones of the Earp and Hell-to-finish are organically lean as expected.

At normal depths of burial, all units in the southern area are thermally mature or overmature. Organic matter is mature in units as old as Percha toward the north and is overmature in rocks as young as lower Horquilla toward the south (table 10).

In the middle part of the study area, a major thrust fault has displaced Precambrian, Paleozoic, and Mesozoic rocks northeastward over the Mojado. Because the latter is overmature, the section below probably is overmature or thermally metamorphosed. Operators who plan to drill several tens of thousands of feet to reach the lower plates in the current overthrust play should become aware of this evidence. Any oil generated probably has been thermally degraded to gas, and gas may not be preserved at the greater depths.

In the northern part of the area, fair source units for gas and oil have been identified in U-Bar limestones and Mojado mudstones. Only poor source units have been identified in the El Paso, Montoya, Percha, Escabrosa, and Hell-to-finish. All are mature. Middle and upper Paleozoic units were removed by pre-Hell-to-finish erosion on the southern part of the Burro Uplift.

With the geochemical evidence from this pilot study, operators may accept the fundamental conclusion that adequate petroleum-source units have been identified, and that further exploration should be encouraged in southwestern New Mexico and adjoining areas. However, additional work is needed on these same key wells and on outcrop sections for quantitative estimates of the petroleum potential.

Each surface and subsurface section should be analyzed in sufficient detail so that boundaries of individual source and reservoir units can be documented in vertical profiles. The stratigraphic framework should be improved so that such thin units can be correlated between sections with some degree of confidence. The sedimentologic control should be increased so that such units can be projected along depositional and diagenetic trends into favorable subsurface prospects.

In the past, wildcat locations in this area appear to have been chosen generally on structural prospects alone. In the future, locations should be chosen on structural prospects within favorable source and reservoir trends. The two best reservoir units identified so far, upper Horquilla dolostones and lower Mojado sandstones in the Big Hatchet area, have not been tested yet in the subsurface. Also, many wells have been located on Basin and Range uplifts where reservoirs tend to be flushed by fresh water. Preservation of oil and gas in commercial quantities is more likely in the Basin and Range depressions, especially the deep graben valleys.

For thorough evaluation of the prospects, adequate drilling programs should be planned to insure that good cuttings are obtained for representative samples over the entire section drilled. In too many cases, the cuttings are missing, are too fine, or are too mixed with cavings or other extraneous material to be analyzed with any degree of confidence. A team of mudloggers should be on 24-hour watch while drilling through Mesozoic and Paleozoic units in search of oil and gas shows. Canned cuttings should be collected in source units for analyses of hydrocarbon gases and light oils in this gas-prone province. Major source and reservoir units should be cored to provide critical data not available in even the best of cuttings. Drill-stem tests should be run on any reservoir unit, with or without a show of oil or gas, to measure subsurface pressures and provide samples of hydrocarbons or formation waters for analyses. A full suite of first-class, wire-line logs should be run. Such a complete program is expensive, but considering the great sums of money spent on leasing, geophysics, other preliminary exploration, and the basic drilling costs themselves, the acquisition of essential subsurface data should be given adequate priority within the total investment framework.

Along with additional control of source units in previous and future wells, improvements in geochemical analyses and interpretation guides may be considered. Scales of organic-carbon richness for carbonates and mudstones appear reliable for end-member rock types, but other scales may be needed for muddy carbonates and calcareous mudstones. If amounts of specific kerogen types could be estimated at least to the nearest 10 percent, the amount of inertinite could be discounted routinely from organic richness, and the amounts of oil- and gas-prone types could be used to calculate the expected proportions of each phase. Some types, such as herbaceous kerogen, may have proportions split between oil and gas generation. An integrated system may be designed for weighting organic carbon percentage, kerogen proportions, C_{15+} amounts, and other geochemical data so that oil- and gas-source indices can be calculated for a given sample of a source unit. When plotted in vertical profiles for each stratigraphic section, the results would provide quantitative summations of the evaluations, including volumetric estimates of generation capacities.

Some improvements are needed in the Rock-Eval instrument, or another method of pyrolysis should be considered for this gas-prone area. Results in this study were overly negative in comparison with those of more standard geochemical analyses. All pyrolysis determinations were made with dried cuttings. Some should be made with canned cuttings to see if sample preservation is at least part of the problem. Rock composition no doubt is an important factor, and adjustments may be needed for rocks of Paleozoic age. If Rock-Eval or another instrument can be tested successfully in the Permian Basin area, it should be reliable in the Pedregosa Basin area. However, pyrolysis determinations even with present problems should continue to be made on selected samples.

Final emphasis should be given again to the concept that source-rock analysis is the most basic consideration, but the whole space-time spectrum of petroleum generation-migration-entrapment-preservation should be analyzed within the geologic framework of each prospective area. With such comprehensive study, and with drilling of thorough exploration wells on the best prospects, any commercial accumulations of oil or gas in southwestern New Mexico should be found.

ACKNOWLEDGEMENTS

Several individuals and organizations mentioned in this and previous reports have contributed cuttings, logs, descriptions, and other subsurface information that were essential materials in this investigation. They are gratefully acknowledged as a group.

At the New Mexico Bureau of Mines and Mineral Resources, Frank E. Kottlowski, Director, has provided the main support for the general research program on the petroleum geology of southwestern New Mexico and for much of this specific project on the analyses of source and reservoir rocks. Robert A. Bieberman and Richard R. Chavez provided cuttings on the Cockrell wells, mounted-cuttings strip logs, basic well data, and other information from the Subsurface Library. Lynne McNeil typed the manuscript, tables, and data on figs. 4-17. Debra Vetterman drafted figs. 1-3 and the base for figs. 4-17. These and other personnel at NMBMMR are also gratefully acknowledged.

At GeoChem Laboratories, Inc. in Houston, Texas, the critical source-rock analyses were run. Several individuals have provided help and guidance that went beyond their excellent service to clients. Geoffrey S. Bayliss, Donald G. Van Delinder, and Michael R. Smith helped with the general planning. Paul J. Cernock supervised the analyses on the KCM wells and the Humble well. The paper prepared by Cernock and Bayliss (1977) on the KCM No. 1 Forest Federal was the first publication of comprehensive geochemical analyses on a key well in New Mexico; GeoChem donated the major part of the expenses for that study. L. Paul Tybor supervised the analyses on the Hachita Dome and Cockrell wells.

He provided answers to many basic questions that arose during the preparation of this report, kindly reviewed the manuscript, and made several suggestions for improvement. Ann B. Reaugh, palynologist/biostratigrapher, analyzed the kerogens in the wells submitted during the current study, revised some previous analyses, and provided useful information concerning the current concepts of oil or gas generation from specific kerogen types.

At the New Mexico Energy Institute on the campus of New Mexico Institute of Mining & Technology, Charles C. Nathan, Director, approved and administered the grant that provided funds for geochemical and other analyses done outside of NMBMMR. With understanding of the busy activity in southwestern New Mexico, he approved extensions of the grant period from 1978 until the termination of the NMEI at New Mexico Tech on June 30, 1981. He also kindly reviewed the manuscript of this report and suggested several improvements. Lorraine A. Archuleta, his secretary and administrative assistant, was helpful with many items.

At the Energy and Minerals Department in Santa Fe, Louis Seig, Administrator, and Peter Vogel, Liaison Officer, of the newly formed New Mexico Energy Research and Development Institute, granted an extension until August 31, 1981 so that a comprehensive report could be prepared with the latest analyses from GeoChem. They and others at EMD also approved the grant proposal, funding, and extensions. Copies of the manuscript were reviewed by the EMD staff. All their help is appreciated.

REFERENCES

Cernock, P.J., 1976, Hydrocarbon source-rock evaluation study, KCM No. 1 Cochise State A well, Hidalgo County, New Mexico: GeoChem Laboratories, Inc. (Houston), New Mexico Bureau of Mines and Mineral Resources, Open-file report OF-96, 21 p.

Cernock, P.J., 1977, Hydrocarbon source-rock evaluation study, Humble Oil & Refining Co. No. 1 State BA well, Hidalgo County, New Mexico: GeoChem Laboratories, Inc. (Houston), New Mexico Bureau of Mines and Mineral Resources, Open-file report OF-97, 34 p.

Cernock, P.J. and Bayliss, G.S., 1977, Organic geochemical analyses, in Geology, petroleum source rocks, and thermal metamorphism in KCM No. 1 Forest Federal well, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 152, p. 37-47.

Dane, C.H. and Bachman, G.O., 1965, Geologic map of New Mexico: U.S. Geological Survey, scale 1:500,000.

Deal, E.G., Elston, W.E., Erb, E.E., Peterson, S.L., Reiter, D.E., Damon, P.E., and Shafiqullah, M., 1978, Cenozoic volcanic geology of the Basin and Range province in Hidalgo County, southwestern New Mexico: New Mexico Geological Society, Guidebook 29th field conference, p. 219-229.

Drewes, H.D., 1978, The Cordilleran orogenic belt between Nevada and Chihuahua: Geological Society of America Bulletin, v. 89, no. 5, p. 641-657.

Drewes, H.D., 1980, Tectonic map of southeastern Arizona: U.S. Geological Survey, Misc. Geol. Inv. Map I-1109, scale 1:125,000.

Drewes, H.D. and Thorman, C.H., 1978, Major geologic structures between Lordsburg, New Mexico and Douglas and Tucson, Arizona: New Mexico Geological Society, Guidebook 29th field conference, p. 291-295.

Drewes, H.D. and Thorman, C.H., 1980, Geologic map of the Cotton City Quadrangle and the adjacent part of the Vanar Quadrangle, Hidalgo County, New Mexico: U.S. Geological Survey, Misc. Geol. Inv. Map I-1221, scale 1:24,000.

Elston, W.E., Erb, E.E., and Deal, E.G., 1979, Tertiary geology of Hidalgo County, New Mexico, guide to metals, industrial minerals, petroleum, and geothermal resources: New Mexico Geology, v. 1, no. 1, p. 1-6.

Greenwood, E., Kottlowski, F.E., and Thompson, S. III, 1977, Petroleum potential and stratigraphy of Pedrogosa Basin: comparison with Permian and Orogrande Basins: American Association of Petroleum Geologists Bulletin, v. 61, no. 9, p. 1448-1469.

Hosterman, J.W. and Whitlow, S.I., 1981, Munsell color value as related to organic carbon in Devonian shale of Appalachian Basin: American Association of Petroleum Geologists Bulletin, v. 65, no. 2, p. 333-335.

Hunt, J.M., 1979, Petroleum geochemistry and geology: San Francisco, W.H. Freeman and Company, 617 p.

Katz, B.J., 1981, Limitations of Rock-Eval pyrolysis for typing organic matter (abstract): American Association of Petroleum Geologists Bulletin, v. 65, no. 5, p. 944.

Kottlowski, F.E., and Thompson, S. III, 1980, Estimate of Energy

Resources of New Mexico: New Mexico Bureau of Mines and Mineral Resources, Annual Report 1978-1979, p. 58-67.

Renault, J.R., 1980a, Application of carbonate thermoluminescence to petroleum exploration: New Mexico Energy Institute at New Mexico Tech, final report for grant no. 78-3314, 14 p.

Renault, J.R., 1980b, Application of crystallite-size variation in cherts to petroleum exploration: New Mexico Energy Institute at New Mexico Tech, final report for grant no. 78-3315, 17 p.

Smith, M.R. and Bayliss, G.S., 1980, Source-rock evaluation reference manual: GeoChem Laboratories, Inc. (Houston), 60 p.

Thompson, S. III, 1976, Tectonic and igneous effects on petroleum accumulations in southwestern New Mexico: New Mexico Geological Society, Spec. Pub. no. 6, p. 122-126.

Thompson, S. III, 1977, Subsurface geology and the petroleum-exploration signigicance <u>in</u> geology, petroleum source rocks, and thermal metamorphism in KCM No. 1 Forest Federal well, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 152, p. 5-23.

Thompson, S. III, 1980, Pedregosa Basin's main exploration target is Pennsylvanian dolostone: Oil and Gas Journal, v. 78, no. 42, p. 202, 207, 210, 215.

Thompson, S. III, Behnken, F.H., Budding, A.J., Broadhead, R.F., Cernock, P.J., Bayliss, G.S., Ewing, R.C., Elston, W.E., Erb, E.E., 1977, Geology, petroleum source rocks, and thermal metamorphism in KCM No. 1 Forest Federal well, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 152, 62 p.

Thompson, S. III and Jacka, A.D., 1981, Pennsylvanian stratigraphy, petrography, and petroleum geology of Big Hatchet Peak section, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 176, 125 p.

Thompson, S. III, Tovar R., J.C., and Conley, J.N., 1978, Oil and gas exploration wells in the Pedregosa Basin: New Mexico Geological Society, Guidebook 29th field conference, p. 331-342.

Tissot, B.P. and Welte, D.H., 1978, Petroleum formation and occurrence: Berlin, Springer Verlag, 538 p.

Tybor, L.P., 1981a, Hydrocarbon source-rock evaluation study, Hachita Dome, Inc., No. 1 Tidball-Berry Federal well, Hidalgo County, New Mexico: GeoChem Laboratories, Inc. (Houston), New Mexico Bureau of Mines and Mineral Resources, Open-file report OF-140, 13 p.

Tybor, L.P., 1981b, Hydrocarbon source-rock evaluation study, Cockrell Corp. No. 1 Coyote State well, Grant County, New Mexico: GeoChem Laboratories, Inc. (Houston), New Mexico Bureau of Mines and Mineral Resources, Open-file report OF-149, 17 p.

Tybor, L.P., 1981c, Hydrocarbon source-rock evaluation study, Cockrell Corp. No. 1 Playas State well, Hidalgo County, New Mexico: GeoChem Laboratories, Inc. (Houston), New Mexico Bureau of Mines and Mineral Resources, Open-file report OF-151, 23 p.

Tybor, L.P., 1981d, Hydrocarbon source-rock evaluation study, Cockrell Corp. No. 1 Pyramid Federal well, Hidalgo County, New Mexico: GeoChem Laboratories, Inc. (Houston), New Mexico Bureau of Mines and Mineral Resources, Open-file report OF-152, (in progress).

Woodward, L.A. and DuChene, H.R., 1981, Overthrust belt of southwestern New Mexico: comparison with Wyoming-Utah overthrust belt: American Association of Petroleum Geologists Bulletin, v. 65, no. 4, p. 722-729.

Zeller, R.A., 1958, Reconnaissance geologic map of Playas fifteen-minute quadrangle: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 7, scale 1:62,500.

Zeller, R.A., 1965, Stratigraphy of the Big Hatchet Mountains, New Mexico Bureau of Mines and Mineral Resources, Memoir 16, 128 p.

Zeller, R.A., 1970, Geology of the Little Hatchet Mountains, Hidalgo and Grant Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 96, 23 p.

Zeller, R.A., 1975, Structural geology of Big Hatchet Peak quadrangle, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 146, 23 p.

Zeller, R.A. and Alper, A.M., 1965, Geology of the Walnut Wells quadrangle, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 84, 105 p.

TABLES

Table 1 - Stratigraphic units exposed in Big Hatchet Mountains.
Table 2 - Exploration wells drilled to Precambrian, Paleozoic, or Mesozoic rocks in southern Hidalgo and Grant Counties, New Mexico.
Table 3 - Petroleum-source data, Cockrell No. 1 Pyramid Federal.
Table 4 - Petroleum-source data, Cockrell No. 1 Coyote State.
Table 5 - Petroleum-source data, KCM No. 1 Cochise State A.
Table 6 - Petroleum-source data, Hachita Dome No. 1 Tidball-Berry Federal.
Table 7 - Petroleum-source data, Cockrell No. 1 Playas State.
Table 8 - Petroleum-source data, KCM No. 1 Forest Federal.
Table 9 - Petroleum-source data, Humble No. 1 State BA.
Table 10 - Summary of basic evaluations (from tables 3-9).

Table 1 - Stratigraphic units exposed in Big Hatchet Mountains (from Zeller, 1965)

Age			*Rock units*			*Measured thicknesses (feet)*	*Lithology and remarks*
TERTIARY							Basal unit consists of several hundred feet of limestone fanglomerate. This is overlain by thick sequence of volcanic tuffs and flows.
			Angular unconformity				
EARLY CRETACEOUS	Albian	Washita		Mojado Formation	Upper member	5195	Sandstone and shale. Thin to medium beds of strongly cross-laminated brown and gray sandstone are interbedded with thin units of shale. Lens-shaped sandstone masses probably represent channel fillings. Most of formation is of terrestrial origin. Calcareous fossiliferous marine beds are present in upper member and increase in number upward.
					Lower member		
		Fredericksburg		U-Bar Formation	Suprareef ls. mem.	3500	Limestone. Most of formation consists of medium and thin beds of bioclastic limestone alternating with thin gray shale beds. Lenses and thin beds of sandstone are found in lower part. Massive limestone near top of formation is a reef which ranges in thickness from 500 to 20 feet within the area.
					Reef ls. member		
		Trinity			Ls.-sh. member		
	Aptian				Oyster ls. member		
					Brown ls. member		
	?	?		Hell-to-Finish Formation		1274	"Red beds." Composed mostly of interbedded red arkose and sandstone, red and gray shale, and red siltstone. Basal bed is conglomerate composed of chert pebbles derived from Concha Limestone.
				Erosional unconformity			
PERMIAN	Leonard		Naco Group	Concha Limestone		1376	Limestone. Medium-bedded limestone characterized by abundance of purple chert nodules and silicified productid brachiopods. Upper beds often dolomitized. Pre-Cretaceous erosion removed varying amounts of upper beds.
	Leonard or Wolfcamp			Scherrer Formation		5-20	Quartz sandstone and limestone. Sandstone occurs as strata and lenses in limestone.
				Epitaph Dolomite		1480-1519	Dolomite. Medium-bedded light to dark gray dolomite with small knots of quartz. Lower part has a few lumpy limestone and dolomitic limestone beds. A red-weathered interval in lower part has red siltstone and, in one area, massive gypsum.
				Colina Limestone		355-505	Limestone. Thin-bedded limestone which is black on fresh fracture and which weathers light gray. Upper contact lies at different levels depending upon depth in section of Epitaph dolomitization.
				Earp Formation		997	Siltstone and claystone. Composed mainly of interbedded terrestrial brown-weathered cross-laminated siltstone and light gray claystone. Upper part contains marine limestone beds which increase in abundance upward.
				Local disconformity			
	Wolfcamp			Horquilla Limestone		3245-3530	Limestone. Lower third is medium-bedded bioclastic limestone which includes oolitic and crinoidal beds and some zones rich in gray chert nodules. Upper two-thirds is complicated by basin, reef, and shelf facies. The crest of the Big Hatchet Mountains in general follows the reefs; the basin lies southwest of the range; the shelf lies along the east side of the range. The reefs consist of massive bioclastic limestone with dolomitized areas. Basin deposits consist of dark shale and black thin-bedded limestone. The shelf beds consist of light-colored medium-bedded bioclastic limestone.
PENNSYLVANIAN	Virgil						
	Missouri						
	Des Moines						
	Derry						
	Morrow?						
?	?			*Erosional unconformity*			
MISSISSIPPIAN	Chester			Paradise Formation		318	Limestone. Thin-bedded yellowish-brown-weathered bioclastic and oolitic limestone rich in well-preserved fossils. Quartz sandstone beds and lenses near top have plant fossils. Pre-Horquilla erosion removed varying amounts of upper beds.
	Meramec			Escabrosa Limestone	Upper member	1261	Limestone. Lower member composed of thin-bedded limestone and a few shale beds. Middle member consists of rhythmic succession of thin limestone strata and nodular chert strata. Upper member composed largely of crinoidal limestone. Upper two members together usually form single cliff hundreds of feet high.
	Osage				Middle member		
	Kinderhook				Lower member		
?	?						
DEVONIAN				Percha Shale		280	Clay shale. Basal beds include a few strata of calcareous argillaceous siltstone and black shale. Upper beds include thin strata of nodular limestone. Bulk of formation is gray shale.
				Unconformity			
ORDOVICIAN	Cincinnatian			Montoya Dolomite	Cutter Member	385	Dolomite. Basal member consists of 10 to 20 feet of dolomitic quartz sandstone interbedded with dolomite. Aleman Member composed of rhythmic succession of dark gray dolomite strata and strata of black chert nodules.
					Aleman Member		
	Champlainian				Upham Member		
					Cable Canyon Mem.		
				Disconformity			
	Canadian			El Paso Formation	Bat Cave Member	916-1070	Limestone and dolomite. Sierrite Member composed of dolomite and dolomitic limestone; some strata rich in chert nodules and brown reticulated chert laminae. Bat Cave Member consists of bluish-gray-weathered bioclastic limestone. Uppermost beds dolomitized.
					Sierrite Member		
?	?						
LATE CAMBRIAN	Trempealeauian?			Bliss Formation		192-327	Arenaceous rocks. Basal beds composed of arkose and boulder conglomerate. Middle beds consist of white orthoquartzite. Upper beds composed of dolomite with varying quantities of quartz sand. Thickness and lithology of units variable.
	Franconian						
	Dresbachian?						
				Erosional unconformity			
PRECAMBRIAN							Coarsely crystalline porphyritic granite and quartzite.

Table 2 - Exploration wells drilled to Precambrian, Paleozoic, or Mesozoic rocks in southern Hidalgo and Grant Counties, New Mexico (modified from Thompson and others, 1978, table 3)

Location	Name	Completion date	Elevation	Formation tops (Ti = Tertiary intrusive rock)	Total depth	Oil, gas shows
sec. 31, T. 24 S., R. 19 W.; 1,980' FNL; 660' FEL	Cockrell No. 1 Pyramid Fed.	9-30-69	4,244' KB	Surface-Quaternary; 385'-Gila?;1,890'-Tertiary volcanic rock (Ti); 5,795'-Escabrosa (Ti); 6,680'-Percha (Ti); 6,860'-Montoya (Ti); 6,980'-El Paso (Ti); 7,130'-Bliss (Ti); 7,340'-Precambrian	7,404' Precambrian	None
sec. 14, T. 25 S., R. 16 W.; 700' FSL, 700' FWL	Cockrell No. 1 Coyote State	8-24-69	4,354' KB	Surface-Quaternary; above 360'-Tertiary (or Cretaceous) volcanic rock; 1,790'-Mojado (Ti); 6,400'-U-Bar (Ti); 7,100'-Hell-to-finish; 7,240'-Montoya; 7,720-El Paso; 8,360'-Bliss; 8,580'-Precambrian	9,282' Precambrian	Oil: 4,140'
sec. 4, T. 26 S., R. 17 W.; 330' FSL; 1,980' FEL	Powers No. 1 State	12-3-72	4,377' KB	Surface-Quaternary; above 920'-Tertiary (or Cretaceous) volcanic rock; 1,190'-Mojado; 3,930'-Tertiary intrusive rock	4,007' Tert. intrus.	None reported
sec. 16, T. 27 S., R. 16 W.; 1,600' FSL; 850' FEL	Wininger and Berry No. 1 State	9-13-43	4,675' GL	Surface-Quaternary; 28'-Ringbone?; 580'-Mojado?	1,500' Mojado?	Oil: 610'-620'; oil,gas: 1,270'-1,330'; gas: 1,415'-1,430'
sec. 18, T. 28 S., R. 17 W.; 1980' FNL; 1,980' FEL	KCM No. 1 Cochise St. A	3-22-75	4,416' KB	Surface-Quaternary; above 70'-Gila; 2,370'-Mojado	5,916' Mojado	Gas: 2,050'; 2,220'; 2,650'
sec. 12, T. 30 S., R. 15 W.; 1,655' FSL; 2,012' FWL	Hachita Dome No. 1 Tidball-Berry Fed.	5-23-57	4,349' DF	Surface-Quaternary; 224'-Escabrosa; 800'-Percha (Ti); 1,395'-Montoya; 1,653'-El Paso; 2,590'-Bliss; 2,723'-Precambrian	2,726' Precambrian	Gas: 1,500'; 2,310'; 2,430'; oil: 2,590'
sec. 12, T. 30 S., R. 15 W., 1,980' FSL; 660' FWL	Graham No. 1 Hatchet Fed.	11-21-78	4,331' GL	Surface-Quaternary; 540'-Escabrosa (Ti); 960'-Percha; 1,240'-Montoya; 1,710'-El Paso	2,455' El Paso	None
sec. 14, T. 30 S., R. 17 W.; 600' FNL; 1,980' FEL	Cockrell No. 1 Playas State	6-11-70	4,455' KB	Surface-Quaternary; 100'-Gila; 2,480'-Horquilla; 3,836'-Paradise; 4,127'-Escabrosa; 5,192'-Percha; 5,568'-Montoya; 5,890'-El Paso; 6,764'-Bliss; 7,030'-Precambrian?	7,086' Precambrian?	Dead oil: 5,780'
sec. 12, T. 31 S., R. 17 W.; 1,980' FNL; 660' FEL	Cockrell No. 1 State-1125	11-24-70	4,480' KB	Surface-Quaternary; 150'-Gila; 2,465'-Tertiary volcanic (and sedimentary?) rock; 2,595'-Epitaph; 3,770'-Colina	4,005' Colina	None reported
sec. 3, T. 31 S., R. 18 W.; 1,494' FNL; 1,753' FEL	KCM No. 1 Forest Fed.	1-22-75	5,156' KB	Surface-Earp (Ti); 255'-Horquilla (Ti); 2,225'-metamorphosed Horquilla and Tertiary intrusive rock	4,464' Tert. intrus.	None
sec. 25, T. 32 S., R. 16 W.; 990' FNL; 1,980' FEL	Humble No. 1 State BA	12-24-58	4,587' KB	Surface-Quaternary; 230'-U-Bar; 648'-Hell-to-finish; 995'-Concha; 1,522'-Scherrer; 1,532'-Epitaph (repeated by reverse fault); 4,450'-Colina; 5,258'-Earp; 6,265'-Horquilla; 10,995'-Paradise; 11,425'-Escabrosa; 12,500'-Percha; 12,830'-Montoya; 13,214'-El Paso	14,585' El Paso	Gas: 4,190'-4,219'

Table 3 - Petroleum-source data, Cockrell No. 1 Pyramid Federal (adapted from Tybor, 1981d)

1	2	3	4	5	6	7	8	9	10	11
Depth interval (ft)	Rock Type	Color notation	Organic Carbon (%)	Kerogen P;S;T	Thermal alt. index (1-5)	Vitrinite reflect. (% Ro)	C_{15+} (ppm) Total;P-N;Arom	C.P.I.-B; ip19/ip20	Pyrolysis (mg/g) S_1;S_2;S_3;T°C Max	Basic Evaluation Org.;O/G;Mat.
Escabrosa:										
5,990-6,000	Ls	N6	0.14	H*-W;Am-I;-	$\underline{3}$ to 3+					F;O,G;M
6,060-6,070	Ls	5YR3/1	0.10							P
6,160-6,170	Ls,mdy	5YR2/1	0.09							P
6,490-6,500	Ls	5YR7/1	0.04							P
6,560-6,570	Ls	5YR6/1	0.05							P
6,620-6,630	Ls	5YR3/1	0.09	Am;-;H-W-I	$\underline{3}$ to 3+					P;O;M
Percha:										
6,680-6,690	Ms	5YR2/1	0.16							P
6,760-6,770	Ms	5YR2/1	0.26	W-I;Am-H;-	$\underline{3}$ to 3+					P;G,O;M
6,790-6,800	Ms	5YR2/1	0.30							P
6,840-6,850	Ms	5YR2/1	0.68	W-I;Am-H;-	$\underline{3}$ to 3+	1.54-2.24	264;49;20	1.08;1.58	0.09;0.16;0.21;354	F;G,O;M
Montoya:										
6,940-6,950	Ds	5YR5/1	0.01							P
6,970-6,980	Ds	5YR3/1	0.05	Am(Al);-;-	$\underline{3}$ to 3+					P;O;M
El Paso:										
7,000-7,010	Ds	5YR5/1	0.04							P
7,100-7,110	Ds	5YR3/1	0.04	Am;-;-	3 to 3+					P;O;M-O

(See text for explanation of symbols.)

Table 4 - Petroleum-source data, Cockrell No. 1 Coyote State (adapted from Tybor, 1981b)

1	2	3	4	5	6	7	8	9	10	11
Depth interval (ft)	Rock Type	Color notation	Organic Carbon (%)	Kerogen P;S;T	Thermal alt. index (1-5)	Vitrinite reflect. (% Ro)	C_{15+} (ppm) Total;P-N;Arom	C.P.I.-B; ip19/ip20	Pyrolysis (mg/g) S_1;S_2;S_3;T°C Max	Basic Evaluation Org.;O/G;Mat.
Mojado:										
1,950-1,960	Ms	10Y4/2	0.21	H;W;-	2 to 2+					P;G,O;M
2,140-2,150	Ms	10Y4/2	1.34						0.10;0.40;0.40;441	G
2,330-2,340	Ms	10Y4/2	0.34							P
2,480-2,490	Ms	10Y3/2	0.38	W;H;-	2 to 2+					P;G,O;M
2,560-2,570	Ms	10Y4/2	0.20							P
2,660-2,670	Ms	10Y4/2	0.23							P
2,990-3,000	Ms	10Y4/2	0.23							P
3,220-3,230	Ms	10Y4/2	0.33							P
3,310-3,320	Ms,calc	10Y3/2	0.41	W;H;-	2 to 2+					P;G,O;M
3,560-3,570	Ms	10Y5/2	0.59							P
3,730-3,740	Ms,calc	10YR2/2	0.80	W;H;-	2 to 2+	0.80-1.05			0.10;1.00;0.14;430	F;G,O;M
3,970-3,980	Ms	10Y4/2	0.27							P
4,100-4,110	Ms	5GY3/2	0.42							P
4,300-4,310	Ms,calc	10YR2/2	0.76	H;W;-	2				0.06;0.21;0.17;433	F;G,O;M
4,400-4,410	Ms,calc	10YR2/2	0.71							F
4,490-4,500	Ms	5YR2/1	0.74							F
4,730-4,740	Ms	5YR2/1	0.62							F
5,080-5,090	Ms,calc	5YR2/1	0.66	W;H;-	2 to 2+		(5,100-5,230:)			F;G,O;M
5,160-5,170	Ms	5YR2/1	1.17	W;H;-	2- to 2		282;109;67	1.04;1.89	0.21;0.02;0.10;436	G;G,O;M
5,250-5,260	Ms,calc	5YR2/1	0.72	W;H;-	2- to 2					F;G,O;M
5,620-5,630	Ms	5YR2/1	9.98			3.49-4.81	(5,650-5,900:)			E
5,800-5,810	Ms	5Y3/2	1.43	H-W;-;-	2- to 2		161; 45;18	1.13;1.61	0.17;0.00;0.11;392	G;G,O;I
6,070-6,080	Ms,calc	5Y2/2	0.56	W;H;-	2 to 2+					F;G,O;M
U-Bar:							(6,340-6,430:)			
6,400-6,410	Ls	5YR3/1	0.46	W;H;Am	3-		.87;-;-	1.11;1.34	0.01;0.01;0.09;497	G;G,O;M
6,490-6,500	Ls	5YR3/1	0.40							G
6,810-6,820	Ls	10YR6/2	0.05							P
7,080-7,090	Ms,calc	5YR2/1	0.14	W;H;-	2 to 2+					P;G,O;M
Hell-to-finish:										
7,120-7,130	Ms	5R3/2	0.36	W;-;H	2- to 2					P;G;M
Montoya:										
7,290-7,300	Ds	10YR3/2	0.03	Am;-;-	2+ to 3-					P;O;M
7,430-7,440	Ds	10YR3/2	0.03							P
7,530-7,540	Ds	10YR3/2	0.03	Am;-;-	2+ to 3-					P;O;M
7,670-7,680	Ds	5YR3/1	0.04							P
El Paso:										
7,880-7,890	Ds	5YR3/1	0.05	Am(Al);-;-	3-					P;O;M
7,980-7,990	Ls	10YR3/2	0.05							P
8,130-8,140	Ds	10YR3/2	0.07	Am(Al);-;-	3- to 3					P;O;M
8,220-8,230	Ls	5YR3/1	0.04							P
8,370-8,380	Ds	5YR4/1	0.02	Am;-;-	3- to 3					P;O;M

Table 5 - Petroleum-source data, KCM No. 1 Cochise State A (adapted from Carnock, 1976)

1	2	3	4	5	6	7	8	9	10	11
Depth interval (ft)	Rock Type	Color notation	Organic Carbon (%)	Kerogen P;S;T	Thermal alt. index (1-5)	Vitrinite reflect. (% Ro)	C_{15+} (ppm) Total;P-N;Arom	C.P.I.-B; ip19/ip20	Pyrolysis (mg/g) S_1;S_2;S_3;T°C Max	Basic Evaluation Org.;O/G;Mat.
Mojado:										
2,390-2,400	Ms	N1	0.29							P
2,490-2,500	Ms	N1	0.43	W-I;H;Am	3+ to 4		129;-;-	2.27;0.58		P;G,O;O
2,590-2,600	Ms	N1	0.46							P
2,690-2,700	Ms	N1	0.61	W-I;H-Am;-	3+ to 4		168;-;-	1.33;0.22		F;G,O;O
2,790-2,800	Ms,calc	N1	0.98	W-I;H;Am	3+ to 4		104;-;-	1.50;0.27		F;G,O;O
2,890-2,900	Ms,calc	N2	0.91	W-I;H;Am	3+ to 4		70;-;-	1.35;1.35		F;G,O;O
2,990-3,000	Ms,calc	N1	0.81	W-I;H;Am	3+ to 4		114;-;-	1.52;0.60		F;G,O;O
3,090-3,100	Ms	N2	0.65							F
3,190-3,200	Ms,calc	N1	0.63	W-I;H;Am	3+ to 4		193;19;18	-;0.43		F;G,O;O
3,290-3,300	Ms,calc	N1	0.42							P
3,490-3,500	Ms,calc	N1	0.37	W-I;H;Am	3+ to 4		101;-;-	A-1.67;0.11		P; G,O;O
3,690-3,700	Ms	N3	0.40	W-I;Am;H	3+ to 4		109;-;-	A-0.94;0.37		P;G,O;O
3,890-3,900	Ss	5GY7/2	0.13							P
4,190-4,200	Ss	N8	0.06	Am;W-I;H	3+ to 4		61;-;-	A-0.95;0.42		P;O,G;O
4,490-4,500	Ss	N8	0.05							P
4,990-5,000	Ss	N8	0.16	Am;H-W-I;-	3+ to 4		100;-;-	1.65;0.07		P;O,G;O
5,290-5,300	Ss	N8	0.11							P

Table 6 - Petroleum-source data, Hachita Dome No. 1 Tidball-Berry Federal (adapted from Tybor, 1981a)

1	2	3	4	5	6	7	8	9	10	11
Depth interval (ft)	Rock Type	Color notation	Organic Carbon (%)	Kerogen P;S;T	Thermal alt. index (1-5)	Vitrinite reflect. (% Ro)	C_{15+} (ppm) Total;P-N;Arom	C.P.I.-B; ip19/ip20	Pyrolysis (mg/g) $S_1;S_2;S_3$;T°C Max	Basic Evaluation Org.;O/G;Mat.
Escabrosa:										
224- 232	Ls,chty	10YR4/2	0.06							P
265- 286	Ls,chty	5YR3/1	0.03							P
305- 325	Ls,chty	5YR3/4	0.04							P
380- 385	Ls,chty	10YR6/2	0.04							P
435- 450	Ls	10YR3/2	0.04							P
495- 500	Ls	10YR4/2	0.03							P
560- 570	Ls	10YR2/2	0.05							P
610- 640	Ls	10YR2/2	0.05	Am;-;-	3-					P;O;M
680- 700	Ls	10YR6/2	0.04							P
750- 790	Ls	10YR2/2	0.05							P
Percha:										
820- 840	Ms,calc	5Y2/1	0.13							P
910- 950	Ms,calc	5Y2/1	0.16							P
970- 980	Ms,calc	5Y2/1	0.19							P
1,020-1,050	Ms,calc	5Y2/1	0.17							P
1,070-1,090	Ms,calc	5Y2/1	0.26	W-I;H;-	3 to 3+					P;G,O;M-O
1,150-1,160	Ms,calc	5Y2/1	0.18							P
1,200-1,210	Ms,calc	5Y2/1	0.19							P
1,290-1,300	Ms,calc	5Y2/1	0.33	W-I;-;Am-H	3 to 3+				0.07;0.05;0.42;406	P;G;M-O
1,355-1,375	Ms	5Y2/1	0.60	W-I;-;Am-H	3 to 3+	3.35-5.43 (reworked)	740;153;254	1.23;1.53	0.04;0.03;0.67;427	P;G;M-O
Montoya:										
1,400-1,405	Ds	5YR6/1	0.05							P
1,460-1,465	Ds	5YR6/1	0.03							P
1,505-1,510	Ds	5YR4/1	0.09	Am(Al);-;-	3					P;O;M
El Paso:										
1,645-1,650	Ls	5YR3/1	0.12	Am(Al);-;-	3+				0.01;0.03;0.51;415	P;O;O
1,680-1,685	Ls	5Y4/1	0.06							P
1,750-1,755	Ls	5YR2/1	0.09							P
1,800-1,805	Ls	5YR2/1	0.07							P
1,860-1,865	Ls	5YR3/1	0.08							P
1,920-1,925	Ls	5YR3/1	0.08							P
1,980-1,985	Ls	5YR3/1	0.10							P
2,040-2,045	Ls	5YR2/1	0.07							P
2,095-2,100	Ls	5YR3/1	0.11							P
2,150-2,155	Ls	5YR2/1	0.12						0.03;0.04;0.36;431	P
2,220-2,225	Ls	5YR3/1	0.08	Am(Al);-;-	3+					P;O;O
2,280-2,285	Ls	5YR4/1	0.07							P
2,340-2,345	Ls	5YR3/1	0.15	Am;-;-	3+				0.04;0.02;0.45;398	P;O;O
2,410-2,415	Ls	10YR6/2	0.08							P
2,500-2,505	Ls	10YR6/2	0.06							P
2,558-2,560	Ms	N1	0.62	Am;-;-	3+				0.02;0.08;1.08;401	VG;O;O

Table 7 - Petroleum-source data, Cockrell No. 1 Playas State (adapted from Tybor, 1981c)

1	2	3	4	5	6	7	8	9	10	11
Depth interval (ft)	Rock Type	Color notation	Organic Carbon (%)	Kerogen P;S;T	Thermal alt. index (1-5)	Vitrinite reflect. (% Ro)	$C_{15}+$ (ppm) Total;P-N;Arom	C.P.I.-B; ip19/ip20	Pyrolysis (mg/g) $S_1;S_2;S_3$;T°C Max	Basic Evaluation Org.;O/G;Mat.
Horquilla:										
2,490-2,500	Ls	5YR4/1	0.06	Am;-;-	2+ to 3-					P;O;M
2,590-2,600	Ls	5YR4/1	0.05							P
2,690-2,700	Ls	5YR3/1	0.06	Am;-;H	2+ to 3-					P;O;M
2,760-2,770	Ls	5YR4/1	0.09							P
2,840-2,850	Ls	5YR3/1	0.05	Am;-;H	2+ to 3-					P;O;M
2,970-2,980	Ls	5YR3/1	0.06							P
3,070-3,080	Ls	5YR3/1	0.13	Am;-;H	2+ to 3-					F;O;M
3,150-3,160	Ls	5YR3/1	0.12							P
3,250-3,260	Ls	5YR3/1	0.23	H*;Am-W-I;-	2+ to 3-	.39- .53	371;69;26	1.04;1.40	0.08;0.01;0.21;427	F;O,G;M
3,310-3,320	Ls	5YR3/1	0.17							F
3,410-3,420	Ls	5YR3/1	0.18	W-I;Am-H*;-	2+ to 3-					F;G,O;M
3,500-3,510	Ls	5YR4/1	0.10							P
3,640-3,650	Ls	5YR4/1	0.19	H*;W-I;Am	3-					F;O,G;M
3,700-3,710	Ls	5YR4/1	0.13							F
Paradise:										
3,880-3,890	Ls	5YR4/1	0.28	W-I;-;H	3 to 3+	2.04-3.09				G;G;M-O
3,900-3,910	Ls	5YR4/1	0.34							G
4,000-4,010	Ls	5YR4/1	0.78	W-I;H;Am	3 to 3+	2.06-3.08	347;120;55	1.04;1.39	0.11;0.00;0.44;0	VG;G,O;M-O
4,050-4,060	Ms	5YR2/1	0.44							P
4,100-4,110	Ls	5YR4/1	0.45	W-I;-;Am-H	3 to 3+					G;G;M-O
Escabrosa:										
4,130-4,140	Ls	5YR7/1	0.36	W-I;H;Am	3 to 3+	2.71-3.81	444;-;-	1.02;1.31	0.05;0.01;0.65;411	G;G,O;M-O
4,540-4,550	Ls	5YR7/1	0.12							F
4,590-4,600	Ls	5YR3/1	0.15							F
4,670-4,680	Ls	5YR3/1	0.11	H*;Am-W-I;-	3 to 3+					P;O,G;M
4,720-4,730	Ls	5YR3/1	0.18							F
4,820-4,830	Ls	5YR3/1	0.10	H*;Am;W-I	3 to 3+					P;O,G;M-O
4,930-4,940	Ls	N9	0.07							P
5,120-5,130	Ls	N6	0.12	W-I;Am-H*;-	3 to 3+					F;G,O;M-O
5,150-5,160	Ls	5YR3/1	0.14							F
Percha:										
5,200-5,210	Ms	10Y7/4	0.11	I;-;-	4- to 4?					P;-;O
5,290-5,300	Ms	5Y2/1	0.18							P
5,360-5,370	Ms	5YR2/1	0.26	I;-;Am	3 to 3+					P;-;M-O
5,460-5,470	Ms	5YR2/1	0.29							P
5,560-5,570	Ms	5YR2/1	0.83	I;-;Am	3 to 3+	(no vit.)	1,163;-;-	1.04;1.31	0.11;0.00;0.29;0	F;-;M-O
Montoya:										
5,570-5,580	Ds	10YR3/2	0.17							F
5,670-5,680	Ds	5YR2/1	0.26	Am(Al);I;-	3 to 3+		1,382;-;-	1.06;0.74	0.10;0.00;0.26;0	G;O;O
5,750-5,760	Ds	5YR3/1	0.13							F
El Paso:										
5,900-5,910	Ls	5YR4/1	0.08	Am(Al);-;I	3 to 3+					P;O;O
6,030-6,040	Ls	5YR4/1	0.08							P
6,120-6,130	Ls	5YR4/1	0.06	Am;-;-	3+ to 4-					P;O;O
6,230-6,240	Ls	5YR3/1	0.08							P
6,340-6,350	Ls	5YR4/1	0.09	Am;-;I	3+ to 4-					P;O;O
6,470-6,480	Ds	5YR5/1	0.04							P
6,570-6,580	Ds	5YR3/1	0.07							P
6,630-6,640	Ds (Ms)	5YR2/1	0.36	Am;I;-	3+ to 4-					G;O;O
6,750-6,760	Ds	5YR3/1	0.09							P
Bliss:										
6,810-6,820	Ds,sdy	5YR3/1	0.17	I;Am;-	3+ to 4-					P;O;O

Table 8 - Petroleum-source data, KCM No. 1 Forest Federal (adapted from Cernock and Bayliss, 1977)

1	2	3	4	5	6	7	8	9	10	11
Depth interval (ft)	Rock Type	Color notation	Organic Carbon (%)	Kerogen P:S:T	Thermal alt. index (1-5)	Vitrinite reflect. (% Ro)	C_{15+} (ppm) Total;P-N;Arom	C.P.I.-B; ip19/ip20	Pyrolysis (mg/g) $S_1;S_2;S_3;T°C$ Max	Basic Evaluation Org.;O/G;Mat.
Earp:										
70- 80	Ls	N6	0.13	Am;W-I;H	3-					F;O,G;M
Horquilla:										
260- 270	Ls	10YR7/2	0.10	W-I;H;Am	3-					P;G,O;M
310- 320	Ls	5YR2/1	0.42	W-I;H*;-	3+					G;G,O;O
470- 480	Ls	5YR4/1	0.55	W-I;H*;-	4- to 4					VG;G,O;O
510- 520	Ls	10YR8/2	0.15	caved	4- to 4					F
750- 760	Ls	5Y6/1	0.22	W-I;H*;-	4- to 4					F;G,O;O
790- 800	Ms,calc	5YR3/1	0.51	W-I;-;H*	4- to 4	1.20-3.71				F;G;O
890- 900	Ms,calc	5YR3/1	0.31	W-I;-;H*	4- to 4	2.27-3.79				P;G;O
990-1,000	Ms,calc	5YR3/1	0.55	W-I;-;H*	4- to 4	2.02-3.98	920;-;-	A-1.00;0.94		F;G;O
1,090-1,100	Ms,calc	5YR2/1	0.94	W-I;H*;-	4- to 4	2.06-4.90	1070;-;-	A-0.96;0.92		F;G,O;O
1,200-1,210	Ms,calc	5YR2/1	0.95	W-I;H*;-	4- to 4	2.06-3.62	554;-;-	A-0.97;0.70		F;G,O;O
1,300-1,310	Ms,calc	5YR2/1	0.47	W-I;-;H*	4- to 4	1.95-3.78	912;184;94	1.29;1.03		P;G;O
1,390-1,400	Ms,calc	5YR2/1	0.49	W-I;-;H*	4- to 4	1.99-3.68	476; 90;28	1.05;1.04		P;G;O
1,490-1,500	Ms,calc	5YR2/1	0.53	W-I;-;-	4- to 4	1.92-3.32	343; 17; 8	1.28;1.48		F;G;O
1,590-1,600	Ls	N5	0.33	W-I;H*;-	4- to 4	2.05-3.74	381; 26;13	1.21;1.36		G;G,O;O
1,690-1,700	Ls	N5	0.26	Am*;W-I;-	4- to 4		222; 20;10	1.33;1.38		G;G;O
1,790-1,800	Ls,mdy	N2	0.30	Am*;W-I;-	4- to 4		311; 10;14	1.27;1.35		G;G;O
1,890-1,900	Ls	N6	0.12	Am*;I;-	4- to 4					F;G;O
1,990-2,000	Ls	N6	0.21	I;Am*;-	4- to 4					F;G;O
2,190-2,200	Ls	N6	0.16							P

(Samples from 2,290-4,400 are of metamorphosed Horquilla and Tertiary intrusive rocks; source-rock analyses in these intervals were run on caved limestones and mudstones.)

Table 9 - Petroleum-source data, Humble No. 1 State BA (adapted from Cornock, 1977)

1	2	3	4	5	6	7	8	9	10	11
Depth interval (ft)	Rock Type	Color notation	Organic Carbon (%)	Kerogen P;S;T	Thermal alt. index (1-5)	Vitrinite reflect. (% Ro)	C_{15}+ (ppm) Total;P-N;Arom	C.P.I.-B; ip19/ip20	Pyrolysis (mg/g) S_1;S_2;S_3;T°C Max	Basic Evaluation Org.;O/G;Mat.
U-Bar:										
460 - 470	Ls,mdy	5YR3/1	0.44	H*;-;W-I	2 to 2+					G;O;M
Hell-to-finish:										
740 - 750	Ms	10R4/4	0.05							P
Concha:										
1,510- 1,520	Ls	10YR7/2	0.01							P
Epitaph:										
1,560- 1,570	Ds	10YR5/2	0.03							P
1,680- 1,690	Ds	10YR4/2	0.02							P
1,810- 1,820	Ds	10YR6/2	0.02							P
2,010- 2,020	Ds,sdy	10YR5/2	0.03							P
2,210- 2,220	Ds	10YR4/2	0.04							P
2,400- 2,410	Ds	10YR2/2	0.18	Am-W;H-I;-	2+ to 3-					F;O,G;M
2,500- 2,510	Ds	10YR3/2	0.05							P
2,750- 2,760	Ds	10YR3/2	0.09							P
2,940- 2,950	Ds	10YR2/2	0.18							F
3,030- 3,040	Ds	10YR2/2	0.22	W;H;I	2+ to 3-					F;G,O;M
3,280- 3,290	Ds	10YR2/2	0.17							F
Note: section from 3,310-4,260 is a repeat of 2,310-3,310 by reverse faulting										
4,160- 4,170	Ds	10YR2/2	0.43	H*-W;-;I	2 to 2+					G;O,G;M
4,170- 4,180	Ds	10YR3/2	0.56	H*;W;I	2 to 2+					VG;O,G;M
4,180- 4,190	Ds	10YR2/2	0.68	H*;W;I	2 to 2+					VG;O,G;M
4,190- 4,200	Ds	10YR3/2	0.72	H*;U;I	2 to 2+					VG;O;M
4,200- 4,210	Ds	10YR3/2	0.83	H*;W;-;I	2 to 2+					VG;O,G;M
4,210- 4,220	Ds	10YR2/2	0.90	W;H*;I	2 to 2+					VG;G,O;M
4,350- 4,360	Ls	10YR3/2	0.36	W;H-I;-	2+ to 3-		59;-;-	1.20;0.61		G;G,O;M
				(:4,350-4,390)						
Colina:										
4,450- 4,460	Ls	10YR4/2	0.14							P
4,550- 4,560	Ls	10YR3/2	0.23	W;H;I	2+ to 3-					F;G,O;M
4,750- 4,760	Ls	10YR3/2	0.16							F
4,890- 4,900	Ls	10YR3/2	0.23	H;W;I	2+ to 3-					F;G,O;M
5,050- 5,060	Ls	10YR3/2	0.15							P
5,200- 5,210	Ls	10YR4/2	0.13							F
Earp:										
5,290- 5,300	Ms	10R4/4	0.04							P
5,640- 5,650	Ls	10YR5/2	0.05							P
5,920- 5,930	Ls,mdy	10YR4/2	0.05							P
Horquilla										
6,350- 6,360	Ls,mdy	5Y3/1	0.09							P
6,550- 6,560	Ls	5Y3/1	0.11	W;I;H	3 to 3+					P;G;M-O
6,650- 6,660	Ls	5Y3/1	0.12							F
6,850- 6,860	Ls	5Y3/1	0.12							F
7,100- 7,110	Ls,mdy	5YR3/1	0.12							F
7,260- 7,270	Ls,mdy	5Y3/1	0.11							P
7,400- 7,410	Ls	5YR3/1	0.10	(7,450-7,500:)						P
7,470- 7,480	Ms,calc	10YR2/2	1.09	W;H-I;-	3 to 3+		89;-;-	A-1.02;0.85		G;G,O;M-O
7,660- 7,670	Ls,mdy	5YR3/1	0.07							P
7,920- 7,930	Ms	5YR2/1	0.24	(7,940-7,980:)						P
7,940- 7,950	Ms,calc	5YR2/1	0.85	H;W;I	3 to 3+		99;-;-	A-1.08;0.92		F;G,O;M-O
8,070- 8,080	Ls	10YR4/2	0.08							P
8,240- 8,250	Ms	5YR2/1	0.26	(8,360-8,400:)						P
8,390- 8,400	Ms,calc	5YR2/1	0.39	W;H;I	3 to 3+		86;-;-	A-0.95;0.73		P;G,O;M-O
8,590- 8,600	Ms,calc	5YR2/1	0.34	(8,750-8,800:)						P
8,790- 8,800	Ms	5YR2/1	1.36	W;H;I	3+		66;-;-	A-1.11;0.77		G;G,O;O
8,840- 8,850	Ms	5YR2/1	0.66							F
8,970- 8,980	Ms,calc	5YR2/1	0.59	(9,050-9,100:)						F
9,080- 9,090	Ms	5YR2/1	0.97	W;H;I	3+		172;-;-	A-1.03;0.69		F;G,O;O
9,290- 9,300	Ms,calc	5YR2/1	0.89							F
9,470- 9,480	Ls	10YR4/2	0.11							P
9,570- 9,580	Ls	5YR4/1	0.22							F
9,850- 9,860	Ms,calc	5YR2/1	0.50							F
9,960- 9,970	Ms,calc	5YR2/1	0.69	W;H;I	3+ to 4-					F;G, O;O
10,050-10,060	Ms,calc	5YR2/1	1.10	W;H-I;-	3+	1.76-2.36	163;-;-	A-0.97;1.00		G;G,O;O
10,180-10,190	Ls	5YR4/1	0.18	(:10,050-10,100)						F
10,460-10,470	Ls	5YR3/1	0.10							P
10,820-10,830	Ls	5YR3/1	0.06							P
Paradise:										
10,990-11,000	Ms,calc	5YR2/1	0.29	(11,100-11,150:)						P
11,100-11,110	Ms	5YR2/1	0.54	I;W;H	3+ to 4-		126;-;-	A-1.04;0.42		F;G;O
11,350-11,360	Ls	5YR3/1	0.16							F
Escabrosa:										
11,490-11,500	Ls	N8	0.08							P
11,690-11,700	Ls	5YR4/1	0.02							P
11,900-11,910	Ls,mdy	5YR2/1	0.13							F
12,090-12,100	Ls,mdy	5YR2/1	0.12							F
12,300-12,310	Ls	N8	0.02							P
12,400-12,410	Ls	5YR3/1	0.09							P
Percha:				(12,600-12,640:)						
12,600-12,610	Ms,calc	5YR2/1	0.30	I;H;Am-W	3+ to 4-		106;-;-	A-1.09;1.03		P;G,O;O
12,700-12,710	Ms,calc	5YR2/1	0.27	(12,760-12,820:)						P
12,800-12,810	Ms	5YR2/1	0.88	I;W;Am-H	3+ to 4-		190;27;23	A-1.15;0.72		F;G;O
Montoya:										
12,900-12,910	Ds	5YR3/1	0.05							P
13,000-13,010	Ds	5YR2/1	0.12							F
13,140-13,150	Ds	5YR3/1	0.08							P
El Paso:										
13,300-13,310	Ls	5YR3/1	0.10							P
13,450-13,460	Ls	5YR3/1	0.10							P
13,600-13,610	Ls	5YR3/1	0.08							P
13,750-13,760	Ls	5YR3/1	0.09	Am;H-I;-	4- to 4					P;O,G;O
13,900-13,910	Ls	5YR3/1	0.09							P
14,050-14,060	Ls	5YR2/1	0.10							P
14,200-14,210	Ls	5YR3/1	0.05	(14,400-14,440:)						P
14,400-14,410	Ls	5YR3/1	0.22	W;H;I	4- to 4		70;-;-	A-1.30;0.44		F;G,O;O
14,560-14,570	Ls,sdy	5YR4/1	0.13							F

Table 10 - Summary of basic evaluations (from tables 3-9). Symbols are: for organic richness, P = poor, F = fair, G = good, VG = very good, E = excellent; for tendency for oil or gas generation at maturity, O = oil generation, G = gas generation, - = neither; for stage of thermal maturation, I = immature, M = mature, O = overmature, T = thermally metamorphosed.

Well:	Cockrell No. 1 Pyramid Fed.	Cockrell No. 1 Coyote St.	KCM No. 1 Cochise St. A	Hachita Dome No. 1 Tidball-Berry Fed.	Cockrell No. 1 Playas St.	KCM No. 1 Forest Fed.	Humble No. 1 State BA	Map fig. no.
Formation:								
Mojado	absent	P-E;G,O;M	P-F;G,O;O	absent	absent	absent	absent	4
U-Bar	"	P-G;G,O;M	not drilled	"	"	"	G;O;M	5
Hell-to-finish	"	P;G;M	"	"	"	"	P	6
Concha	"	absent	"	"	"	"	P	7
Epitaph	"	"	"	"	"	"	P-VG;O,G;M	8
Colina	"	"	"	"	"	"	F;G,O;M	9
Earp	"	"	"	"	"	F;O,G;M	P	10
Horquilla	"	"	"	"	P-F;O,G;M	P-VG;G,O;M-T	P-G;G,O;M-O	11
Paradise	"	"	"	"	P-VG;G,O;M-O	not drilled	P-F;G;O	12
Escabrosa	P-F;O,G;M	"	"	P;O;M	P-G;G,O;M-O	"	P-F	13
Percha	P-F;G,O;M	"	"	P-F;G,O;M-O	P-F;-;M-O	"	P-F;G,O;O	14
Montoya	P;O;M	P;O;M	"	P;O;M	F-G;O;O	"	P-F	15
El Paso	P;O;M-O	P;O;M	"	P-VG;O;O	P-G;O;O	"	P-F;G,O;O	16
Bliss	no anal.	no anal.	"	no anal.	F;O;O	"	not drilled	17

FIGURES

Figure 1 - Generalized geologic map of southern Hidalgo and Grant Counties, New Mexico.
Figure 2 - Location map of petroleum-exploration wells drilled to Precambrian, Paleozoic, or Mesozoic rocks.
Figure 3 - Exploration wells selected for petroleum-geochemical analyses.
Figure 4 - Petroleum-source map of Mojado Formation (Lower Cretaceous).
Figure 5 - Petroleum-source map of U-Bar Formation (Lower Cretaceous).
Figure 6 - Petroleum-source map of Hell-to-finish Formation (Lower Cretaceous).
Figure 7 - Petroleum-source map of Concha Formation (Permian).
Figure 8 - Petroleum-source map of Epitaph Formation (Permian).
Figure 9 - Petroleum-source map of Colina Formation (Permian).
Figure 10 - Petroleum-source map of Earp Formation (Permian).
Figure 11 - Petroleum-source map of Horquilla Formation (Pennsylvian-Permian)
Figure 12 - Petroleum-source map of Paradise Formation (Mississippian).
Figure 13 - Petroleum-source map of Escabrosa Formation (Mississippian).
Figure 14 - Petroleum-source map of Percha Formation (Devonian).
Figure 15 - Petroleum-source map of Montoya Formation (Ordovician).
Figure 16 - Petroleum-source map of El Paso Formation (Ordovician).
Figure 17 - Petroleum-source map of Bliss Formation (Cambrian-Ordovician).

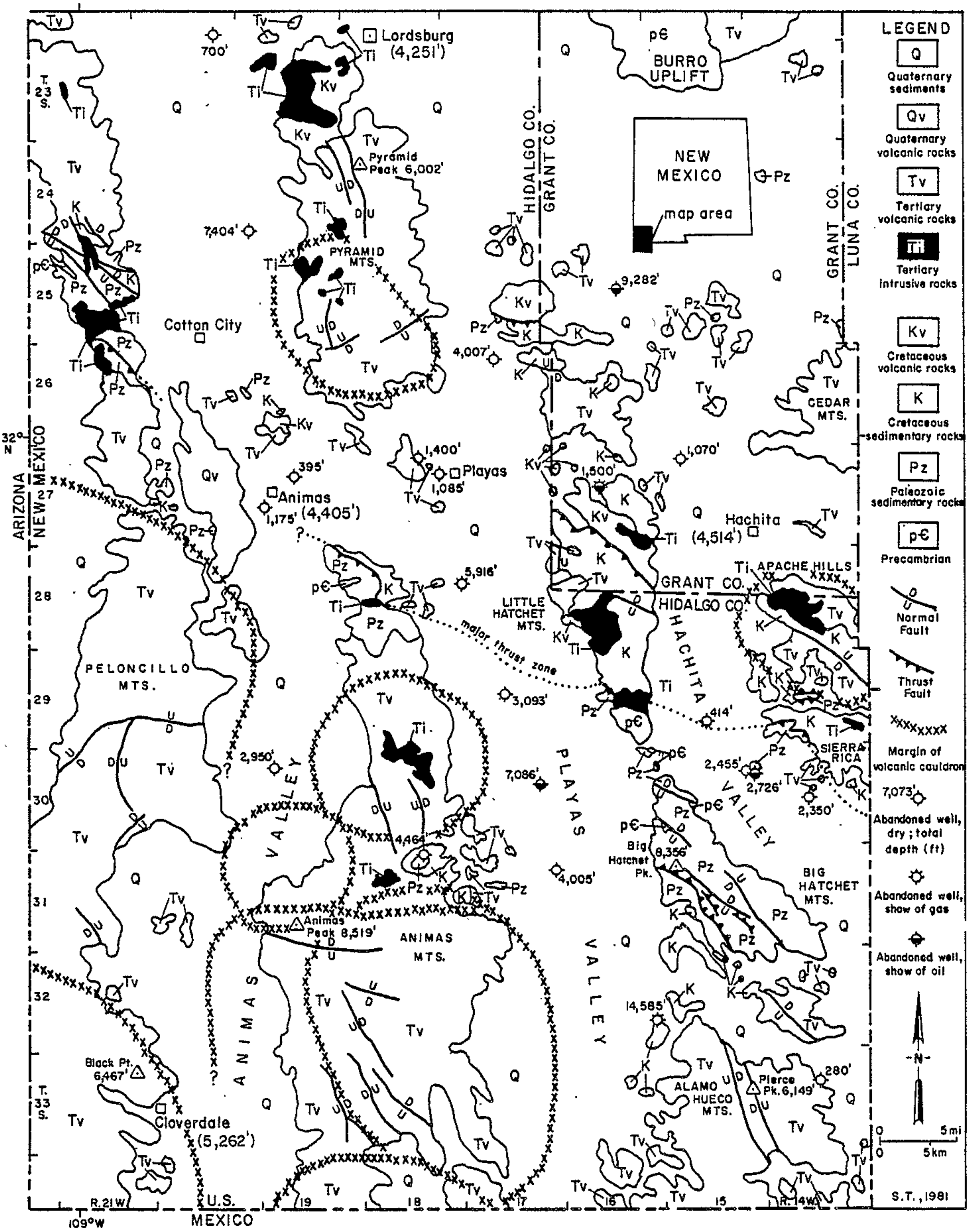

Figure 1 - Generalized geologic map of southern Hidalgo and Grant Counties, New Mexico (modified from Dane and Bachman, 1965; margins of volcanic cauldrons from Elston and others, 1979).

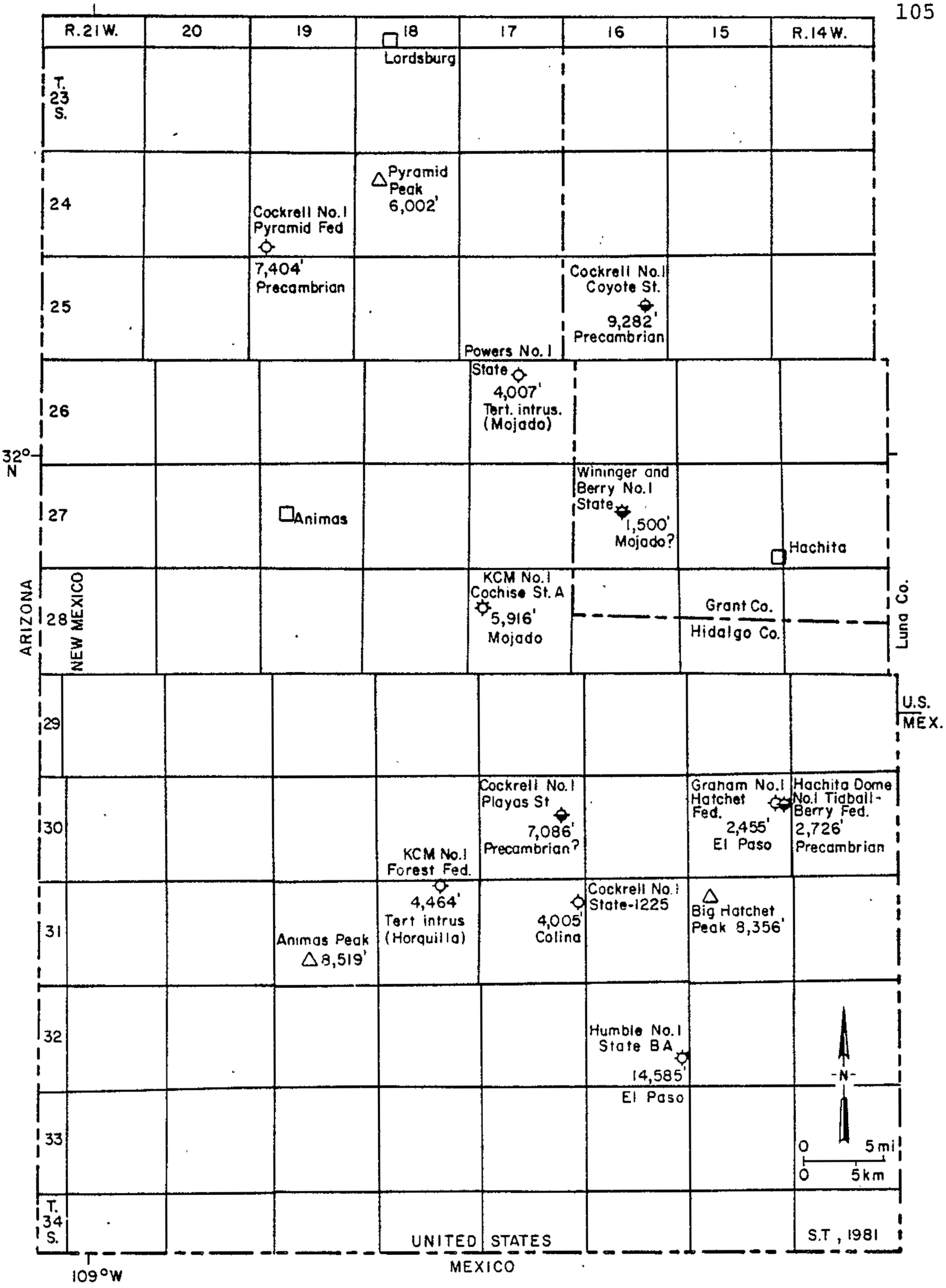

Figure 2 - Location map of petroleum-exploration wells drilled to Precambrian, Paleozoic, or Mesozoic rocks (same area and well symbols as in fig. 1); stratigraphic unit at total depth (ft) of each well is identified.

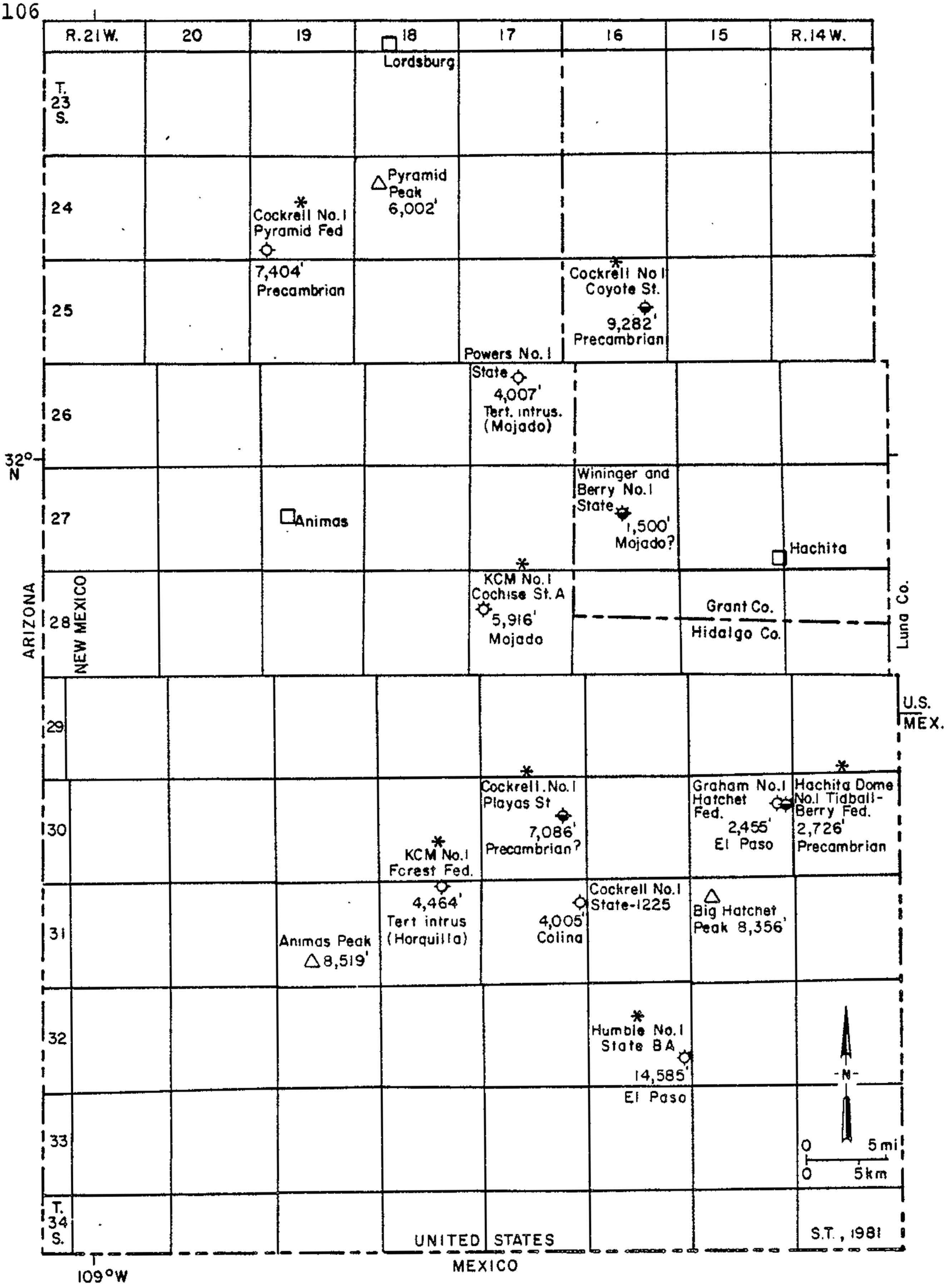

Figure 3 - Exploration wells selected for petroleum-geochemical analyses; designated with asterisk (*) above well name.

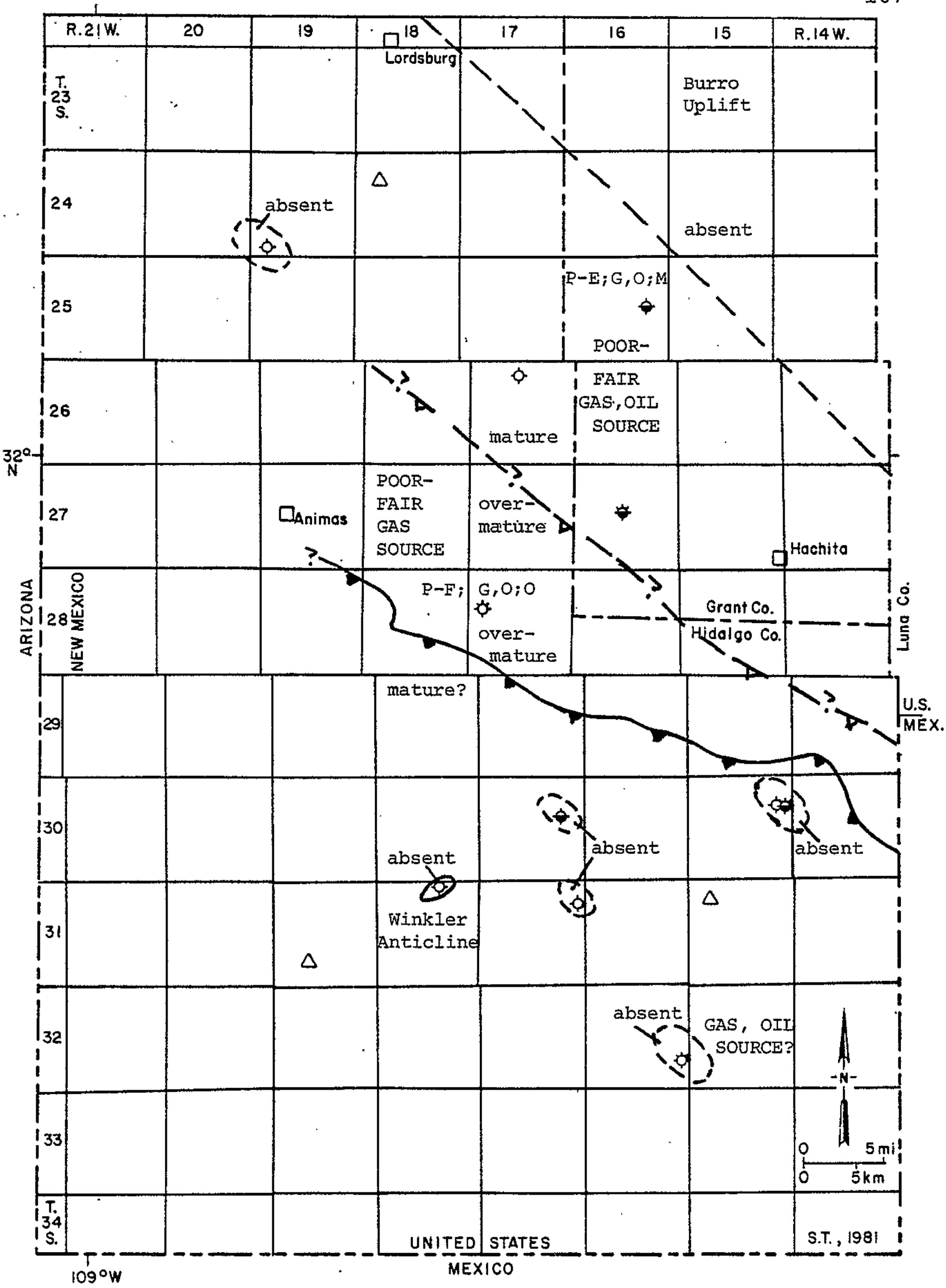

Figure 4 - Petroleum-source map of Mojado Formation (Lower Cretaceous); see table 10 for explanation of basic-evaluation symbols spotted at wells.

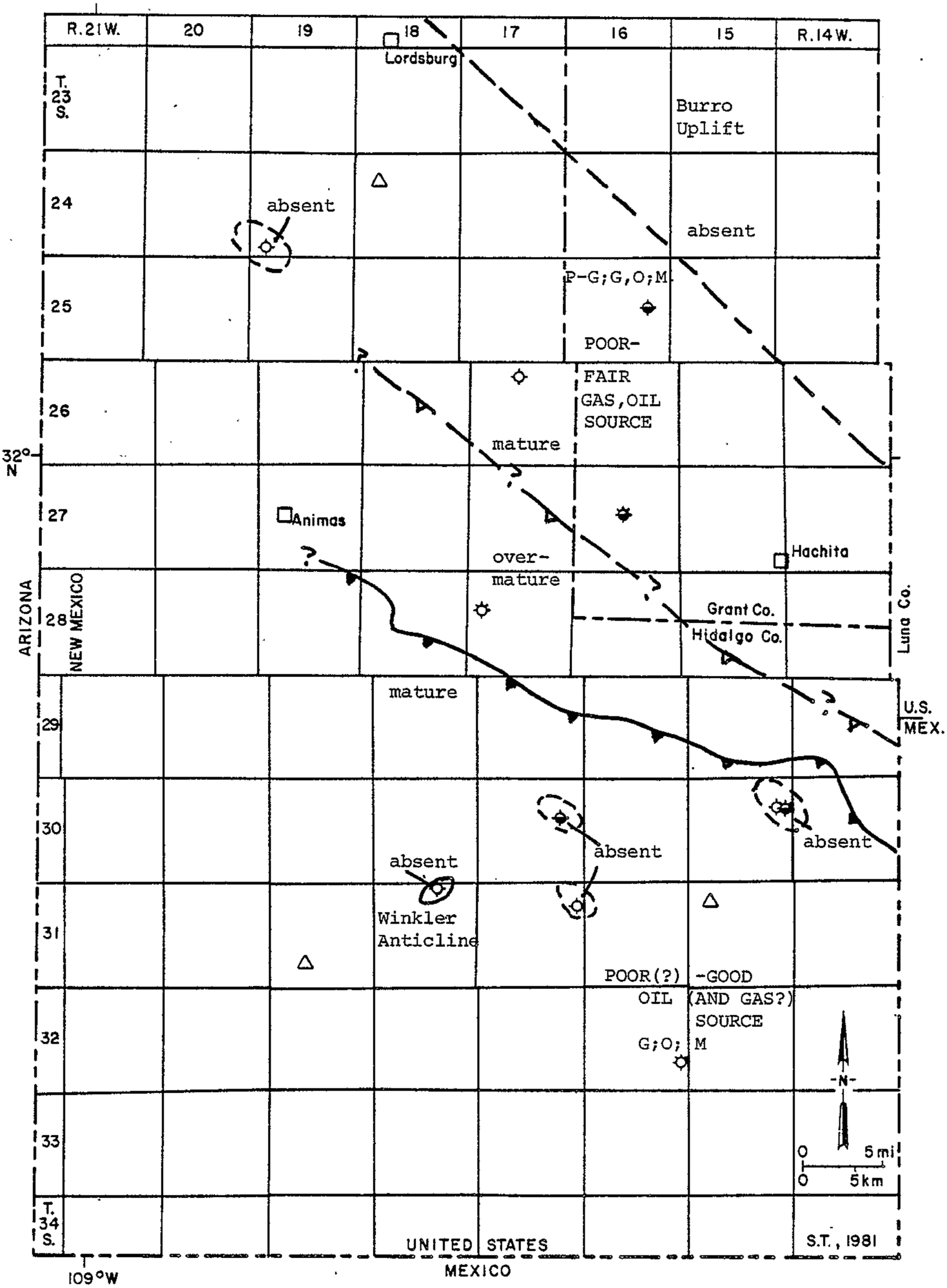

Figure 5 - Petroleum-source map of U-Bar Formation (Lower Cretaceous).

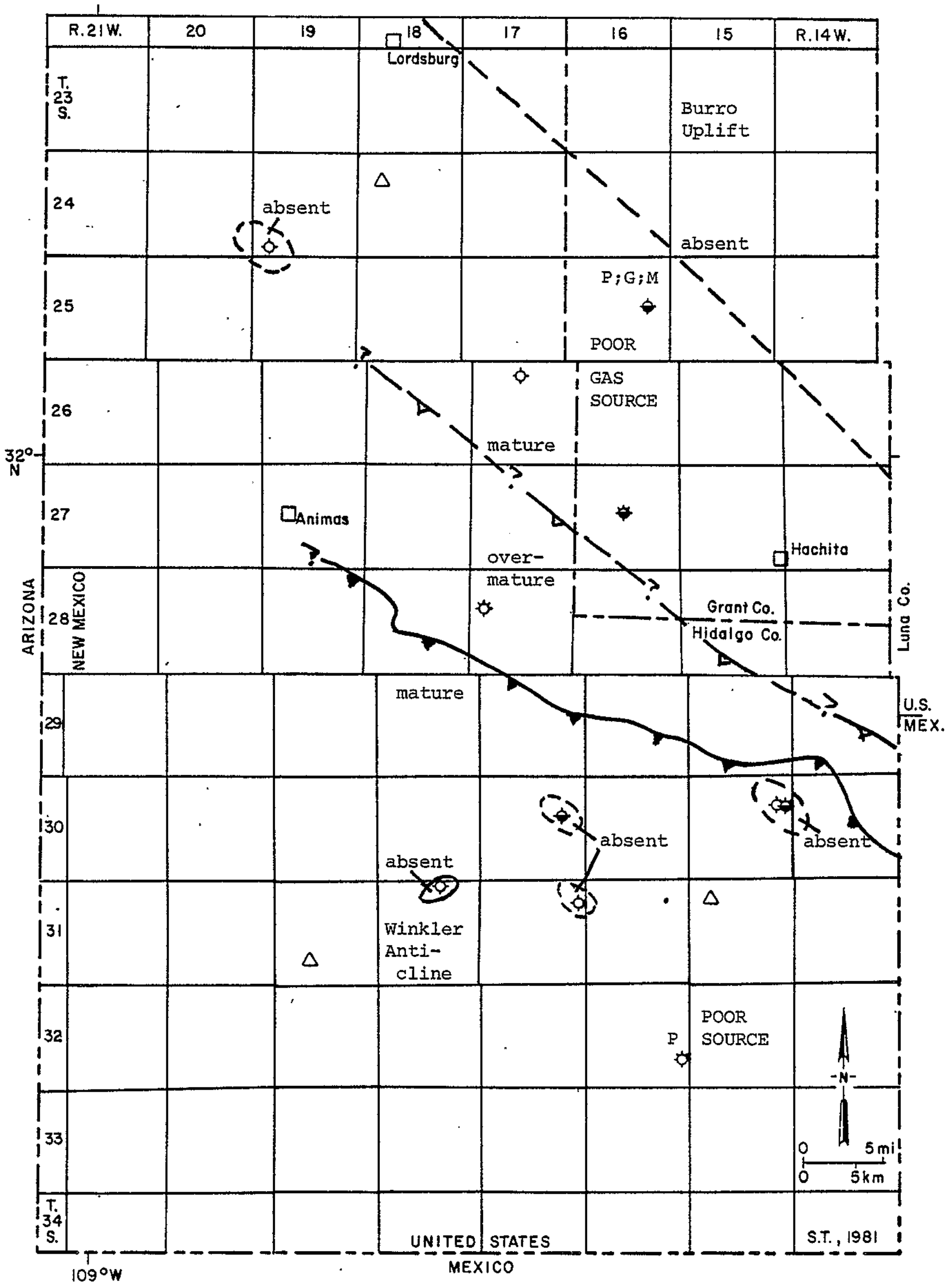

Figure 6 - Petroleum-source map of Hell-to-finish Formation (Lower Cretaceous).

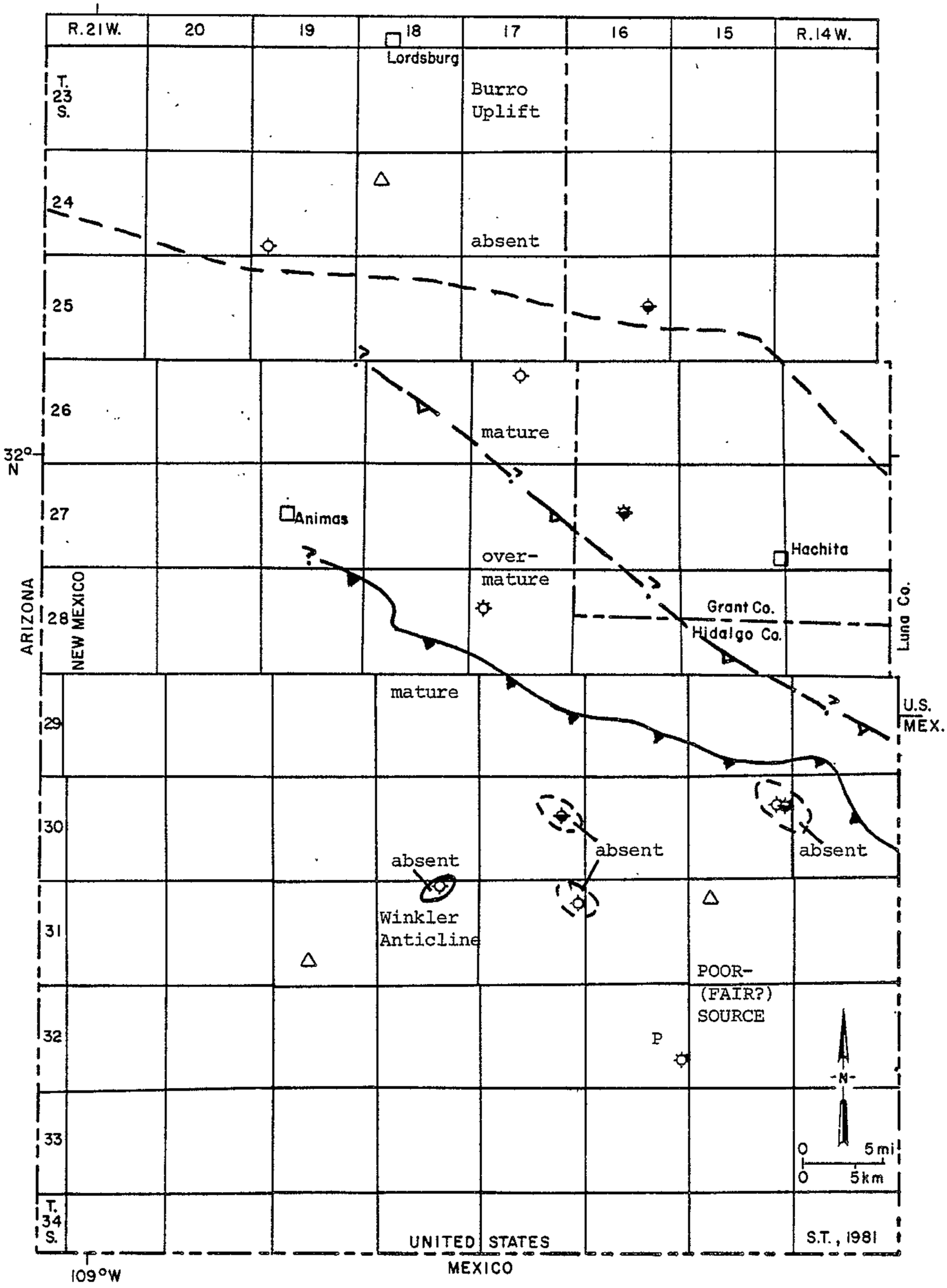

Figure 7 - Petroleum-source map of Concha Formation (Permian).

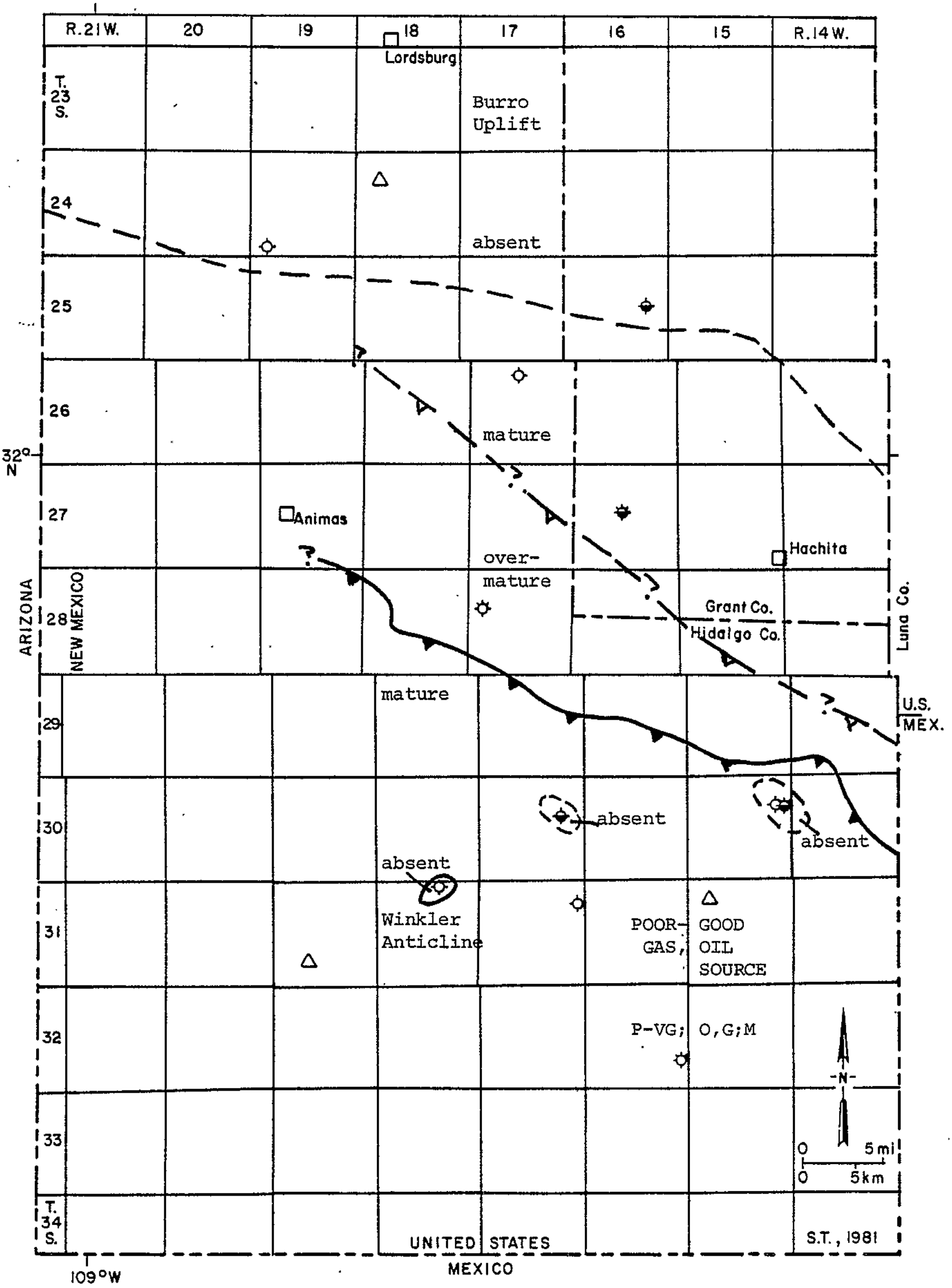

Figure 8 - Petroleum-source map of Epitaph Formation (Permian).

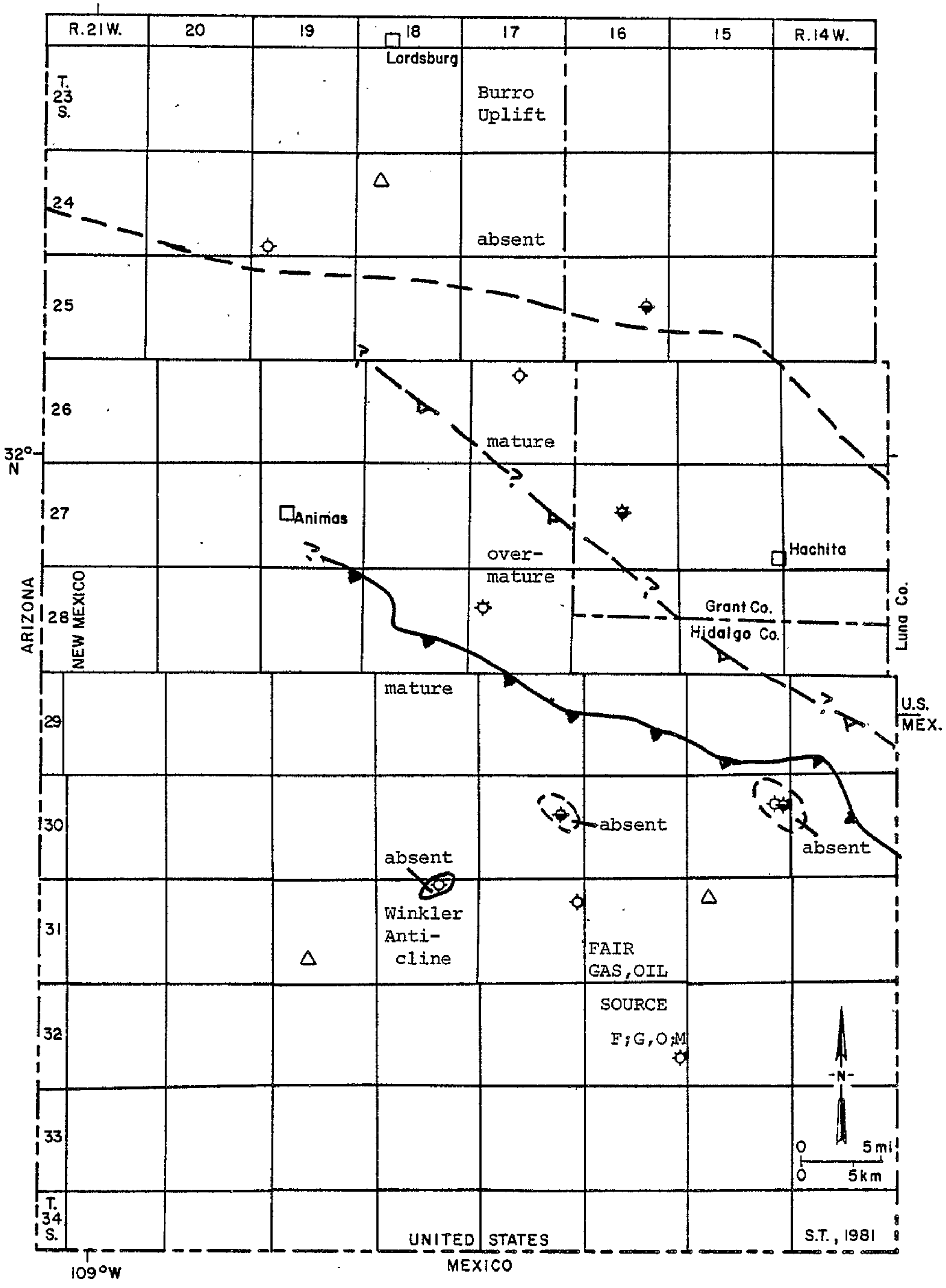

Figure 9 - Petroleum-source map of Colina Formation (Permian).

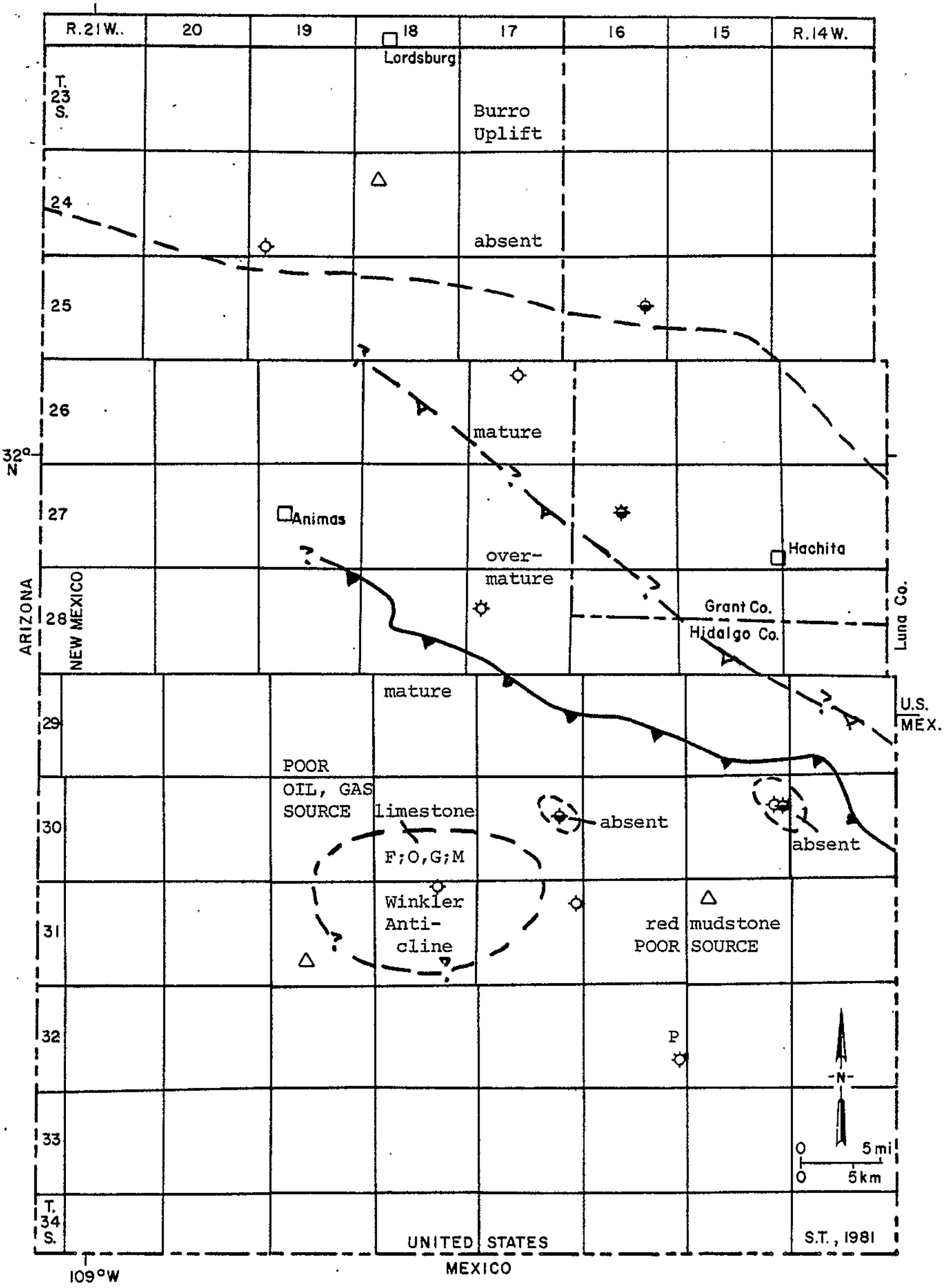

Figure 10 - Petroleum-source map of Earp Formation (Permian).

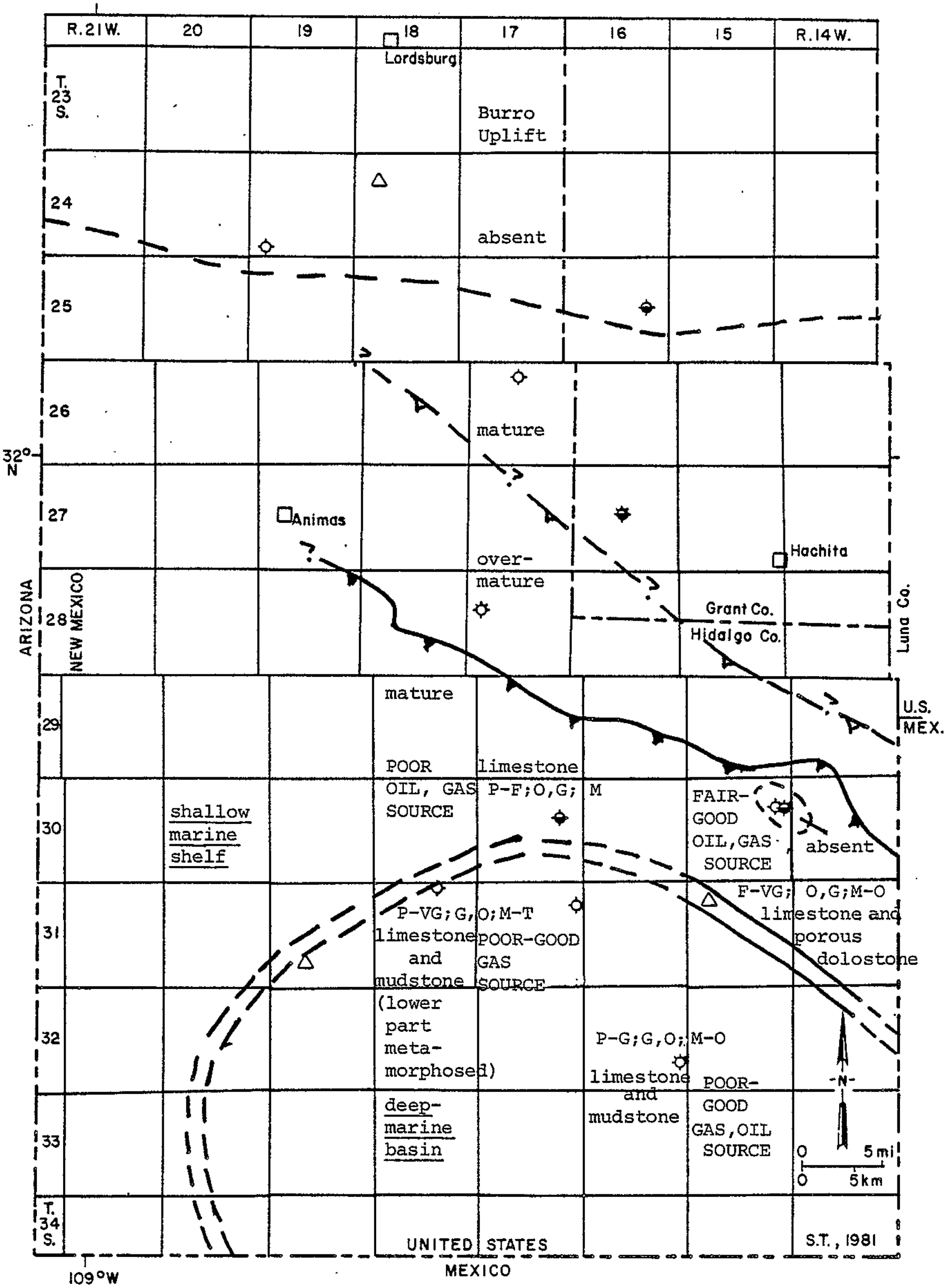

Figure 11 - Petroleum-source map of Horquilla Formation (Pennsylvanian-Permian).

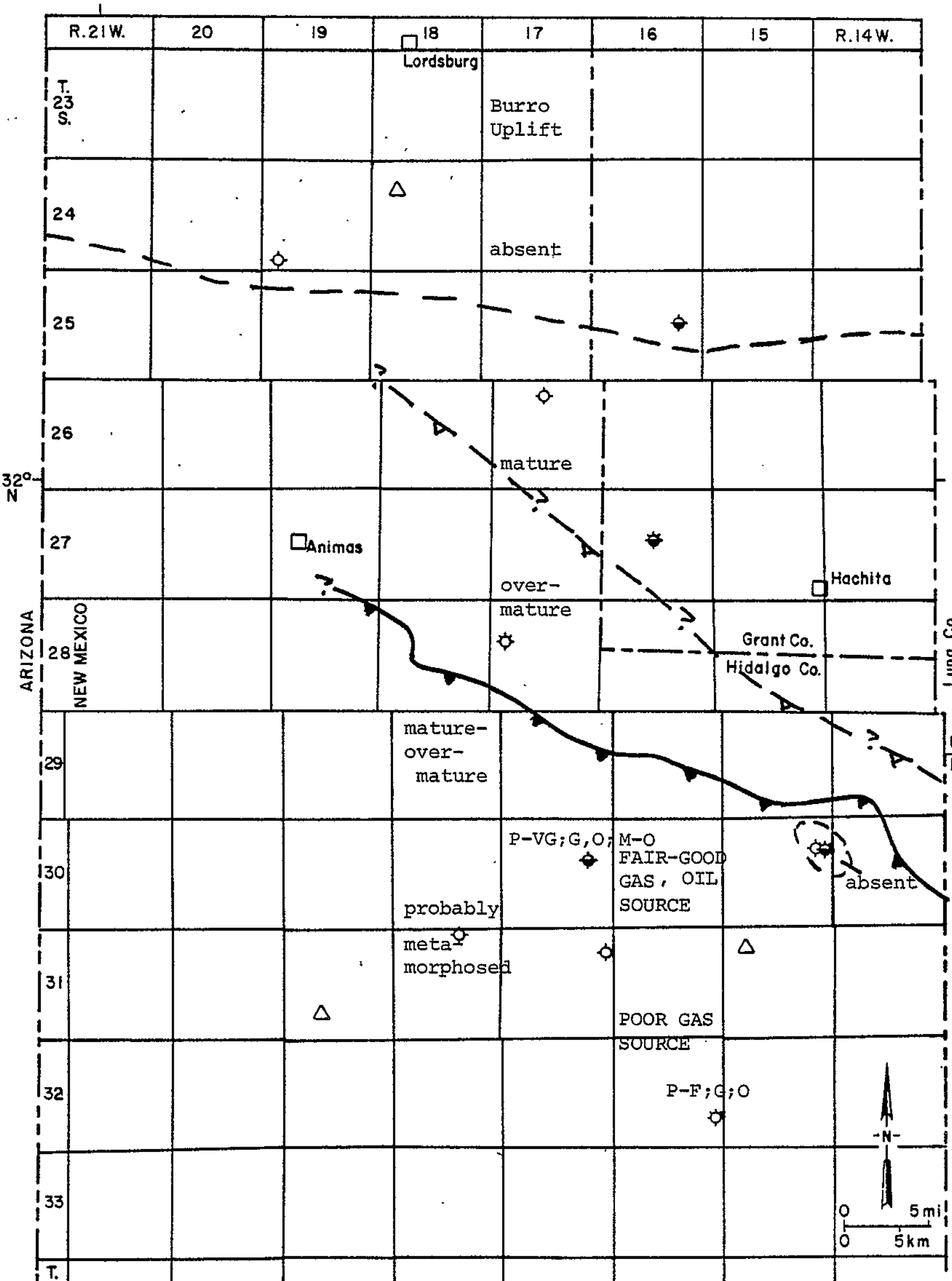

Figure 12 - Petroleum-source map of Paradise Formation (Mississippian).

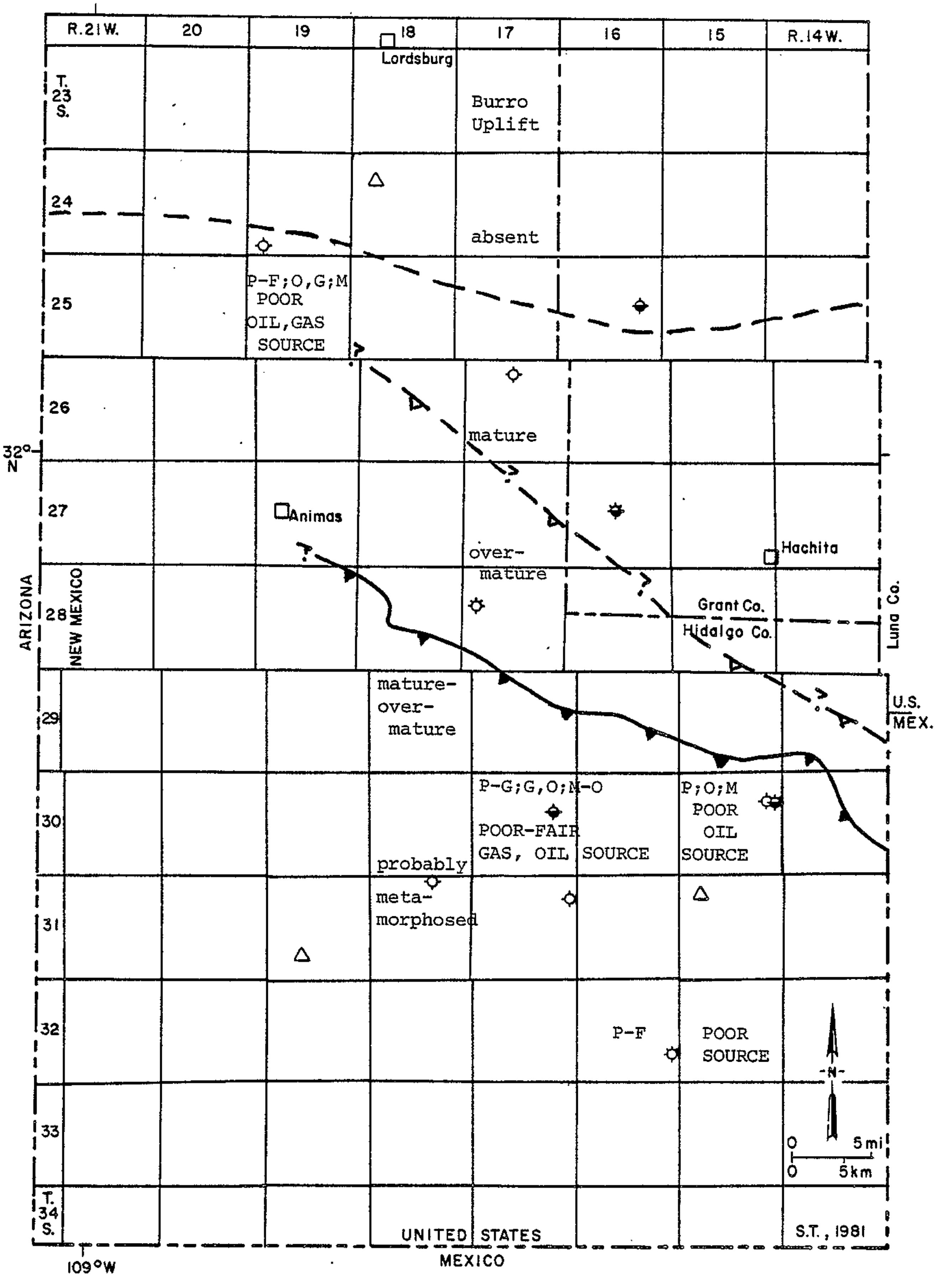

Figure 13 - Petroleum-source map of Escabrosa Formation (Mississippian).

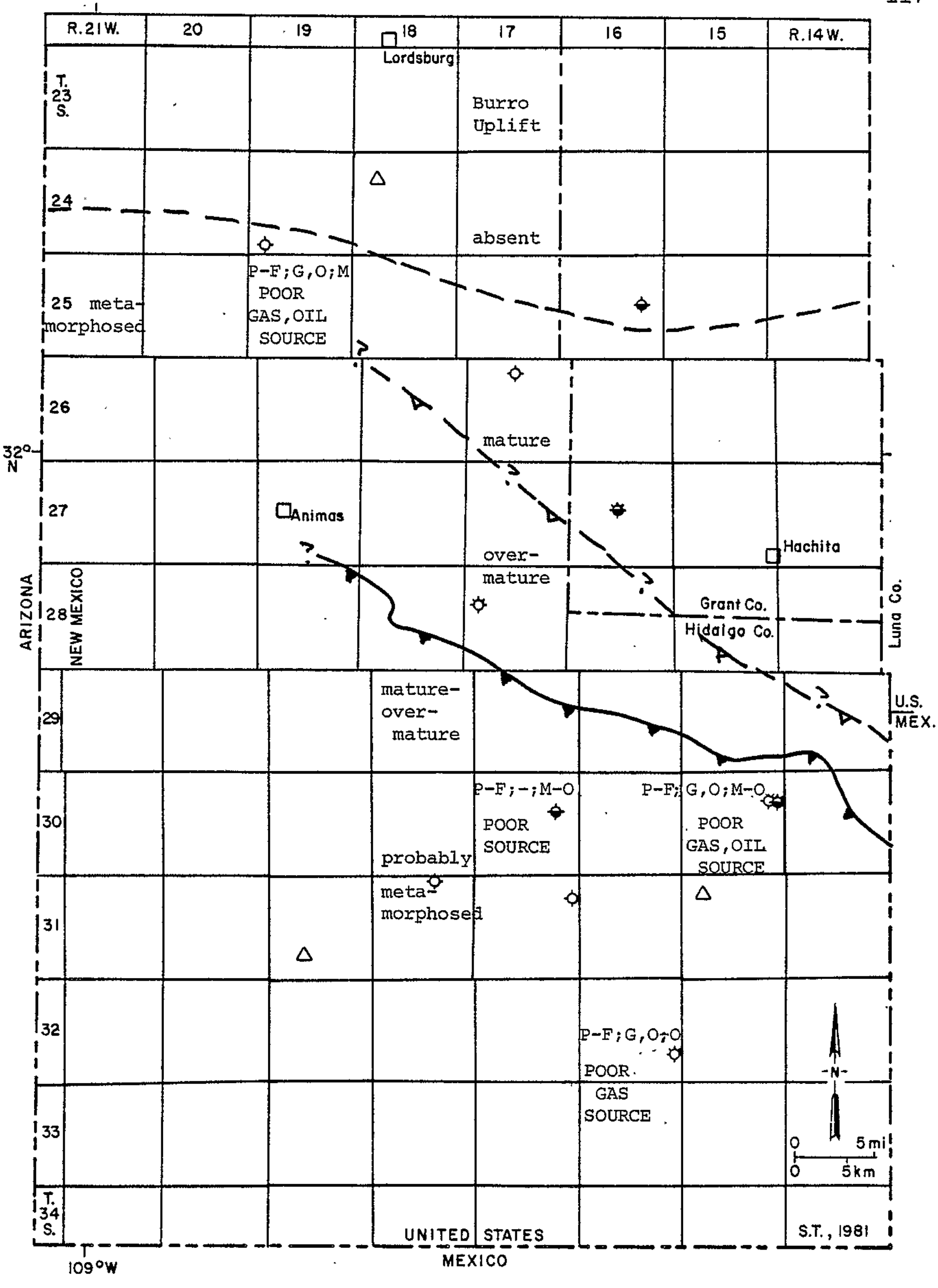

Figure 14 - Petroleum-source map of Percha Formation (Devonian).

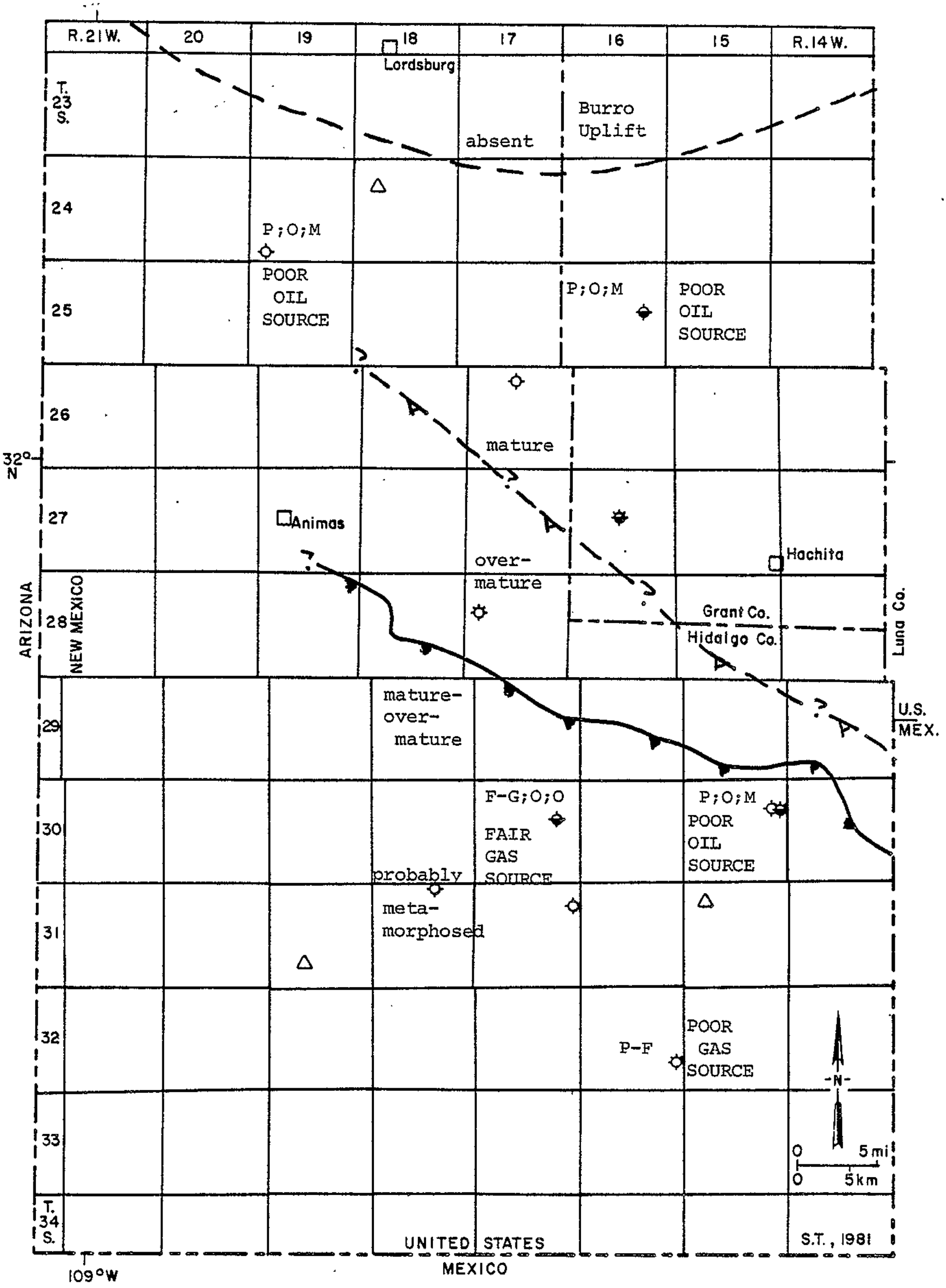

Figure 15 - Petroleum-source map of Montoya Formation (Ordovician).

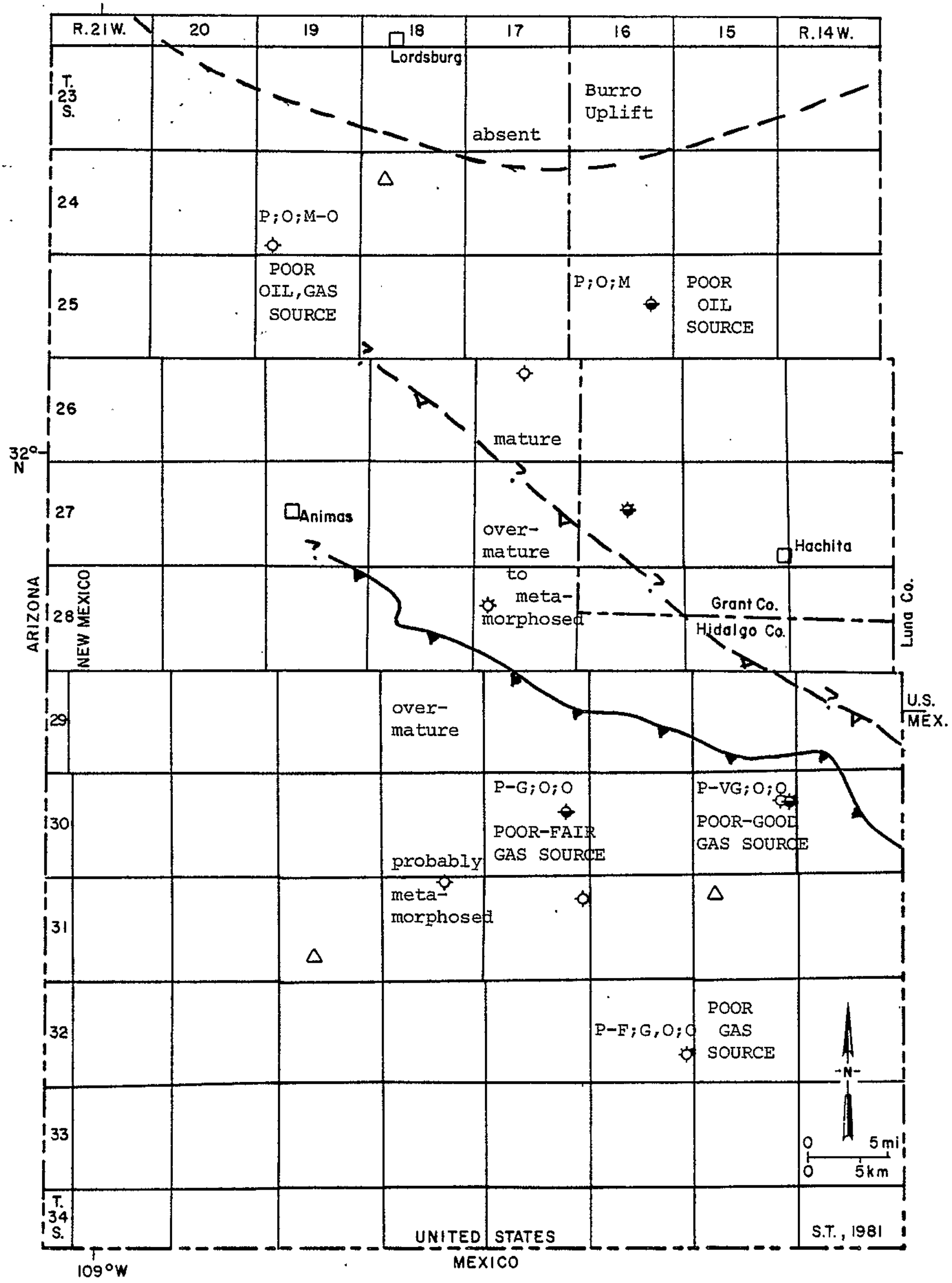

Figure 16 - Petroleum-source map of El Paso Formation (Ordovician).

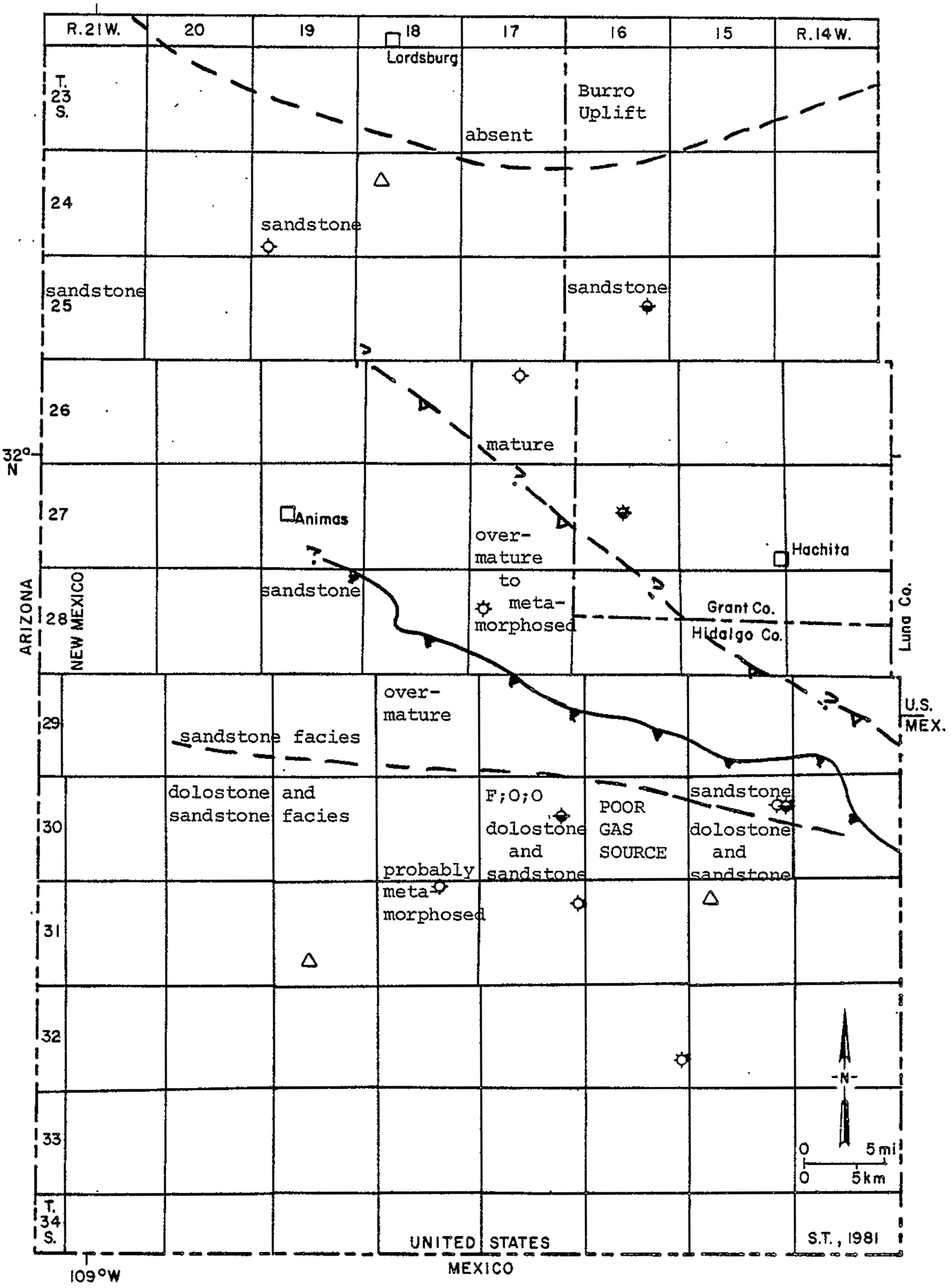

Figure 17 - Petroleum-source map of Bliss Formation (Cambrian-Ordovician).