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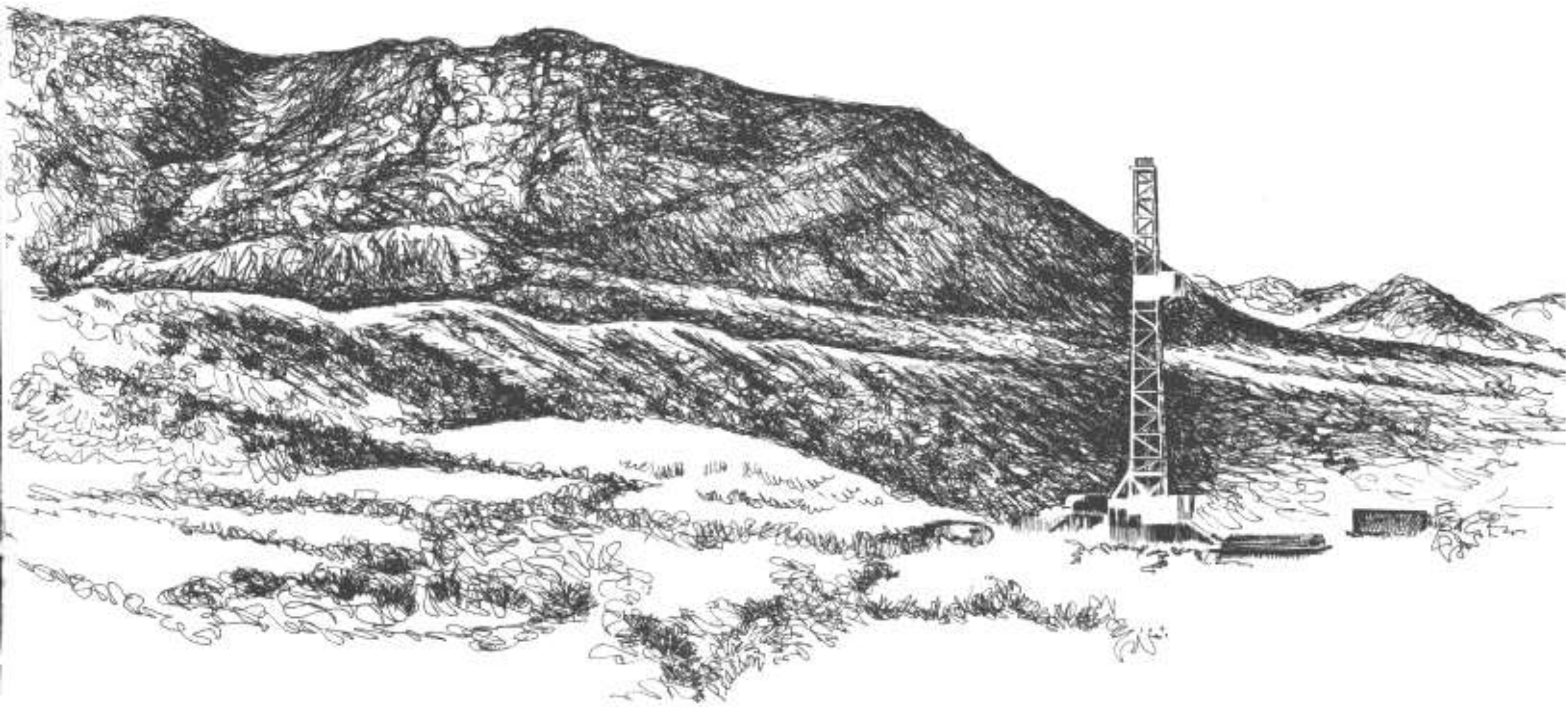

Geology, petroleum source rocks, and thermal metamorphism in KCM No.1 Forest Federal well, Hidalgo County, New Mexico

by Sam Thompson HI and others

New Mexico Bureau of Mines & Mineral Resources

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Circular 152

New Mexico Bureau of Mines & Mineral Resources

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NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY

Geology, petroleum source rocks, and thermal metamorphism in KCM No. 1 Forest Federal well, Hidalgo County, New Mexico

compiled by Sam Thompson III

with contributions by
Fred H. Behnken, Antonius J. Budding and Ronald F. Broadhead, Paul J. Cernock and
Geoffrey S. Bayliss, Rodney C. Ewing, and Wolfgang E. Elston and Edward E. Erb

Cover: Drilling rig for the KCM No. 1 Forest Federal situated on Permian limestones exposed in the Winkler anticline. Beyond are Tertiary volcanic rocks forming Gillespie Mountain in the Animas range. View to northwest.

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Preface

In southwestern New Mexico and adjoining areas, the Paleozoic and Mesozoic sedimentary section contains several petroleum source and reservoir units; however, metamorphism by Tertiary plutons has deterred exploration. Preliminary investigations indicate that the most severe effects of thermal metamorphism are limited vertically and laterally to relatively short distances around the plutons.

In this circular, we show that the KCM No. 1 Forest Federal well encountered fair to possibly good source units of petroleum in the deep-marine mudstones and limestones of the Permian-Pennsylvanian section. We also show that the lower part of the section was metamorphosed by Tertiary intrusives and that the thermal effects decrease in the upper part.

This KCM well provides an unusual opportunity to observe such thermal effects in a vertical sequence containing petroleum source units. The KCM Company generously released the samples, logs, and other essential well data for these studies. Several specialists were invited to contribute the needed research from their respective fields. The results of this research are compiled as a collection of individual papers. Some repetition of main points is necessary for each paper to be complete.

The introduction of the first paper presents the regional geologic setting and the surface location of the well on the Winkler anticline. The main part of the paper presents the general results of the subsurface geology followed by documentation with specific results of stratigraphic and other analyses. The summary emphasizes the significance of these results in the exploration for petroleum.

The second and third papers treat special aspects of the basic geology. Behnken presents the paleontological evidence based on conodonts used in dating the stratigraphic section; *he* also discusses the conodont alteration index of Epstein and others. Budding and Broadhead identify the igneous and metamorphic rocks in the well and document the intensity of contact metamorphism.

Cernock and Bayliss in the fourth paper determine organic geochemical zones, discuss the thermal maturity based mainly on kerogen analysis, and evaluate the hydrocarbon source potential. Ewing and Thompson in the fifth paper review concepts dealing with organic metamorphic facies and estimate the level of organic metamorphism in the well.

Elston and Erb in the last paper present field evidence that the Tertiary volcanic cauldrons around the well are surface expressions of the plutonic complex below. The limits of the cauldrons aid in projecting the lateral extent of thermal alteration.

The work by Elston and Erb is part of the project "Application of volcanology to petroleum exploration in southwestern New Mexico" funded by the New Mexico Energy Research and Development Program, New Mexico Energy Resources Board (grant numbers 74-104 and 75-109). A part of these funds was used to support some of the analyses in the previous papers.

GeoChem Laboratories, Inc. donated the major part of the cost of Cernock and Bayliss's analyses. The other authors were supported by their university employers.

With the dedicated efforts of the authors, the research results were completed so that this circular could be released at the meeting of the Geological Society of America's South-central Section in El Paso, Texas, March 17-18, 1977. At that meeting, several of the authors are scheduled to participate in the symposium *Thermo-maturation of organic residues.*

The results given in this publication are sufficient for a basic interpretation of the geology and an evaluation of the source units of petroleum in this KCM well. However, most of these authors are continuing their research on this well; other specialists are adding knowledge from different fields. Other wells and surface exposures are being studied to increase our knowledge of the geologic framework, determine the position of petroleum source and reservoir units within the framework, and delineate the limits of thermal alteration that may have affected the accumulations of oil and gas in southwestern New Mexico.

Sincere appreciation is expressed to everyone who helped prepare this circular; specific acknowledgments are given in individual papers.

Sam Thompson III
Petroleum Geologist
New Mexico Bureau of Mines
& Mineral Resources

Socorro
February 16, 1977

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SUBSURFACE GEOLOGY AND THE PETROLEUM-EXPLORATION SIGNIFICANCE

of KCM No. 1 Forest Federal Well, Hidalgo County, New Mexico

by Sam Thompson 111, *New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801*

ABSTRACT

The KCM No. 1 Forest Federal well was drilled on the Winkler anticline in the Animas Mountains of Hidalgo County, New Mexico, during late 1974 and early 1975. This well began in the Earp Formation (Permian), drilled a nearly complete section of the Horquilla Formation (Permian to Pennsylvanian), and bottomed in a quartz-monzonite pluton of mid-Tertiary age at a total depth of 4,464 ft. The Earp consists of nonmarine carbonaceous limestone and unconformably overlies the Horquilla at a depth of 255 ft. The Wolfcampian part of the Horquilla consists of a shelf limestone unit down to 706 ft and a basin unit of mudstone and limestone below to 1,526 ft. The Pennsylvanian part consists of increasingly recrystallized limestones down to 2,255 ft, and a complex of marbles, hornfelses, and quartz-monzonite intrusives from there to total depth. During this subsurface study, samples were selected for laboratory analyses; the results are given in other papers in this circular.

No significant shows of oil or gas were encountered during drilling; the well is classified as a dry wildcat. This test virtually condemns the Winkler anticline as a petroleum prospect; however, the acquired information is valuable in exploration for petroleum resources in other parts of the region. The basin facies of the Horquilla contains source rocks for petroleum. This well helps locate the shelf-margin facies where excellent dolostone reservoirs occur. The Tertiary pluton metamorphosed the lower part of the sedimentary section, intensively degrading any preexisting source or reservoir units; the most severe effects appear to be limited vertically to only a few thousand feet. A possible fault at 1,947 ft may have been formed while the Animas Mountains were being uplifted during the Basin and Range deformation; the fresh water in this fault zone probably would have flushed any shallower reservoirs.

INTRODUCTION

The main purpose of this paper is to analyze the subsurface geologic data of the KCM No. 1 Forest Federal and to evaluate the significance of this well in the exploration for petroleum resources in southwestern New Mexico. The regional setting within the Pedregosa-Alamo Hueco Basins and the surface location on the Winkler anticline are discussed in this introduction.

ACKNOWLEDGMENTS—I wish to thank the many organizations and individuals who supported this study. The KCM Company and their associates are acknowledged for: cooperation at the wellsite; open communication during the drilling of this confidential well; and release of samples, logs, and other data so essential to this subsurface study as well as the other investigations presented in the circular. Specific acknowledgments are given in later sections. Part of the funds for several analyses were provided by the Energy Resources Board of New Mexico. Roy W. Foster of the New Mexico Bureau of Mines and Mineral Resources reviewed the manuscript and made several suggestions to improve it.

Regional Setting

The KCM well was drilled in the northern part of the Pedregosa Basin, a basin of subsidence with 2,000 ft or more of Pennsylvanian sedimentary rocks as defined by Greenwood, Kottlowski, and Thompson (in press). The Pedregosa area contains a Paleozoic sequence of dominantly shallow-marine shelf carbonates similar to that found in the petroliferous Permian Basin of southeastern New Mexico and western Texas. This Paleozoic sequence contains the most important objectives for petroleum exploration in the Pedregosa area; however, a thick Lower Cretaceous sequence of limestone and sandstone overlies the Paleozoic here and also contains important objectives.

Specifically, the KCM well helps to delineate the northern margin of the Alamo Hueco Basin, a deep-marine basin of upper Pennsylvanian and lower Permian sedimentary rocks defined by Zeller (1965) as lying within the Pedregosa Basin. Fig. 1 shows the position of the margin of the Alamo Hueco Basin as determined by Zeller and others in the Big Hatchet Mountains; the approximate (dashed) extension of this boundary between the shelf and basin facies of the Horquilla Formation (Pennsylvanian to Permian) is based on present knowledge of the surface and subsurface control.

The deep-marine basin rocks, composed of dark mudstones and limestones, contain sufficient organic carbon to be judged as source rocks for petroleum. Oil and gas probably migrated upslope from the source units into porous dolostone reservoirs in the shelf-margin facies and were trapped by the relatively impermeable limestones of the shallower shelf facies. The shelf-margin dolostones around the Alamo Hueco Basin are judged to be the best petroleum objective in this part of southwestern New Mexico. An intensive study is underway to delineate the Horquilla facies as accurately as possible with outcrop and well data, to analyze the depositional and diagenetic history, and to measure the source and reservoir parameters.

Tectonic and igneous events from late Cretaceous into Tertiary time in this part of the Basin and Range province generally were detrimental to the previous accumulations of oil and gas. The adverse effect of these events makes this area more of a challenge for exploration than the productive Permian Basin (Thompson, 1976). To meet this challenge in part, a joint research project is in progress with Wolfgang E. Elston of the University of New Mexico and other volcanologists who

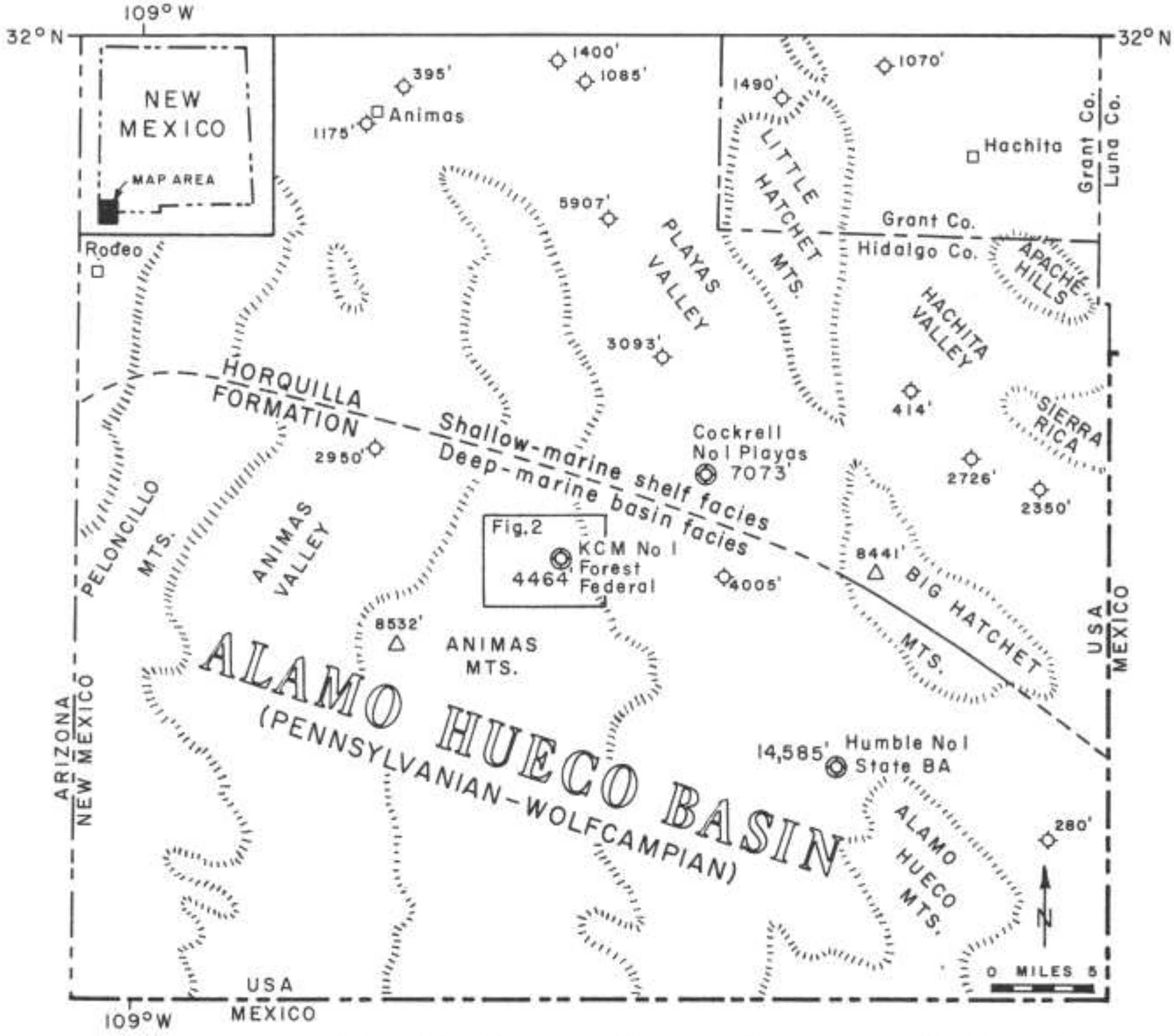


FIGURE 1—Location of KCM No. 1 Forest Federal in the Alamo Hueco Basin, southwestern New Mexico. The margin of the basin was defined by Zeller, 1965, in the Big Hatchet Mountains. Two other key wells, the Humble No. 1 State BA and the Cockrell No. 1 Playas, control the margin. Total depths are shown for all oil and gas tests in the area.

are mapping the cauldron margins in the southwestern part of the state. One objective is to determine the extent of the volcanic effects on the older sedimentary section and on the preservation of petroleum in the subsurface. This KCM well, located on or near three of the cauldron margins, offers an excellent opportunity to observe the volcanic effects. The volcano-tectonic setting of this well is discussed by Elston and Erb in this circular.

Winkler Anticline

Fig. 2 shows the location of the KCM well on the Winkler anticline in the Animas Mountains of Hidalgo County, New Mexico (1,494 ft from the north line and 1,753 ft from the east line of sec. 3, T. 31 S., R. 18 W.). Prior to the drilling of this well, interpretations differed about whether the structure was intruded.

Zeller and Alper (1965, plate 1 and p. 67-69) first mapped and described this anticline in detail. They present evidence that the anticline started growing sometime between medial Permian and early Cretaceous and continued through several periods of deformation into Tertiary time. At the Permian-Cretaceous unconformity in this area, they indicate the following: about 3,000 ft of Permian rocks have been eroded, a slight angular discordance is present, pre-Cretaceous faults developed along the northeast-trending anticlinal axis, and about 2,000 ft of the basal Cretaceous beds are missing (possibly by onlap onto the anticline). Zeller and Alper imply (p. 71) that the most intense deformation of the anticline occurred during the development of the unconformity between the Cretaceous and Tertiary rocks, that is, during the Laramide orogeny. At this unconformity, they indicate that: about 5,000 ft of Cretaceous rocks have been eroded, deformation during this orogeny affected the

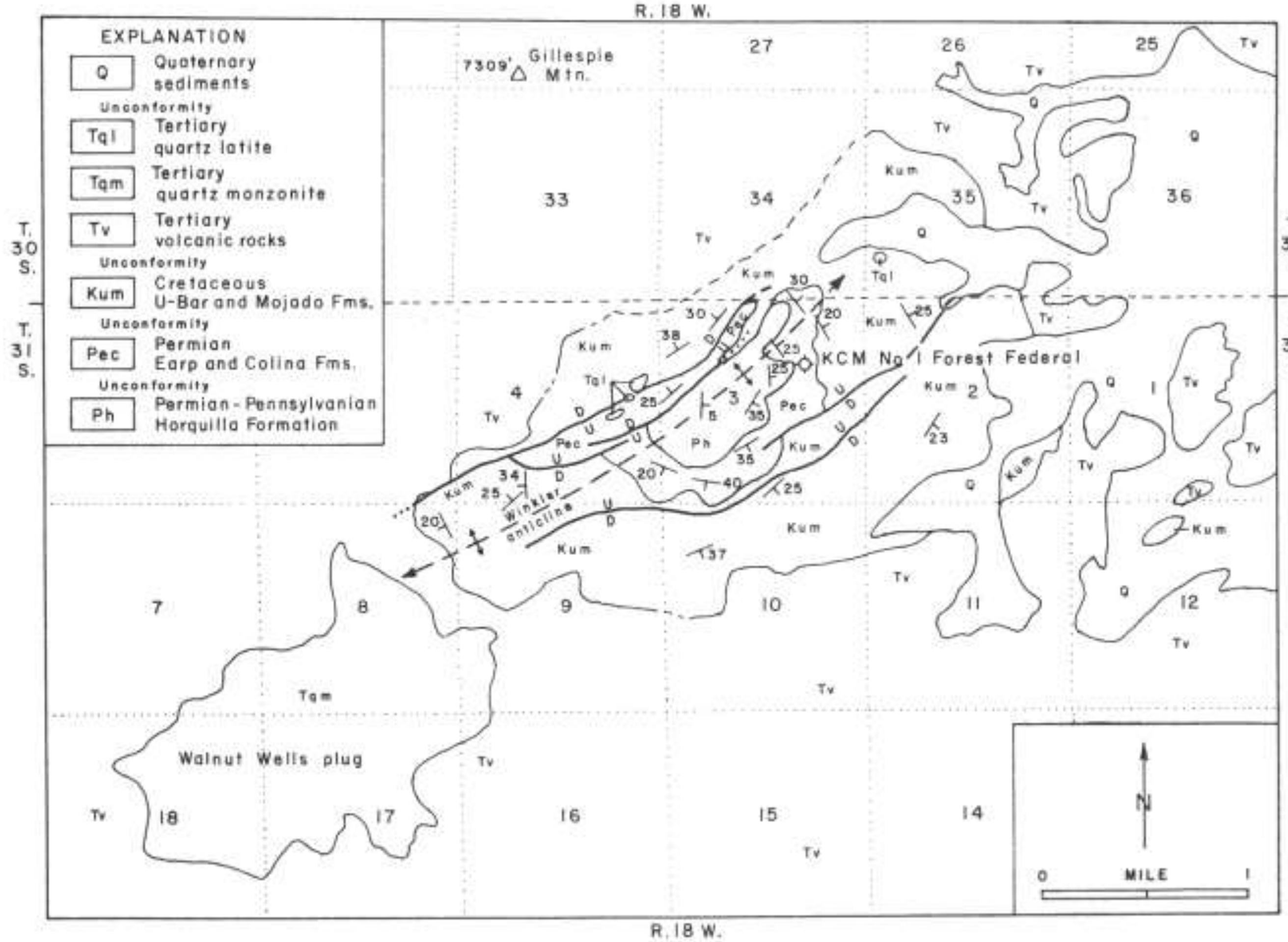


FIGURE 2—Location of KCM No. 1 Forest Federal on the Winkler anticline in the Animas Mountains, Hidalgo County, New Mexico. Geologic map generalized from Zeller and Alper, 1965, plate 1.

Cretaceous and older rocks but not the overlying Tertiary ones, and pre-Tertiary faulting included rejuvenation of the northeast-trending faults near the anticlinal axis. Although they recognize (p. 77) that the folding in the volcanic rocks suggests continued growth of the Winkler anticline, they do not discuss the possibility that at least part of the folding was produced by Tertiary intrusion; nor do they show a Tertiary pluton beneath the anticline on their cross section (plate *2, A - A'*).

Wengerd (1970, p. 103) considered the Winkler anticline to be a prime prospect for petroleum exploration in southwesternmost New Mexico. The northeasterly trend of the anticlinal axis was considered controlled by a Precambrian structural feature with pre-Cretaceous and subsequent growth, in contrast to the general northwesterly trend of the Laramide folds in this region.

Ellis (1971, p. 33-37) and McAnulty (1972, p. 3) indicate that the Winkler anticline may have begun in Permian time, but that the greatest development probably was the result of Tertiary igneous intrusion. Corbitt and Woodward (1973, p. 2213) suggest that the northeasterly trending anticline was produced by Tertiary intrusive doming. Lloyd W. Krumrey, Jr., a consulting geologist studying the fluorspar mineralization of the area in detail, points out (personal communication) that the radial fracture pattern indicates an intrusive dome rather than a compressional anticline.

After the drilling of the KCM well (which encountered quartz-latite dikes, quartz-monzonite plutons, and contact metamorphism of the sedimentary section described by Budding and Broadhead in this circular), the evidence is clear that the structure is intruded and virtually condemned as a petroleum prospect. Elston and Erb conclude in this circular that the Winkler anticline began during Oligocene volcanism and was formed initially by doming above an intrusion into the ring-fracture zone on the south side of the Juniper cauldron. However, much of the evidence presented by Zeller and Alper (1965) of local folding and faulting, especially in early Mesozoic and Laramide times, still appears valid. If so, the Walnut Wells plug and the intrusions in the KCM well may have been emplaced along a preexisting northeasterly trending zone of weakness. Additional field work and other studies are needed to resolve the question of what percentages of the total structural relief can be attributed to the Tertiary intrusion and the other deformational episodes.

SUBSURFACE GEOLOGY

General Results

Fig. 3 shows the general subsurface geology of the KCM well based on the information in this circular. This well began in the Earp Formation (Permian), drilled a nearly complete section of the Horquilla Formation (Permian to Pennsylvanian), and bottomed in a quartz-monzonite pluton of mid-Tertiary age at a total depth of 4,464 ft. The Paleozoic sedimentary section consists mainly of limestones deposited on a coastal to shallow-marine shelf, but some dark mud-stones and limestones were deposited in a deep-marine basin environment. The darker rocks contain sufficient organic carbon to be fair to good source units for petroleum generation. Generally the reservoir quality is poor. In the recrystallized and metamorphosed Paleozoic rocks, the petroleum source and reservoir qualities are extremely poor; they may have been poor prior to the Tertiary intrusion. No shows of oil or gas were encountered during the drilling of the well.

The Earp Formation (Leonardian?) consists of non-marine carbonaceous limestone unconformably over-lying the Horquilla at a depth of 255 ft. The beds at the surface dip about 25°, so this interval is equivalent to the lower 231 ft of the true Earp thickness which totals 612 ft or more in this area (Zeller and Alper, 1965, p. 11). The plant material may constitute a fair source of gas.

Wolfcampian to Desmoinesian (?) beds of the Horquilla Formation are identified with fusulinids and conodonts. The gross interval of 4,209 ft (from depths of 255 ft to 4,464 ft) probably does not include all the Horquilla but does include 683 ft of Tertiary plutonic intrusives. The net interval of 3,526 ft is equivalent to about the upper 3,195 ft of the true thickness of the Horquilla, assuming that the beds continue to dip 25°. Zeller (1965, p. 37) gives the maximum thickness of the Horquilla in the Big Hatchet Mountains as 3,600 ft.

The Wolfcampian part of the Horquilla consists of a shallow-marine shelf-limestone unit from 255 ft to 706 ft and a deep-marine basin-mudstone unit from 706 ft to 1,526 ft. The latter is the best source unit for petroleum in the well, and may be a better source for gas than for oil judging by the kerogen content and the degree of maturation. The Virgilian part from 1,526 ft to 1,890 ft contains some dark, muddy limestones; possibly they are also deep-marine basin deposits.

A major fracture or possible fault is indicated at 1,947 ft by calcite filling, cycle skipping on the sonic log, and a fresh-water anomaly on the electric log. However, any displacement probably is small, because a significant difference in the age of the section above and below was not recognized. The Missourian part of the Horquilla is inferred to be from 1,890 ft to 2,321 ft. Some limestones above the fault at 1,947 ft are lighter in color than the Virgilian limestones and may indicate a shallower marine environment. Below the fault, the Missourian limestones exhibit an increasingly recrystallized aspect. These translucent, silicified rocks contain metamorphic minerals. The original depositional environment of the rocks, as well as their original petroleum source and reservoir quality, are difficult to determine.

Below 2,255 ft, the remainder of the well is in an igneous-metamorphic complex of marbles, hornfelses, and quartz-monzonite intrusives. The marbles in the Missourian (2,255 ft to 2,321 ft) are more finely crystalline and grade into recrystallized limestone. The Desmoinesian (?) section is inferred to be below 2,321 ft; the lower part may be Atokan (?) to Chesterian (?). The upper part, 2,321 ft to 2,790 ft, consists of marbles, generally white, clear, and coarsely crystalline, that may have been shallow-marine shelf limestones. The hornfels rocks are white to light gray and may have been cherty limestones. In the lower part, from 2,790 ft to 3,870 ft, the marbles are darker and probably were muddy limestones but also may have been shallow-marine shelf deposits. The greenish, fissile hornfelses below 3,870 ft may have been cherty limestones or mudstones prior to metamorphism.

Practically no contact metamorphism is associated with the thin quartz-latite dikes that intrude Earp Formation from 200 ft to 230 ft; inclusions of calcite have been assimilated from the country rock. On the other hand, the quartz-monzonite intrusives in the Horquilla, occurring between 2,387 ft and total depth, have metamorphosed nearly the whole section below 2,255 ft. Only some thin mudstones or muddy lime-stones may have been less affected by the intrusions. Above 2,255 ft, the metamorphism is progressively less up to the fault at 1,947 ft. If it predated the intrusion, this fracture may have been a barrier to contact metamorphism from below. Conversely, the fracture may have developed later during the Basin and Range deformation along a zone of weakness between the slightly metamorphosed rocks below and the normal sedimentary rocks above.

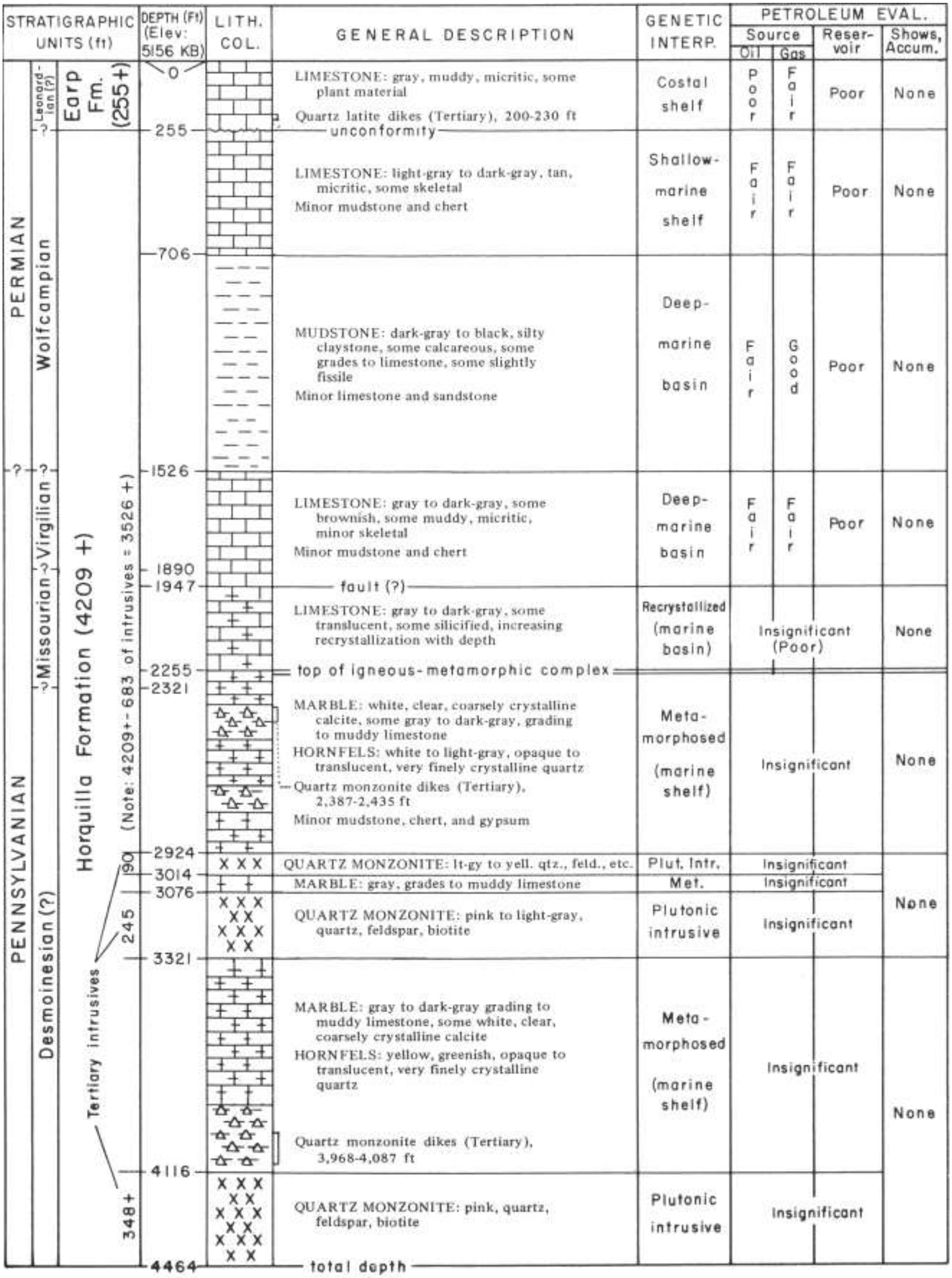
The quartz monzonites and latites may belong to the same Tertiary intrusive complex as the Walnut Wells plug and the dikes mapped by Zeller and Alper (1965). The magma body that fed these intrusives, and probably the Animas stock to the north, appears to have covered at least 40 sq mi. More intrusives and metamorphosed Paleozoic rocks may be expected below the bottom of the KCM well; however, the zone of contact metamorphism appears to be limited vertically to only a few thousand feet above the pluton.

Specific Results

To document the general results of this subsurface study, and to serve as a guide to subsequent papers in this circular, the following summaries of specific results are presented. The results are much more comprehensive than are usually published on an individual well but are not final. Most analyses were made on selected samples from depths several tens to hundreds of feet apart. The main objectives were to establish as many of the essential points as possible, to see how the KCM well fits into the geologic framework, and to use the findings in evaluating the petroleum potential.

Analyses of basic well data

Table 1 summarizes the well record of the KCM No. 1 Forest Federal. This table is based on data in the files of the New Mexico Bureau of Mines and Mineral Resources (including the scout ticket from Petroleum



STRATIGRAPHIC UNITS (ft)			DEPTH (Ft) (Elev: 5156 KB)	GENERAL DESCRIPTION	GENETIC INTERP.	PETROLEUM EVAL.			
						Source		Reser-voir	Shows, Accum.
						Oil	Gas		
PERMIAN	Leonard-ian (?)	Earp Fm. (255+)	0	LIMESTONE: gray, muddy, micritic, some plant material Quartz latite dikes (Tertiary), 200-230 ft	Costal shelf	Poor	Fair	Poor	None
	-?-		255	unconformity					
	Wolfcampian	Horquilla Formation (4209 +)	255	LIMESTONE: light-gray to dark-gray, tan, micritic, some skeletal Minor mudstone and chert	Shallow-marine shelf	Fair	Fair	Poor	None
			706	MUDSTONE: dark-gray to black, silty claystone, some calcareous, some grades to limestone, some slightly fissile Minor limestone and sandstone	Deep-marine basin	Fair	Good	Poor	None
-?-	-?-		1526	LIMESTONE: gray to dark-gray, some brownish, some muddy, micritic, minor skeletal Minor mudstone and chert	Deep-marine basin	Fair	Fair	Poor	None
PENNSYLVANIAN	Virgilian		1890						
	-?- Missourian		1947	fault (?) LIMESTONE: gray to dark-gray, some translucent, some silicified, increasing recrystallization with depth	Recrystallized (marine basin)	Insignificant (Poor)			None
			2255	top of igneous-metamorphic complex					
	-?- Desmoinesian (?)		2321	MARBLE: white, clear, coarsely crystalline calcite, some gray to dark-gray, grading to muddy limestone HORNFELS: white to light-gray, opaque to translucent, very finely crystalline quartz Quartz monzonite dikes (Tertiary), 2,387-2,435 ft Minor mudstone, chert, and gypsum	Meta-morphosed (marine shelf)	Insignificant			None
		Tertiary intrusives 90	2924	QUARTZ MONZONITE: lt-gy to yell. qtz., feld., etc.	Plut. Intr.	Insignificant			None
			3014	MARBLE: gray, grades to muddy limestone	Met.	Insignificant			
		Tertiary intrusives 245	3076	QUARTZ MONZONITE: pink to light-gray, quartz, feldspar, biotite	Plutonic intrusive	Insignificant			
			3321	MARBLE: gray to dark-gray grading to muddy limestone, some white, clear, coarsely crystalline calcite HORNFELS: yellow, greenish, opaque to translucent, very finely crystalline quartz Quartz monzonite dikes (Tertiary), 3,968-4,087 ft	Meta-morphosed (marine shelf)	Insignificant			None
		Tertiary intrusives 348+	4116	QUARTZ MONZONITE: pink, quartz, feldspar, biotite	Plutonic intrusive	Insignificant			
			4464	total depth					

(Note: 4209+ - 683 of intrusives = 3526 +)

FIGURE 3—GENERAL SUBSURFACE GEOLOGY OF KCM NO. 1 FOREST FEDERAL.

[New Mexico Bureau Mines & Mineral Resources, Circular 152, 1977]

TABLE 1—SUMMARY OF WELL RECORD.

Well name: KCM Co. No. 1 Forest Federal   API No.: 30-023-20007
Location: 1,494 ft from north line and 1,753 ft from east line, sec. 3, T. 31 S., R. 18 W., Hidalgo County, New Mexico
Elevation: 5,156 ft, kelly bushing (KB); 5,144 ft, ground level (GL)
Total Depth: 4,460 ft, driller; 4,464 ft, wire-line logger

. . . .

Drilling contractor: Tri-Service Drilling Co.
Spud: November 26, 1974   Complete: January 22, 1975
Drilling method: Rotary   Status: Wildcat, dry and abandoned
Drilling fluid: Fresh water to 1,650 ft, fresh mud to 4,460 ft.
Bit size: 17½ inches to 305 ft; 12¼ inches to 1,976 ft; 8¾ inches to 4,460 ft
Casing size: 13 3/8 inches at 305 ft with 330 sacks of cement (298 ft by logger)
Drilling problems:
  Hole deviation: 2° to 5°, 240 ft to 1,820 ft; 7° to 8°, 1,910 ft to 4,460 ft
  (No lost circulation; used 27 bits)
Cost of well: $333,500.32

. . . .

Hydrocarbon logging: Simco, Inc., 40 ft to 4,460 ft
Shows of oil: None   Shows of gas: None
Cores: None   Drill-stem tests: None
Wire-line logging: Schlumberger Well Services
  Dual Induction and Laterolog: 298 ft to 4,446 ft
  Borehole-Compensated Sonic Log: surface to 4,455 ft
Geologic summary:
  Earp Formation (Permian), surface to 255 ft
  Horquilla Formation (Permian-Pennsylvanian), 255 ft to 4,464 ft
  Possible fault in Horquilla at 1,947 ft
  Quartz-monzonite intrusives (Tertiary) and metamorphosed Horquilla, 2,255 ft to 4,464 ft
  Total depth is in quartz monzonite (Tertiary)

Information), data on the well logs, and communications from personnel who worked on the well. The geologic summary is based on the present study.

The KCM Company, their contractors and their consultants, all combined to produce a first-class exploration effort in the planning and drilling of the Forest Federal well. Such short-term associations frequently develop into an effective team, but too often such efforts are taken for granted. In such frontier areas as southwestern New Mexico, this kind of exploration teamwork is needed to get the high quality data essential in the search for new petroleum resources. Although the results from this well were satisfactory, some specific suggestions for improving future wildcat ventures are offered in the following discussions.

Craig C. Johnson, Chief Geologist of the KCM Company, is particularly acknowledged for his permission to visit the wellsite and to work directly with the personnel there; he also generously donated samples, logs, and other well data, and released all this information for publication. Eugene Greenwood, consulting geologist, recommended the prospect and much of the exploration program. U. V. Jones, consulting geologist, supervised the geologic operations at the wellsite. All were helpful in the geologic investigation.

Don Coleman, tool pusher for Tri-State Drilling Company, supervised the drilling of this rank wildcat. An objective of economic basement was reached in spite of the hard-rock drilling in Paleozoic limestones, metamorphic rocks, and Tertiary igneous rocks, and in spite of deviation problems resulting from steeply dipping beds. The best possible hole conditions were maintained to evaluate any shows of oil or gas, as well as the quality of any petroleum source and reservoir units. Fortunately, mud with a low water loss was used as a drilling fluid to insure good quality data in wire-line logging and in analysis of the cuttings. (Drilling with air or mist, as some operators have done in this region, would have been faster and cheaper, but the quality of data would have deteriorated.)

George W. Sturgis, Simco, Inc., ran the hydrocarbon-logging operation. With this one-man unit, he kept up with the drilling, analyzed the cuttings, and maintained the mud-gas detector in good working order. In addition, he made a special collection of the canned cuttings for organic geochemical analyses. Usually a two- or three-man unit is recommended to maintain a 24-hr watch for shows of high-gravity oil that disappear quickly. Also, additional observations may be made. For example, analyses of cuttings gas aid in the evaluation of petroleum source quality. In this case no shows of oil or gas were reported; probably none were missed because the wellsite geologist (Jones) worked shifts with Sturgis. Furthermore, the collection of canned cuttings yielded much better source-rock analyses.

Although drill-stem tests were not run, the excellent plans included tests of porous zones for formation water as well as any shows of oil or gas. Such data are badly needed for analyses of the subsurface fluid systems in the region, especially around plutonic-volcanic centers, and in the uplift areas where flushing by meteoric waters is a problem. (A fresh-water zone in the fracture at 1,947 ft is indicated on the electric log, but a drill-stem test would have been impractical with the bottom of the hole at 4,464 ft.) Cores were not planned. A minimum of one core every thousand feet would have yielded more reliable results of all the analyses, including source and reservoir quality, petrography, and paleontology. A core of the igneous rock at the bottom of the well would have been useful in identifying the basement and in determining an accurate potassium-argon date. Nevertheless, the analyses with cuttings have yielded results judged to be fairly reliable.

The wire-line logging program included a borehole-compensated sonic log and a dual induction-laterolog, the basic tools needed for formation evaluation. An additional porosity tool such as a neutron-density log would have been helpful. A continuous dipmeter would have shown the direction and amount of inclination of the beds and other surfaces. A directional survey would have shown the position of the hole. Tom Kitts and others with Schlumberger Well Services ran good quality logs. L. K. Segars of Schlumberger's Hobbs, New Mexico, office offered valuable suggestions for the following log analyses.

The gamma ray-sonic log is excellent and confirms the generally poor reservoir quality observed in the cuttings. Porosities calculated from the sonic curve are less than 5 percent in the limestones down to 2,255 ft. Porosities are less than 2 percent in the igneous-metamorphic complex from 2,255 ft to total depth. This log was also useful in interpreting the succession of lithologic units and in delineating stratigraphic boundaries. Unfortunately, the caliper curve was not recorded on this log.

Several washout zones are indicated on the electric log down to the fault at 1,947 ft. The negative anomalies on the spontaneous potential curve and the lower readings on the resistivity curves occur in mudstones and muddy limestones. The anomalies probably represent zones of sloughing produced during drilling of the large 121/4-inch hole down to 1,976 ft. Perhaps an intermediate logging run at that depth would have given better results. The large positive anomaly on the spontaneous potential curve indicates fresh water in the fault at 1,947 ft. From there to total depth the low resistivity values also confirm the low porosity in the igneous-metamorphic complex. Calculations of water saturations and other evaluations of the subsurface fluids were not attempted because of the low porosities and the anomalies on the spontaneous potential curve.

Copies of these logs may be obtained from Electrical Log Services of Midland, Texas (reference numbers K5995F and K5995J). David Clark of that office granted permission to publish reproductions after clearance with the KCM Company.

Stratigraphic analyses

The specific results of the stratigraphic analyses are covered in three parts: a description of the geologic log, a discussion of the lithologic study with a binocular microscope, and an explanation of the interpretations for major stratigraphic intervals. In this explanation, the few paleontologic determinations available for the age assignments are given; the paleontologic analyses are discussed further in a later section. The petrographic evidence (given by Budding and Broadhead, this circular) is the main basis for the identification and genetic interpretation of the igneous and metamorphic rocks; that evidence is discussed in this section.

Comprehensive analyses of the structural geology in this well cannot be made without a dipmeter log. However, some fractures and one possible fault are indicated.

GEOLOGIC LOG (fig. 4)—The gamma ray-sonic log is used as the base (standard scale 1 inch to 100 ft). At this scale, each 10-ft interval is represented. The tie between the stratigraphic and other analyses of the drill cuttings is also shown. No significant skips occur in the series of samples except for the gap from the surface down to 40 ft.

On the gamma-ray (left) side of the log, the important stratigraphic boundaries are determined and provide a tie to the general geology shown on fig. 3. The paleontologic age control is also given. On the sonic (right) side, the general rock type of each 10 ft of section is plotted in the lithologic column (symbols are explained at the end of fig. 4). Where boundaries of important stratigraphic units could be recognized on the gamma-ray or sonic curves, they were determined to the nearest 1 ft on the detail section of that log. The petrographic control is plotted to the right of the lithologic column at the depth from which each sample was taken. In a few cases, a lag correction of no more than 10 ft is made to show the probable position of the rock type according to the curves.

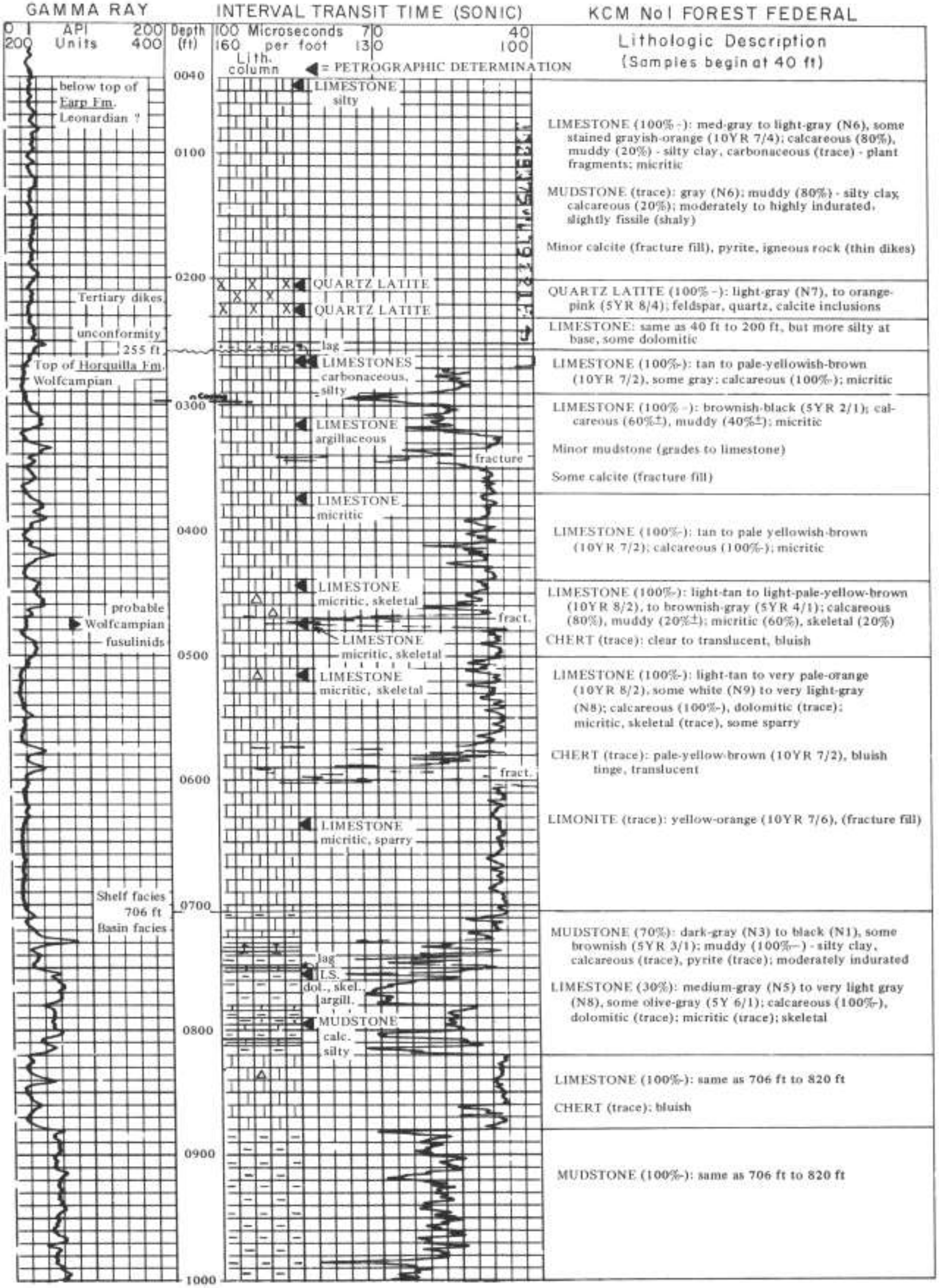
The lithologic description (far right side of log) is somewhat generalized for each lithostratigraphic column unit. Boundaries of these descriptive units were chosen at significant lithologic changes, even if they were not obviously represented by changes in the gamma-ray or sonic curves. However, many lithologic changes were raised by about 10 ft of lag to plot alongside changes in the curves.

LITHOLOGIC STUDY—After the well was drilled and all of the logs were available, the lithologic study of the drill cuttings in each 10-ft sample was begun with a binocular microscope under 10-power lenses. Lloyd W. Krumrey, Jr., consulting geologist, furnished a copy of his description which was helpful as a guide. Several differences may be attributed to studying separate sets of samples, others may reflect variations in interpretation. Theresa M. Cookro, a graduate student in geology at New Mexico Institute of Mining and Technology, assisted in the preparation of the cuttings for examination and checked the description of each sample. A main purpose of this joint study was to insure that a selected rock type from a particular sample was picked as specified for subsequent analyses.

In the sedimentary section, two major rock types were encountered. The limestone type is composed mainly of calcite with minor dolomite in some intervals, and contains varying amounts of mud or other impurities. The primary textures are generally micritic with some skeletal fragments of crinoids, fusulinids, and other microfossils found suspended in the matrix. Other grain types such as oolites or pellets were not observed. The mudstone type is composed mainly of terrigenous silt and clay, in most cases also containing significant percentages of calcareous material. In some intervals the mudstone is sufficiently fissile to be classified as a true shale; this designation is not deemed important.

The distinction between muddy limestone and calcareous mudstone was based on whether the insoluble residue, after several minutes in dilute hydrochloric acid, is less or greater than 50 percent. These results were checked on the gamma-ray (and other curves) and documented in some cases with the petrographic analyses. This distinction, a difficult one even in thin section, is especially fundamental in the basin facies. Minor rock types include chert and sandstone. Some mineral calcite and limonite are interpreted as fracture fillings, especially where fractures are indicated by cycle skipping on the sonic log. Other minerals such as pyrite and gypsum are present in small amounts.

In the igneous and metamorphic complex, best guesses of the rock types were made under the binocular microscope. The results, however, were unsatisfactory. The rock types given in the lithologic description of quartz latite, quartz monzonite, marble, and hornfels were taken from the petrographic determinations. Under 10-power magnification, those quartz monzonites and hornfelses that were both white and silica rich were indistinguishable; the colored types were more distinguishable. The marbles could be inferred by an abundance of coarsely crystalline calcite with a granoblastic texture; they were determined with confidence



LIMESTONE (100% -): med-gray to light-gray (N6), some stained grayish-orange (10YR 7/4); calcareous (80%), muddy (20%) - silty clay, carbonaceous (trace) - plant fragments; micritic

MUDSTONE (trace): gray (N6); muddy (80%) - silty clay, calcareous (20%); moderately to highly indurated, slightly fissile (shaly)

Minor calcite (fracture fill), pyrite, igneous rock (thin dikes)

QUARTZ LATITE (100% -): light-gray (N7), to orange-pink (5YR 8/4); feldspar, quartz, calcite inclusions

LIMESTONE: same as 40 ft to 200 ft, but more silty at base, some dolomitic

LIMESTONE (100%-): tan to pale-yellowish-brown (10YR 7/2), some gray; calcareous (100%-); micritic

LIMESTONE (100% -): brownish-black (5YR 2/1); calcareous (60%±), muddy (40%±); micritic

Minor mudstone (grades to limestone)

Some calcite (fracture fill)

LIMESTONE (100%-): tan to pale yellowish-brown (10YR 7/2); calcareous (100%-); micritic

LIMESTONE (100%-): light-tan to light-pale-yellow-brown (10YR 8/2), to brownish-gray (5YR 4/1); calcareous (80%), muddy (20%±); micritic (60%), skeletal (20%)

CHERT (trace): clear to translucent, bluish

LIMESTONE (100%-): light-tan to very pale-orange (10YR 8/2), some white (N9) to very light-gray (N8); calcareous (100%-), dolomitic (trace); micritic, skeletal (trace), some sparry

CHERT (trace): pale-yellow-brown (10YR 7/2), bluish tinge, translucent

LIMONITE (trace): yellow-orange (10YR 7/6), (fracture fill)

MUDSTONE (70%): dark-gray (N3) to black (N1), some brownish (5YR 3/1); muddy (100%–) - silty clay, calcareous (trace), pyrite (trace); moderately indurated

LIMESTONE (30%): medium-gray (N5) to very light gray (N8), some olive-gray (5Y 6/1); calcareous (100%-), dolomitic (trace); micritic (trace); skeletal

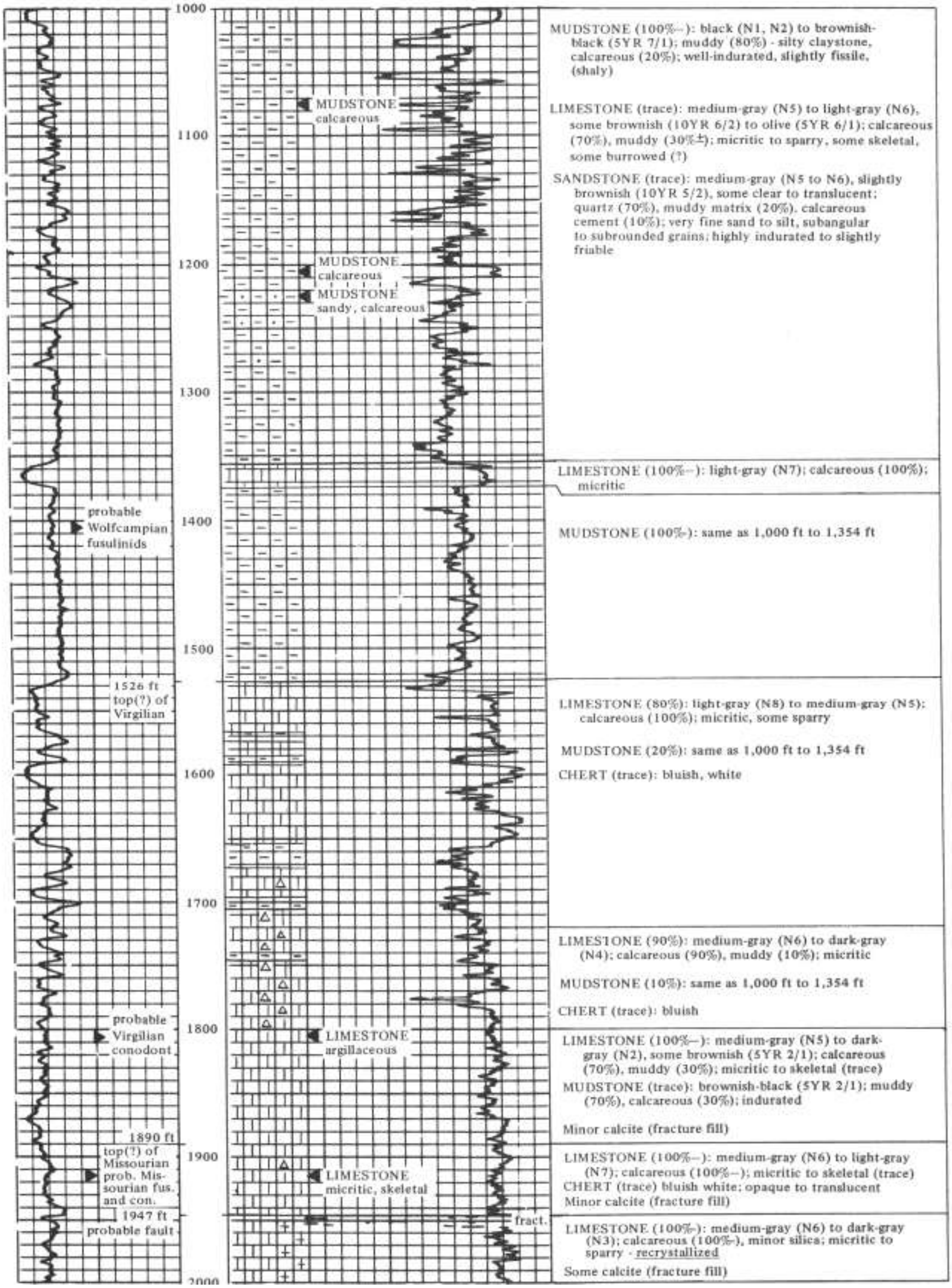
LIMESTONE (100%-): same as 706 ft to 820 ft

CHERT (trace): bluish

MUDSTONE (100%-): same as 706 ft to 820 ft

FIGURE 4—GEOLOGIC LOG OF KCM NO. 1 FOREST FEDERAL. Borehole-Compensated Sonic Log by Schlumberger Well Services; reproduction by Electrical Log Services, Midland, Texas, Ref. No. K5995F; see text for sources of geologic data; symbols for rocks listed on page 16.

Fig. *4 continued*



MUDSTONE (100%–): black (N1, N2) to brownish-black (5YR 7/1); muddy (80%) - silty claystone, calcareous (20%); well-indurated, slightly fissile, (shaly)

LIMESTONE (trace): medium-gray (N5) to light-gray (N6), some brownish (10YR 6/2) to olive (5YR 6/1); calcareous (70%), muddy (30%±); micritic to sparry, some skeletal, some burrowed (?)

SANDSTONE (trace): medium-gray (N5 to N6), slightly brownish (10YR 5/2), some clear to translucent; quartz (70%), muddy matrix (20%), calcareous cement (10%); very fine sand to silt, subangular to subrounded grains; highly indurated to slightly friable

LIMESTONE (100%–): light-gray (N7); calcareous (100%); micritic

MUDSTONE (100%–): same as 1,000 ft to 1,354 ft

LIMESTONE (80%): light-gray (N8) to medium-gray (N5); calcareous (100%); micritic, some sparry

MUDSTONE (20%): same as 1,000 ft to 1,354 ft

CHERT (trace): bluish, white

LIMESTONE (90%): medium-gray (N6) to dark-gray (N4); calcareous (90%), muddy (10%); micritic

MUDSTONE (10%): same as 1,000 ft to 1,354 ft

CHERT (trace): bluish

LIMESTONE (100%–): medium-gray (N5) to dark-gray (N2), some brownish (5YR 2/1); calcareous (70%), muddy (30%); micritic to skeletal (trace)

MUDSTONE (trace): brownish-black (5YR 2/1); muddy (70%), calcareous (30%); indurated

Minor calcite (fracture fill)

LIMESTONE (100%–): medium-gray (N6) to light-gray (N7); calcareous (100%–); micritic to skeletal (trace)

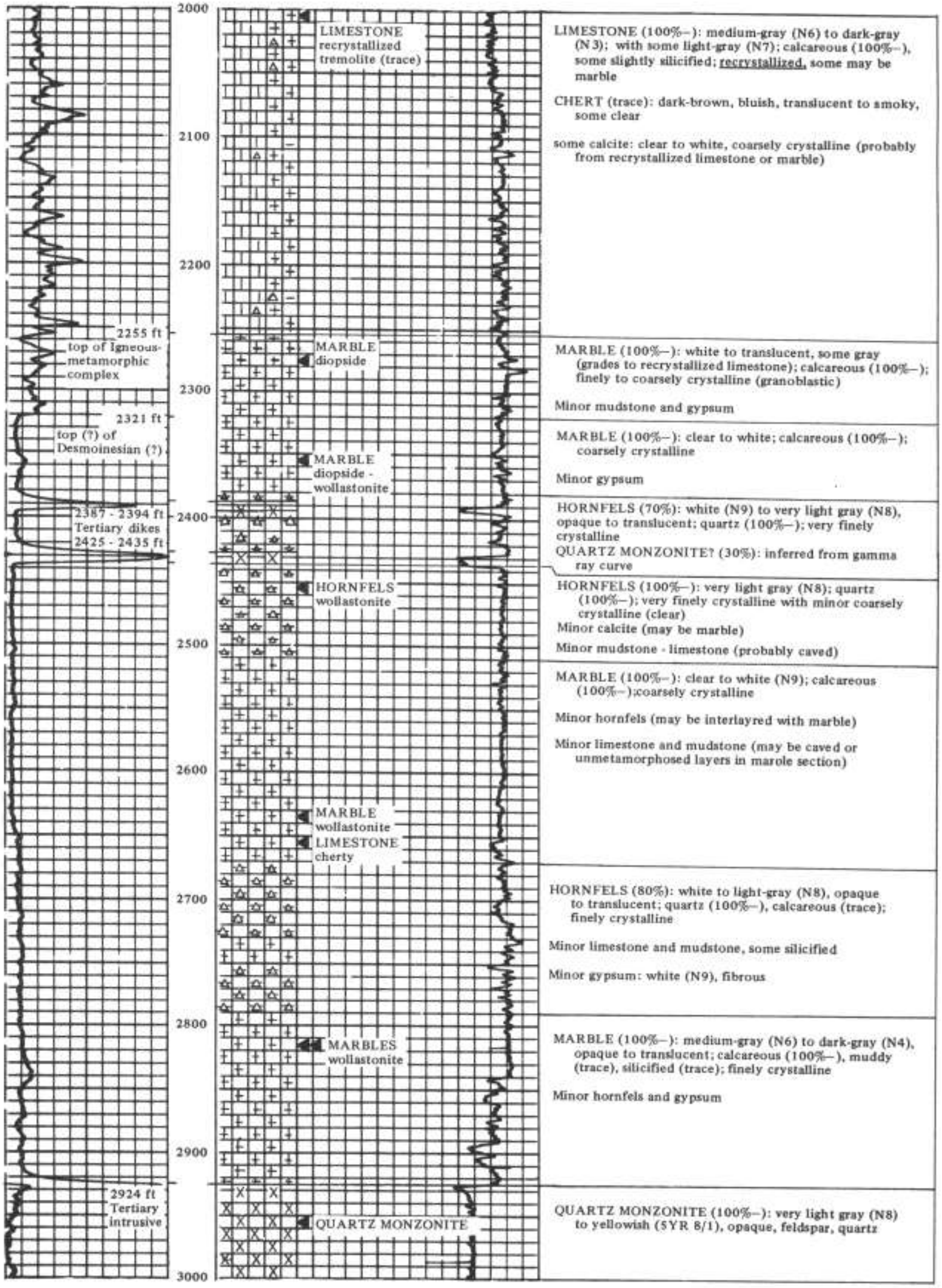
CHERT (trace) bluish white; opaque to translucent

Minor calcite (fracture fill)

LIMESTONE (100%–): medium-gray (N6) to dark-gray (N3); calcareous (100%–), minor silica; micritic to sparry - recrystallized

Some calcite (fracture fill)

Fig. 4 continued



LIMESTONE (100%–): medium-gray (N6) to dark-gray (N3); with some light-gray (N7); calcareous (100%–), some slightly silicified; <u>recrystallized</u>, some may be marble

CHERT (trace): dark-brown, bluish, translucent to smoky, some clear

some calcite: clear to white, coarsely crystalline (probably from recrystallized limestone or marble)

MARBLE (100%–): white to translucent, some gray (grades to recrystallized limestone); calcareous (100%–); finely to coarsely crystalline (granoblastic)

Minor mudstone and gypsum

MARBLE (100%–): clear to white; calcareous (100%–); coarsely crystalline

Minor gypsum

HORNFELS (70%): white (N9) to very light gray (N8), opaque to translucent; quartz (100%–); very finely crystalline

QUARTZ MONZONITE? (30%): inferred from gamma ray curve

HORNFELS (100%–): very light gray (N8); quartz (100%–); very finely crystalline with minor coarsely crystalline (clear)

Minor calcite (may be marble)

Minor mudstone - limestone (probably caved)

MARBLE (100%–): clear to white (N9); calcareous (100%–);coarsely crystalline

Minor hornfels (may be interlayred with marble)

Minor limestone and mudstone (may be caved or unmetamorphosed layers in marole section)

HORNFELS (80%): white to light-gray (N8), opaque to translucent; quartz (100%–), calcareous (trace); finely crystalline

Minor limestone and mudstone, some silicified

Minor gypsum: white (N9), fibrous

MARBLE (100%–): medium-gray (N6) to dark-gray (N4), opaque to translucent; calcareous (100%–), muddy (trace), silicified (trace); finely crystalline

Minor hornfels and gypsum

QUARTZ MONZONITE (100%–): very light gray (N8) to yellowish (5YR 8/1), opaque, feldspar, quartz

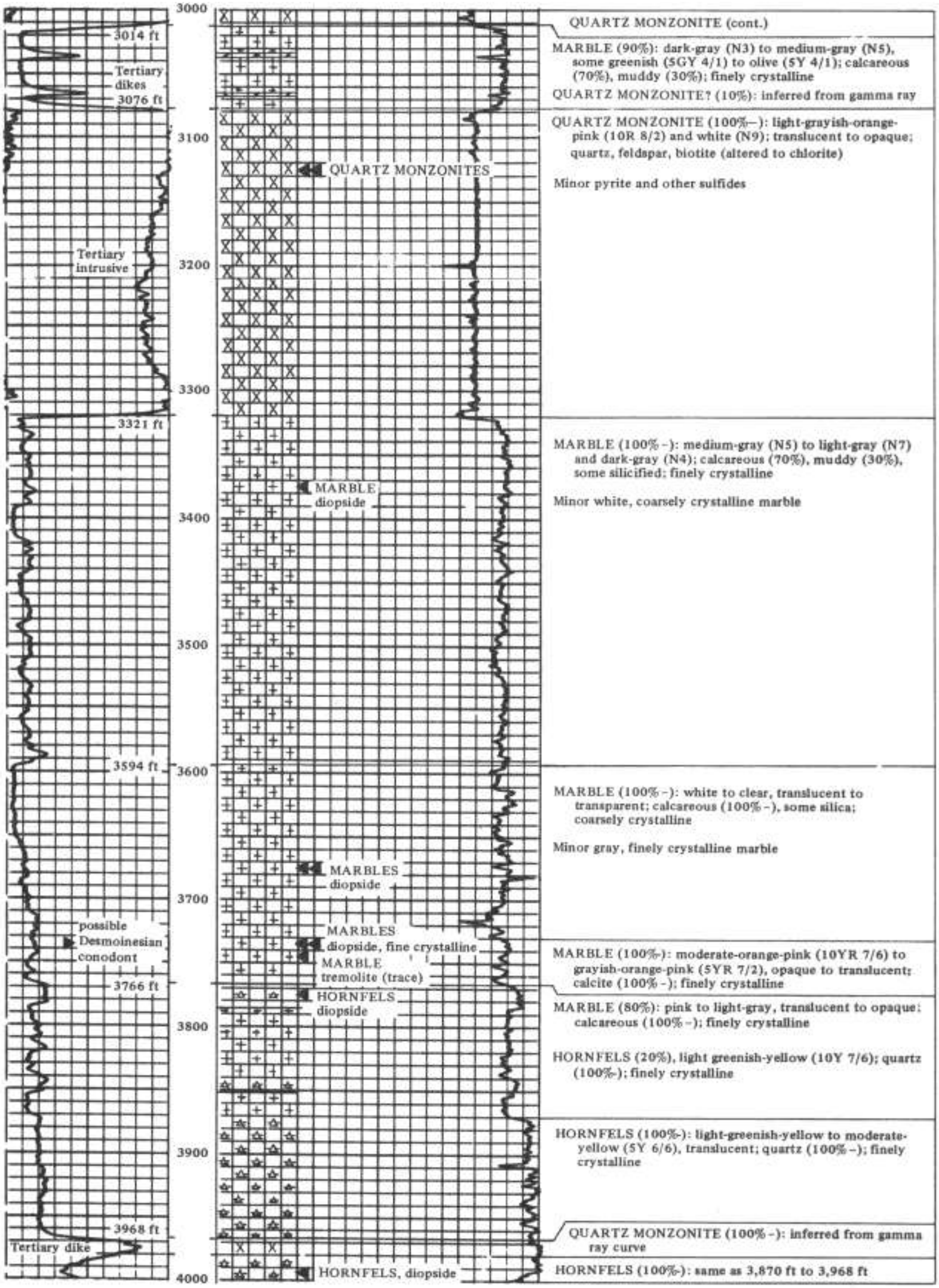


Fig. 4 continued

QUARTZ MONZONITE (cont.)

MARBLE (90%): dark-gray (N3) to medium-gray (N5), some greenish (5GY 4/1) to olive (5Y 4/1); calcareous (70%), muddy (30%); finely crystalline

QUARTZ MONZONITE? (10%): inferred from gamma ray

QUARTZ MONZONITE (100%–): light-grayish-orange-pink (10R 8/2) and white (N9); translucent to opaque; quartz, feldspar, biotite (altered to chlorite)

Minor pyrite and other sulfides

MARBLE (100%-): medium-gray (N5) to light-gray (N7) and dark-gray (N4); calcareous (70%), muddy (30%), some silicified; finely crystalline

Minor white, coarsely crystalline marble

MARBLE (100%-): white to clear, translucent to transparent; calcareous (100%-), some silica; coarsely crystalline

Minor gray, finely crystalline marble

MARBLE (100%-): moderate-orange-pink (10YR 7/6) to grayish-orange-pink (5YR 7/2), opaque to translucent; calcite (100%-); finely crystalline

MARBLE (80%): pink to light-gray, translucent to opaque; calcareous (100%-); finely crystalline

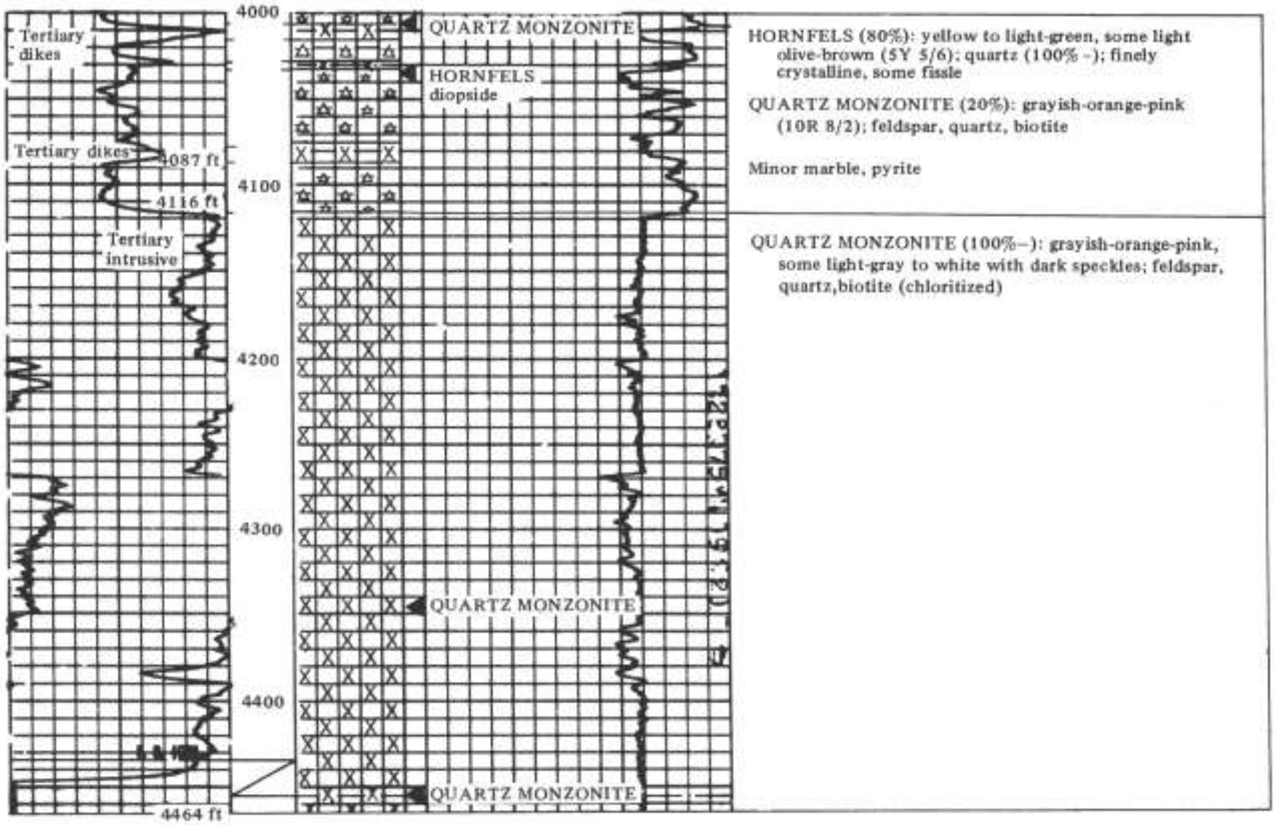
HORNFELS (20%), light greenish-yellow (10Y 7/6); quartz (100%-); finely crystalline

HORNFELS (100%-): light-greenish-yellow to moderate-yellow (5Y 6/6), translucent; quartz (100%-); finely crystalline

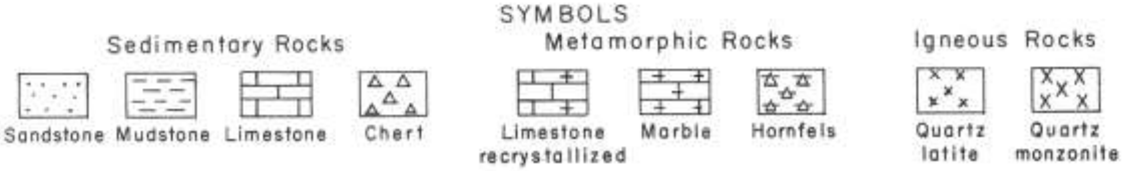
QUARTZ MONZONITE (100%-): inferred from gamma ray curve

HORNFELS (100%-): same as 3,870 ft to 3,968 ft

Fig. 4 continued



Total depth in Tertiary plutonic intrusive into Horquilla Formation (Desmoinesian?)



only when the metamorphic minerals were identified in thin section.

In the lithologic description prepared for the geologic log (fig. 4), the amount of each rock type within the column unit is estimated to the nearest 10 percent; an amount less than that is considered to be a trace. Under the rock type, the color of the wet cuttings in white light is given along with the standard designations of the Geological Society of America rock-color chart. Components within the sedimentary rock types are estimated to the nearest 10 percent; those of the igneous and metamorphic rocks are given by Budding and Broadhead in this circular. Texture, induration, and other properties observable under the binocular microscope are given where appropriate.

Further details about each 10-ft sample, including notes on the quality and size of the cuttings and on the amount of caving, are recorded in a data file. Some cuttings are so small (less than 1 mm) that lithologic or even petrographic analyses are severely handicapped. Large amounts of caving seldom persisted for more than 100 ft below the deepest depth indicated on the log curves. In several cases over 50 percent of the cuttings were judged to be caved. Thus the lithologic log and description are interpretive, and a 10-ft sample selected at random may not represent the lithologic type inferred for the corresponding depth on the log.

The following discussions of major stratigraphic intervals are in order of depth.

SURFACE TO 255 FT—This interval includes the lower part of the Earp Formation, considered at the present time to be Leonardian in age. In future work the Earp may be assigned at least partly to the Wolfcampian. In this area, none of the characteristic red beds are present; mostly the Earp is carbonaceous muddy limestone. In surface exposures it is finely laminated. The depositional environment is inferred to be a lagoon on a coastal shelf.

The Tertiary quartz latites, intruding the interval from 200 ft to 230 ft, contain so much calcite in inclusions that at first they appeared to be a tufa or some other kind of hot spring deposit. However, the petrographic determinations by Budding and Broadhead indicate a fine-grained igneous rock into which carbonates were assimilated from the country rock. The intrusive rocks so dominate the interval that they are interpreted to be dikes about 10 ft thick (drilled interval) with thin limestones between that cannot be plotted on the scale of the log. These quartz latites do not appear to contain radioactive potassium (K^{40}) as do the quartz monzonites below (that register very high on the gamma-ray curve).

The unconformity between the Earp and Horquilla Formations is placed below the small gamma-ray peak at 255 ft. A lithologic change is seen in the sample from 260 ft to 270 ft, indicating a lag correction of about 10 ft. The two petrographic samples in that interval are both from the Earp Formation. One sample is the normal gray, carbonaceous limestone (270a), and the other is silty limestone stained orange by iron oxides (270b). The latter contains much terrigenous silt and was probably stained by surface oxidation during the development of the unconformity (personal communication, Alonzo D. Jacka, Texas Tech University). Immediately below are the tan limestones of the Horquilla.

255 FT TO 706 FT—This upper part of the Horquilla Formation is characterized by light-tan to brown, generally pure micritic limestones; they contain the most abundant skeletal material seen in this well. The poorly preserved microfauna are mainly fragments of crinoids, fusulinids, and other foraminifers; some algal remains are probably present. Minor amounts of chert probably are in large nodules as seen in surface exposures of this unit.

Zeller and Alper (1965, p. 10) document the Wolfcampian age of the upper Horquilla where exposed nearby on the Winkler anticline. The fusulinids from the well sample at 470 ft to 480 ft are probably Wolfcampian.

The light-colored micritic to skeletal limestones are characteristic of shallow-marine stable-shelf deposits. Unfortunately these rocks contain too little organic carbon to be classified as good source units of petroleum; their porosity-permeability values are so low that they are only poor reservoirs at best.

706 FT TO 1,526 FT—This part of the Horquilla consists mainly of dark calcareous mudstone, dark to light limestone and minor amounts of sandstone. These lithologic types, along with the Wolfcampian age of the fusulinids at 1,400 ft to 1,410 ft, correlate readily with the deep-marine basin facies of the Horquilla seen in the southern part of the Big Hatchet Mountains and in the Humble No. 1 State BA well (Zeller, 1965, p. 42). Based on Zeller's reconstructions, the water depth in the basin may have been 1,000 ft or more.

These mudstones, containing the largest amounts of organic carbon seen in the well, are judged to be fair to possibly good source rocks of petroleum, especially gas (Cernock and Bayliss, this circular). During the filling of the basin, these mudstones were deposited relatively rapidly in a reducing, deep-marine environment; the hydrocarbon-source materials were well preserved. The mottling of the limestones has some aspects that suggest burrowing by deep-marine organisms. The very muddy, quartzose sandstones at 1,220 ft to 1,230 ft and below may be turbidites; they exhibit a very poor reservoir quality.

The upper contact of this unit is transitional with the overlying shelf limestones, indicating a relatively gradual shallowing to marine-shelf conditions. The lower contact is abrupt and may suggest more rapid subsidence when the basin deepened to accommodate the thick mudstone sequence.

1,526 FT TO 1,890 FT—This part of the Horquilla consists mainly of medium- to dark-gray limestone that is muddy and micritic. Some of the lighter colors, especially those recorded near the top, may be attributed to the grinding action of the drill bit.

This interval is also inferred to be a deep-marine basin facies; however, this interval probably was not involved in as rapid a subsidence as the overlying mudstone sequence.

A conodont of probable Virgilian age occurred from 1,800 ft to 1,810 ft. The Wolfcampian-Virgilian boundary is placed at the top of the limestone unit at 1,526 ft. This boundary could be placed lower or even up in the mudstone section.

1,890 FT TO 1,947 FT—In the sample from 1,910 ft to 1,920 ft, a fusulinid and a conodont of probable Missourian age were found. The top of this interval of lighter colored, more skeletal limestones occurs at a slight lithologic change at 1,890 ft that is not readily discernible on the gamma-ray or sonic curves. The top of the Missourian is drawn at this depth, but it could be as high as 1,810 ft.

The lighter colors and slight increase in skeletal material may suggest a shallower marine facies. On the other hand, the limestones may have been darker originally. Hints of recrystallization and silicification were seen in this interval that were not found in the thin section for 1,910 ft to 1,920 ft.

At 1,947 ft, a fault or a major fracture zone is based on several lines of evidence. The cycle skipping on the sonic curve and the fresh-water anomaly on the spontaneous potential curve aid in determining the depth. On the hydrocarbon log, at 1,940 ft, a pronounced drop occurs in the drilling rate from about 50 min/10 ft to 20 min/10 ft. Calcite fills fractures between angular pieces of limestone in some cuttings. Significant displacement cannot be demonstrated, so this surface is designated as a fault (?) to distinguish it from relatively minor fractures. Moreover, any stratigraphic throw probably is small because discernible repetition or omission of the sequence in the Horquilla is not obvious.

1,947 FT TO 2,255 FT—This interval consists mainly of medium- to dark-gray limestones partially recrystallized by thermal metamorphism. The recrystallization is recognized in the cuttings by a grainy aspect of the sparry limestones suggesting a granoblastic texture, along with indications of silicification. In the thin section for 2,000 ft to 2,010 ft, Budding and Broadhead found tremolite, indicating a low degree of thermal metamorphism in these recrystallized limestones.

This incipient metamorphism was not so severe as to mask all of the primary features of the limestones; the dark colors may indicate that these rocks also are deep-marine basin deposits. The percentage of organic carbon is low. Therefore, the source as well as the reservoir quality probably was poor prior to metamorphism. Both are classified now as insignificant (fig. 3).

The small amount of skeletal material is very poorly preserved; only crinoid fragments were recognized in the cuttings. No paleontological age determinations have been made in this interval; it also may be Missourian.

The presence of the possible fault (or major fracture) at the top of this interval may indicate that a zone of weakness was developed between the slightly metamorphosed limestones below and normal limestones above. Moreover, the darker, impure limestones above 1,947 ft may have inhibited the upward surge of the contact metamorphism from the plutons below. (But the fault may have developed earlier, becoming a barrier to the ascending metamorphism.)

2,255 FT TO 2,321 FT-This unit lies at the top of the igneous-metamorphic complex that extends to total depth. Budding and Broadhead identified diopside marble in the thin section for 2,260 ft to 2,270 ft, establishing significant metamorphism at least as high as that interval. Although significant metamorphism may be higher, up to 2,010 ft, the top is drawn at 2,255 ft below a gamma-ray peak. This peak corresponds closely to the 2,260-ft depth where a dominance of coarsely crystalline calcite with a granoblastic texture begins to be seen in the cuttings.

Also in this unit are some darker marbles with a finely crystalline texture grading to recrystallized limestone. The similarity to the section above indicates a Missourian age and a deep-marine environment.

Throughout the metamorphic sequence here and below, the petroleum source and reservoir qualities are rated as insignificant. The rating of these qualities prior to metamorphism will be assessed after the nearest unmetamorphosed equivalents have been evaluated.

2,321 FT TO 2,924 FT-The top of this unit is placed at a marked decrease in the gamma-ray curve corresponding to an abrupt lithologic change to white, coarsely crystalline marble. This rock type probably was a pure white limestone prior to metamorphism, similar to some seen in the upper Desmoinesian part of the Horquilla in the Big Hatchet Mountains. Without paleontological control between 1,920 ft and 3,370 ft, the top (?) of the Desmoinesian (?) is placed tentatively at 2,321 ft on this lithostratigraphic boundary.

The light-colored hornfelses probably were cherts or cherty limestones, also characteristic of the Desmoinesian. These light-colored marbles and hornfelses, as well as the remainder of the metamorphic section below, probably were originally shallow-marine shelf deposits.

Two gamma-ray peaks at 2,387 ft to 2,394 ft and 2,425 ft to 2,435 ft probably are quartz-monzonite dikes. Though not recognized in the cuttings, these quartz-rich rocks are hard to distinguish within the white hornfels section. These thin dikes may be branches from a large pluton nearby; alone they probably cannot account for the high degree of metamorphism.

2,924 FT TO 3,321 FT-Two thick intrusives of quartz monzonite are indicated on the gamma-ray curves from 2,924 ft to 3,014 ft and from 3,076 ft to 3,321 ft; some thin dikes intrude the marble section between. The upper intrusive is light colored, quartz rich, and thus hard to recognize as an igneous rock with only a binocular microscope; however, the lower one has a pink cast suggesting potash feldspars.

3,321 FT TO 4,116 FT-In this part of the complex down to 3,968 ft, thick intrusives are not present, while thin ones are not recognized. The marbles from 3,321 ft to 3,730 ft are similar to those in the Desmoinesian (?) section up to 2,321 ft.

The lowest marbles in the well from 3,730 ft to 3,870 ft have a distinct pink color that may not be inherited from the sedimentary rock but could indicate greater metamorphism. A conodont species occurs at the top of this section in the sample from 3,730 ft to 3,740 ft. This species ranges from Chesterian into Leonardian. In this instance the age should not be younger than the Desmoinesian determination above. Because relict oolites or other distinctive characteristics of the Paradise Formation are not seen in this interval, it probably is not Chesterian in age. The limestones in the lower Horquilla of Morrowan (?) to Atokan age also contain oolites recognizable as relicts when metamorphosed; therefore, the lower part of the metamorphic section is probably Desmoinesian (?).

The greenish color of the hornfelses from 3,766 ft to 4,116 ft may also have been induced by metamorphism. However, this color and the fissility of some parts suggest that those hornfelses may have been mudstones. Such a lithologic change would also suggest a stratigraphic position in the lower Desmoinesian part of the Horquilla.

4,116 FT TO 4,464 FT-This thick, plutonic intrusive at the bottom of the well is mid-Tertiary in age as discussed by Elston and Erb. The petrographic affinities of these quartz monzonites with the other igneous rocks higher in the well suggest that they were all intruded about the same time, as discussed by Budding and Broadhead.

More of the same igneous rock may be expected beneath the total depth of the well; the well did not reach the base of this intrusive body. The rest of the Horquilla and the older Paleozoic section may be found at some depth below, but these sedimentary rocks also probably are highly metamorphosed.

Selection of samples for subsequent analyses

Fig. 5 shows the stratigraphic distribution of samples selected for subsequent laboratory analyses that are summarized in the sections that follow. Except for some samples collected for organic geochemistry while the well was drilling, samples were generally selected for each specific purpose from the best quality cuttings at strategic positions as determined by the stratigraphic analyses. This procedure tends to yield the most significant results with the least number of samples and to conserve the research time of the analysts. Each analyst was consulted regarding quality and quantity of samples, but I assume responsibility for the selection of each sample. Where possible, samples were selected for related analyses from the same depths so that the results would correlate.

Samples were collected from 10-ft intervals, for example, from 1910 ft to 1920 ft. Subsequently, each sample is designated with a prefix for the KCM No. 1 Forest Federal "KCM1FF" and a suffix denoting the bottom of the sample interval, for example, "1,920 ft." Only depth suffixes are shown on fig. 5. This system of designating samples allows the interspersing of addi-

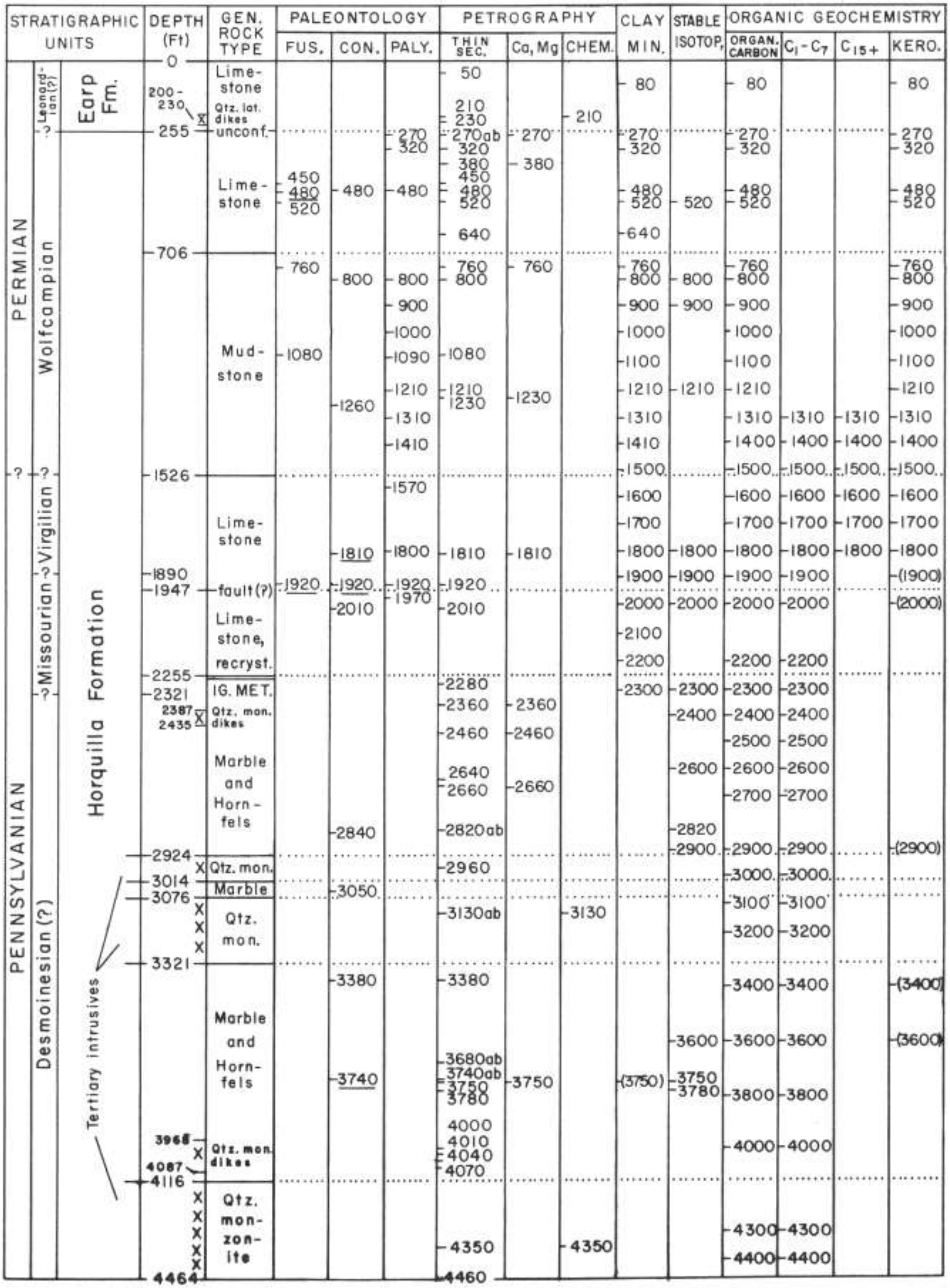


FIGURE 5—STRATIGRAPHIC DISTRIBUTION OF SAMPLES SELECTED FOR LABORATORY ANALYSES FROM THE KCM No. 1 FOREST WELL.

[New Mexico Bureau Mines & Mineral Resources, Circular 152, 1977]

tional control as needed. Where two different rock types were collected from the same interval, samples were designated "a" and "b."

With the special cuts of samples donated by the KCM Company, a sufficient volume of cuttings has been available for these analyses. The main problem was picking a specific rock type in sufficient quantity from a selected sample. This process is time consuming but essential for reliable analytical results with drill cuttings. Two geology students at New Mexico Institute of Mining and Technology did most of this work. Theresa M. Cookro picked part of the samples for the petrographic and geochemical analyses, and Ronald F. Broadhead completed the job.

In the following sections, some specific results are discussed for each type of analysis. These discussions are not complete summaries, but rather serve only as guides to subsequent papers in this circular.

Paleontology

In the paleontology column on fig. 5, the sample distribution for three types of fossils is indicated. These are fusulinids (Fus.), conodonts (Con.), and palynomorphs (Paly.).

Donald A. Myers, with the U.S. Geological Survey, identified fusulinids collected from the sample at 480 ft. Although a generic determination was not possible, suggestions of *Schwagerina, Triticites,* and other forms indicate an early to mid-Wolfcampian age. He also studied the petrographic thin sections in which fusulinids and other microfossils were found; the most significant is a possible *Triticites* (at 1,920 ft) that is possibly Missourian. He agreed essentially with the interpretation of depositional environments; any evidence of alteration seen in the fusulinids could be attributed to normal diagenetic processes. These brief results, helpful in the present study, are cited as a personal communication.

Harold L. Williams, with the Paleontological Laboratory in Midland, Texas, prepared a report for KCM; these results are presented with his permission. He found fusulinids of Wolfcampian age in two intervals. *Pseudowagerina, Schwagerina,* and *Triticites* were identified from 450 ft to 480 ft. *Schwagerina* was identified from 1,400 ft to 1,410 ft. The fusulinids in the lower interval support the Wolfcampian age assignment down to 1,526 ft. He placed a tentative top of the Mississippian (?) at 2,340 ft on a lithologic change; however, this boundary is inferred to be the top of the Desmoinesian (?) (log top at 2,321 ft).

Fred H. Behnken (this circular) studied conodonts in 10 samples selected to his specifications. Three yielded definite results; more material was sent for further processing. The conodonts at 1,810 ft indicate a Virgilian to late Missourian age, those at 1,920 ft a Missourian or latest Desmoinesian age, and those at 3,740 ft a late Mississippian to Early Permian range but a probable age of Desmoinesian or older. He also studied the possible effects of thermal alteration on conodonts (as suggested by Epstein and others) with inconclusive results.

Robert M. Kosanke, also with the U.S. Geological Survey, agreed to a search for palynomorphs in 14 samples selected to his specifications. Unfortunately, parts of some samples were spilled during shipment; all were barren of spore and pollen grains.

The few paleontological determinations that have been made so far appear meager and indefinite. Yet they have provide critical documentation for the stratigraphic interpretation. The age assignments are fairly well controlled down to the fault at 1,947 ft but not below. A more intensive search for diagnostic fossils is planned with another set of samples.

Petrography

Antonius J. Budding and Ronald F. Broadhead analyzed 42 thin sections made from samples of the drill cuttings (fig. *5);* their results are given in a separate paper in this circular. Five of these thin sections were of a minor rock type (for example, 270b) that exhibited a different color or texture from the major rock type; however, both proved to be the same basic rock type.

Generally, samples were selected from thick intervals of the important rock types so that the precise position would not be critical; a small lag correction of about 10 ft had to be made in a few cases to tie to the gamma-ray and sonic curves (for example, the two samples at 270 ft are given a lag correction on fig. 4). In one case, at 2,660 ft, a rock type determined as cherty limestone is a minor constituent of the sample. This rock type probably is caved from the sedimentary section (or possibly may be a thin bed that escaped metamorphism) and is not plotted in the lithologic column.

The highlights of the petrographic results were discussed as an integral part of the stratigraphic analyses and are not reviewed here. These results were important controls in the subsurface study, especially in the igneous-metamorphic complex.

Thea Ann Davidson, New Mexico Bureau of Mines and Mineral Resources, developed a technique for making thin sections from drill cuttings. At Budding's request, calcium-magnesium compositions ("Ca, Mg" column on fig. 5) were determined by Lynn A. Brandvold and students in the Bureau's analytical laboratory; three complete chemical analyses ("Chem." column) on samples of igneous rocks were made by John Husler at the University of New Mexico.

Alonzo D. Jacka, Texas Tech University, made a preliminary study of selected thin sections from the sedimentary sequence and offered several observations which were useful in the stratigraphic analyses. He is making a detailed petrographic study of this well as part of the program to document the depositional and diagenetic history of the source and reservoir facies of the Horquilla Formation.

Clay mineralogy

George S. Austin, New Mexico Bureau of Mines and Mineral Resources, and Marc W. Bodine, New Mexico Institute of Mining and Technology, are studying the clay minerals in 23 samples (fig. 5). Their preliminary results down to 2,000 ft show that chlorite dominates the clay fraction especially in limestones. Illite and mixed layer illite-smectite are significant constituents in mudstones between 900 ft and 1,500 ft. Talc, smectite, and vermiculite are present, possibly as contaminants from the drilling fluid. The evidence from clay mineralogy tends to confirm the estimates of paleotemperature as discussed later under thermal history. The results of Austin and Bodine will be published in a separate paper.

Stable isotope analyses

Gary P. Landis, University of New Mexico, began spectrographic analyses of the stable isotopes of carbon and oxygen. He planned to provide another line of evidence to distinguish the sedimentary, metamorphic, and perhaps hydrothermal types of calcite. Of the 15 samples shown in the stable isotope column in fig. 5, he made determinations on 7: 1,900 ft, 2,000 ft, 2,300 ft, 2,400 ft, 2,600 ft, 2,900 ft, and 3,600 ft.

Based mainly on the variations of the carbon isotopes, he found that those in the sedimentary section varied over a narrow range characteristic of marine limestones. A wider range characteristic of metamorphism was seen in the marbles, but no interaction with organic materials was evident. Because his findings were only confirming the petrographic determinations, he reported these results as a personal communication.

Organic geochemistry

Paul J. Cernock and Geoffrey S. Bayliss, GeoChem Laboratories, Inc., report the organic geochemical analyses of samples from this KCM well. GeoChem provided the major part of the expenses for this study; the remainder was provided out of a grant from the Energy Resources Board of New Mexico.

Over the range of 35 sample depths from 80 ft to 4,400 ft, four types of analyses are shown on fig. 5. The total organic carbon (Org. Carbon) content is a fundamental parameter of petroleum source quality and was measured over the entire range. Determinations of the gases (C_1-C_7) and the heavy oils (C_{15+}) help to establish the states of hydrocarbon maturation and migration. The types of kerogen (Kero.) indicate whether the original source was oil or gas prone; the color indicates the degree of thermal alteration.

Samples for hydrocarbon gases must be collected during the drilling operation and preserved in cans with a bactericide. Although permission was obtained from KCM to do this work and Sturgis consented to make the collection of canned cuttings, the essential materials were not taken to the wellsite until the depth of 1,310 ft had been reached. These analyses began at that depth. The usual procedure recommended by GeoChem and other geochemical analysts calls for a composite sample representing each 100 ft of drilled section. To tie the geochemical analyses to other anlayses, solitary samples were collected at each 100 ft, realizing that gaps remain in the sequence. To know what rock type was in each sealed can, a small sample representing each collection was put in a separate bag.

Using these small samples, the canned cuttings from depths of 1,310 ft to 2,000 ft were selected for initial geochemical analysis. Cernock and Bayliss selected and analyzed the remainder to total depth. Based on the results with hydrocarbon gases (C_1C_7) and total organic carbon, they selected the samples from 1,310 ft to 1,800 ft for analyses of the heavy oils (C_{15+}) and kerogens.

After the stratigraphic analyses were completed, samples from 80 ft to 1,210 ft were selected for analyses of total organic carbon and kerogen. In contrast to the random samples collected while drilling, these selected samples permit more accurate placement of the boundaries of petroleum source units. In an attempt to extend the control of kerogen alteration down into the metamorphic zone, samples from 1,900 ft to 3,600 ft were selected. The small amounts of organic matter make the results unreliable. The random samples in the igneous-metamorphic complex below 2,200 ft contain 0.2 percent or less of total organic carbon. Some even give this reading in the quartz-monzonite intrusives. These small amounts and the gases probably are from the minor mudstones and limestones that have caved down into this complex.

The paper by Cernock and Bayliss is the first quantitative evaluation and published documentation of petroleum source rocks in southwestern New Mexico. Also, their paper is an exceptional publication of complete organic geochemical analyses on an entire well. Although GeoChem and some laboratories of private companies have been doing this type work for several years in other areas, the results usually remain confidential.

Summary of thermal history

Fig. 6 is a summary of the thermal history of the KCM well. The present temperature ranges from about 10°C at the surface to 80°C at total depth. The bottom-hole temperature measured by Schlumberger is 62°C (144°F); this value is corrected to 80°C following the suggestion of Hood, Gutjahr, and Heacock (1975, p. 990). An accurate temperature survey is needed on this well, such as those made by Marshall A. Reiter and others of the New Mexico Bureau of Mines and Mineral Resources for their heat-flow studies. However, the expense of keeping the KCM rig on location for several weeks (to obtain a very precise temperature log) was not funded. The present geothermal gradient is about 68°C/km. This gradient is above normal and may indicate a marginal source of geothermal energy.

In his analyses of the igneous-metamorphic petrology, Budding calculated the temperatures for the gradient as it appeared immediately prior to the mid-Tertiary intrusion as ranging from 130°C at the stratigraphic position of the present surface to 160°C at the position of the bottom of the well, with an estimated overburden of 4 km. The straight lines for this geothermal gradient and the present gradient are only generalized representations; additional control probably would produce at least minor irregularities.

Budding provided estimates of paleotemperatures for the gradient as it appeared immediately after the Tertiary intrusion. These estimates are based on petrographic data from 2,010 ft to total depth. In the quartz monzonites the temperatures were about 720°C, and in the contact metamorphic units the temperatures ranged from 400°C (where tremolite is present) to 600°C (where wollastonite is present). This part of the geothermal gradient is the best controlled but is also somewhat generalized.

The fault at 1,947 ft is shown to produce a flattening

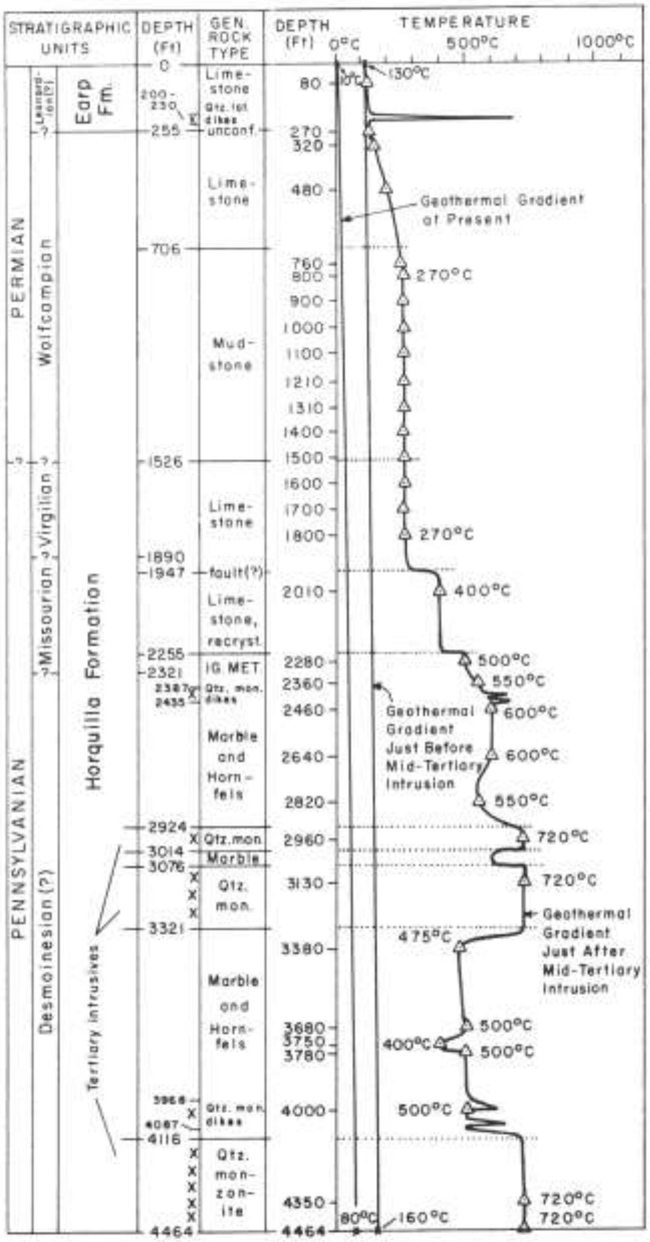


FIGURE 6—Summary of thermal history of KCM No. 1 Forest Federal. Geothermal gradients at present, just before Tertiary intrusion, and just after intrusion. Paleotemperature determinations from 2,010 ft to total depth based on petrography by Budding and Broadhead, from 1800 ft to surface based on kerogen analysis by Cernock and Bayliss and estimates of level of organic metamorphism by Ewing and Thompson.

of the curve. The inferred missing section probably would show a more gradual decline in paleotemperature from the low-grade metamorphic rocks below to the unmetamorphosed ones above.

Cernock and Bayliss state that the kerogen maturation index is at Stage 4 to 4- (Stage 5 indicates metamorphism) from 1,800 ft up to 760 ft. Using the level of organic metamorphism (LOM) concept given by Hood and others (1975), Ewing and Thompson (this circular) estimate a paleotemperature of 270°C for this interval. Additional control with vitrinite reflectance determinations would permit a more accurate representation.

The kerogen maturation index decreases to Stage 3 at 480 ft and to Stage 2 at 80 ft. Paleotemperature values are not given but probably range between the 270°C below and the 130°C estimated for the top of the geothermal gradient prior to the intrusion. Budding suggests that the quartz latite dikes from 200 ft to 230 ft had a paleotemperature of nearly 700°C.

Data from clay mineralogy by Austin and Bodine will help control the paleotemperature curve above 2,000 ft. Their preliminary results show that the temperature in the interval up to 760 ft did not exceed 400°C (probably not above 300°C); the shallower part did not exceed 200°C.

SIGNIFICANCE FOR PETROLEUM EXPLORATION

The KCM No. 1 Forest Federal is one of three key wells to drill the Horquilla Formation (Permian to Pennsylvanian) in Hidalgo County, New Mexico (fig. 1). The position near the margin of the Alamo Hueco Basin helps locate the critical boundary between the deep-marine and shallow-marine facies of the Horquilla. This well drilled 820 ft of dark mudstones and limestones in the deep-marine basin facies of Wolfcampian age (from depths of 706 ft to 1,526 ft). These rocks contain sufficient organic matter to be classified as fair to possibly good sources of petroleum, especially gas (Cernock and Bayliss, this circular). Oil and gas probably migrated upslope from these Wolfcampian rocks and the upper Pennsylvanian source rocks of the basin facies into the porous dolostone reservoirs at the shelf margin. The oil and gas probably were trapped by the relatively impermeable limestones of the shallower marine facies, and sealed by such shelf limestones overlying the basin section. With this documentation of the petroleum source quality, the next critical objective will be to evaluate the reservoir quality of the shelf-margin dolostones. This project is underway and will include analyses of the depositional and diagnetic history by A. D. Jacka.

Exploration in southwestern New Mexico and adjoining areas is plagued by the complex Tertiary history of igneous intrusion that has altered the petroleum source and reservoir units in the Paleozoic and Cretaceous rocks, and has disrupted the subsurface fluid systems. This KCM well appears to be the first in the immediate area to encounter a metamorphosed Paleozoic section. This well provides a rare opportunity to observe the thermal alteration of petroleum source rocks. Source rocks usually consist of relatively impermeable mudstones and muddy limestones that inhibit the extent of the contact metamorphism and therefore tend to be less affected than the reservoirs. The effect on the reservoir rocks probably is more widespread. The effect on the subsurface fluids probably is even more widespread, but not yet documented for this area.

In this well the significant metamorphism was first encountered at a depth of 2,255 ft. The first indication of a sizeable intrusive body is the zone of thin dikes from 2,387 ft to 2,435 ft that may be branches off a major pluton. The thick quartz monzonites at 2,924 ft to 3,014 ft, 3,076 ft to 3,321 ft, and 4,116 ft to below total depth, can account for: the contact metamorphism determined by Budding and Broadhead; the recrystallization of the limestones up the fault at 1,947 ft; and the more subtle thermal effects up into the sedimentary section as determined with kerogen analysis by Cernock and Bayliss, and with an estimate of the level of organic metamorphism (LOM) by Ewing and Thompson. However, in this case, the vertical range of significant metamorphism and recrystallization (intensively degrading any preexisting petroleum source or reservoir units) is about 1,000 ft or less above the pluton. This vertical distance may have been limited by the muddy nature of the sedimentary rocks above and/or by the fault at 1,947 ft. Also, the vertical range may be apparently shortened if the fault is normal and the omitted section contains a more gradual change from slightly metamorphosed to unmetamorphosed beds. The lateral extent is not known, but apparently it does not reach the Cockrell No. 1 Playas well about 8 mi to the northeast (fig. I). With the evidence available, the most severe effects of Tertiary metamorphism appear limited vertically and laterally, ranging a few thousand feet or less around the plutons.

The Tertiary extrusives consist of lava and pyroclastic rocks covering wide areas; they have little effect on the older sedimentary rocks. However, the cauldrons (described by Elston and Erb, this circular) are 10-20 mi in diameter. The associated geothermal waters probably disrupt the normal subsurface fluids within a large portion of those areas. Moreover, the cauldrons are surface expressions of the plutonic intrusives that may have metamorphosed the sedimentary section.

Basin and Range faulting later in Tertiary time also disrupted the fluid systems. In a raised block, such as the Animas uplift where the KCM well was drilled, flushing by meteoric water is expected. The possible fault (or major fracture zone) at 1,947 ft may have developed during the Basin and Range deformation. It contains fresh water (probably meteoric) that likely flushed any reservoirs it cut. The eastern boundary fault of the uplift probably is buried beneath the alluvium at the western edge of the Playas Valley. The throw is probably less than the structural relief between this KCM well and the Cockrell No. 1 Playas, reported to be about 2,000 ft lower on the top of the Pennsylvanian.

Although the KCM No. I Forest Federal practically condemns the Winkler anticline as a petroleum prospect, information from this well helps guide exploration in the Playas Valley where chances are better for oil and gas to be preserved in the subsurface. Future wildcat ventures should also provide high quality data in this search for new resources of petroleum.

REFERENCES

Corbitt, L. L., and Woodward, L. A., 1973, Tectonic framework of Cordilleran foldbelt in southwestern New Mexico: Am. Assoc. Petroleum Geologists, Bull., v. 57, p. 2207-2216

Ellis, R. D., 1971, Geology and ore deposits of the Winkler anticline Hidalgo County, New Mexico: M.S. thesis, Univ. Texas at El Paso, 76 p.

Greenwood, Eugene, Kottlowski, F. E., and Thompson, Sam, III, in press, Petroleum potential and stratigraphy of the Pedregosa Basin in comparison with the Permian and Orogrande Basins: Am. Assoc. Petroleum Geologists, Bull.

Flood. A., Gutjahr, C. C. M., and Heacock, R. L., 1975, Organic metamorphism and the generation of petroleum: Am. Assoc. Petroleum Geologists, Bull., v. 59, p. 986-996

McAnulty, W. N., Sr., 1972, Winkler anticline fluorspar, Hidalgo County, New Mexico: New Mexico Bureau Mines Mineral Resources, Target Exploration Rept. E-3, 7 p.

Thompson, Sam, III, 1976, Tectonic and igneous effects on petroleum accumulations in southwestern New Mexico: New Mexico Geol. Soc., Spec. Pub. No. 6, p. 122-126

Wengerd, S. A., 1970, Petroleum prospects in southwesternmost New Mexico: New Mexico Geol. Soc., Guidebook 21st field conf., p. 91-104

Zeller, R. A., Jr., 1965, Stratigraphy of the Big Hatchet Mountains area. New Mexico: New Mexico Bureau Mines Mineral Resources, Mem. 16, 128 p.

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

CONODONT DETERMINATIONS,

KCM No. 1 Forest Federal well, Hidalgo County, New Mexico

by Fred H. Behnken, *Department of Geosciences, Texas Tech University, Lubbock, Texas 79409*

ABSTRACT

Conodonts were recovered from three intervals within the Horquilla Formation (Permian-Pennsylvanian) from the KCM No. 1 Forest Federal well, Hidalgo County, New Mexico. Ten samples were processed with a mean weight of 77 g to obtain a meager fauna of five elements. *Anchignathodus* cf. A. *minutus* (Ellison) from a depth of 3,740 ft is long ranging (Late Mississippian to Early Permian). *Streptognathodus* cf. *S. elegantulus* Stauffer & Plummer was recovered from 1,810 ft and 1,920 ft. *S. elegantulus* ranges from latest Desmoinesian into earliest Wolfcampian. One element of the multielement genus *Hindeodus* Rexroad & Furnish (1964) was recovered from 1,920 ft, and resembles Missourian to Virgilian forms. The inferred age at 1,920 ft is Missourian or, less likely, latest Desmoinesian. The fauna at 1,810 ft seems to represent the Virgilian to late Missourian part of the Horquilla. The Virgilian-Wolfcampian boundary proposed by Thompson (this circular) at 1,526 ft cannot be corroborated because conodonts were not recovered above 1,810 ft. Conodont alteration indices (CAI, Epstein, 1975) in this study range from 5 (black) at 1,810 ft and 1,920 ft to 2 (amber) at 3,740 ft. These conodonts should show increasing CAI values with increasing proximity to Tertiary intrusives present. Decreasing CAI values from 5 to 2 are unexplainable according to Epstein's model (1975) because retrograde color change has not been reported in field or laboratory studies. The anomalous CAI value at 3,740 ft may be due to contamination from above 1,810 ft.

INTRODUCTION

Ten samples of well cuttings were processed for conodont analysis from selected stratigraphic intervals of the Horquilla Formation (Permian-Pennsylvanian) from KCM No. I Forest Federal well, Hidalgo County, New Mexico (table 1).

The mean sample size of the drill cuttings was 77 g, with a range of 40 to 167 g. The cuttings were of medium sand to granule size, and most of the samples passed through a No. 18 U.S. Bureau of Standards screen (aperture of 1.0 mm). These samples were significantly smaller in both weight and particle size than those used in standard conodont biostratigraphic studies. The samples were processed for conodonts according to laboratory techniques outlined by Collinson (1963).

TABLE 1—CONODONT DETERMINATIONS FOR KCM NO. 1 FOREST FEDERAL WELL, HIDALGO COUNTY, NEW MEXICO

Sample depth (ft)	Conodonts	Conodont alteration index (CAI)	Age determination
480	0	–	
800	0	–	
1260	0	–	
1810	1	5	*Streptognathodus* cf. *S. elegantulus* (Ranges from latest Desmoinesian into Wolfcampian)
1920	3	5	1–undescribed element in *Hindeodus* sp. B 2–posterior fragment of *S.* cf. *S. elegantulus* (Ranges from latest Desmoinesian into Wolfcampian)
2010	0	–	
2840	0	–	
3050	0	–	
3380	0	–	
3740	1	2	*Anchignathodus* cf. *A. minutus* (Ranges from Chesterian into Leonardian)

Five conodonts (fig. 1) were recovered from three samples (table 1); the specimens were associated with occasional fish teeth. Conodont samples were processed for both biostratigraphic and conodont color alteration analysis as outlined by Epstein (1974, 1975a, b). Epstein has proposed a conodont alteration index (CAI) as a measure of the degree of metamorphism based upon collections from metamorphic belts in the Appalachians and upon laboratory studies. A general systematic change in conodont color from pale amber (CAI = 1) to black (CAI = 5) was noted to be a combined result of increasing time- and temperature-dependent factors. It was hoped that the CAI could serve as an independent geothermometer within the KCM well where several mid-Tertiary intrusives metamorphosed the Horquilla below 2,255 ft.

ACKNOWLEDGMENTS—Part of the funds for this study were provided by the Energy Resources Board of New Mexico. Sam Thompson of the New Mexico Bureau of Mines and Mineral Resources provided the samples of drill cuttings and offered background information during the study.

The Anatomy Laboratory, Texas Tech Medical School, provided access to the ISI Mini-Scanning Electron Microscope through the cooperation of Dr. John Yee. Franklin Bailey, technician for the Biological Sciences Department, provided helpful advice on nonconductive formvar coatings.

Dr. Glen K. Merrill, College of Charleston, reviewed the manuscript and offered constructive suggestions.

CONODONT DISTRIBUTIONS

Diagnostic conodonts for the Middle Pennsylvanian-Early Permian interval are the platform conodonts: *Streptognathodus* Stauffer & Plummer, *Idiognathodus* Gunnell, *Neognathodus* Dunn, *Cavusgnathus* Harris & Hollingsworth, and *Gondolella* Stauffer & Plummer. These genera are readily broken due to their large size (0.5-2.0 mm) as evidenced in the fauna from cuttings in this study. The meager broken fauna from ten samples can be attributed to the sample weight and the size of the cuttings. Fig. 1 shows that the platform conodonts

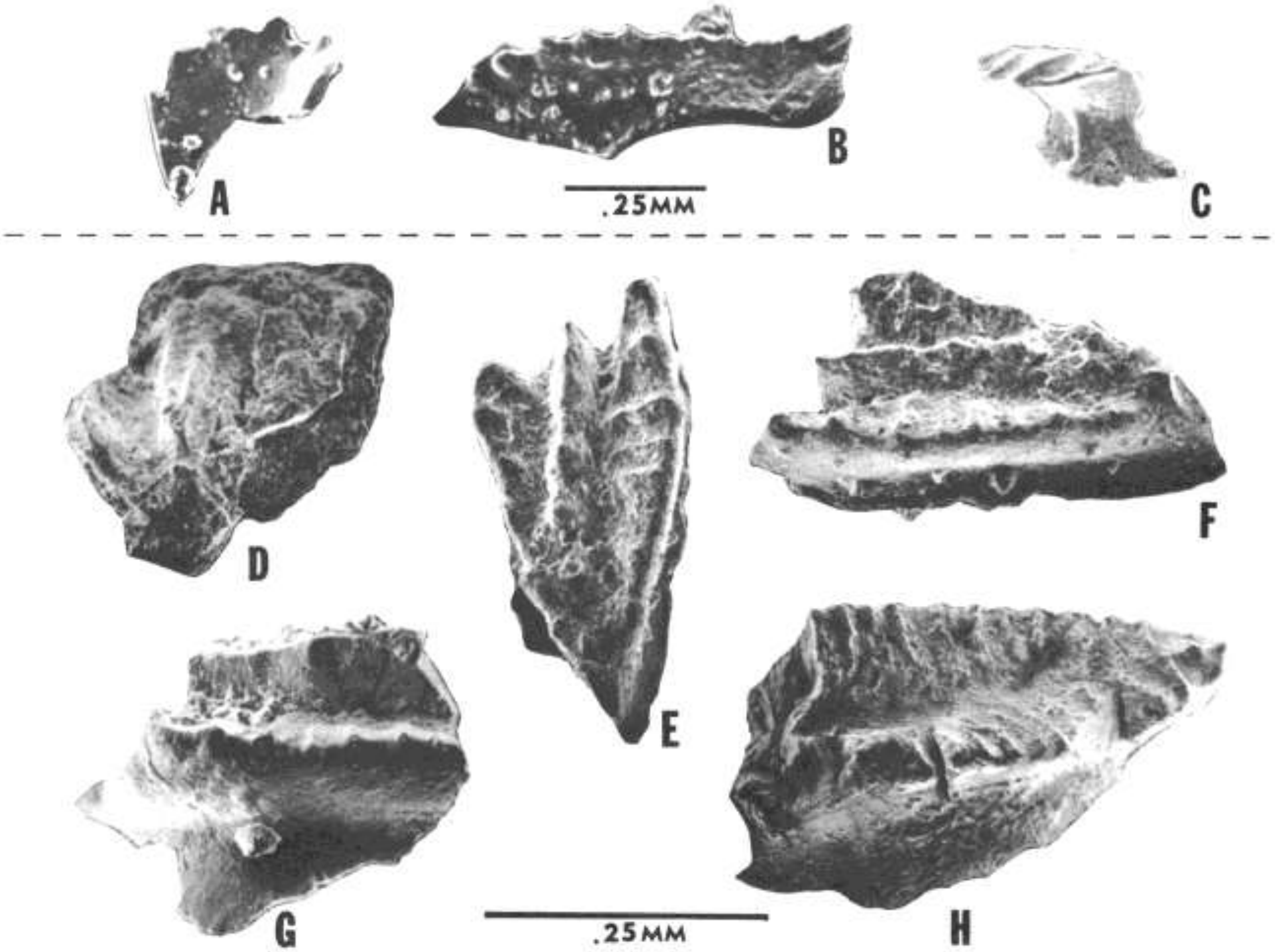


FIGURE 1—CONODONTS FROM KCM NO. 1, FOREST FEDERAL WELL. **a,** *Hindeodus* sp. B Perlmutter, TTU-N012/01, sample depth 1920; **b,** *Anchignathodus* cf. *A. minutus* (Ellison), TTU-N012/02, sample depth 3740; **c-d,** fish dermal plates, TTU-N012/06,/07, sample depth 1920; **e-f,** same specimen, *Streptognathodus* cf. *S. elegantulus* Stauffer & Plummer, TTU-N012/13 sample depth 1810; **g,** *Streptognathodus* sp., TTU-N012/04, sample depth 1920; and **h,** *Streptognathodus* cf. *S. elegantulus* Stauffer & Plummer, TTU-N012/05, sample depth 1920. Scale indicated by bar for upper and lower portions of the figure as 0.25mm.

(e-h) are broken and even seem to bear "drill-bit marks."

The conodonts were recovered from three depths within the Horquilla Formation as determined by Thompson: 1,810 ft, 1,920 ft, and 3,740 ft. Only one complete specimen was recovered from 3,740 ft *[Anchignathodus* cf. *A. minutus* (Ellison) fig. 1 b]. One posterior fragment of a platform conodont was recovered from 1,810 ft *(Streptognathodus* cf. *S. elegantulus* Stauffer & Plummer, fig. I e, f). Additionally, three elements were recovered from 1,920 ft: a single element which is part of a multielement apparatus described as *Hindeodus* sp. **B** by Perlmutter (1975) fig. la; a single specimen referred to *S.* cf. *S. elegantulus,* fig. lh; and a fragment questionably referred to *Streptognathodus* sp., fig. lg.

Streptognathodus elegantulus ranges from the latest Desmoinesian through the early Wolfcampian. The oldest probable age for the sample at 1,920 ft seems to be Missourian, while a stronger possibility exists that the sample at 1,810 ft represents the Virgilian to late Missourian portion of the Horquilla Formation. Using other criteria, Thompson has tentatively determined the Wolfcampian-Virgilian boundary within the Horquilla to *be* at 1,526 ft. Conodonts confirm the possibility of Virgilian age because of the range of *S. elegantulus.* Unfortunately conodonts were not recovered in the three samples above 1,810 ft to corroborate Thompson's assignment. The element of *Hindeodus* sp. **B** recovered from 1,920 ft is not a biostratigraphically definitive form, but seems to resemble forms having a Missourian to Virgilian range. *Anchignathodus* cf. *A. minutus* from 3,740 ft is poorly preserved. This species has a range of Chesterian into Leonardian.

The fragmentary conodont evidence from the KCM No. **1** Forest Federal well strongly suggests that the lower Horquilla at 3,740 ft is probably not younger than Desmoinesian, being below *S.* cf. *S. elegantulus* (1,920 ft) that first occurs in latest Desmoinesian. The upper Horquilla Formation between 1,920 ft and 1,810 ft is at least as young as Missourian and may be Virgilian or earliest Wolfcampian. The lithologic change at 255 ft noted by Thompson is designated as the Horquilla-Earp Formation boundary. As noted previously, Thompson regards the Virgilian-Wolfcampian boundary to be within the uppermost Horquilla at approximately 1,526 ft. Conodont evidence is inconclusive in determining the boundary.

CONODONT COLOR ALTERATION

The conodonts were examined to determine if the conodont color alteration index (CAI) proposed by Epstein (1975) could be related to footage from the Tertiary pluton. Conodonts illustrated in fig. 1e-f were photographed with a scanning electron microscope using a translucent formvar coating as outlined by Pease & Bailey (1975) to preserve the utility of future CAI work on these specimens.

The Horquilla Formation consists of increasingly recrystallized limestones from 1,526 to 2,255 ft, and a complex of marbles, hornfels, and quartz-monzonite intrusives from 2,255 to 4,464 ft (Thompson, this circular). According to the conodont color-alteration model proposed by Epstein, the color change in conodonts is due to carbon fixation as a response to time, depth of burial, and increasing temperature. A CAI value of 1 is indicated by a pale amber color, while increasing CAI values represent increasing carbon fixation until the conodont is black and has a CAI value of 5. Opaque white (CAI = 7) and crystal clear (CAI = 8) conodonts were reported from marbles intercalated with garnet-mica schists (Epstein, 1975), and they are a last stage prior to total disintegration of the conodont. Conodont color alteration then is a retrograde process from black to translucent, if carried to extremes of temperature, for example, to greenschist facies. Epstein and others (1974, 1975) reported that high water-vapor pressures and reducing conditions retard color alteration based upon preliminary laboratory experiments.

Epstein and others (1974, p. 723) reproduced the CAI values determined from field studies within the laboratory "by high-temperature (300-600°C) long-term (1050 days) runs in open air." The studies by Epstein do not, and for practical reasons cannot, take into account the confining pressure, higher vapor pressure, and longer time intervals to which conodonts are subjected in natural temperature changes. The absolute temperature values attached to conodont alteration indices determined in an open-air furnace should be used with caution until more field studies have been carried out. Work must be done incorporating conodont color alteration, petrographic alteration, and inferred vapor and lithostatic pressure. Experimental work should take lithostatic and vapor pressure into account.

The conodonts recovered in this study provide CAI values ranging from 5 at depths of 1,810 ft and 1,920 ft to a CAI value of 2 at 3,740 ft. All of these samples are from the basinal section of the Horquilla Formation with abundant pyrite present. The CAI change from black (= 5) to amber (=2) is unexplainable according to the observations of Epstein (1975) inasmuch as gradual retrograde color changes have not been reported. CAI values only move from 5 (black) to 8 (crystal clear). The anomalous CAI values from this study could be due to *Anchignathodus* cf. *A. minutus* being a contaminant plucked from above 1,810 ft by circulating drilling mud; however, because other amber conodonts were not recovered (other than that at 3,740 ft) I deemphasize, but do not disregard, this possibility. The conodonts recovered from 1,810 ft and 1,920 ft show the etching noted by Epstein (1975) on conodonts with CAI values greater than 4.5.

CONCLUSIONS

Conodonts recovered from three well cutting samples in the KCM No. 1 Forest Federal well provide biostratigraphic evidence that the interval from 255 ft to 3,740 ft regarded by Thompson as the Horquilla Formation is Pennsylvanian. The portion of the Horquilla above 1,810 ft and below the Earp Formation at 255 ft did not yield conodonts and may be Virgilian or early Wolfcampian based upon the fauna at 1,810 ft.

Conodonts were analyzed for conodont color alteration indices (CAI) and results were inconclusive, if not contradictory, to the expected color alteration. Marbles and hornfels (3,740 ft) should yield indigenous conodonts with CAI values greater than 5. Conodonts at 1,810 ft and 1,920 ft had CAI values of 5, while closer to the pluton at 3,740 ft a single complete conodont had a CAI value of 2. Either this conodont is out of place, possibly from much higher in the section, or retrograde color alteration may be more gradual than determined by Epstein (1975).

SYSTEMATIC PALEONTOLOGY

Conodonts recovered in this study are reposited at the Texas Tech University Museum, Micropaleontological Collections, under repository number TTU-N012/. Specimens N012/03-7 were coated with a nonconductive translucent formvar film using techniques outlined by Pease and Bailey (1975). Photographs were taken using Polaroid Type 55 P/N film on an ISI Mini-Scanning Electron Microscope. Synonomies are not complete but include only principal references.

Anchignathodus **cf.** *A. minutus* **(Ellison)**

fig. 1 b

Anchignathodus minutus (Ellison) Behnken, 1975, p. 297, Pl. 1, figs. 16-18: Merrill, 1973, p. 305, Pl. I. figs. 1-14, P1.2, figs. 1-28.

REMARKS—This single specimen closely resembles Pennsylvanian representatives of *A. minutus* illustrated by Merrill (1973). The element bears 11 denticles, including the main cusp. Main cusp and adjacent three denticles form an anterior blade. Basal cavity confined to posterior of unit, flaring beneath the highest denticles on the posterior half of the element.

OCCURRENCE—KCM No. 1 Forest Federal well, 3,740 ft. TTU-N011/02.

CONODONT ALTERATION INDEX-1.5-2, light amber.

Hindeodus **sp. B**

fig. l a

Hindeodus sp. B, Perlmutter, 1975, p. 102, Pl. 2, fig. 16, 17, 20, 21.

REMARKS—An asymmetrical element with two processes joining at an angle of 90 to 100 degrees. A short posterior process bearing three broken denticles joins with the anterior process bearing four posteriorly inclined denticles. A basal pit is located at the junction of the processes and extends posteriorly and anteriorly as a longitudinal groove.

OCCURRENCE—KCM No. 1 Forest Federal well, 1,920 ft. TTU-N011/01.

CONODONT ALTERATION INDEX-5, black.

Streptognathodus cf. *S. elegantulus* Stauffer & Plummer
fig. le, f, h

Streptognathodus elegantulus Stauffer & Plummer. Von Bitter, 1972, p. 52, Pl. **1**, fig. 1*a-e.*

Streptognathodus sp. aff. *S. elegantulus* Stauffer & Plummer. Von Bitter, 1972, p. 53, Pl. I, fig. 3a-b.

REMARKS—The two specimens tentatively referred to *S. elegantulus* lack the anterior blade and anterior portion of the platform. Because these specimens are incomplete, no assignment can be made with confidence. The specimen from 1,810 ft superficially resembles a species of *Neognathodus (N. medadultimus* Merrill), but it lacks the diagnostic fusion of the carina and one of the lateral node rows, as well as the well developed posterior carina. This small specimen has characters resembling juvenile *S. elegantulus* illustrated by von Bitter (fig. 3b); lateral oral troughs which deepen anteriorly and a carina which extends posteriorly almost to the terminus of the unit also characterize *S. elegantulus.* The rows of nodes are asymmetrically developed with one possessing strongly developed transverse ridges.

A second broken specimen (1,920 ft) does not possess a carina but possesses one or two complete transverse ridges (fig. 1H) at the posterior end of the platform. This feature was pointed out as typical of *S. elegantulus* by von Bitter (1972, p. 52). Two rows of transverse nodes are separated by a broad V-shaped trough towards the anterior.

OCCURRENCE—KCM No. 1 Forest Federal well, 1,810 ft and 1,920 ft, TTU-N011/03 and TTU-N011/05, respectively.

CONODONT ALTERATION INDEX-5, black.

Streptognathodus sp.
fig. lg

REMARKS—Because of the broken nature of this specimen, it is not possible to assign to a genus.

OCCURRENCE—KCM No. 1 Forest Federal well, 1,920 ft, TTU-N011/04.

CONODONT ALTERATION INDEX-5, black.

REFERENCES

Behnken, F. H., 1975, Leonardian and Guadalupian (Permian) conodont biostratigraphy in western and southwestern United States: Jour. Paleontology, v. 49, p. 284-315

Collinson, C., 1963, Collection and preparation of conodonts through mass production techniques: Illinois State Geol. Survey, Circ. 343

Epstein, A., 1975, Conodont color alteration—an index to organic metamorphism, U.S. Geol. Survey Open-file Rept. 75-379, 54 p.

Epstein, A., Epstein, J. B., and Harris, L. D., 1974, Incipient metamorphisms, structural anomalies, and oil and gas potential in the Appalachian Basin determined from conodont color: Geol. Soc. America, Abs. with Programs, v. 6, p. 723-724

, 1975, Conodont color alteration—an index to diagenesis of organic matter: Am. Assoc.' Petroleum Geologists, Ann. Mtg., Abs., v. 2, p. 21-22.

Merrill, G. **K.,** 1973, Pennsylvanian nonplatform conodont genera, I: *Spathognathodus:* Jour. Paleontology, v. 47, p. 289-314

Pease, R. W., and Bailey, J. F., 1975, Thin polymer films as non-charging surfaces for scanning electron microscopy: Jour. Microscopy, v. 104, p. 281-285

Perlmutter, B., 1975, Conodonts from the uppermost Wabaunsee Group (Pennsylvanian) and the Admire and Council Grove Groups (Permian) in Kansas: Geol. et Palaeontol., v. 9, p. 95-115

von Bitter, P. H., 1972, Environmental control of conodont distribution in the Shawnee Group (Upper Pennsylvanian) of eastern Kansas: Univ. Kansas, Paleontol. Contr., Art. 59, 105 p.

IGNEOUS AND METAMORPHIC PETROLOGY

of Drill Cuttings from the KCM No. 1 Forest Federal Well, Hidalgo County, New Mexico

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ABSTRACT

The KCM No. 1 Forest Federal well in Hidalgo County, New Mexico, drilled several intervals of mid-Tertiary quartz monzonite and quartz latite, which have brought about contact metamorphism as the Pennsylvanian sedimentary section was intruded. This paper reports the results of mineralogical and chemical investigations of drill cuttings of selected igneous, sedimentary, and metamorphic rocks. Contact metamorphism has changed the original siliceous dolomitic limestones, argillaceous limestones, and calcareous mudstones into marbles and hornfelses. These rocks contain tremolite, diopside, forsterite, garnet, and wollastonite as metamorphic minerals. Unmetamorphosed sediments are predominant in the upper part of the well (above a depth of 1,947 ft) whereas the lower part (from 1,947 ft to 4,464 ft) consists of quartz monzonite and metamorphosed calcareous rocks.

Emplacement of the quartz monzonite occurred under an overburden of approximately 3.1 km to 4.4 km, corresponding to a lithostatic pressure of 0.8 kilobars to 1.1 kilobars. Chemical composition of the quartz monzonite near the minimum melting composition in the ideal granite system suggests an intrusion temperature above 720°C. Metamorphic mineral assemblages are indicative of a temperature interval ranging from about 410°C to 670°C, spanning the albite-epidote hornfels facies, the hornblende hornfels facies, and possibly the pyroxene hornfels facies of contact metamorphism.

INTRODUCTION

The KCM No. 1 Forest Federal well in sec. 3, T. 31 S., R. 18 W., Hidalgo County, New Mexico, drilled several intervals of igneous and metamorphic rocks that could not be identified specifically under the binocular microscope (Thompson, this circular). Thin sections for petrographic study were prepared from the drill cuttings. In consultation with Thompson, critical intervals were chosen in the available set of 10-ft samples. Chips were selected under a binocular microscope and washed to exclude contaminants such as well cavings and drilling mud.

Thin sections were prepared in the following manner. A flexible plastic ice tray is coated with a thin layer of vaseline, and thin epoxy is poured into each compartment to just cover the bottom. A suitable mixture consists of 11 parts thin epoxy and one part hardener. About 5 grams of sample are poured onto the epoxy, which in turn are covered by epoxy to a depth of one-quarter inch. This procedure prevents the formation of air bubbles in the sample. After hardening overnight, the samples are removed from the tray, ground on a lap using 240 grit, washed, smoothed with 600 grit, and dried. The samples were then glued to a frosted glass microscope slide, using viscous epoxy. After curing the samples at 250°F for two hours, they were cut to 200 microns and ground to 50 microns. After final handgrinding to 30 microns and drying, cover slips were glued on with viscous epoxy.

ACKNOWLEDGMENTS—Most samples for this study were selected by Sam Thompson III of the New Mexico Bureau of Mines and Mineral Resources. We also had many stimulating discussions of the petrographic analyses relative to the geology of this well, and the regional implications for petroleum exploration. We are also grateful to Wolfgang E. Elston of the University of New Mexico for arranging for the chemical analyses of the igneous rocks, and to Lynn A. Brandvold of the New Mexico Bureau of Mines and Mineral Resources for the chemical analyses of the sedimentary and metamorphic rocks. Jacques Renault of the New Mexico Bureau of Mines and Mineral Resources reviewed the manuscript.

IGNEOUS ROCKS

Quartz monzonite and quartz latite constitute approximately 10 percent of the drilled section (log by Thompson). The name quartz monzonite is used for igneous rocks with 10 to 50 percent quartz and 35 to 65 percent of total feldspar consisting of potassium feldspar. Quartz latite is the equivalent of monzonite with grain size less than 0.1 mm.

Thin sections of cuttings from shallow depths of 210 ft and 230 ft consist mostly of quartz latite that probably forms thin dikes or sills. Quartz monzonite is identified at several depths from 2,960 ft to 4,460 ft. Based on the interpretation of the gamma ray curve, Thompson shows quartz monzonite at several depths from 2,387 ft to the bottom of the well at 4,464 ft. The drilled thicknesses of these intrusive bodies range from about 5 ft to over 348 ft at the bottom where the entire body was not penetrated. Similarities in mineralogical composition between the quartz latites and monzonites suggest a common origin, and the textural characteristics, varying from hypidiomorphic at greater depths to porphyritic at shallower depths. are compatible with a plutonic to hypabyssal origin. The sonic curve of the KCM well log shows a nearly constant interval velocity of 5.86 km/sec in the intrusive at the bottom of the well. This velocity conforms with P wave velocities reported for felsic intrusive rocks (Press, 1966).

The quartz monzonite has a hypidiomorphic texture in which quartz and feldspars form more than 95 percent of the total constituents (fig. la). Size of quartz and feldspar grains ranges from 0.2 mm to 0.5 mm. The quartz monzonites at 2,960 ft and 3,130 ft (fig. lb) have a porphyritic texture, with the larger crystals averaging 0.5 mm in diameter, within a groundmass of small crystals averaging 0.1 mm in diameter. Samples from

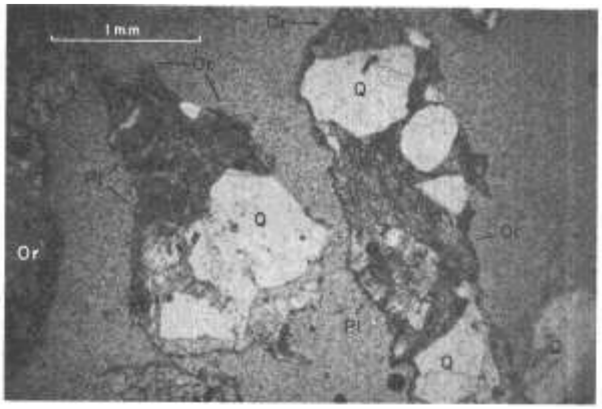

Fig. 1a. Quartz monzonite at 4,350 ft, parallel light.

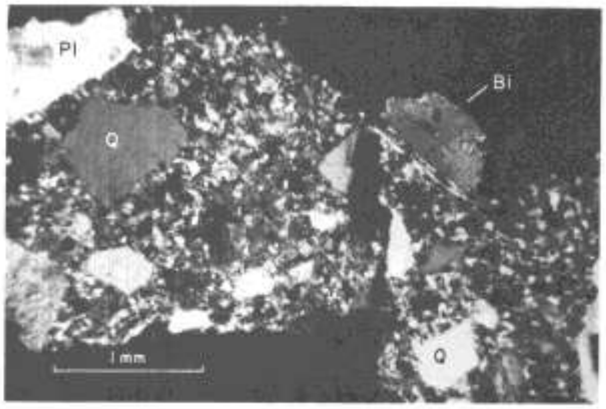

Fig. 1b. Quartz monzonite at 3,130 ft, crossed polarizers.

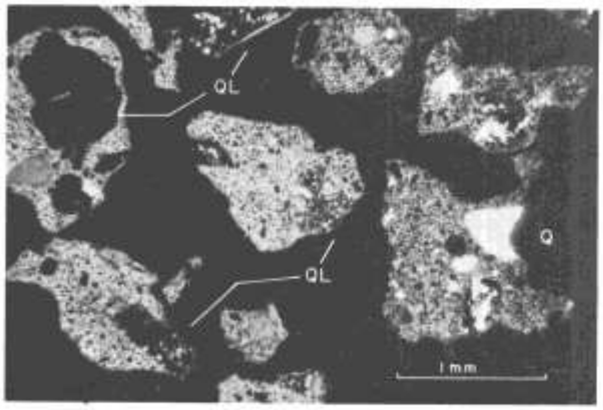

Fig. 1c. Quartz latite at 210 ft, crossed polarizers; groundmass partly replaced by calcite.

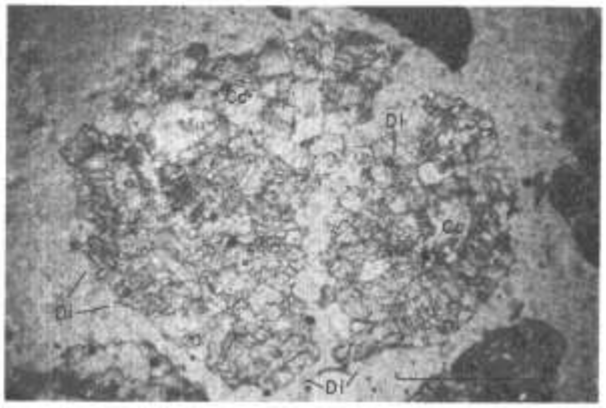

Fig. 1d. Diopside marble at 3,680 ft, parallel light.

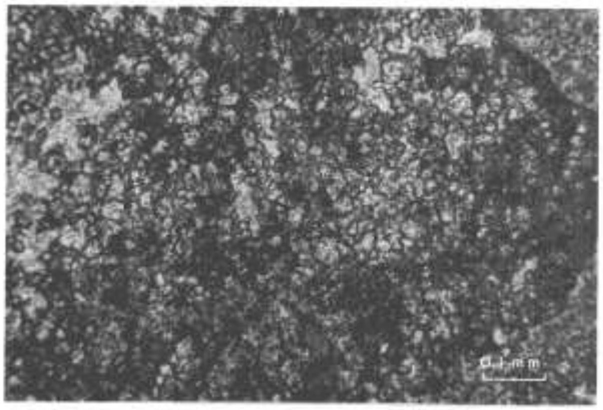

Fig. 1e. Diopside hornfels at 4,040 ft, parallel light; fine-grained mixture of diopside and quartz.

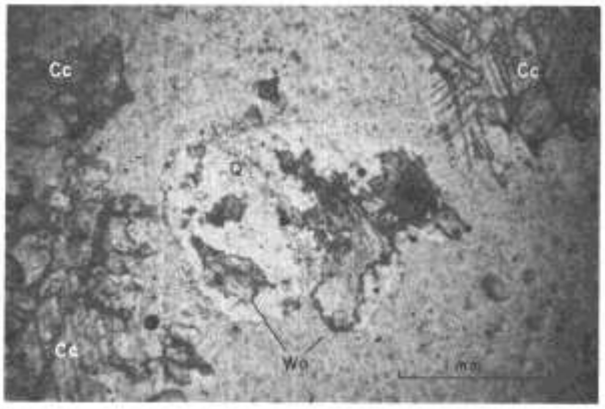

Fig. 1f. Diopside-wollastonite marble at 2,360 ft, parallel light.

FIGURE 1—PHOTOMICROGRAPHS OF THIN SECTIONS FROM ROCKS OF THE KCM WELL. Q, quartz; Or, orthoclase; Pl, plagioclase; Bi, biotite; QL, quartz latite; Cc, calcite; Di, diopside; Wo, wollastonite

210 ft (fig. 1c) and 230 ft show the greatest range in grain size, from less than 0.1 mm in the groundmass to 1.2 mm in the phenocrysts. Modal analyses of the igneous rocks are listed in table 1.

Quartz forms rounded, somewhat embayed, anhedral phenocrysts. Plagioclase occurs as slightly altered, subhedral to euhedral crystals with abundant polysynthetic twinning according to the albite law. Its composition, as determined by optical methods, is oligoclase to albite (An„ to And. Microperthitic potassium feldspar, with occasional Carlsbad twinning, is most likely orthoclase ($2V_x$ = 50°) and also forms part of the porphyritic phase. In the samples above 3,968 ft, this feldspar is more common in the fine-grained groundmass where orthoclase forms a micrographic intergrowth with quartz.

Mafic minerals are rare and are mainly restricted to euhedral biotite (0.5 mm) which is partially altered to chlorite; green hornblende is very rare. Fine-grained, colorless mica is an alteration product of plagioclase. Small, irregular patches of calcite and thin calcite veins occur predominantly in the groundmass.

Accessory constituents include opaque minerals (probably pyrite and hematite), fluorite in irregular crystals, sphene, and zircon as inclusions in biotite. Chemical analyses of three igneous rocks are listed in table 2. In comparison with quartz monzonites, the quartz latite is unusually high in CaO, MgO, and CO_2. In thin section, the rock shows inclusions of coarsely crystalline calcite, and the groundmass has been partly replaced by fine-grained calcite. Therefore, magmatic assimilation of Paleozoic limestone, followed by hydrothermal alteration with calcium carbonate-bearing solutions, may be held responsible for the aberrant chemical composition of quartz latite.

TABLE 2—CHEMICAL COMPOSITION OF SELECTED IGNEOUS ROCKS. Values are given in weight percent; chemical analyses by John Husler, Department of Geology, University of New Mexico.

Chemical constituents	Rock type (depth)		
	Quartz latite (210 ft)	Quartz monzonite (3,130 ft)	Quartz monzonite (4,350 ft)
SiO_2	54.04	74.06	72.60
Al_2O_3	6.09	12.95	12.53
Fe_2O_3	3.09	0.18	0.51
FeO	1.00	0.76	0.50
MgO	2.20	0.27	0.47
CaO	17.00	1.80	2.76
Na_2O	1.04	3.43	3.05
K_2O	1.33	4.70	5.25
$H_2O^+ + CO_2$	13.75	1.44	1.69
H_2O^-	0.26	0.05	0.00
TiO_2	0.35	0.21	0.23
P_2O_5	0.070	0.033	0.030
MnO	0.057	0.050	0.040
SrO	0.038	0.007	0.006
Sulfur	0.09	<0.05	<0.05
TOTAL	100.40	99.94	99.67

Elston and Erb (this circular) present evidence that the quartz monzonite is of mid-Tertiary age. At the time of the intrusion, the amount of sedimentary and volcanic overburden at the well location was about 3,100 m to 4,400 m as estimated from the drilled interval of Paleozoic rocks and the geologic column of Zeller and Alper (1965). Assuming an average density of 2.60 for the overburden, a lithostatic pressure between 0.8 kilobars and 1.1 kilobars is indicated.

The chemical analyses of quartz monzonite in samples at 3,130 ft and 4,350 ft have been used to calculate normative quartz, orthoclase, albite, and anorthite. Results are shown in the triangular diagram of fig. 2, which also shows the position of the cotectic line in the system quartz-orthoclase-albite at P_{H2O} = 1,000 bars (after Bowen and Tuttle, 1958). M is the composition of the temperature minimum in this system. Both quartz monzonites contain from 6 to 8 percent normative anorthite, and the addition of this mineral to the system has the effect of displacing the minimum melting composition away from the albite corner of the diagram (Winkler, 1974).

The quartz monzonites plot close to the cotectic line and to the temperature minimum. Their intrusion temperatures, therefore, were probably near 720°C, if the melt was water saturated. According to Bowen and Tuttle (1958), 720°C is the minimum melting temperature in the "granite system" at 1,000 bars water pressure.

SEDIMENTARY ROCKS

Petrographic examination of thin sections of the sedimentary rocks was performed mainly to obtain an insight into the mineralogy, texture, and compositional variation. Sedimentary rocks encountered in the KCM well are Permian and Pennsylvanian, and consist predominantly of mixtures of carbonates, chert, and detrital sedimentary materials, such as quartz and clay minerals.

TABLE 1—MODAL ANALYSES OF QUARTZ MONZONITES AND QUARTZ LATITES. Values are given in volume percent; additional thin sections of igneous rocks were studied from depths of 230 ft (quartz latite), 2,960 ft and 3,130 ft (quartz monzonite).

Sample depth (ft)	Quartz	K-feldspar	Plagioclase	Fine-grained groundmass	Biotite	Opaque minerals	Apatite	Zircon	Calcite	Fluorite	Rock type
210	6	6	4	80	trace	3	–	–	trace	–	Quartz latite
4,010	23	40	35	–	1	1	–	–	–	–	Quartz monzonite
4,350	32	43	24	–	1	trace	–	–	trace	trace	Quartz monzonite
4,460	27	38	30	–	2	1	trace	trace	1	–	Quartz monzonite

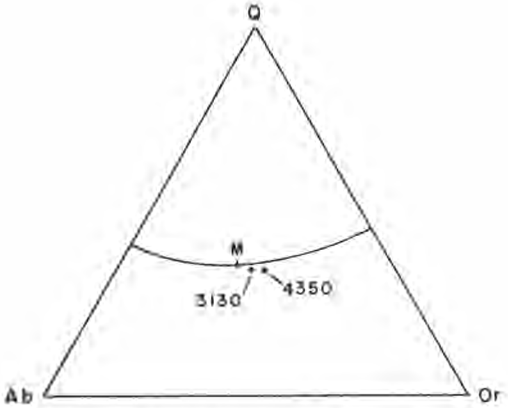

FIGURE 2—Quartz-Albite-Orthoclase diagram at 1 kilobar water pressure, after Bowen and Tuttle, 1958. Shows cotectic line and minimum melting composition M; normative compositions of quartz monzonites from 3,130 ft and 4,350 ft are plotted.

The carbonate mineral is mainly calcite, although dolomite has been identified and may be more common than suspected. Terms used to describe crystal sizes in this thin-section study are: finely crystalline calcite (grain size less than 0.01 mm), medium-crystalline calcite (grain size between 0.01 mm and 0.1 mm), and coarsely crystalline calcite (grain size larger than 0.1 mm).

Finely crystalline calcite is a main constituent of both pure limestones as well as silty and argillaceous limestones. Much of this calcite is light brown in thin section, presumably the result of finely divided clay minerals or organic materials. Such impure calcite probably was not affected by diagenetic recrystallization. The distribution of the argillaceous and organic material often imparts a closely spaced lamination to the limestones.

Medium-crystalline calcite is variable in grain size but commonly averages 0.05 mm in diameter. Crystals of this size generally are composed of clear calcite and occur in lens-shaped aggregates. The lenses are separated by thin dark films, probably of clay minerals. At least some of these separate lenses probably were produced by diagenetic recrystallization of finely crystalline calcite.

Coarsely crystalline calcite forms grains larger than 0.1 mm, commonly between 0.3 mm and 0.4 mm in diameter. This calcite fills cavities in fossils and fossil fragments, occurs as irregular aggregates, and forms thin veins that cut across or are parallel to the lamination. Twinning according to (0112) is observed occasionally.

Dolomite was identified in a few rocks, but it probably occurs more commonly among the carbonate minerals (table 3). In the sample at 760 ft, the mineral forms rhomb-shaped crystals in a medium-crystalline ground mass.

Quartz occurs as detrital grains and in the finely crystalline form as chert. The chert grains are less than 0.01 mm in diameter and appear to be replacements of calcite. Rare, fibrous aggregates have the appearance of chalcedony. Angular quartz clasts, averaging 0.05 mm in diameter, are found in the silty and argillaceous limestones.

TABLE 3—CaO and MgO content of selected sedimentary and metamorphic rocks. Values are given in weight percent; CaO and MgO analyses by Ingeborg Vogelmann, student assistant, New Mexico Bureau of Mines and Mineral Resources.

Sample depth (ft)	Rock type	CaO	MgO
270	Sandy, dolomitic limestone	22.38	4.11
380	Limestone	53.75	1.05
760	Dolomitic limestone	48.85	4.01
1,230	Sandy, calcareous mudstone	22.46	2.88
1,810	Argillaceous limestone	34.43	2.88
2,360	Diopside-wollastonite marble	50.32	1.89
2,460	Wollastonite hornfels	33.66	1.52
2,660	Cherty limestone	43.29	1.44
3,750	Tremolite marble	45.07	6.87

Clay minerals, an important constituent of the calcareous mudstones and the silty or argillaceous limestone, occur in small amounts in some of the purer limestones. However, they are so fine grained that more specific identifications were not attempted.

The compositions of the sedimentary rocks in terms of the above constituents are listed in table 4.

METAMORPHIC ROCKS

Contact metamorphism produced by the quartz monzonite intrusions has changed the texture and mineralogy of the sedimentary rocks below the depth of 2,255 ft (log by Thompson). Some minerals have been recrystallized, and new ones have been formed including tremolite, diopside, forsterite, garnet, and wollastonite. Marbles are contact-metamorphic rocks with more than 50 percent calcite. Hornfelses are contact-metamorphic rocks with more than 50 percent silicates. Where mineral names are used as modifiers, they are given in order of increasing abundance. For example, in a diopside-wollastonite hornfels, the amount of wollastonite exceeds that of diopside.

Tremolite occurs as a minor constituent of the samples at 2,010 ft and 3,750 ft. This mineral forms colorless fibrous crystals, grouped in radiating aggregates, in a calcite matrix. The extinction angle Z vs c (direction of largest refractive index vs the c crystallographic direction) is equal to 18°. Sparry calcite makes up less than 10 percent of the rock.

In the sample from 3,680 ft, forsterite forms large rounded crystals .0.5 mm in diameter that are partially altered to minerals of the chlorite or serpentine groups. Optically continuous remnants of the original forsterite crystals are embedded in a fine-grained, scaly matrix of alteration products.

Diopside is the most common metamorphic mineral. It forms colorless, short prismatic crystals with an average diameter of 0.2 mm and an extinction angle Z vs c = 40°. Diopside has replaced calcite and is also found in close association with chert (fig. le).

Wollastonite commonly forms colorless fibrous masses and radiating aggregates (fig. 10. Fibers average 2.0 mm in length and 0.2 mm in width. The mineral occurs with both chert and calcite.

Colorless garnet (probably grossularite) in the sample

TABLE 4—MINERALOGICAL COMPOSITION OF SEDIMENTARY ROCKS. Values are given in volume percent; additional thin sections were studied from depths of 50 ft, silty limestone; 450, 480, and 520 ft, fossiliferous limestones; 760 ft, recrystallized fossiliferous dolomitic limestone; 1,920 ft, argillaceous limestone (slightly recrystallized).

Sample depth (ft)	Calcite + dolomite Finely crystalline	Medium crystalline	Coarsely crystalline	Chert	Quartz, clastic	Clay minerals	Rock type
270	74	15	–	–	11	–	Sandy, dolomitic limestone
320	6	67	2	2	2	21	Argillaceous limestone
380	14	65	18	2	1	–	Limestone
640	59	25	10	5	1	–	Limestone
800	7	38	2	–	1	52	Calcareous mudstone
1,080	3	46	10	–	1	40	Calcareous mudstone
1,210	–	54	1	–	4	41	Calcareous mudstone
1,230	26	30	1	–	18	25	Sandy, calcareous mudstone
1,810	1	57	12	11	1	18	Argillaceous limestone
2,660	53	30	1	16	–	–	Cherty limestone

at 3,780 ft is associated with calcite, diopside, and tremolite.

In the marbles, calcite grains are usually larger than 1 mm in diameter and form a mosaic of interlocking crystals, imparting a granoblastic texture to the rocks. Frequently the calcite in the marbles is twinned according to (0112).

Mineralogical compositions of some metamorphic rocks are listed in table 5. Several samples are from depths within 30 ft above or below the quartz monzonite intrusives. Samples from 2,360 ft, 2,460 ft, 4,000 ft, and 4,040 ft contain wollastonite and diopside, but the same minerals occur at depths several hundred feet above or below intrusive bodies. These occurrences may be related to intrusive bodies not drilled but sufficiently close to the well bore to have caused the metamorphic effects displayed in these samples.

DISCUSSION OF CONTACT METAMORPHISM

The original sedimentary rocks were composed of calcite, dolomite, quartz, and some clay minerals. All metamorphic minerals, with the exception of rare garnet, are free of $A1_20_3$. Therefore, the system of calcite (Cc) — dolomite (Do) — quartz (Q) is well suited to describe approximately the metamorphic mineral associations and reactions. Fig. 3 shows graphically the mineral associations observed in the metamorphic rocks.

In the metamorphism of siliceous, dolomitic limestones, talc is usually the first mineral to form; however, this mineral was not recognized in any of the thin sections. Any talc-bearing rocks may not have been picked for the limited number of samples studied in thin section, or they may have been so finely comminuted by the drill bit that the mineral was not satisfactorily recovered in the cuttings. On the other hand, the lack of talc is common, even in many well-exposed contact aureoles, and may also be attributed to the formation of phlogopite in preference to talc, if sufficient K_20 is available.

Contact metamorphism of siliceous magnesian limestones can result in a large number of metamorphic reactions (Winkler, 1974, p. 111-112). Some of these reactions have been studied by experimental and thermodynamic methods. All mineral reactions produce CO_2 that mingles with pore water to constitute the fluid phase. Mineral stabilities are shown in an isobaric diagram of temperature versus mole fraction in which the total fluid pressure is specified. Lithostatic pressure at the time of quartz monzonite intrusion was about 1 kilobar. This value will be adopted for the total fluid pressure.

The most common metamorphic minerals in the rocks of the KCM well are tremolite (Tr), diopside (Di), forsterite (Fo), and wollastonite (Wo). The origin and stability range of these minerals are discussed below; their association is illustrated in fig. 3.

Tremolite can result from reactions between talc and calcite, or between talc, calcite, and quartz. Because talc has not been found, the tremolite probably formed as a result of the reaction:

$$5\ Do + 8Q + 1H_2O = 1Tr + 3\ Cc + 7CO2$$

Stable associations, those present over a range of temperatures, would include Do + Tr -I- Cc and Q -I- Tr Cc.Based on the observation of mineral grain contacts

TABLE 5—MINERALOGICAL COMPOSITION OF METAMORPHIC ROCKS. Values are given in volume percent; additional thin sections studied from depths of 2,280 ft, diopside marble; 2,820 ft, wollastonite marble; 3,380 ft, diopside marble; 3,750 ft, tremolite marble; 3,780, 4,000, and 4,040 ft, diopside hornfelses.

Sample depth (ft)	Calcite, all varieties	Quartz including chert	Tremolite	Forsterite and chlorite/serpentine	Diopside	Wollastonite	Rock type
2,010	95	5	trace	–	–	–	Tremolite-bearing limestone
2,360	78	12	–	–	4	6	Diopside-wollastonite marble
2,460	9	78	–	–	1	12	Wollastonite hornfels
2,640	92	4	–	–	1	3	Wollastonite marble
3,680	78	5	–	3	11	3	Diopside marble
3,740	97	1	–	–	2	–	Marble

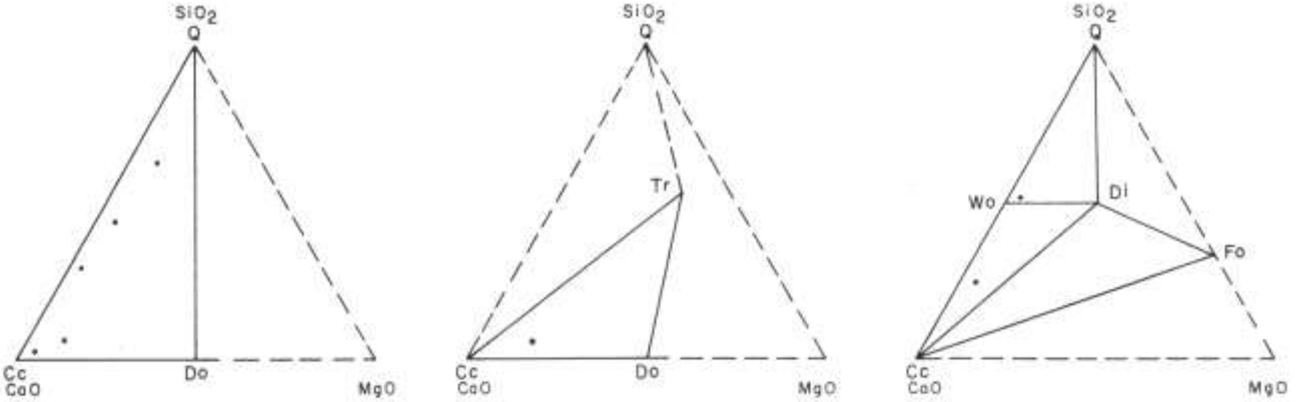

Fig. 3a. Mineral assemblage prior to metamorphism. Dots indicate chemical compositions of five unmetamorphosed sediments from 270 ft, 380 ft, 760 ft, 1,810 ft, and 2,660 ft.

Fig. 3b. Mineral assemblage encountered in albite-epidote hornfels facies rocks. Observed associations include Cc + Tr, and Cc + Do + Tr. Dot represents chemical analysis of sample from 3,750 ft.

Fig. 3c. Mineral assemblages encountered in hornblende hornfels facies rocks. Observed associations include Cc + Fo, Cc + Fo + Di, Cc + Di, Q + Di, Q + Wo, Cc + Wo + Di, Cc + Wo, and Cc + Q + Wo. Dots indicate chemical compositions of the two analyzed samples from 2,360 ft and 2,460 ft.

FIGURE 3—CaO-MgO-SiO_2 DIAGRAM OF SILICEOUS CARBONATE ROCKS FROM KCM WELL. See text for explanation of letter symbols used and table 3 for chemical analyses.

in thin sections, the association of Tr + Cc has been found at depths of 2,010 ft and 3,780 ft. According to Slaughter, Kerrick, and Wall (1975), the temperature range of the above reaction is from 410°C to 450°C.

Diopside can be produced by several different metamorphic reactions. Two possible ones are:

$$1Do + 2Q = 1Di + 2CO_2$$

$$1Tr + 3Cc + 2Q = 5Di + 3CO_2 + 1H_2O$$

The resulting associations are Tr + Cc + Di and Cc + Q + Di. The association Tr + Q + Di can only occur in rocks that contain magnesite prior to metamorphism.

The following mineral associations with diopside have been observed in thin section:

Cc + Di, in samples from 2,360 ft, 2,820 ft and 3,380 ft
Q + Di, in samples from 3,380 ft and 4,040 ft Tr +
Cc + Di, in the sample from 3,780 ft.

The reactions that form diopside also depend on the composition of the fluid phase. Such a reaction with tremolite, calcite, and quartz results in the formation of CO_2 and H_2O in a molar ratio of 3:1, and the reaction will therefore have a temperature maximum for a mole fraction of CO_2 in the fluid phase (X_{co2}) = 0.75. The temperature range of the above reactions is between 440°C and 490°C.

Forsterite may result from the reaction:

$$1Tr + 11Di = 8\ Fo + 13\ Cc + 9\ CO_2 + 1\ H_20$$

Possible mineral associations resulting from this reaction are Tr + Fo + Cc and Di + Fo + Cc. The association forsterite and calcite has been observed in the sample from 3,680 ft. The above reaction also is sensitive to the composition of the fluid phase; a maximum temperature will occur at $X_{CO2} = 0.9$. Temperatures of 500°C to 550°C are indicated from the experimentally determined stability curve of this reaction (fig. 4).

Whether forsterite forms prior to diopside or vice versa is not clear from the observed mineral associations. Many published accounts of contact metamorphic aureoles in limestone describe the former relationship (Tilley, 1951). Skippen (1974) has found that above a fluid pressure of 3 kilobars, forsterite can develop at large X_{CO2} before tremolite plus calcite plus quartz react to form diopside. At lower pressures diopside can form before forsterite. However, the data on forsterite stabilities in siliceous dolomitic limestone are contradictory at present; additional experimental investigations are needed to clarify this point.

Wollastonite is the product of the reaction:

$$1\ Cc + 1\ Q = 1\ Wo\ 1\ CO2$$

This reaction becomes bivariant if the diluting effect of pore water is considered. At a constant fluid pressure, the equilibrium temperature increases with increasing X_{CO2}. Greenwood (1967) has determined equilibrium temperatures for this reaction for a total fluid pressure of 1 kilobar. The equilibrium temperature ranges from 530°C to 670°C, with increasing X_{CO2}. Wollastonite occurs in samples ranging from 2,360 ft to 3,680 ft, representing a difference in load pressure of several hundred bars. This circumstance, combined with differences in X_{CO2} during metamorphism at different levels in the rock column, indicates that possibly univariant conditions were present in that interval. The equilibrium association of calcite, quartz, and wollastonite is indeed encountered in the sample from 2,360 ft.

SUMMARY—The sedimentary rocks in the KCM well have been intruded by igneous rocks ranging from quartz monzonite to quartz latite. The mineral associations are characteristic of medium- to high-grade metamorphism (Winkler, 1974). In terms of metamorphic facies, mineral associations in the metamorphic rocks indicate the presence of the albite-epidote hornfels facies, the hornblende hornfels facies, and possibly the pyroxene hornfels facies.

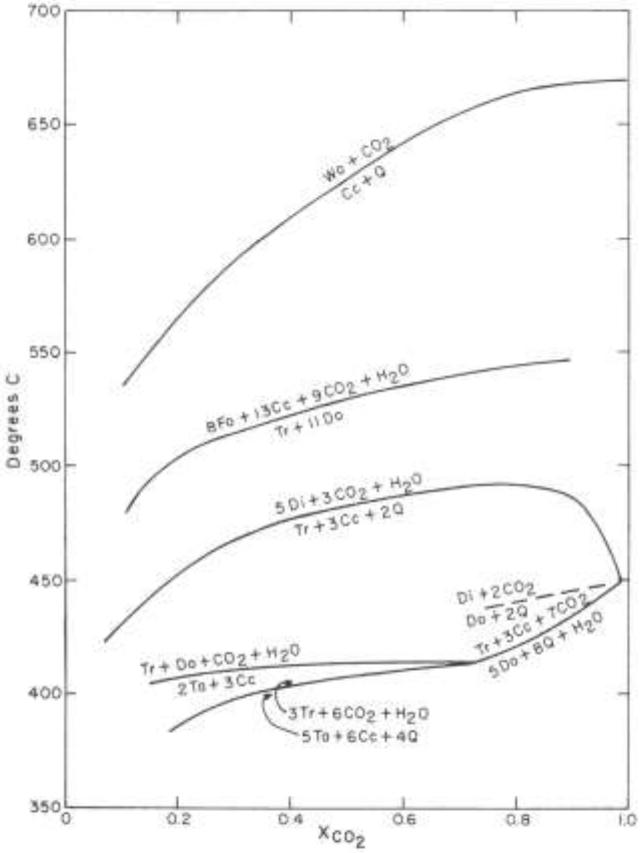

FIGURE 4—ISOBARIC SECTION AT FLUID PRESSURE = 1 KILOBAR FOR METAMORPHIC REACTIONS INVOLVING CaO, MgO, SiO_2, CO_2, AND H_2O. Equilibrium curves after Greenwood (1967), and Slaughter and others (1975). Temperature is given in degrees Celsius on the ordinate, and mole fraction of CO_2 in the fluid phase (X_{CO_2}) is given on the abcissa. See text for abbreviations of minerals.

REFERENCES

Greenwood, H. J., 1967, Wollastonite: stability in H_2O-CO_2 mixtures and occurrence in a contact-metamorphic aureole near Salmo, British Columbia, Canada: Am. Min., v. 52, p. 1669-1680

Press, Frank, 1966, Seismic velocities, *in* Clark, S. P., Jr., ed., Handbook of physical constants: Geol. Soc. America, Mem. 97

Skippen, George. 1974, An experimental model for low pressure metamorphism of siliceous dolomitic marble: Am. Jour. Science, v. 274, p. 487-509

Slaughter, J., Kerrick, D. M., and Wall, V. J., 1975, Experimental and thermodynamic study of equilibria in the system CaO-MgO-SiO_2 H_2O-CO_2: Am. Jour. Science, v. 275, p. 143-162

Tilley, F. J., 1951, A note on the progressive metamorphism of siliceous limestones and dolomites: Geol. Mag., v. 88, p. 175-178

Tuttle, O. F., and Bowen. N. L., 1958, Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$-$KAlSi_3O_8$¯SiO_2-H_2,O: Geol. Soc. America, Mem. 74, 153 p.

Winkler, H. G. F., 1974, Petrogenesis of metamorphic rocks: 3rd edition, New York, Springer-Verlag, 320 p.

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

ORGANIC GEOCHEMICAL ANALYSES

of Drill Cuttings from KCM No. 1 Forest Federal Well, Hidalgo County, New Mexico

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ABSTRACT

The stratigraphic section penetrated by the KCM No. 1 Forest Federal well in Hidalgo County, New Mexico, is subdivided into two organic geochemical zones based on the amounts of light hydrocarbon gases (C_1-C_7) and on the percentages of organic carbon in samples of drill cuttings. This geochemical zonation is determined independently of the stratigraphic units.

Zone A, from a depth of 80 ft (or above) to about 1,850 ft, consists of Permian and Pennsylvanian mudstones and limestones with an overall poor to fair rating for the generation of hydrocarbons; these source rocks are thermally very mature. The source potential for oil is poor to fair, for wet gas (with condensate) is very poor, and for dry gas (without condensate) is poor to fair. The samples from Zone A contain near-zero amounts of wet gas (C_2-C_4) and gasoline-range hydrocarbons (C_5-C_7), and poor to fair percentages of organic carbon (0.10% to 0.95%, mean 0.42%). In Subzone A_1 from 80 ft to 1,450 ft, two samples from 1,310 ft and 1,400 ft contain fair amounts (476 ppm and 912 ppm, mean 694 ppm) of C_{15+} solvent-extractable bitumen, and fair to good amounts (118 ppm and 278 ppm, mean 198 ppm) of C_{15+} total hydrocarbons in the extract. Subzone **A2** from 1,450 ft to 1,850 ft contains poor to very poor amounts of C_{15+} bitumen and total hydrocarbons. Woody and coaly types of kerogen predominate in Zone A and indicate a gas-prone source; the oil-prone amorphous-sapropelic kerogen is secondary.

Zone B, from a depth of about 1,850 ft to 4,464 ft (total depth), consists of limestones that are increasingly recrystallized down to 2,255 ft, and a complex of marbles, hornfelses, and Tertiary plutonic intrusives from 2,255 ft to total depth. These varied rock types have experienced a very mature to metamorphic thermal history and are not considered to be sources of oil or gas. This poor source rating is evidenced by extremely low amounts of wet gas (C_2-C4), gasoline-range hydrocarbons (C_5-C_7), and total organic carbon in the Pennsylvanian sedimentary and metamorphic rocks. Geochemical evidence at hand is inconclusive regarding whether the hydrocarbon source ratings of both Zones A and B were much better prior to metamorphism.

INTRODUCTION

Organic geochemical analyses were run on samples of drill cuttings from the KCM No. 1 Forest Federal well located in Hidalgo County, New Mexico. The purpose of these analyses was to:

1) Investigate the richness, type (gas, condensate, or oil), and state of thermal maturity of the hydrocarbon source rocks, and to determine their stratigraphic distribution within the sequence penetrated by the KCM well

2) Characterize geochemical zones within the stratigraphic section of this well as a basis for any subsequent correlations of crude oil to source rock that may be required in the future

3) Evaluate the exploration significance of the results with respect to future drilling in the local area of this KCM well, and with respect to regional exploration.

This paper summarizes the results of three studies requested by Sam Thompson Ill of the New Mexico Bureau of Mines and Mineral Resources. The initial study was of 24 samples of canned cuttings collected at the wellsite from depths of 1,310 ft to 4,400 ft (sample Nos. 528-001 through -024, table 1). One followup study was requested for further analyses of selected samples below 1,800 ft; the other was requested for analyses of uncanned cuttings from depths above 1,300 ft (sample Nos. 723-001 through -011, table 2).

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ANALYTICAL PROCEDURE

The light hydrocarbon gas (C1-C7) content of all 24 cans of drill cuttings from 1,310 ft to 4,400 ft was determined by analyzing both a sample of the cuttings and the air space at the top of each can (tables la, lb and lc; fig. 1). The cuttings were washed, dried, and individually picked to exclude any obvious cavings. The picked cuttings from all 24 samples were analyzed for richness of organic carbon (table 2; fig. 2). Using these data only 6 samples were selected for more detailed organic geochemical analyses. The analyses performed on samples ranging in depth from 1,310 ft to 1,800 ft (samples Nos. 528-001 thorugh -006) included C15+ soxhlet extraction, deasphaltening, and quantitative liquid chromatography (tables 3a, 3b, and 3c; fig. 2); paraffin-naphthene (P-N) analyses by gas chromatography (table 4; fig. 3); and visual assessment of kerogen and degree of maturation (tables 2 and 5; fig. 2).

At Thompson's suggestion, 5 additional samples from 1,900 ft to 3,600 ft (sample Nos. 528-007, -008, -015, -019, -020) were analyzed for visual assessment of kerogen and degree of maturation, but these results were considered unreliable because of the very low organic carbon content. Uncanned drill cuttings from depths above 1,300 ft (sample Nos. 723-001 through -011) were also analyzed for organic carbon content and visual kerogen type and degree of maturation. The

TABLE 1—C_1-C_7 HYDROCARBON ANALYSES OF AIR SPACE AND CUTTINGS GAS. Values in ppm are volumes of gas per million volumes of cuttings; dash indicates 0.0.

A. C_1-C_7 Hydrocarbon Analyses of Air Space

GeoChem Sample Number	Well Depth (feet)	Methane C_1 ppm	Ethane C_2 ppm	Propane C_3 ppm	Isobutane iC_4 ppm	Butane nC_4 ppm	Total C_5-C_7 ppm	Total C_1-C_4 ppm	Total C_2-C_4 ppm	Gas Wetness %	iC_4/nC_4
528-001	1310	54.3	9.4	2.2	-	-	7.7	66.0	11.6	17.6	-
528-002	1400	461.0	15.6	3.6	-	3.6	13.4	483.9	22.8	4.7	-
528-003	1500	205.2	7.3	4.0	-	-	2.7	216.6	11.4	5.2	-
528-004	1600	7094.5	8.5	7.7	-	-	2.0	7110.9	16.3	0.2	-
528-005	1700	3271.5	-	5.7	-	-	0.7	3277.2	5.7	0.1	-
528-006	1800	44.8	5.9	4.3	-	-	1.7	55.0	10.2	18.6	-
528-007	1900	246.2	16.4	9.8	60.6	-	32.6	333.1	86.9	26.0	-
528-008	2000	420.1	165.9	106.7	54.1	-	52.3	747.0	326.8	43.7	-
528-009	2200	209.6	45.1	28.5	18.0	-	23.9	301.4	91.7	30.4	-
528-010	2300	265.9	40.5	33.2	21.7	-	30.5	361.4	95.4	26.4	-
528-011	2400	5172.5	17.3	21.7	32.4	-	20.6	5244.1	71.5	1.3	-
528-012	2500	56.2	19.5	12.3	27.8	-	14.0	116.0	59.7	51.5	-
528-013	2600	48.6	10.4	9.9	14.3	-	6.8	83.3	34.7	41.6	-
528-014	2700	52.6	11.6	10.0	3.3	-	16.5	77.7	25.1	32.3	-
528-015	2900	89.1	24.6	20.0	12.3	22.6	-	168.8	79.7	47.2	0.54
528-016	3000	62.2	15.8	14.9	11.8	-	36.9	104.9	42.7	40.6	-
528-017	3100	211.0	78.8	39.9	14.1	-	15.8	343.9	132.9	38.6	-
528-018	3200	130.2	43.0	41.8	10.3	-	37.8	225.5	95.2	42.2	-
528-019	3400	82.8	23.2	14.9	25.5	-	11.4	146.5	63.7	43.4	-
528-020	3600	124.6	29.6	18.8	5.2	-	14.1	178.4	53.8	30.1	-
528-021	3800	69.8	18.0	24.1	11.5	-	2.4	123.4	53.6	43.4	-
528-022	4000	59.8	20.9	10.9	-	6.4	31.2	98.2	38.4	39.1	-
528-023	4300	72.6	24.7	17.9	15.8	-	7.9	131.2	58.5	44.6	-
528-024	4400	89.9	64.1	20.5	6.8	5.0	48.3	186.5	96.6	51.8	1.35

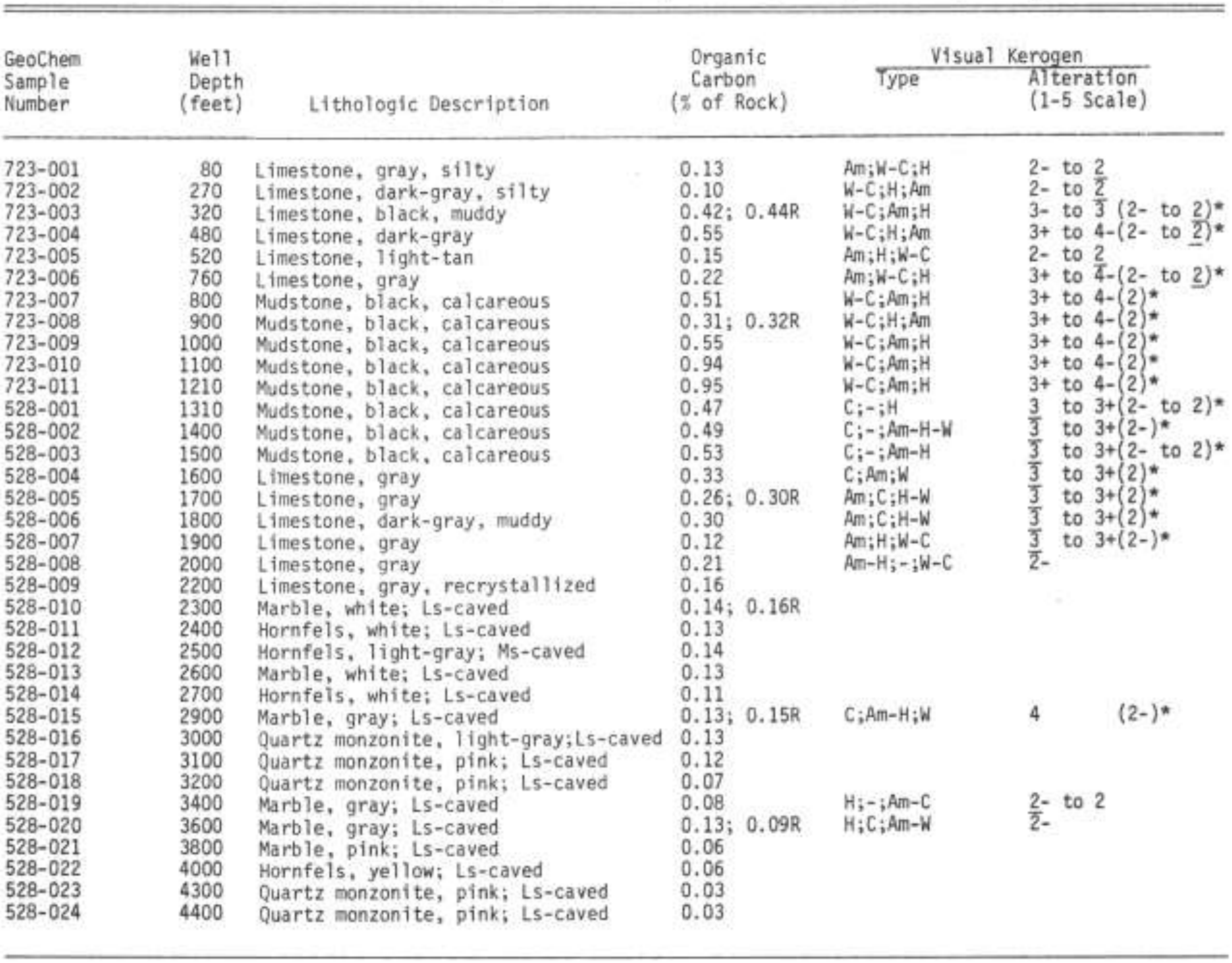
B. C_1-C_7 Hydrocarbon Analyses of Cuttings Gas

528-001	1310	369.7	5.7	3.7	3.4	-	-	382.7	13.0	3.4	-
528-002	1400	543.7	11.7	4.9	2.3	-	-	562.7	18.9	3.3	-
528-003	1500	366.7	10.2	3.6	-	-	2.4	380.6	13.9	3.6	-
528-004	1600	241.5	4.8	2.6	0.9	-	2.2	249.9	8.4	3.3	-
528-005	1700	225.7	6.6	3.5	-	-	2.0	236.0	10.2	4.3	-
528-006	1800	214.3	8.0	3.8	-	1.9	0.9	228.2	13.8	6.0	-
528-007	1900	254.7	9.2	2.7	1.2	-	13.9	268.0	13.2	4.9	-
528-008	2000	320.0	7.9	2.4	-	-	1.1	330.4	10.3	3.1	-
528-009	2200	288.0	8.8	2.7	-	1.2	1.9	300.8	12.7	4.2	-
528-010	2300	230.8	4.6	1.6	0.7	1.0	-	239.0	8.2	3.4	0.70
528-011	2400	144.4	2.9	1.4	0.7	-	2.4	149.6	5.2	3.4	-
528-012	2500	139.0	5.9	2.7	2.4	-	11.4	150.1	11.1	7.3	-
528-013	2600	126.7	3.4	10.8	2.9	-	42.8	143.9	17.2	11.9	-
528-014	2700	173.0	6.9	5.9	1.4	-	0.2	187.4	14.4	7.6	-
528-015	2900	174.8	8.4	5.6	0.2	0.8	18.8	189.9	15.1	7.9	0.27
528-016	3000	203.2	6.8	2.2	-	0.3	0.1	212.6	9.3	4.4	-
528-017	3100	251.5	4.3	4.7	-	3.2	85.6	263.9	12.3	4.6	-
528-018	3200	58.4	1.8	4.2	-	2.7	-	67.3	8.8	13.2	-
528-019	3400	188.9	2.8	2.1	-	-	22.3	193.9	5.0	2.5	-
528-020	3600	355.7	3.1	4.0	-	1.7	0.1	364.6	8.9	2.4	-
528-021	3800	229.0	5.6	5.1	-	2.3	1.2	242.2	13.1	5.4	-
528-022	4000	27.2	1.9	4.1	-	-	-	33.3	6.0	18.2	-
528-023	4300	33.4	1.2	0.6	-	-	-	35.3	1.9	5.4	-
528-024	4400	22.9	3.7	4.6	1.7	-	8.2	33.1	10.2	30.8	-

C. C_1-C_7 Hydrocarbon Analyses of Air Space and Cuttings Gas

528-001	1310	424.0	15.2	5.9	3.4	-	7.7	448.7	24.7	5.5	-
528-002	1400	1004.8	27.3	8.5	2.3	3.6	13.4	1046.6	41.8	3.9	0.63
528-003	1500	571.9	17.6	7.7	-	-	5.2	597.2	25.3	4.2	-
528-004	1600	7336.1	13.4	10.4	0.9	-	4.2	7360.8	24.7	0.3	-
528-005	1700	3497.2	6.6	9.2	-	-	2.8	3519.2	15.9	0.4	-
528-006	1800	259.1	14.0	8.1	-	1.9	2.6	283.2	24.1	8.5	-
528-007	1900	501.0	25.6	12.5	62.9	-	46.6	602.1	101.1	16.8	-
528-008	2000	740.1	173.8	109.2	54.1	-	53.5	1077.4	337.2	31.3	-
528-009	2200	497.7	53.9	31.2	18.0	1.2	25.8	602.1	104.4	17.3	14.76
528-010	2300	496.8	45.1	34.9	22.4	1.0	30.6	600.4	103.6	17.2	20.79
528-011	2400	5316.9	20.3	23.1	33.2	-	23.0	5393.6	76.7	1.4	-
528-012	2500	195.3	25.4	15.1	30.2	-	25.5	266.2	70.8	26.6	-
528-013	2600	175.3	13.9	20.8	17.2	-	49.7	227.2	51.9	22.8	-
528-014	2700	225.6	18.6	16.0	4.8	-	16.8	265.2	39.5	14.9	-
528-015	2900	263.9	33.0	25.6	12.5	23.5	18.8	358.7	94.8	26.4	0.53
528-016	3000	265.5	22.7	17.1	11.8	0.3	37.0	317.6	52.0	16.4	37.15
528-017	3100	462.5	83.1	44.7	14.1	3.2	101.4	607.8	145.3	23.9	4.31
528-018	3200	188.6	44.9	46.1	10.3	2.7	37.8	292.8	104.1	35.5	3.83
528-019	3400	271.7	26.1	17.0	25.5	-	33.8	340.4	68.7	20.1	-
528-020	3600	480.3	32.8	22.9	5.2	1.7	14.2	543.0	62.7	11.5	3.03
528-021	3800	298.8	23.7	29.2	11.5	2.3	3.6	365.7	66.8	18.2	5.01
528-022	4000	87.0	22.9	15.0	-	6.4	31.2	131.5	44.5	33.8	-
528-023	4300	106.1	26.0	18.6	15.8	-	7.9	166.5	60.4	36.3	-
528-024	4400	112.8	67.9	25.1	8.6	5.0	56.6	219.7	106.8	48.6	1.71

TABLE 2—SUMMARY OF ORGANIC CARBON CONTENT AND VISUAL KEROGEN ANALYSES. Sample Nos. 723-001 through -011 and lithologic description furnished by Thompson; R indicates repeated analysis of organic carbon percentage.



GeoChem Sample Number	Well Depth (feet)	Lithologic Description	Organic Carbon (% of Rock)	Visual Kerogen	
				Type	Alteration (1-5 Scale)
723-001	80	Limestone, gray, silty	0.13	Am;W-C;H	2- to $\underline{2}$
723-002	270	Limestone, dark-gray, silty	0.10	W-C;H;Am	2- to $\overline{2}$
723-003	320	Limestone, black, muddy	0.42; 0.44R	W-C;Am;H	3- to $\overline{3}$ (2- to $\underline{2}$)*
723-004	480	Limestone, dark-gray	0.55	W-C;H;Am	3+ to 4-(2- to $\underline{2}$)*
723-005	520	Limestone, light-tan	0.15	Am;H;W-C	2- to $\underline{2}$
723-006	760	Limestone, gray	0.22	Am;W-C;H	3+ to $\overline{4}$-(2- to $\underline{2}$)*
723-007	800	Mudstone, black, calcareous	0.51	W-C;Am;H	3+ to 4-(2)*
723-008	900	Mudstone, black, calcareous	0.31; 0.32R	W-C;H;Am	3+ to 4-(2)*
723-009	1000	Mudstone, black, calcareous	0.55	W-C;Am;H	3+ to 4-(2)*
723-010	1100	Mudstone, black, calcareous	0.94	W-C;Am;H	3+ to 4-(2)*
723-011	1210	Mudstone, black, calcareous	0.95	W-C;Am;H	3+ to 4-(2)*
528-001	1310	Mudstone, black, calcareous	0.47	C;-;H	$\underline{3}$ to 3+(2- to 2)*
528-002	1400	Mudstone, black, calcareous	0.49	C;-;Am-H-W	$\overline{3}$ to 3+(2-)*
528-003	1500	Mudstone, black, calcareous	0.53	C;-;Am-H	$\overline{3}$ to 3+(2- to 2)*
528-004	1600	Limestone, gray	0.33	C;Am;W	$\overline{3}$ to 3+(2)*
528-005	1700	Limestone, gray	0.26; 0.30R	Am;C;H-W	$\overline{3}$ to 3+(2)*
528-006	1800	Limestone, dark-gray, muddy	0.30	Am;C;H-W	$\overline{3}$ to 3+(2)*
528-007	1900	Limestone, gray	0.12	Am;H;W-C	$\overline{3}$ to 3+(2-)*
528-008	2000	Limestone, gray	0.21	Am-H;-;W-C	$\overline{2}$-
528-009	2200	Limestone, gray, recrystallized	0.16		
528-010	2300	Marble, white; Ls-caved	0.14; 0.16R		
528-011	2400	Hornfels, white; Ls-caved	0.13		
528-012	2500	Hornfels, light-gray; Ms-caved	0.14		
528-013	2600	Marble, white; Ls-caved	0.13		
528-014	2700	Hornfels, white; Ls-caved	0.11		
528-015	2900	Marble, gray; Ls-caved	0.13; 0.15R	C;Am-H;W	4 (2-)*
528-016	3000	Quartz monzonite, light-gray;Ls-caved	0.13		
528-017	3100	Quartz monzonite, pink; Ls-caved	0.12		
528-018	3200	Quartz monzonite, pink; Ls-caved	0.07		
528-019	3400	Marble, gray; Ls-caved	0.08	H;-;Am-C	$\underline{2}$- to 2
528-020	3600	Marble, gray; Ls-caved	0.13; 0.09R	H;C;Am-W	$\overline{2}$-
528-021	3800	Marble, pink; Ls-caved	0.06		
528-022	4000	Hornfels, yellow; Ls-caved	0.06		
528-023	4300	Quartz monzonite, pink; Ls-caved	0.03		
528-024	4400	Quartz monzonite, pink; Ls-caved	0.03		

* Secondary population of less altered kerogen

KEROGEN KEY

Predominant;Secondary;Trace
60-100% 20-40% 1-20%

Al = Algal
Am = Amorphous-Sapropel
H = Herbaceous-Spore/Cuticle
W = Woody
C = Coaly
U = Unidentified material

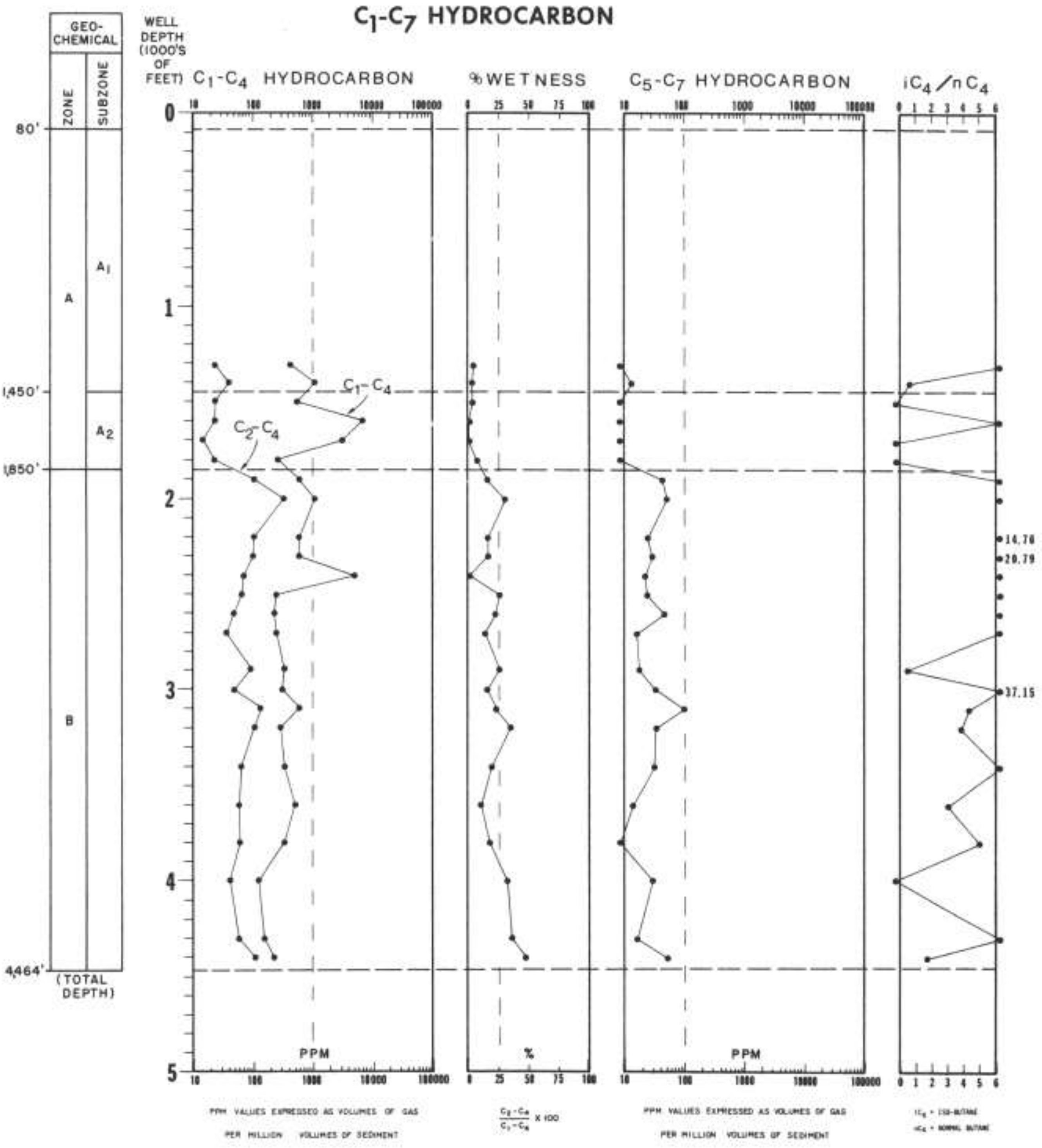


FIGURE 1—Well profile of C_1-C_7 hydrocarbons from canned cuttings.

[New Mexico Bureau Mines & Mineral Resources, Circular 152, 1977]

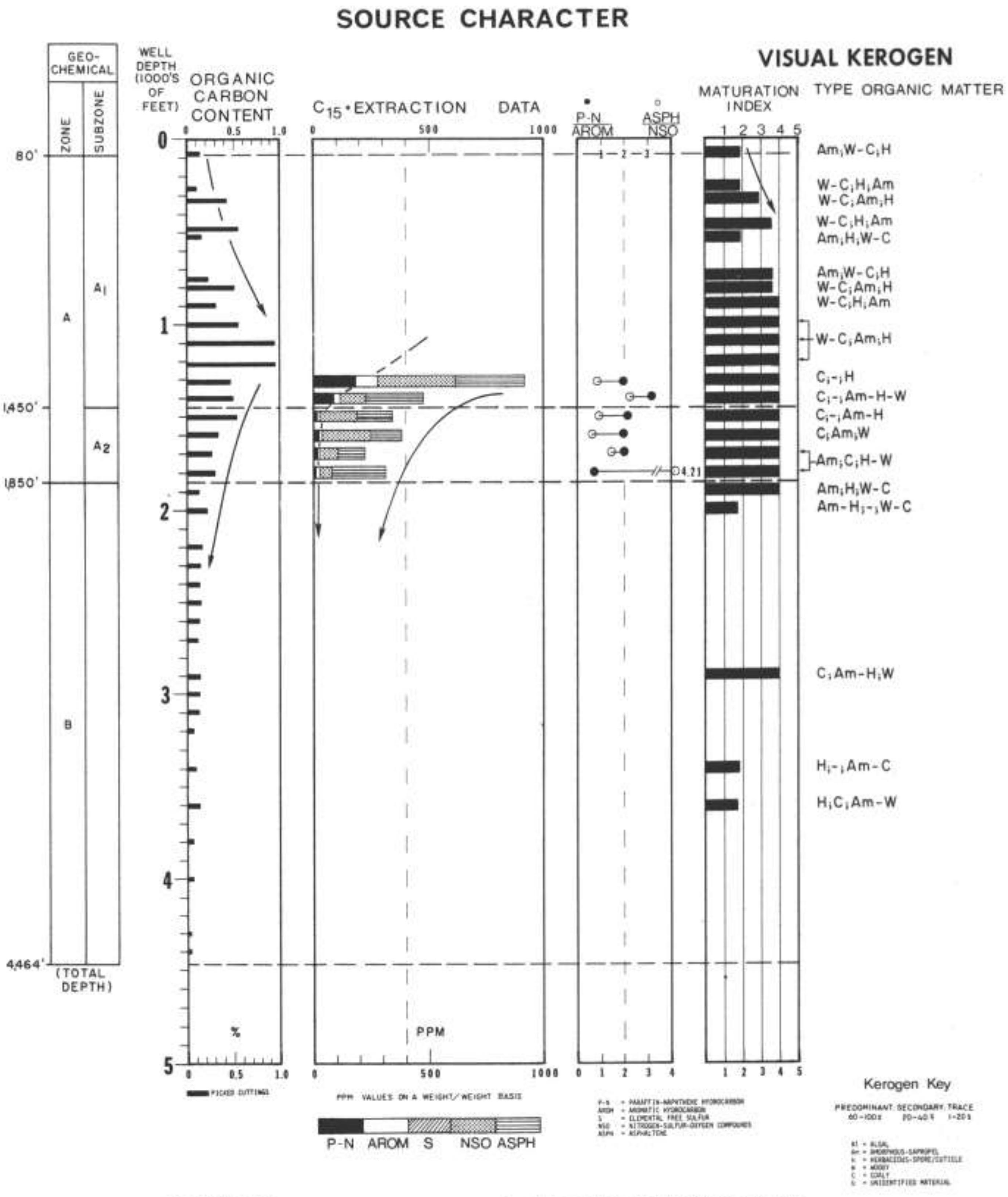


FIGURE 2—Well profile of organic carbon, C_{15+} extraction, and visual kerogen data.

TABLE 3—SUMMARY OF C_{15+} SOXHLET EXTRACTION, DEASPHALTENING, AND LIQUID CHROMATOGRAPHY. Values in ppm are on a weight/weight basis; dash indicates 0.0.

A. Weights of Extracts and Chromatographic Fractions

						Weight of Chromat. Fractions				
GeoChem Sample Number	Well Depth (feet)	Weight of Rock Extd. (grams)	Total Extracts (grams)	Precipitated Asphaltenes (grams)	n-C_5 Soluble (grams)	Sulfur (grams)	Paraffin-Naphthenes (grams)	Aromatics (grams)	Eluted NSO's (grams)	Noneluted NSO's (grams)
528-001	1310	100.0	0.0912	0.0292	0.0620	-	0.0184	0.0094	0.0031	0.0311
528-002	1400	100.0	0.0476	0.0249	0.0227	-	0.0090	0.0028	0.0015	0.0094
528-003	1500	100.0	0.0343	0.0152	0.0191	-	0.0017	0.0008	0.0014	0.0152
528-004	1600	100.0	0.0381	0.0135	0.0246	-	0.0026	0.0013	0.0013	0.0194
528-005	1700	100.0	0.0222	0.0114	0.0108	-	0.0020	0.0010	0.0008	0.0070
528-006	1800	100.0	0.0311	0.0232	0.0079	-	0.0010	0.0014	0.0010	0.0045

B. Concentration of Extracted Materials in Rock

			Hydrocarbon			Nonhydrocarbon				
GeoChem Sample Number	Well Depth (feet)	Total Extract (ppm)	Paraffin Naphthene (ppm)	Aromatic (ppm)	TOTAL (ppm)	Sulfur (ppm)	Preciptd. Asphaltene (ppm)	Eluted NSO's (ppm)	Noneluted NSO's (ppm)	TOTAL (ppm)
528-001	1310	912	184	94	278	-	292	31	311	634
528-002	1400	476	90	28	118	-	249	15	94	358
528-003	1500	343	17	8	25	-	152	14	152	318
528-004	1600	381	26	13	39	-	135	13	194	342
528-005	1700	222	20	10	30	-	114	8	70	192
528-006	1800	311	10	14	24	-	232	10	45	287

C. Composition of Extracts

		Hydrocarbon			Nonhydrocarbon						
GeoChem Sample Number	Well Depth (feet)	Paraffin Naphthene %	Aromatic %	PN/AROM	Sulfur %	Eluted NSO's %	Noneluted NSO's %	Precipitd. Asphaltene %	Asph/ NSO	HC's %	HC/non HC %
528-001	1310	20.2	10.3	1.96	-	3.4	34.1	32.0	0.85	30.5	0.43
528-002	1400	18.9	5.9	3.20	-	3.2	19.7	52.3	2.28	24.8	0.32
528-003	1500	5.0	2.3	2.17	-	4.1	44.3	44.3	0.91	7.3	0.07
528-004	1600	6.8	3.4	2.00	-	3.4	50.9	35.4	0.65	10.2	0.11
528-005	1700	9.0	4.5	2.00	-	3.6	31.5	51.4	1.46	13.5	0.15
528-006	1800	3.2	4.5	0.71	-	3.2	14.5	74.6	4.21	7.7	0.08

organic carbon data and kerogen assessments are presented in tables 2 and 5, and are illustrated in fig. 2.

RESULTS AND INTERPRETATIONS

Stratigraphic Zonation

A detailed log of the KCM No. 1 Forest Federal well, describing the stratigraphic units, the lithologic column, the depositional environments, and the petroleum source and reservoir units, is presented by Thompson (this circular). Generally, the well penetrated Permian and Pennsylvanian sedimentary rocks down to 2,255 ft, and a complex of Pennsylvanian metamorphic rocks and Tertiary plutonic intrusives from 2,255 ft to the total depth of 4,464 ft.

Geochemical Zonation

The stratigraphic section penetrated by the KCM well is subdivided into two geochemical zones based on the amounts of light hydrocarbon gases (C_1-C_7) and on the percentages of organic carbon in samples of canned and uncanned drill cuttings. This geochemical zonation, determined independently of the stratigraphic units, is shown below (depths are approximate):

	From	To
Zone A	80 ft	1,850 ft
Subzone A_1	80 ft	1,450 ft
Subzone A_2	1,450 ft	1,850 ft
Zone B	1,850 ft	4,464 ft (Total Depth)

ZONE A

Zone A, which may begin above the first sample at 80 ft and extends down to about 1,850 ft (between the samples at 1,800 ft and 1,900 ft), consists of Permian and Pennsylvanian mudstones and limestones with an overall poor to fair rating for the generation of hydrocarbons. These source rocks are thermally mature to very mature.

TABLE 4—C_{15+} PARAFFIN-NAPHTHENE (P-N) HYDROCARBON ANALYSES EXPRESSED IN PERCENT. Paraffin distribution is normalized; Sample Nos. 528-001 through -006; well depth (feet); dash indicates 0.0.

C_{15+} (n, Normal paraffin; i, Isoprenoid)	Normalized Paraffin Distribution (%)					
	No. 528-001 (1,310')	No. 528-002 (1,400')	No. 528-003 (1,500')	No. 528-004 (1,600')	No. 528-005 (1,700')	No. 528-006 (1,800')
nC_{15}	4.4	3.9	8.4	2.3	3.1	3.2
nC_{16}	6.2	4.8	7.7	4.9	4.7	5.2
nC_{17}	6.4	5.5	7.3	4.8	4.5	3.6
$ip\text{-}C_{19}$	5.6	4.3	5.5	3.9	3.5	5.3
nC_{18}	8.1	5.6	5.9	4.7	4.0	6.2
$ip\text{-}C_{20}$	5.4	4.1	3.6	2.8	2.5	3.9
nC_{19}	9.4	6.7	4.0	4.1	3.8	4.1
nC_{20}	10.6	7.5	3.3	3.9	3.5	3.1
nC_{21}	9.4	7.2	3.4	4.5	3.7	4.1
nC_{22}	7.7	8.1	6.7	9.1	8.4	9.9
nC_{23}	7.7	9.9	10.9	14.5	15.5	14.8
nC_{24}	4.4	9.4	11.0	15.1	17.1	15.3
nC_{25}	5.0	7.4	8.8	11.9	13.2	10.3
nC_{26}	3.1	5.6	5.3	7.4	7.4	5.8
nC_{27}	3.3	4.3	3.3	3.2	3.3	2.6
nC_{28}	1.4	2.4	1.5	1.3	0.8	0.8
nC_{29}	0.4	1.0	1.4	0.6	0.3	0.4
nC_{30}	0.6	1.2	0.7	0.1	-	0.2
nC_{31}	-	0.3	0.3	-	-	0.1
nC_{32}	-	-	-	-	-	0.1
nC_{33}	-	-	-	-	-	-
nC_{34}	-	-	-	-	-	-
nC_{35}	-	-	-	-	-	-
% Paraffin	3.90	5.24	9.38	9.25	10.90	15.53
% Isoprenoid	0.48	0.48	0.95	0.67	0.70	1.60
% Naphthene	95.60	94.27	89.66	90.07	88.39	82.85
CPI Index A	1.25	1.03	1.03	0.99	1.01	0.96
CPI Index B	1.29	1.05	1.28	1.21	1.33	1.27
$ip\text{-}C_{19}/ip\text{-}C_{20}$	1.03	1.04	1.48	1.36	1.38	1.35

Geochemical characteristics—Samples from Zone A are characterized by fair amounts of dry gas (C_1), near zero amounts of wet gas (C_2-C_4) and gasoline-range hydrocarbons (C_5-C_7), and by poor to fair amounts of organic carbon (0.10% to 0.95%, mean 0.42%) (tables 1 and 2, figs. 1 and 2). Within Zone A, Subzone A_1 from 80 ft to about 1,450 ft is characterized by fair amounts (476 ppm to 912 ppm, mean 694 ppm) of C_{15+} solvent-extractable bitumen (table 3, fig. 2), by fair to good amounts (118 ppm to 278 ppm, mean 198 ppm) of **C_{15+}** total hydrocarbons in the extract (table 3, fig. 2), by the predominance of heavy naphthenes in the Ci s+ paraffin-naphthene (P-N) fraction (table 4, fig. 3), and by the predominance of coaly and woody types of kerogen (tables 2 and 5, fig. 2). Subzone **A_2**, from about 1,450 ft to 1,850 ft, is characterized by poor amounts (222 ppm to 381 ppm, mean 314 ppm) of C_{15+} solvent-extractable bitumen, by very poor amounts (24 ppm to 39 ppm, mean 30 ppm) of C_{15+} total hydrocarbons in the extract, by mature paraffin and naphthene hydrocarbons (curves skewed toward the lower molecular weight fraction in fig. 3), and by predominant or secondary amounts of amorphous-sapropelic types of kerogen.

Thermal maturity—Several geochemical indicators may be used to determine the thermal history of a sedimentary section and to assess the maturation rank of hydrocarbon source rocks. The thermal maturation index, based on the work of Staplin (1969) and others, is determined from the coloration and preservation of the plant-cuticle and spore-pollen debris within the kerogen. Maturation indices range from Stage 1 at immaturity, indicated by light-greenish-yellow cuticle, to Stage 5 at maximum maturity, consistent with black cuticle and petrographic evidence of metamorphism.

The results from the kerogen assessment of the KCM well samples are shown in table 5. The shallowest two samples at 80 ft and 270 ft (Nos. 723-001 and -002) have an index of Stage 2- to 2 indicating a moderately immature thermal history (these samples are from the Permian Earp Formation, whereas those below are from the Permian-Pennsylvanian Horquilla Formation). The two slightly deeper samples at 320 ft and 480 ft (Nos. 723-003 and -004) have an index of Stage 3- to Stage 4- indicating a mature to very mature thermal history.

The anomalous sample at 520 ft (No. 723-005) suggests a less mature zone with a return to the 2- to 2 range; in fact, this immature kerogen found in samples from 320 ft to 1,800 ft may be explained by caving from above or by contamination from the drilling mud. Samples from 900 ft and 1,000 ft (Nos. 723-008 and -009) contain a post-Miocene pollen with an index of 2, obviously a contaminant.

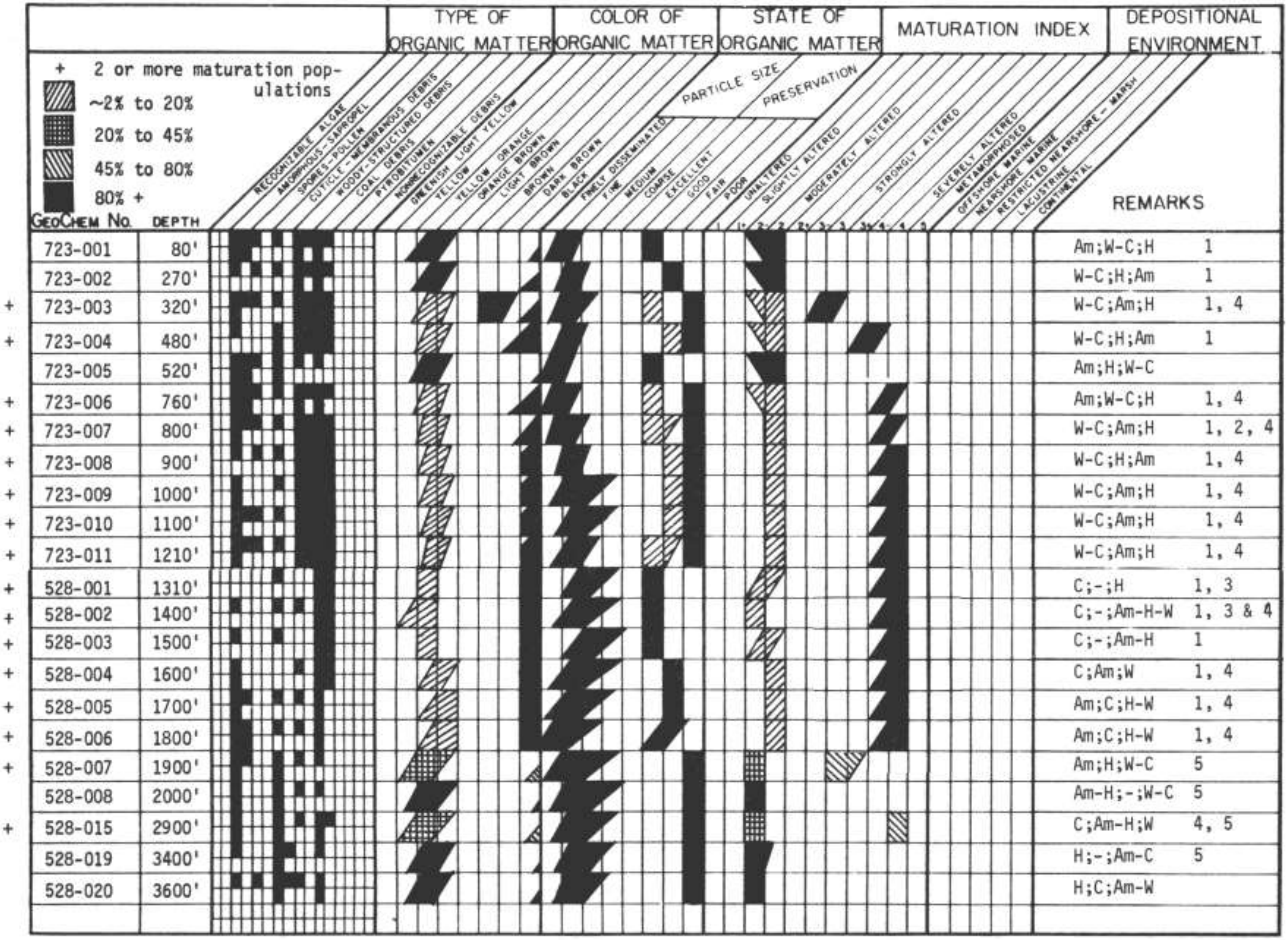
Most of Zone A has experienced a very mature thermal history as characterized by the dark-brown to black coloration of the cuticle from 760 ft to 1,800 ft (Nos. 723-006 to -011, and 528-001 to -006). This coloration is consistent with a thermal maturation index of Stage 4- to 4. The dark-brown and black colors are barely distinguishable, but the absence of metamorphism in this zone, as determined petrographically by Budding and Broadhead, precludes the assignment of an index of Stage 5. A mature history is indicated by the ratio of paraffin-naphthene to aromatic hydrocarbons ranging from 0.71 to 3.20, mean 2.01 (P-N/AROM, table 3c).

A predominance of odd-numbered over even-numbered normal paraffins in the **C_{23} to C_{33}** range of paraffin-naphthene hydrocarbons defines immaturity. With increased maturity and generation of hydrocarbons from the kerogens, the odd carbon preference will be masked and ultimately disappear. The odd or even carbon preference is computed as a carbon preference index (CPI Index B in table 4), which approaches 1.0 with increasing maturity (Bray and Evans, 1961, and Cernock, 1974). The CPI Index B for the heavier hydrocarbons extracted from the Zone A samples ranges from 1.05 to 1.33 and indicates a mature thermal history.

Hydrocarbon source evaluation—Overall, Zone A is given a poor to fair rating for the generation of petroleum-related hydrocarbons. The predominance of woody and coaly types of kerogen indicate a more gas-prone source, whereas the more oil-prone amorphous-sapropelic type of kerogen is present only in secondary amounts. Moreover, the very mature thermal history suggests that most of the oil initially generated would have been thermally degraded to methane gas.

The source potential for oil in Zone A is rated as poor to fair based mainly on the percentages of organic carbon (0.10% to 0.95% in mudstones and limestones) and the kerogen type. However, in Subzone A_1 from 80 ft to 1,450 ft, the two samples at 1,310 ft and 1,400 ft (in the deep-marine basin mudstones of the Horquilla Formation) contain fair to good amounts of C15+ bitumen and total hydrocarbons (table 3b), and repre-

TABLE 5—VISUAL KEROGEN ASSESSMENT WORKSHEET. Maturation index modified after Staplin (1969) and Burgess (personal communication). In Remarks column, letters denote kerogen type as per key in table 2. Numbers indicate: 1, mineral charcoal; 2, loss of circulation material; 3, walnut hulls; 4, relic amorphous; 5, sample data unreliable because of very little organic matter.



+ 2 or more maturation populations
▨ ~2% to 20%
▦ 20% to 45%
▧ 45% to 80%
■ 80% +

	GEOCHEM No.	DEPTH	REMARKS	
	723-001	80'	Am;W-C;H	1
	723-002	270'	W-C;H;Am	1
+	723-003	320'	W-C;Am;H	1, 4
+	723-004	480'	W-C;H;Am	1
	723-005	520'	Am;H;W-C	
+	723-006	760'	Am;W-C;H	1, 4
+	723-007	800'	W-C;Am;H	1, 2, 4
+	723-008	900'	W-C;H;Am	1, 4
+	723-009	1000'	W-C;Am;H	1, 4
+	723-010	1100'	W-C;Am;H	1, 4
+	723-011	1210'	W-C;Am;H	1, 4
+	528-001	1310'	C;-;H	1, 3
+	528-002	1400'	C;-;Am-H-W	1, 3 & 4
+	528-003	1500'	C;-;Am-H	1
+	528-004	1600'	C;Am;W	1, 4
+	528-005	1700'	Am;C;H-W	1, 4
+	528-006	1800'	Am;C;H-W	1, 4
+	528-007	1900'	Am;H;W-C	5
	528-008	2000'	Am-H;-;W-C	5
+	528-015	2900'	C;Am-H;W	4, 5
	528-019	3400'	H;-;Am-C	5
	528-020	3600'	H;C;Am-W	

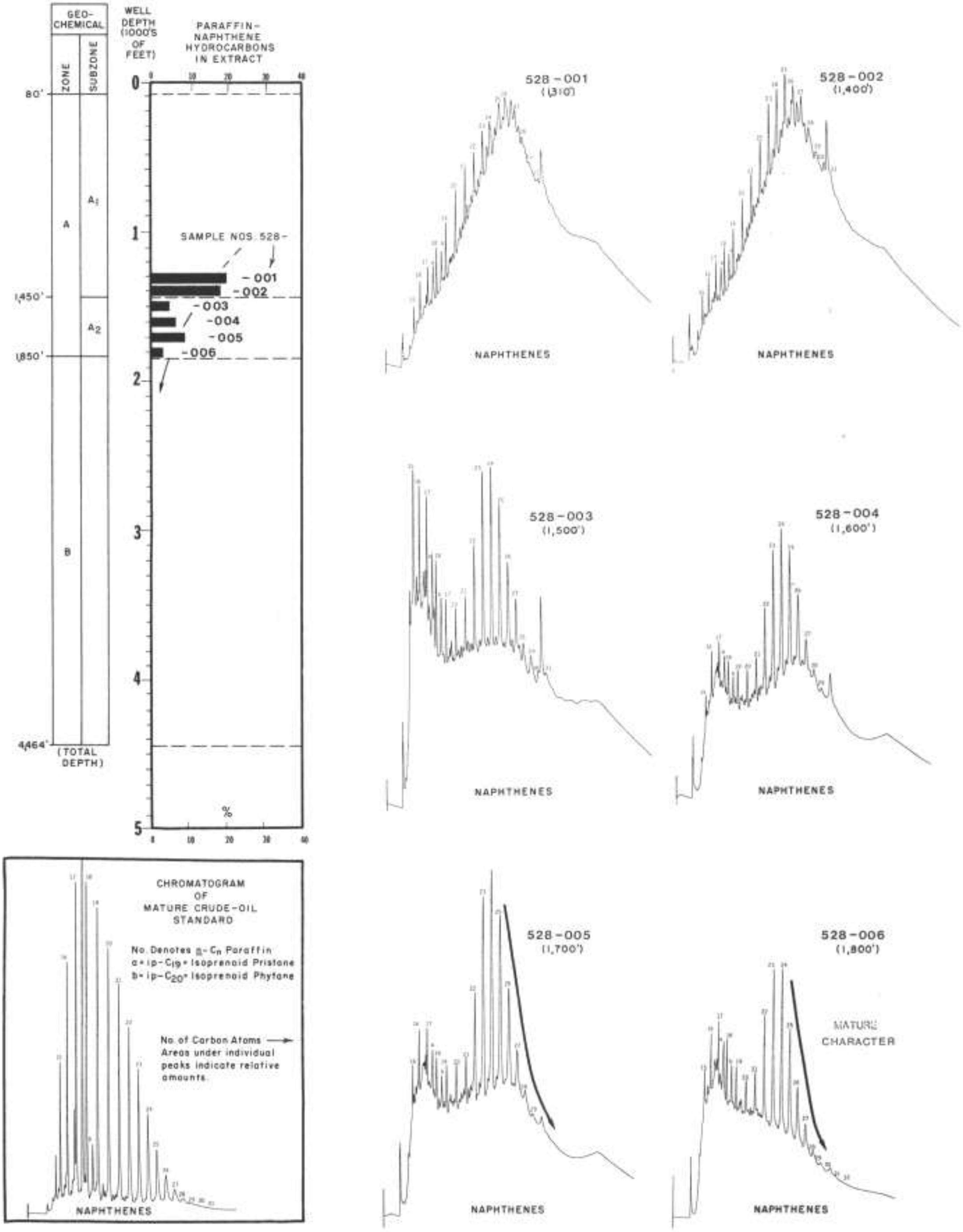


FIGURE 3—Chromatograms of C_{15+} paraffin-naphthene hydrocarbon fractions. Sample Nos. 528-001 through -006, well depth (feet).

[New Mexico Bureau Mines & Mineral Resources, Circular 152, 1977]

sent the best interval for possible oil generation in the KCM well. Additional C_{15+} analyses at shallower depths (up to the top of the basin mudstone at 706 ft) would help to determine the top of this possible oil-source unit. The analyses from Subzone A2 (from 1,450 ft to 1,850 ft) show poor to very poor amounts of C_{15+} bitumen and total hydrocarbons. These low values are below the base of this possible oil-source unit (the basal contact of the basin mudstone with the underlying limestone is at 1,526 ft).

Although the lower part of Subzone A_1 may be prospective for generating light gravity oil (based on the evidence above), the gas chromatographic analyses introduce some doubts regarding this evaluation. The chromatograms of the C_{15+} paraffin-naphthene (P-N) fractions isolated from the samples at 1,310 ft and 1,400 ft (Nos. 528-001 and 528-002, fig. 3), could be attributed to pipe-dope contamination, as well as to oil-in-place at these depths. Similarly, the chromatograms of the samples from 1,500 ft to 1,800 ft (Nos. 528-003 through -006) may represent cavings, drilling-mud additives, or an in-place, very mature type hydrocarbon.

The source potential for wet gas (with condensate) in Zone A is very poor, based on the lean amounts of C_2-C_4 and C_5-C_7 hydrocarbons (table 1). The source quality for dry gas (without condensate) is rated as poor to fair on the basis of lean to moderately rich quantities of methane (C_1, table 1c); the optimum interval is indicated by the samples at 1,600 ft to 1,700 ft (Nos. 528-004 and -005).

Subzone A_1 may have generated fair amounts of hydrocarbons in the area of the KCM well, but Subzone A_2 probably generated only poor amounts except for the minor source of dry gas around 1,600 ft to 1,700 ft. The general organic leanness (low average of 0.42% organic carbon) and the lack of oil precursor amorphous-sapropelic kerogens indicate that Zone A as a whole would not be a source for producible quantities of crude oil, but it could still be a source for producible quantities of natural gas.

ZONE B

Zone B begins about 1,850 ft (between samples at 1,800 ft and 1,900 ft), and extends to the total depth of the well at 4,464 ft (last sample at 4,400 ft). This zone consists of Pennsylvanian limestones which are increasingly recrystallized down to 2,255 ft, and a complex of Pennsylvanian marbles and hornfelses that were metamorphosed by Tertiary plutonic intrusives from 2,255 ft to total depth. These varied rock types, having experienced a very mature to metamorphic thermal history, are not considered as possible sources of significant amounts of oil or gas.

Geochemical characteristics-Samples of this zone are characterized by poor to fair amounts of dry gas (C_1), low amounts (generally less than 100 ppm) of wet gas (C_2-C_4) and gasoline-range hydrocarbons (C_5-C_7), and by very poor percentages of organic carbon (0.03% to 0.21%, mean 0.11%). These poor values discouraged further geochemical analyses.

The low values may represent minor cavings of limestone and mudstone from Zone A. The cuttings from 2,300 ft (No. 528-010, table 2) and below (dominantly white marbles, hornfelses, and quartz monzonites) probably contain little or no organic matter. Some of the darker marbles and the green hornfelses may have had significant amounts of organic carbon prior to metamorphism.

Thermal maturity-The very poor percentages of organic carbon suggest that the kerogen analyses of samples from Zone B (table 5, Nos. 528-007, -008, -015, -019, -020, at depths of 1,900 ft, 2,000 ft, 2,900 ft, 3,400 ft, and 3,600 ft) may not be valid. Moreover, the low maturation index of Stage 2- for several of these samples is inconsistent with the observed recrystallized limestones and metamorphic rocks shown on the log by Thompson. Most likely, this maturation rank represents the cavings and contaminants from the drilling mud. The very mature to metamorphosed thermal history of Zone B is based on the petrographic evidence presented by Budding and Broadhead.

Hydrocarbon source evaluation-Even if the geochemical characteristics indicated for Zone B are of the rocks-in-place (and not of the cavings or contaminants), the extremely low values would suggest a poor source of dry gas, and a very poor source of wet gas, condensate, or oil. The organic leanness alone (maximum of 0.21%) indicates that Zone B cannot be a source for commercially producible quantities of oil or gas in the local area of the KCM well.

EXPLORATION SIGNIFICANCE

Organic geochemical analyses show that the KCM No. 1 Forest Federal well penetrated two contrasting zones of hydrocarbon source rocks. Zone A (80 ft to 1,850 ft) contains poor to fair source rocks; Zone B (1,850 ft to 4,464 ft, total depth) contains very poor source rocks.

More specifically, the potential as a source for oil in Zone A is poor to fair, for wet gas (with condensate) is very poor, and for dry gas (without condensate) is poor to fair. Within Zone A, Subzone A_1 from 80 ft to 1,450 ft contains fair to possibly good source rocks for oil. The base of the unit having the best potential as a source for oil is at approximately 1,450 ft; the top is at least as high as 1,310 ft. The top may extend up to the top of the deep-marine mudstone unit (in this basin facies of the Horquilla Formation) at 706 ft, but additional C_{15+} analyses are needed to determine the top more accurately. Subzone A2 from 1,450 ft to 1,850 ft contains poor to very poor source rocks for oil.

The kerogens indicate that the source rocks of Zone A are more gas-prone than oil-prone. The very mature thermal history suggests that most of the oil initially generated would have been thermally degraded to methane gas.

In order of decreasing priority, the source objectives for exploration in the local area of the KCM well are:

1) Subzone A_1 (from 80 ft to 1,450 ft) may have generated commercial amounts of dry gas and minor amounts of mature oil and wet gas (with condensate), particularly from about 1,310 ft (up to 706 ft) to 1,450 ft.

2) Subzone A2 (from 1,450 ft to 1,850 ft) may have generated minor amounts of dry methane gas, particularly from 1,600 ft to 1,700 ft.

3) Zone B from 1,850 ft to 4,464 ft probably did not generate even minor amounts of oil, condensate, or gas.

The geochemical evidence at hand is inconclusive regarding whether the hydrocarbon source ratings of both Zones A and B were much better prior to metamorphism by the Tertiary plutons. When additional wells are evaluated at locations away from the effects of the plutonic intrusives, the source rating of Subzone A_1 may be upgraded significantly. Eventually a regional evaluation of the hydrocarbon sources in the frontier area around southwestern New Mexico may be compared to those of the Permian Basin of southeastern New Mexico and western Texas. In addition, the hydrocarbon sources of other producing Paleozoic basins may also be compared, such as those described in the Williston Basin by Dow (1974) and in the Western Canada Basin by Bailey and others (1974).

REFERENCES

Bailey, N. J. L., Evans, C. R., and Milner, C. W. D., 1974, Applying petroleum geochemistry to search for oil: examples from Western Canada basin: Am. Assoc. Petroleum Geologists, Bull., v. 58, p. 2284-2294

Bray, E. E., and Evans, E. D., 1961, Distribution of n-paraffins as a clue to recognition of source beds: Geochim. Cosmochim. Acta, v. 22, p. 2-15

Cernock, P. J., 1974, Geochemical analyses of potential petroleum source beds: Initial reports of the Deep Sea Drilling Project, U.S. Govt. Printing Office, v. XXIV, p. 791-797

Dow. W. G., 1974, Application of oil-correlation and source-rock data to exploration in Williston basin: Am. Assoc. Petroleum Geologists, Bull., v. 58, p. 1253-1262

Staplin, F. L., 1969, Sedimentary organic matter, organic metamorphism, and oil and gas occurrence: Bull. Canadian Petroleum Geology, v. 17, no. 1, p. 47-66

THERMAL METAMORPHISM OF ORGANIC MATTER

in Drill Cuttings from KCM No. 1 Forest Federal Well, Hidalgo County, New Mexico

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ABSTRACT

Geochemical analyses of organic compounds may be used to determine incipient metamorphic grade. The total organic carbon content as well as compositional variations depend on the duration and temperature of the heating episode, and these variables may be critical in determining organic metamorphic facies.

The KCM No. 1 Forest Federal well, drilled in Hidalgo County, New Mexico, penetrated a Permian to Pennsylvanian sedimentary section that was intruded by mid-Tertiary quartz monzonites. These intrusives produced contact metamorphism up to a depth of 2,255 ft. Above that depth, the thermal effects decrease upward as indicated by petrography, clay mineralogy, and kerogen maturation indices. Additional geochemical analyses are needed to determine more precisely the level of organic metamorphism (LOM) in this part of the well.

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CONCEPT OF ORGANIC METAMORPHIC FACIES

A pressure-temperature region of incipient metamorphism exists between diagenesis and the lowest grade of regional metamorphism. In this region numerous changes occur—reconstitution of clays, authigenic formation of quartz and feldspar, solution and precipitation of carbonates, destruction of high-temperature mineral assemblages, as well as the beginning effects of deformation. When organic compounds are present, they too change in response to this incipient metamorphism.

The modification of hydrocarbons as sediments become lithified, with the concurrent effect of incipient metamorphism on organic compounds, historically has been related to the discussion of the origin of petroleum and coal (White, 1915, 1935; Stadnichenko, 1931; Staplin, 1969; Hood, Gutjahr, and Heacock, 1975; Hood and Castaño, 1975). The generation of hydrocarbons from organic matter during this process has been variously termed "organic metamorphism" (Hood and others, 1975), "transformation" (Dobryansky, 1963), "eometamorphism" (Landes, 1966, 1967), "thermal alteration" (Henderson and others, 1968; Staplin, 1969), "incipient metamorphism" (Baker and Claypool, 1970) and "katagenesis" (Vassoyevish and others, 1970). In coal, metamorphic grade has been related to physical and chemical changes of the kerogens (Staplin, 1969).

More recently authors have examined the changes in hydrocarbons at the low temperatures and pressures of incipient metamorphism by the comparison of recent and ancient sediments (Bray and Evans, 1961, 1965; Clark and Blumen, 1967; Brooks and Smith, 1967, 1969). Others (Baker and Claypool, 1970; Baker, 1972) have suggested the possibility of a "metamorphic facies classification" based on the observed changes in organic compounds. Hood and others (1975) developed a continuous numerical scale to measure the "level of organic metamorphism" (LOM) applicable to the entire thermal range of interest in the generation and destruction of petroleum. The scale relates indicators of organic metamorphism to coal rank.

PREVIOUS WORK

This section summarizes some of the more important changes that have been observed during the process of organic metamorphism and suggests some of the difficulties that hinder an explicit definition of organic metamorphic facies.

In a benchmark study, Baker and Claypool (1970) examined organic metamorphism by comparing the organic compositions of slightly metamorphosed and unmetamorphosed carbonaceous sedimentary rocks. They observed the following changes in organic compounds during incipient metamorphism:

1) A net loss of hydrocarbons
2) Hydrocarbon mixtures from metamorphosed rocks commonly contain a significantly higher proportion of saturated than aromatic hydrocarbons, resulting from a greater loss of aromatics during metamorphism. A similar effect was noted by Hunt (1962) in organic matter that had been thermally metamorphosed adjacent to igneous dikes
3) The color of the aromatic fractions from unmetamorphosed rocks is generally darker than that of similar fractions from metamorphosed rocks. This effect is explained partly by the elimination of nonhydrocarbon (heterocyclic) compounds during the metamorphism of sedimentary rocks
4) The aromatic and saturated fractions from samples of metamorphic rocks have a lower melting point (suggesting a lower molecular weight) than those from samples of unmetamorphosed rocks
5) Determinations on selected samples show a lower molecular weight for metamorphosed hydrocarbons
6) Isotopic studies of dC^{13} values in the saturated and aromatic fractions of metamorphosed and unmetamorphosed rocks were not conclusive, but during thermal metamorphism of kerogenic compounds the dC^{13} value increases with metamorphic grade. Preferential rupture of C^{12}–C^{12}bonds with increasing temperature leaves residual organic carbon enriched in dC^{13}.

Baker and Claypool's (1970) study was limited by several factors. None of the metamorphic suites were

[New Mexico Bureau Mines & Mineral Resources, Circular 152, 1977]

sampled continuously into unmetamorphosed terrain; thus, the effect of varying initial compositions as well as the progressive change in organic compounds with metamorphism could not be evaluated. Secondly, the metamorphosed samples came from surface localities while the unmetamorphosed samples came from subsurface cores. Surface weathering may have produced some of the observed differences. Finally, the ages of the unmetamorphosed samples were not given, so the relative effect of time on the change in organic compounds cannot be determined. Despite these limitations, the data of Baker and Claypool (1970) is consistent with that of others who have noted these, as well as the following additional changes:

1) With increasing age, sediments and sedimentary rocks show a decrease in the carbon preference index (CPI) of paraffins (Bray and Evans, 1961, 1965). Similarly, variations in the ring number distributions of high-boiling naphthenes are defined by Philippi's (1965) naphthene index (NI)

2) The relative abundance of odd-numbered carbons compared to even-numbered carbons in normal fatty acids increase with age

3) With increasing metamorphism of coal, a general decrease is observed in the odd/even ratios and in the average molecular weight of n-alkanes (Brooks and Smith, 1967)

4) On heating brown coals, the alcohols, acids, and hydroxacids are converted to n-alkanes showing no odd or even preference. This heating tends to obliterate the original biologic preference of organic compounds (Brooks and Smith, 1969)

5) Staplin (1969) has summarized thermal effects in his Thermal Alteration Index based on the color and structure alteration of kerogens. This index may be correlated with coal rank

6) Vitrinite reflectance increases with coal rank (McCartney and Teichmüller, 1972) and may be applied to macerals in non-coal-bearing sedimentary rocks

7) Electron spin resonance (ESR) measures the free radicals per gram of kerogen; this value, which increases with the aromatization (for example, heating) of kerogen, may be used to determine the level of organic metamorphism (Pusey, 1973a, b, c).

Thus, organic compounds may serve as sensitive indicators of incipient metamorphism in carbonaceous sedimentary deposits.

As a first step toward a facies classification of incipient metamorphism using organic compounds, Baker and Claypool (1970) used the decrease in the proportion of aromatics and the decrease in total organic carbon to measure incipient metamorphism. Their approach is limited because the conversion of organic compounds to hydrocarbons depends upon time as well as temperature. The data of Bray and Evans (1965) suggest that the conversion is time dependent and that conversion at a rapid rate may obliterate any organic record of the metamorphic event. The LOM scale of Hood and others (1975) considers the combined effect of maximum temperature and effective heating time. Although this scale is a significant improvement over the facies classification of Baker and Claypool (1970), the temperature-time correction is only approximate. The LOM scale can only be considered a relative indicator of metamorphic grade because LOM values vary significantly from one rock type to another. Also, accurate determination of the level of organic metamorphism on the scale requires the accurate measurement of formation temperatures.

LEVEL OF ORGANIC METAMORPHISM IN KCM WELL

The KCM No. 1 Forest Federal well, drilled in Hidalgo County, New Mexico, penetrated a Permian to Pennsylvanian sedimentary section that was intruded by mid-Tertiary plutons. A detailed geologic log from the surface to the total depth of 4,464 ft is presented by Thompson (this circular); Budding and Broadhead document the contact metamorphism, while Cernock and Bayliss summarize the organic geochemical analyses, including an evaluation of the thermal history based on kerogen maturation indices.

From total depth up to 2,255 ft, the well is in an igneous-metamorphic complex of marbles, hornfelses, and quartz monzonites. The amounts of organic carbon in that interval are less than 0.16 percent (some less than 0.03 percent); these values are so low that additional analyses of kerogen maturation and vitrinite reflectance are not feasible.

From 2,255 ft to a fault(?) at 1,947 ft, the effects of contact metamorphism decrease markedly, but the limestones are recrystallized and contain tremolite. No metamorphic minerals were found above the fault(?), and a transition zone to unmetamorphosed sedimentary rock may be missing as a result of normal displacement. From 2,200 ft to 1,900 ft, the amounts of organic carbon in limestones range from 0.12 percent to 0.21 percent, again generally too low for additional analyses.

From 1,800 ft to 760 ft, the amounts of organic carbon in mudstones and limestones range from 0.22 to 0.95 percent. Throughout this interval the maturation index based on kerogen analyses is at Stage 4 to 4-, indicating a high degree of thermal alteration just below metamorphism (Stage 5). From 760 ft to the surface, the amounts of organic carbon in limestones range from 0.10 percent to 0.55 percent. However, enough kerogens are preserved to determine maturation indices that decrease through Stage 3 to Stage 2, indicating a much lower degree of thermal alteration—probably not affected by the Tertiary intrusions.

The level of organic metamorphism (LOM) from 1,800 ft up to the surface ranges from about 16 to 3 on the scale of Hood and others (1975, fig. 2), using only the maturation (thermal alteration) index range from Stage 4 to Stage 2. In equivalent terms of coal rank, the range is from anthracite to lignite. Analyses of vitrinite reflectance are needed to establish the levels more precisely, especially in the higher values of LOM.

Above an LOM of about 13.5, high-temperature (katagenetic) methane may result from thermal degradation of liquid petroleum (Hood and others, 1975, fig. 5). This level corresponds to a maturation index between Stage 3 and Stage 4. Thus, the section from 760 ft to 1,800 ft in the KCM well having an index of Stage 4 is probably a source of dry gas as indicated by Cernock and Bayliss. A stratigraphic equivalent not affected by Tertiary intrusion would have lower LOM's, probably in the range of oil generation.

A rough estimate of the maximum temperature at the time of intrusion can be based on the chart of Hood and others (1975, fig. 3) if LOM and the effective heating time are known. In the interval from 760 ft to 1,800 ft having a maturation index of Stage 4, the equivalent LOM is about 16. Based on information from Elston and Erb (this circular), we have assumed an effective heating time of about I million years for the Tertiary intrusion. Therefore, the maximum temperature in this Stage 4 interval above the intrusion would be about 270°C.

With analyses of vitrinite reflectance, more accurate LOM values may be determined; in turn, more accurate estimates of the maximum temperature may be determined in the important interval from 760 ft to 1,800 ft in the KCM well.

The following additional recommendations and problems should be considered:

1) Analyses should be more closely spaced than the usual 100 ft inasmuch as changes in the geotherm due to contact metamorphism may be on the order of several tens of degrees within a 100-ft interval; organic reaction rates double with each 10°C increase (Lopatin, 1971; Laplante, 1972; and Momper, 1972). With control every 10 ft, fine detail in the variations of organic compositions may be detected

2) More detailed petrographic work may be needed in the interval from 760 ft to 1,800 ft because the degree of conversion of kerogen to petroleum compounds at any given LOM varies significantly from one rock type to another (Vassoyevich and others, 1970)

3) Organic geochemical analyses should be made on correlative facies away from the effects of thermal metamorphism. Powell and McKirdy (1973) have shown that differences in organic source and depositional environment may change the n- alkane distributions

4) Effects of geothermal fluids on organic matter should be studied in these volcanic areas. Germanov and Bannikova (1972) studied the effect of hydrothermal solutions on organic compounds; their results are only sketchily reported. In the outer zones of an ore deposit, the aromatic hydrocarbon compounds were condensed to polycyclic compounds; in the inner zone, organic compounds were oxidized to "resinous and various oxygenated compounds."

Although a good beginning has been made in determining the level of organic metamorphism in the KCM well, additional research is needed here and in the surrounding area to provide an accurate account of the thermal history.

REFERENCES

Baker, D. R., 1972, Organic geochemistry and geological interpretations: Jour. Geol. Education, v. 20, p. 221-233

Baker, D. R., and Claypool, G. E., 1970, Effects of incipient metamorphism on organic matter in mudrock: Am. Assoc. Petroleum Geologists, Bull., v. 54, p. 456-468

Bray, E. E., and Evans, E. D., 1961, Distribution of n-paraffins as a clue to recognition of source beds: Geochim. et Cosmochim. Acta, v. 22, p. 2-15

. 1965, Hydrocarbons in non-reservoir rock source beds: Am. Assoc. Petroleum Geologists, Bull., v. 49, p. 248-257

Brooks, J. D., and Smith, J. W., 1967, The diagenesis of plant lipids during the formation of coal, petroleum and natural gas I: Geochim. et Cosmochim. Acta, v. 31, p. 2389-2397

, 1969, The diagenesis of plant lipids during the formation of coal, petroleum and natural gas II: Geochim. et Cosmochim. Acta, v. 33, p. 1183-1194

Clark, R. C., and Blumen, M., 1967, Distribution of n-paraffins in marine organisms and sediment: Limnology and Oceanography, v. 12, p. 79-87

Dobryansky, A. F., 1963, La transformation du pétrole brut dans la nature: Inst. Francais Pétrole Rev., v. 18, p. 41-49

Germanov, A. I., and Bannikova, L. A., 1972, Alteration of organic matter of sedimentary rocks during hydrothermal sulfide concentrations: U.S.S.R. Acad. Sc., Earth Sc. Sec., v. 203, p. 205-206

Henderson, W., Eglinton, G., Simmonds, P., and Lovelock, J. G., 1968, Thermal alteration as a contributory process to the genesis of petroleum: Nature, v. 219, p. 1012-1016

Hood, A., and Castaño, J. R., 1974, Organic metamorphism: its relationship to petroleum generation and application to studies of authigenic minerals: United Nations ESCAP, COOP, Tech. Bull., v. 8, p. 85-118

Hood, A., Gutjahr, C. C. M., and Heacock, R. L., 1975, Organic metamorphism and the generation of petroleum: Am. Assoc. Petroleum Geologists, Bull., v. 59, p. 986-996

Hunt, J. M., 1962. Geochemical data on organic matter in sediments: Budapest, Hungary, Int. Sc. Oil Conf. Proc., v. 2, p. 394-412

Landes, K. K., 1966, Eometamorphism can determine oil floor: Oil and Gas Jour., v. 64, p. 172-177

1967, Eometamorphism and oil and gas in time and space: Am. Assoc. Petroleum Geologists, Bull., v. 51, p. 828-841

Laplante, R. E., 1972, Petroleum generation in Gulf Coast Tertiary sediments (abs.): Am. Assoc. Petroleum Geologists, Bull., v. 56, p. 635

Lopatin, N. V., 1971, Temperature and geologic time as factors in coalification: Akad. Nauk SSSR lzv. Ser. Geol., no. 3, p. 95-106

McCartney, J. T., and Teichmüller, M., 1972, Classification of coals according to degree of coalification by reflectance of the vitrinite component: Fuel, v. 51, p. 64-68

Momper. J. A., 1972, Evaluating source beds for petroleum (abs.): Am. Assoc. Petroleum Geologists, Bull., v. 56, p. 640

Philippi. G. T., 1965, On the depth, time and mechanism of petroleum generation: Geochim. et Cosmochim. Acta, v. 29, p. 1021-1049

Powell, T. G., and McKirdy, D. M., 1973, The effect of source material, rock type and diagenesis on the n-alkane content of sediments: Geochim. et Cosmochim. Acta, v. 37, p. 623-633

Pusey, W. C., 1973a. The ESR method: A new technique of estimating the organic maturity of sedimentary rocks: Petroleum Times, Jan. 12, p. 21-24 and 32

, 1973b, How to evaluate potential gas and oil source rocks: World Oil, v. 176, p. 71-75

1973c, Paleotemperatures in the Gulf Coast using ESR kerogen method: Gulf Coast Assoc. Geological Societies, Trans., v. 23, p. 195-202

Stadnichenko, T., 1931, Some effects of metamorphism on certain debris in source rocks: Am. Assoc. Petroleum Geologists, Bull., v. 15, p. 161-164

Staplin, F. L., 1969, Sedimentary organic matter, organic metamorphism, and oil and gas occurrence: Canadian Petroleum Geologists, Bull., v. 17, p. 47-66

Vassoyevich, N. B., Korchagina, Yu. I.. Lopatin, N. V., and Chernyshev, V. V., 1970, Principal phase of oil formation: Moskov. Univ. Vestnik, no. 6, p. 3-27

White, D., 1915, Some relation in origin between coal and petroleum: Washington Acad. Sc. Jour., v. 5, p. 189-212

, 1935, Metamorphism of organic sediments and derived oils: Am. Assoc. Petroleum Geologists, Bull., v. 19, p. 589-617

CENOZOIC VOLCANO-TECTONIC SETTING

of KCM No. 1 Forest Federal Well, Animas Mountains, Hidalgo County, New Mexico

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ABSTRACT

The Oligocene quartz monzonite penetrated by the KCM No. 1 Forest Federal well is interpreted as part of a shallow subvolcanic composite pluton, believed to underlie much of the southern and central parts of the Animas Mountains. The surface expression of the pluton is a cluster of three large cauldrons of calcalkalic ash-flow tuff. Petrology of ash-flow tuff sheets shows continuous progression from crystal-poor, fine-grained, quartz latitic Bluff Creek Formation to moderately crystal rich and quartz latitic Oak Creek Tuff (34.3 ± 0.7 m.y.), and to crystal-rich, coarse-grained and more felsic Gillespie Tuff (32.1 :-^{1}-$^{-}$ 0.7 m.y.).

The Winkler anticline, site of the KCM well, lies between inner and outer ring-fracture zones in the southern segment of the resurgent Juniper cauldron, northernmost of the three volcanic centers and source of the Oak Creek Tuff. The Juniper cauldron developed as follows: 1) subsidence along two concentric ring-fracture zones leading to a) filling of the inner subsidence caldera by Oak Creek ash-flow tuff, mingled with caldera-collapse breccias slumped from the caldera wall and b) massive landslides from an escarpment in the outer ring-fracture zone, forming Bennett Creek Breccia; 2) intrusion, including a) quartz monzonite porphyry (Animas stock) in the middle of the Juniper cauldron, causing resurgent doming, b) a quartz monzonite body in the zone between inner and outer ring fractures, encountered by the KCM No. 1 Forest Federal well, and c) eruption of Walnut Wells Monzonite in the ring-fracture zone; 3) filling of moat by Basin Creek Tuff; 4) eruption of domes and flows of Cedar Hill Andesite along the outer ring-fracture zone; 5) quiescence while volcanism continued in the southern part of the Animas Mountains; 6) Basin and Range faulting and increase in structural relief.

Cenozoic structures may have been influenced by earlier (Laramide and between late Permian and early Cretaceous) tectonic events but the evidence is inconclusive. The Winkler anticline probably formed during stage 2b, by doming above the quartz monzonite body encountered by the KCM well. Mineralization of the Winkler anticline area (fluorspar, lead, silver) seems to be related to stage 2 in the development of the Juniper cauldron.

INTRODUCTION

This paper deals with Cenozoic events in the vicinity of the KCM No. 1 Forest Federal well, Winkler anticline, Animas Mountains, Hidalgo County, New Mexico (fig. 1). The Winkler anticline is a site of recent exploration for fluorspar as well as petroleum. We present evidence that the Winkler anticline lies within the ring-fracture zone of a mid-Tertiary ash-flow tuff cauldron and that the anticline was probably formed by doming during a resurgent magma pulse. Many structural complexities can be interpreted as the result of caldera collapse and the formation of landslide blocks and collapse breccias at the caldera margins. These conclusions were first suggested in 1974 by the late R. C. Rhodes and were confirmed by us in several field checks between 1975 and 1977. This is a progress report; final interpretations are likely to be much more complicated than those given here.

We have relied heavily on the previous mapping by Zeller and Alper (1965) and can confirm its general accuracy. The reader is referred to their map for locations mentioned in this paper. If our interpretations are different from theirs, it is only because we have had the benefit of work by Smith, Bailey, and Ross (1961); Steven and Ratté (1965); Christiansen and others (1965); Smith and Bailey (1966); Lipman (1976); and many others, who have documented the internal structure of large ash-flow tuff cauldrons.

ACKNOWLEDGMENTS—We would like to thank Paul E. Damon, University of Arizona, for permission to quote

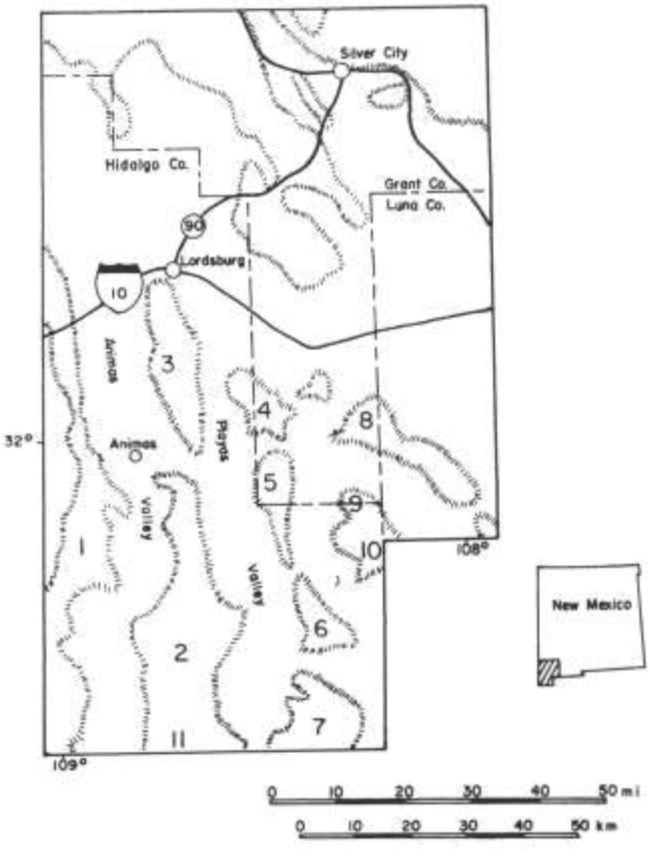

FIGURE I-MOUNTAIN RANGES OF SOUTHWESTERN NEW MEXICO: I) Peloncillo Mountains, 2) Animas Mountains, 3) Pyramid Mountains, 4) Brockman Hills and Coyote Hills, 5) Little Hatchet Mountains, 6) Big Hatchet Mountains, 7) Alamo Hueco (Dog) Mountains, 8) Cedar Mountain Range, 9) Apache Hills, 10) Sierra Rica, 11) San Luis and Whitewater Mountains.

previously unpublished potassium-argon (K-Ar) dates and Jonathan C. Callender, University of New Mexico, and Sam Thompson III, New Mexico Bureau of Mines and Mineral Resources, for reviewing this paper. Our work is part of a larger study of the effects of Cenozoic volcanism on the petroleum potential of the Pedregosa Basin and is being supported by grant 75-109 from the New Mexico Energy Research and Development Program, New Mexico Energy Resources Board.

VOLCANO-TECTONIC SETTING

Cenozoic stratigraphy and structure of the Animas Mountains can best be understood in terms of the four major ash-flow tuff sheets named by Zeller and Alper: Bluff Creek Formation, Oak Creek Tuff, Gillespie Tuff, and Park Tuff. The source of the Bluff Creek Formation probably lies south of the Winkler anticline (fig. 2). The source of the Oak Creek Tuff, here named the Juniper cauldron (after Juniper Spring in SE 1/4 sec. 20, T. 30 S., R. 18 W.), forms the main subject of this paper. The Winkler anticline lies within its ring-fracture zone, just south of the main mass of cauldron fill. Outflow sheets of Gillespie and Park Tuffs once probably covered the Winkler anticline but have now been eroded; their source cauldrons are too far south of the anticline to have affected it. The clustering of cauldrons suggests that parts of the Animas Mountains are underlain by a shallow composite pluton from which the cauldrons were fed, as in the Mogollon Plateau farther north (Elston and others, 1976). In general, ash-flow tuff cauldrons and related subvolcanic intrusions seem to form above cupolas of shallow batholithic intrusions.

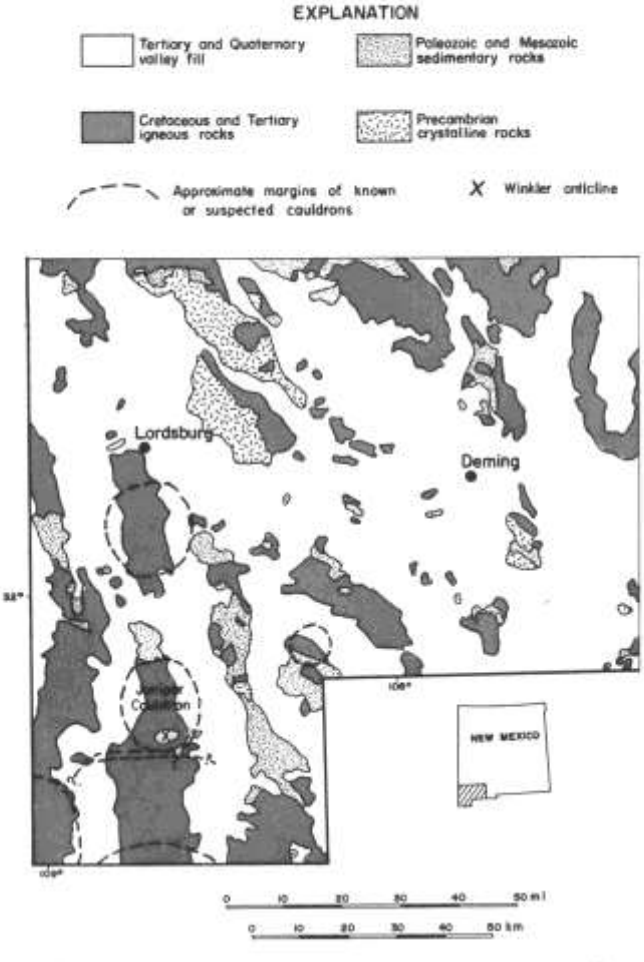

FIGURE 2—GEOLOGIC SKETCH MAP OF SOUTHWESTERN NEW MEXICO, showing the location of the Winkler anticline and the outlines of proposed mid-Tertiary ash-flow cauldrons.

CENOZOIC STRATIGRAPHY

A comparison between the Cretaceous and Tertiary stratigraphic column proposed by Zeller and Alper, and of the same column as reinterpreted by us, is shown in table 1. Definitions of stratigraphic terms, descriptions of pre-Cenozoic sedimentary rocks, and mineralogic and chemical data for Cenozoic igneous rocks were given by Zeller and Alper (1965).

Cowboy Spring-Timberlake Conglomerate

The Mojado Formation, youngest unit known to be Lower Cretaceous, is overlain in many places by cobble-to-boulder conglomerate, with subrounded clasts of Paleozoic and Mesozoic limestone and less abundant clasts of sandstone and chert, a pink sandy matrix, and red sandy interbeds. No volcanic clasts were seen. The maximum thickness, at least 500 m (1,650 ft), is exposed southeast of Cowboy Spring (SE 1/4 sec. 14, T. 32 S., R. 18 W.), but lesser amounts occur in many places southeast of the axis of the Winkler anticline (fig. 3).

Zeller and Alper divided this conglomerate into two units, the Cowboy Spring Formation, regarded as Lower Cretaceous, and the Timberlake Fanglomerate, regarded as Tertiary. This division was made on the basis of 1) apparent gradation of the upper part of the Mojado Formation into the lower part of the conglomerate, 2) apparent gradation of the upper part of the conglomerate into overlying Tertiary volcanic rocks, and 3) an abrupt flattening of dips within the unit, southeast of Cowboy Spring, suggesting an angular unconformity. They suggested that the Timberlake Fanglomerate consists of reworked Cowboy Spring material. However, Zeller and Alper were unable to map a contact.

We suggest combining the two units into one, for the following reasons: 1) like Zeller and Alper, we were unable to locate a contact or lithologic break within the unit; 2) evidence for reworking is lacking; for example, there are no clasts of reworked conglomerate in the upper part (Timberlake) of the unit; 3) individual clasts in the upper part are no more rounded than those in the lower part (Cowboy Spring) of the unit; 4) the flattening of dips does not occur between the lower and upper parts, as inferred by Zeller and Alper; and 5) the upper contact with Tertiary volcanic rocks is sharp and without evidence of intertonguing.

The evidence of the lower contact is conflicting. In SW 1/4 SE 1/4 sec. 13, T. 32 S., R. 18 W., conglomerate that is undoubtedly part of the Mojado Formation has polished and rounded pebble-sized clasts of chert and quartzite. At the base of the Cowboy Spring-Timberlake conglomerate there is an abrupt upward change to carbonate- and sandstone-cobble conglomerate, but intertonguing buff crossbedded sandstone retains a typical Mojado aspect. Elsewhere, as in NE 1/4 sec. 2, T.

TABLE 1—Proposed stratigraphic columns for Lower Cretaceous to Tertiary rocks, Winkler anticline and vicinity.

Age	Zeller and Alper (1965)		Elston and Erb (this paper)
Tertiary	Park Tuff		Park Tuff
	Center Peak Latite		Center Peak Latite
	Gillespie Tuff		Gillespie Tuff
	Bluff Creek Formation Young Ranch Tuff		
	Cedar Hill Andesite	Juniper Cauldron Sequence	Cedar Hill Andesite (incl. Young Ranch Tuff)
	Walnut Wells Monzonite Animas Quartz Monzonite		Basin Creek Tuff
			Walnut Wells Monzonite
	Basin Creek Tuff		Animas Quartz Monzonite
	Oak Creek Tuff		Oak Creek Tuff Bennett Creek Breccia
	Horse Hill Breccia Bennett Creek Breccia		Bluff Creek Formation
	Timberlake Fanglomerate		
			Cowboy Spring-Timberlake conglomerate
Lower or Upper Cretaceous	Cowboy Spring Formation		
Lower Cretaceous	Mojado Formation		Mojado Formation
	U-Bar Formation		U-Bar Formation

31 S., R. 18 W., Cowboy Spring-Timberlake conglomerate lies on Mojado or U-Bar Formation with angular unconformity. Local gradation from Mojado to Cowboy Spring-Timberlake cannot be ruled out, but we prefer to interpret the conglomerate as unconformable with Cretaceous rocks and the sandy beds as material reworked from the Mojado Formation.

The age of the Cowboy Spring-Timberlake conglomerate is bracketed only within broad limits by the Albian Mojado Formation and the Oligocene (?) Bluff Creek Formation. The age is critical to interpretations of regional structure because the conglomerate records the first known breaching of Lower Cretaceous and upper Paleozoic rocks by erosion. The conglomerate seems to be a regional unit, and there is little evidence that its source is related to the Winkler anticline. Zeller and Alper mapped it 15 km south of the anticline but not north of the anticline. In the Little Hatchet Mountains there is a conglomerate of similar lithology, the Skunk Ranch Conglomerate of Lasky (1947), remapped as part of the Ringbone Formation by Zeller (1970). According to Zeller (1970), a late Cretaceous to Eocene plant, *Saba sp.*, is the only fossil reported from the Ringbone Formation. In the Dog Mountains, Zeller (1958) mapped a limestone-boulder fanglomerate in the same stratigraphic position as the Cowboy Spring-Timberlake conglomerate. If an age within the interval from late Cretaceous to Eocene can be confirmed, the Cowboy Spring-Timberlake conglomerate probably formed by erosion of Laramide uplifts, analogous to the Baca and Galisteo Formations of west-central and north-central New Mexico.

Bluff Creek Formation

The Bluff Creek Formation consists of numerous fine-grained crystal-poor ash-flow tuff cooling units, 5-20 m thick, interbedded with tuffaceous sandstone and conglomerate. Small (less than 2 mm) phenocrysts of quartz, sanidine, and plagioclase make up less than 10 percent of the rock; biotite, if present, is largely oxidized. Compressed pumice lenses and sparse inclusions of brownish andesite, up to 1 cm, are characteristic. In the southwestern part of the Animas Mountains, andesite flows and breccias occur below and within the Bluff Creek Formation.

We have found the "Horse Hill Breccia" of Zeller and Alper to be identical with the Bluff Creek Formation. The "Horse Hill Breccia" is unbrecciated (though altered); it crops out in an area of widespread alteration (secs. 16, 17, and 18, T. 32 S., R. 17 W.).

The source of the Bluff Creek Formation seems to have been south of the Winkler anticline. Outflow sheets of Bluff Creek Formation once covered part of

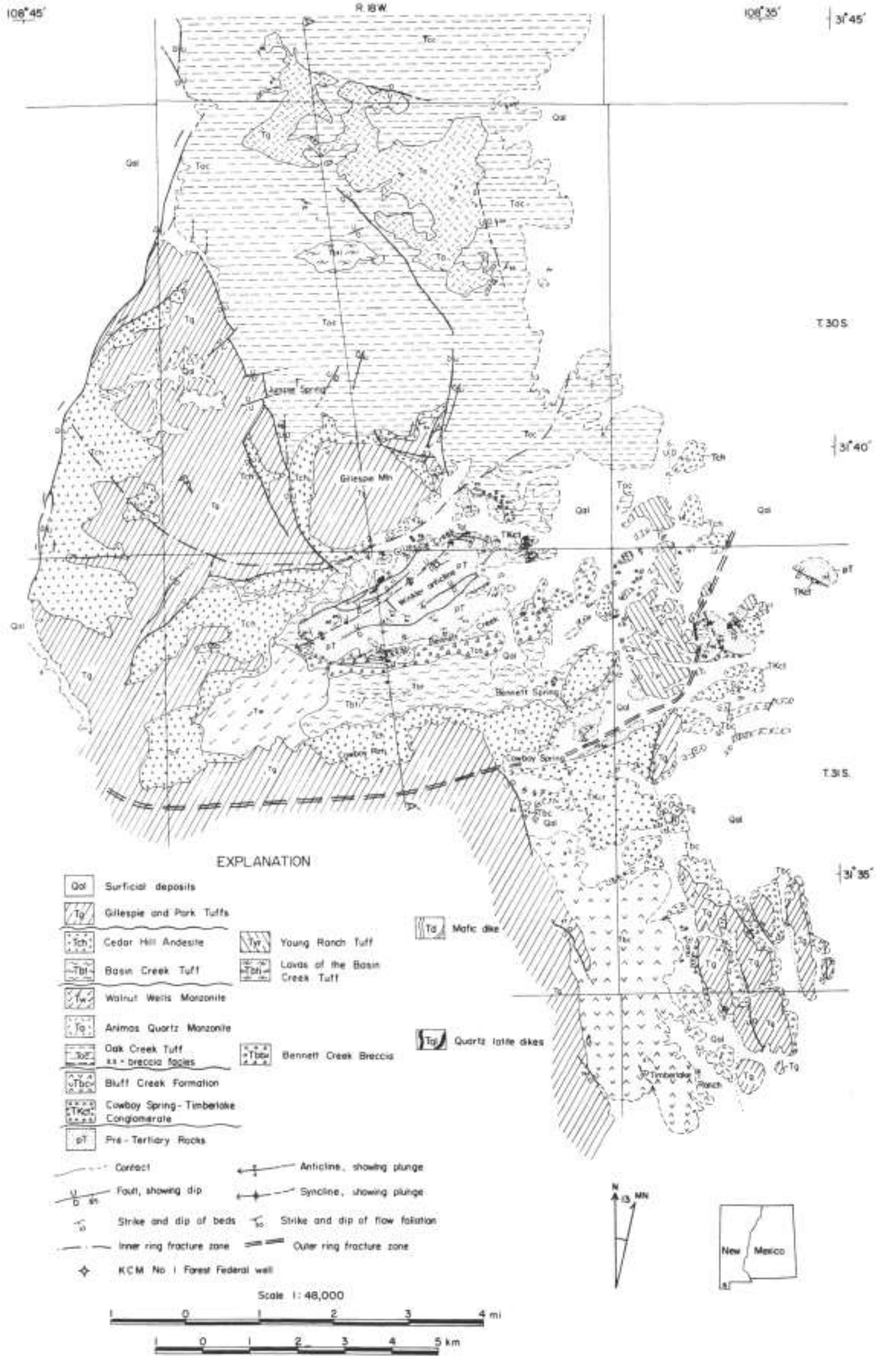

FIGURE 3—GEOLOGIC MAP OF THE WINKLER ANTICLINE AREA, modified from Zeller and Alper (1965).

the Winkler anticline area but are now present only as blocks in landslide deposits and caldera-collapse breccias, such as the Bennett Creek Breccia and the marginal facies of the Oak Creek Tuff. The Bluff Creek Formation is missing just south of the outcrop band of Bennett Creek Breccia (fig. 3), so that at Bennett Spring (NE 1/4 NW 1/4 sec. 13, T. 31 S., R. 18 W.) the Basin Creek Tuff locally lies on Cowboy Spring-Timberlake conglomerate. About 3 km to the east, the Bluff Creek Formation is present only in the bands of "Horse Hill Breccia." Approximately 3 km to the south it thickens abruptly to about 300 m. South of the area covered by fig. 3, on the western face of the Animas Mountains, Erb has measured thicknesses greater than 600 m and has found clasts of flow-banded rhyolite. These relationships document a probable cauldron. Like the earliest mid-Tertiary eruptive centers in other parts of southwestern New Mexico (Goodsight-Cedar Hill depression, Seager, 1973; Crosby Mountain depression, Bornhorst, 1976), the source of the Bluff Creek Formation seems to have been an asymmetrical volcano-tectonic depression that acted like a trap door. This depression was hinged on the east and was filled with many ash-flow tuff beds interlayered with tuffaceous sandstone. Ring-fracture domes were probably confined to the west side, opposite the hinge. We interpret the thick southern sections as caldera fill and the zone in which Bluff Creek Formation is absent, or patchy and altered, as the relatively high and eroded caldera rim. The eastern and western margins of the cauldron appear to be buried under the Playas and Animas Valleys, respectively; the southern margin has not been found because the Bluff Creek Formation dips beneath younger rocks about 10 km north of the Mexican border. To the north, fine-grained and crystal-poor ash-flow tuff sheets have been found at the base of the Tertiary volcanic section of the Coyote Hills by C. H. Thorman (U.S. Geological Survey, personal communication, 1976). These rocks resemble the Bluff Creek Formation. In the Pyramid Mountains, E. G. Deal (Eastern Kentucky University) and Elston are documenting a major volcanic center for ash-flow tuffs that are fine-grained and crystal-poor, like the Bluff Creek Formation. Probably this is not the source of the Bluff Creek Tuff but of other units of about the same age and stage of magmatic evolution.

Zeller and Alper placed the Bluff Creek Formation above rocks that we have assigned to the proposed Juniper cauldron (Oak Creek Tuff, monzonitic rocks, Bennett Creek Breccia, Basin Creek Tuff, and Cedar Hill Andesite). We place the Bluff Creek Formation below the rocks of the Juniper cauldron, in the position that Zeller and Alper assigned to the "Horse Hill Breccia." We base our stratigraphy on the following evidence: 1) ash-flow tuffs of the Bluff Creek Formation and "Horse Hill Breccia" are indistinguishable, 2) clasts of Bluff Creek ash-flow tuff occur in Bennett Creek Breccia and in Oak Creek and Basin Creek Tuffs, but the reverse has not been found, 3) the Bluff Creek Formation never lies on rocks younger than Cowboy Spring-Timberlake conglomerate, and 4) occurrences of Oak Creek and/or Basin Creek Tuff above the Bluff Creek Formation have been found on the east face of the Animas Mountains, near the Timberlake Ranch.

Rocks of the Juniper Cauldron

The Juniper cauldron appears to be a classic resurgent cauldron of the Valles type (Smith, Bailey, and Ross, 1961). The Oak Creek ash-flow tuff forms a thick cylinder of cauldron fill (fig. 4), bounded by an inner ring-fracture zone. Along the margin of cauldron fill are prominent caldera collapse breccias. Bennett Creek Breccia is interpreted as a combination of caldera-collapse megabreccia and post-caldera landslide and mudflow deposits along an outer ring-fracture zone. Basin Creek Tuff fills the caldera moat, and the Cedar Hill Andesite and Walnut Wells Monzonite were emplaced along the outer ring-fracture zone (fig. 5). The stock of Animas Quartz Monzonite Porphyry, exposed in the middle of the cauldron, may be part of the magma body that caused resurgence. The igneous rocks that intruded into the ring-fracture zone, and that were penetrated by the KCM well, may also belong to the resurgent magma pulse.

All these rocks are rich in crystals (usually 30-35 percent), among them shiny black biotite. Alper and Poldervaart (1957) found that Oak Creek Tuff, Animas Quartz Monzonite, and Walnut Wells Monzonite had similar zircon populations and concluded that they came from a common parent magma. This conclusion was confirmed by chemical and petrologic similarities, pointed out by Zeller and Alper, and by our field evidence. It is further confirmed by previously unpublished biotite K-Ar ages reported by Paul E. Damon: Oak Creek Tuff, 34.3 ± 0.7 m.y.; Animas Quartz Monzonite, 34.0 ± 0.7 m.y.; Walnut Wells Monzonite, 33.6 ± 0.7. A preliminary potassium feldspar K-Ar date of about 30 m.y. for the quartz monzonite encountered by the KCM well is close to the 30.5 ± 0.6 m.y. date obtained for sanidine from the Oak Creek Tuff.

Oak Creek Tuff—Oak Creek Tuff consists of about 35 percent phenocrysts, up to 5 mm long, of quartz, oligoclase-andesine, sanidine, and biotite, set in pink matrix with conspicuous lenses of flattened and recrystallized pumice fragments. A large mass of Oak Creek Tuff crops out north of the Winkler anticline. The complexly faulted southern edge of this mass is exposed only in sec. 35, T. 30 S., R. 18 W., where we have drawn the inner cauldron margin (fig. 3, 4). In this vicinity the Oak Creek Tuff is characterized by abundant xenoliths of Cowboy Spring-Timberlake conglomerate, sandstone of the Mojado Formation, several types of pre-Tertiary carbonate rocks, and a conglomerate containing clasts from the Bluff Creek Formation (fig. 5a). Some blocks are greater than 10 m in diameter. Within the tuffaceous matrix, some blocks of Oak Creek Tuff were rotated and covered with an accretionary rind of Oak Creek Tuff. We interpret this xenolith zone as a caldera-collapse mesobreccia, transitional to megabreccia (terminology from Lipman, 1976), that slumped off the inner caldera wall during catastrophic caldera subsidence and eruption of Oak Creek Tuff. The xenoliths can be seen in NW 1/4 SE 1/4 sec. 35, T. 30 S., R. 18 W., in the bed of Gillespie Creek, about where the 5,000-ft topographic contour crosses the creek. Zeller and Alper described large clasts near the base of the Oak Creek Tuff 2.5 km farther north, between Millsite and Ash Creeks, in sec. 24, T. 30 S., R. 18 W.

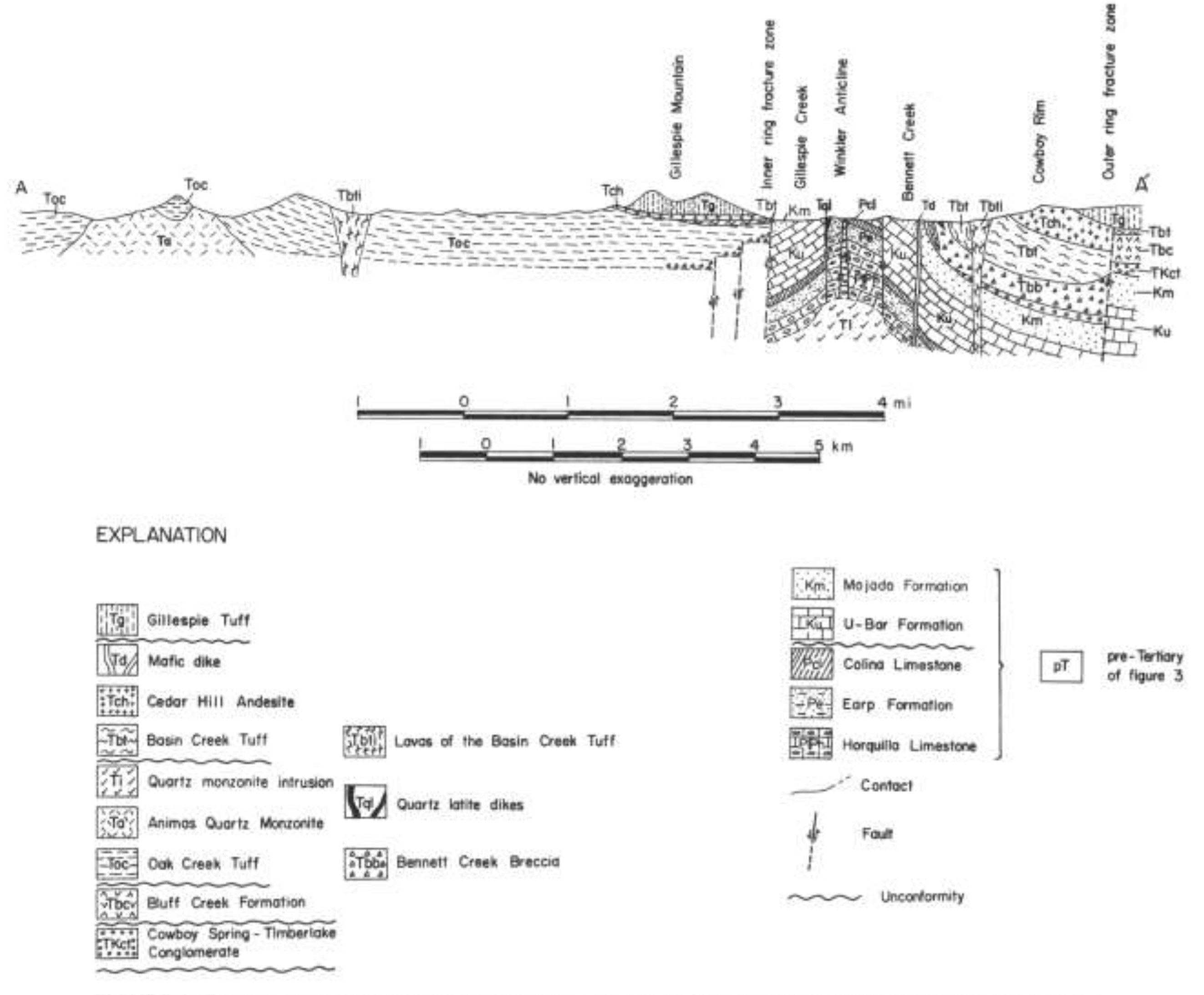

FIGURE 4—GEOLOGIC SECTION ACROSS THE SOUTHERN MARGIN OF THE JUNIPER CAULDRON AND THE WINKLER ANTICLINE, along line *A-A'* of fig. 3. Faults are shown as vertical, but the true dips of fault planes are generally unknown.

Elsewhere, the Oak Creek Tuff has the characteristics of massive caldera fill. The top of the tuff is less welded than the base. Near Juniper Spring some of the less welded material was mapped as Basin Creek Tuff by Zeller and Alper. Judging from dips and vertical relief, thickness of the cauldron fill must be at least in the hundreds of meters and may well exceed 1,000 m. Such thicknesses are not unusual in similar cauldrons elsewhere. The dips recorded by Zeller and Alper suggest that the Oak Creek Tuff forms a broad dome, centered around the Animas stock.

Reconnaissance has suggested that the northern margin of the Juniper cauldron is in the vicinity of Whitmire Pass in the northern part of T. 29 S., R. 18 W. Here the Oak Creek Tuff locally contains blocks of fine-grained rhyolite. Beyond the cauldron, ash-flow tuff outflow sheets of rock resembling Oak Creek Tuff have been found in the southern part of the Pyramid Mountains by E. G. Deal and Elston and in the Coyote Hills by C. H. Thorman.

Bennett Creek Breccia—Bennett Creek Breccia is a spectacular landslide and rock avalance deposit that forms a belt nearly 6 km long and about 500 m wide on the south side of the Winkler anticline. The outcrop belt is concave to the northwest, concentric with the inner margin of the Juniper cauldron. Correct interpretation of the relationships of the Bennett Creek Breccia to the collapse of the Juniper cauldron may be a key to understanding the volcano-tectonic structures of the region.

The Bennett Creek Breccia consists mainly of large slabs (tens of meters long) of ash-flow tuff from the Bluff Creek Formation. These slabs, in various stages of brecciation, are interspersed with a mudflow matrix containing blocks up to 10 m long of Cowboy Spring-Timberlake conglomerate, pre-Tertiary sedimentary rocks, Bluff Creek Tuff, and andesite. Ash-flow tuff, tentatively interpreted as Oak Creek Tuff, appears in the matrix near the base of the deposit. Near the center of sec. 9, T. 31 S., R. 18 W., a shattered block of limestone from the U-Bar Formation (Lower Cretaceous) about 1,200 m long is entirely surrounded by Bennett Creek Breccia, intermingled near the northwest end of the block with Oak Creek Tuff. We interpret

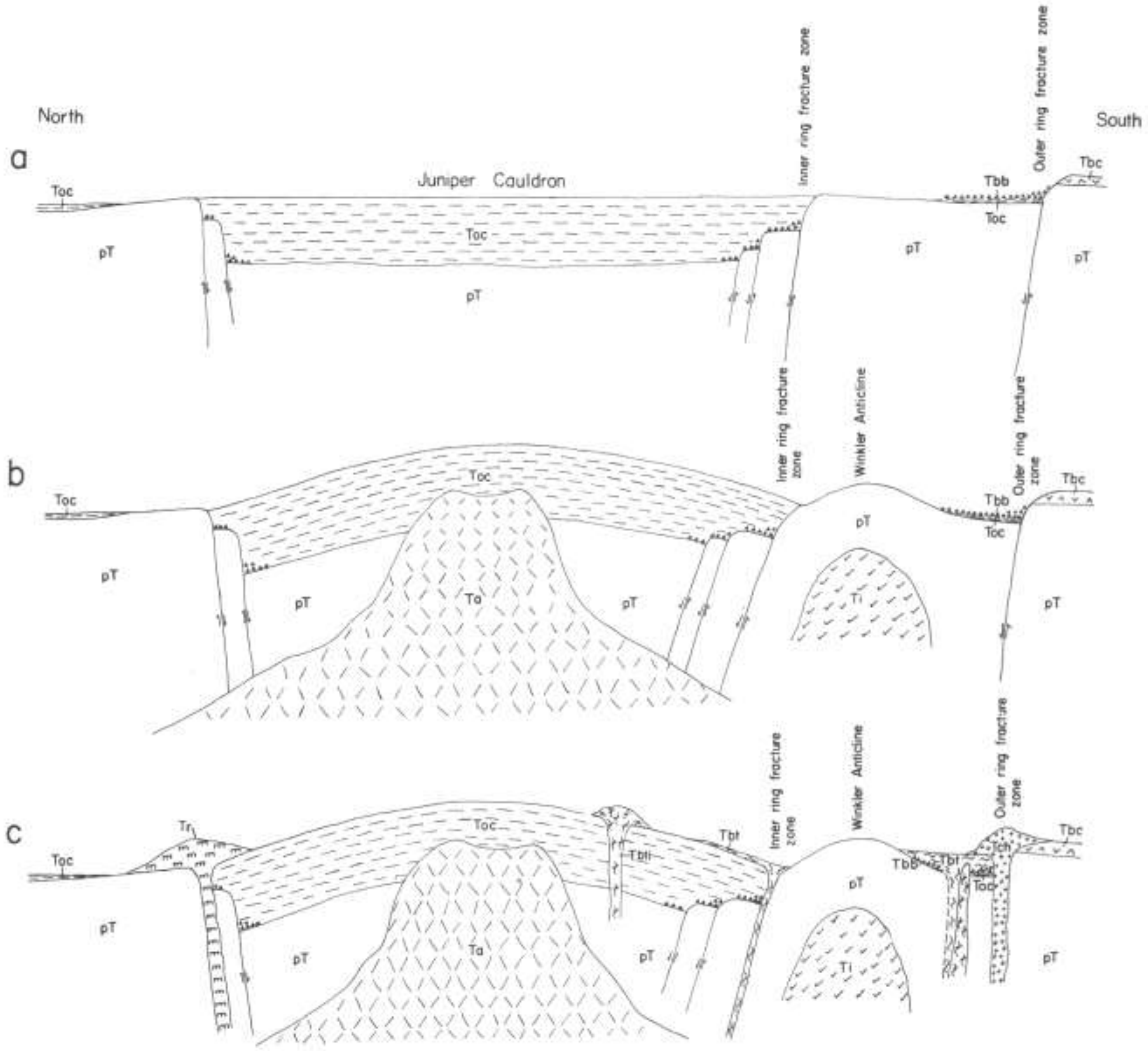

FIGURE 5—Schematic development of the Juniper cauldron and Winkler anticline. pT—pre-Tertiary rocks, including Cowboy Spring-Timberlake conglomerate; Ti—quartz monzonite encountered by KCM No. 1 Forest Federal well; Tr—ring-fracture rhyolite, undifferentiated. All other symbols as in fig. 4. **a**—Caldera collapse and formation of breccias along ring-fracture zones. **b**—Resurgent intrusions and doming. **c**—Eruption of moat deposits and ring-fracture domes. Basin and Range faulting subsequent to volcanism accounts for the greater dips and structural relief in fig. 4, compared with fig. 5c.

the block as a northward-directed slump. Zeller and Alper mapped it as a buried ridge of Timberlake Fanglomerate, but it lacks the subrounded polymictic cobbles and boulders and the sandy matrix that are characteristic of the Cowboy Spring-Timberlake conglomerate. Directly to the north, in SE 1/4 NE 1/4 sec. 9, T. 31 S., R. 18 W., a less brecciated slice of U-Bar limestone could also be a slump block. The evidence is less clear because of structural complications and poor exposures. Zeller and Alper regarded the U-Bar block as a fault slice, and this interpretation cannot be ruled out. The block is about 750 m long and dips vertically to 75°S. It is bordered by Bennett Creek Breccia on the south side and is surrounded by Bennett Creek Breccia on its western end. Elsewhere, its north side is usually separated from steeply-dipping Mojado Formation by intensely altered Oak Creek Tuff and by later dikes of dark diabase.

Dips in the underlying Mojado Formation confirm that the Bennett Creek Breccia was deposited on unstable ground. The Mojado Formation generally dips about 25°-40°S or SE on the southeast flank of the Winkler anticline. Near contacts with Bennett Creek Breccia dips become highly irregular but tend to be 70°-85°S.

We regard the Bennett Creek Tuff as essentially contemporaneous with Oak Creek Tuff. Early in the history of the Juniper cauldron at least two concentric ring-fracture zones seem to have formed on the south side of the cauldron (fig. 5a). The inner ring-fracture zone bordered a subsidence caldera about 18 km in diameter, filled with Oak Creek Tuff and with breccia derived by slumping from the caldera walls. An outer ring fracture formed an oversteepened escarpment about 3 km south of the inner caldera. We interpret the Bennett Creek Breccia as large toreva blocks, landslides, mudflows, and rock avalanches that formed as the escarpment grew in height. The outer ring-fracture zone later controlled the feeders for Cedar Hill Andesite.

The lower part of the Bennett Creek Breccia appears to be a caldera-collapse megabreccia, in the sense of Lipman (1976). The toe of the breccia deposit contains the two previously described blocks of U-Bar limestone. Here there was intermingling between Bennett Creek Breccia and Oak Creek Tuff. Possibly, Oak Creek Tuff spilled out of the cauldron and mingled with the sole of the Bennett Creek landslide. Alternatively, the tuff could have erupted locally from minor fissures between the two major ring-fracture zones and invaded the base of the breccia. We have seen irregular altered patches and dikelike masses of Oak Creek Tuff (and, possibly, porphyritic lava with the same mineral content) on the contacts of both limestone blocks, along faults, and within the lower part of the Bennett Creek Breccia. Patches of similar material have been mapped by Zeller and Alper as quartz latitic dikes on the north side of the Winkler anticline, judging from specimens collected by E. C. Brooks (University of New Mexico). In float, we have seen clasts of Bluff Creek Tuff and U-Bar limestone encrusted with Oak Creek Tuff. Possibly the ash-flow tuff acted as a buoyant cushion at the base of the Bennett Creek Breccia and enhanced the mobility of the slide. A similar suggestion was made by Lipman (1976) for breccias in calderas of the San Juan Mountains of Colorado. The upper part of the Bennett Creek Breccia seems to consist largely of mudflow breccia without intermingled Oak Creek Tuff; this part may have formed later than the initial catastrophic caldera collapse.

Intrusive igneous rocks—Quartz monzonite from the Animas stock has conspicuous phenocrysts of pink orthoclase up to 15 mm long and smaller phenocrysts of oligoclase-andesine, quartz, and biotite. The less silicic Walnut Wells Monzonite porphyry is similar but lacks quartz phenocrysts. Strictly speaking, it is a quartz monzonite porphyry with about 16 percent normative quartz and 18 percent modal quartz in the groundmass. Zeller and Alper probably called it a monzonite porphyry because quartz cannot be seen with the naked eye. Quartz monzonite chips recovered from the KCM well consist of pink orthoclase, plagioclase, and quartz, but no biotite. Some nonporphyritic xenoliths in the Walnut Wells stock have the same mineral assemblage. Other xenoliths in Walnut Wells Monzonite resemble rock from the Animas stock.

Zeller and Alper deduced from outcrop patterns that the Walnut Wells Monzonite Porphyry forms a plug that intruded Basin Creek Tuff; however, they found no contacts to confirm an intrusive relationship. We saw a contact near the head of Bennett Creek, in SW'/4 sec. 9, T. 31 S., R. 18 W., where Basin Creek Tuff seems to lie nonconformably on monzonite porphyry (the Basin Creek Tuff is here shown as Bennett Creek Breccia on the map of Zeller and Alper). There was no evidence of monzonite porphyry cutting across or altering Basin Creek Tuff.

If our interpretations are correct, the monzonite and quartz monzonites were all emplaced in the interval between eruptions of Oak Creek Tuff and Basin Creek Tuff. The monzonitic rocks are part of a resurgent magma pulse that caused doming of the inner cauldron and of the Winkler anticline (fig. 5b). Lead, silver, and fluorspar mineralization in the Gillespie (Red Hill) mining district seems to be related to the same magma pulse, Oak Creek Tuff is the youngest rock known to be mineralized.

If it is older than Basin Creek Tuff, the Walnut Wells Monzonite porphyry is likely to be part of a lava plug that broke through to the surface. The top of the plug stands several hundred meters above the base of the Basin Creek Tuff, and there are no known rocks into which it could have intruded.

Basin Creek Tuff—Basin Creek Tuff is a heterogeneous unit which consists of bedded pumiceous tuff, sandy tuff, ash-flow tuff, lava flows, protrusive domes, and mudflow deposits. The mineral content is quite similar to the Oak Creek Tuff; in fact, some of the Basin Creek Tuff mapped by Zeller and Alper may be poorly welded Oak Creek Tuff. The best exposures of Basin Creek Tuff are on the lower and middle slopes of the Cowboy Rim where the thickness is at least 750 m. At the base of the section in SE1/4 sec. 9, T. 31 S., R. 18 W., an ash-flow tuff dips vertically. Above it lies a steeply dipping, coarsely porphyritic quartz latite, possibly a dike. Clasts of the same rock appear in mudflows at the base of the Basin Creek Tuff near Bennett Spring. Higher in the section, loosely welded tuff breccia and a few more densely welded ash-flow tuff beds predominate and dip about 40° S. We were unable to determine in a reconnaissance traverse whether the rocks at the base of the section owed their steep dips to doming on the flank of the Winkler anticline or to faulting, or whether they were within a volcanic vent. A vent was described by Zeller and Alper in S1/2 sec. 9 and N 1/2 sec. 16, T. 30 S., R. 18 W.

Cedar Hill Andesite—The Cedar Hill Andesite is a heterogeneous unit which consists of andesite flows and domes, quartz latite flows, and quartz latite ash-flow tuff. Plagioclase and biotite phenocrysts are ubiquitous; the more mafic members contain pyroxene and the more felsic ones quartz and sanidine. The Young Ranch Tuff of Zeller and Alper is at about the same strati-graphic level and resembles some members of the Cedar Hill Andesite, but the source of this tuff is unknown.

Outcrops of Cedar Hill Andesite form an arcuate belt that swings south of the Winkler anticline (fig. 3). We interpret this belt as marking the outer ring-fracture zone of the Juniper cauldron. Cedar Hill Andesite and associated rocks apparently erupted from lava domes controlled by ring fractures (fig. 5c). Cedar Hill Andesite (not Gillespie Tuff, as mapped by Zeller and Alper) caps part of the Cowboy Rim directly south of the Winkler anticline. Here the andesite is about 500 m thick.

Younger Rocks

Cedar Hill Andesite is overlain by relatively thin outflow deposits of Gillespie Tuff. To the south, in the northern part of T. 32 S., R. 18 W., Gillespie Tuff thickens abruptly to about 800 m and assumes the characteristics of cauldron fill. North of the Winkler anticline the Gillespie Tuff is anomalously thick on Gillespie Mountain. We attribute this thickening to accumulation in a local depression, perhaps part of the moat of the Juniper cauldron. The biotite K-Ar age of the Gillespie Tuff, determined by P. E. Damon, is 32.1ˉ17 0.7 m.y. Compared with Oak Creek Tuff, the Gillespie Tuff tends to be more felsic. The maximum size of phenocrysts is larger, and phenocrysts are usually more abundant (about 40 percent) and consist of a higher proportion of quartz and sanidine, less plagioclase, and much less biotite. Oak Creek and Gillespie Tuff are both variable in texture and composition.

Park Tuff seems to have originated in a cauldron in the Sierra San Luis, in northwestern Chihuahua. Erb is mapping its outer ring-fracture zone near San Luis Pass, just north of the Mexican border. The phenocryst content of the Park Tuff is only about 15 percent, mostly quartz, sanidine cryptoperthite ("moonstone") and a trace of brassy biotite. A K-Ar sanidine date of 27.8 0.6 m.y. was determined by P. E. Damon. Other units that were mapped by Zeller and Alper near the top of the section (Center Peak Latite, OK-Bar Conglomerate, and Pine Canyon Formation) do not crop out near the Winkler anticline.

SUMMARY OF MAGMATIC HISTORY

Cenozoic magmatic events of the Animas Mountains seem to have followed the same course as in other parts of southwestern New Mexico, such as the Mogollon Plateau. There, Elston and others (1976) suggested that felsic volcanic rocks belong to two magma suites, the earlier calc-alkalic and the later characterized by high-silica alkali rhyolites. In the Animas Mountains, the succession of rocks from Bluff Creek Formation through Gillespie Tuff has calc-alkalic affinities. As on the Mogollon Plateau, phenocrysts of successive ash-flow tuff sheets become systematically larger in size and abundance, and the rocks become more felsic. Park Tuff has the "moonstone tuff" lithology typical of the high-silica alkali rhyolite suite. The decrease in phenocryst abundance between Gillespie Tuff and Park Tuff is typical of the transition between the two suites.

The succession of cauldron types is also typical of other parts of New Mexico; early asymmetrical trap door depressions were followed by resurgent cauldrons of the Valles type. In the Juniper cauldron, as in the Bursum and Emory cauldrons (Coney, 1976; Elston, Seager, and Clemons, 1975), resurgence seems to have occurred between eruption of the main ash-flow tuff unit and the main moat-fill deposit. In the Mogollon Plateau a cluster of high-silica alkali rhyolite cauldrons was interpreted as evidence of an underlying composite pluton. In the Animas Mountains a cluster of cauldrons is tentatively interpreted as evidence of an underlying calc-alkalic composite pluton.

STRUCTURAL HISTORY

Pre-Oligocene History

The pre-Oligocene history of the Winkler anticline area is difficult to document. We know of no conclusive evidence for or against existence of a Winkler anticline prior to collapse of the Juniper cauldron. Zeller and Alper showed that several Cretaceous and Permian formations are thinner here than in the Big Hatchet Mountains to the east, but there is no conclusive evidence that the thinning is related to growth of the Winkler anticline. Pre-Tertiary stratigraphic control is so limited that no detailed isopach maps can be drawn for this area. An unconformity is undoubtedly present between Permian and Cretaceous rocks and accounts for the local absence of several Permian formations. A similar unconformity exists elsewhere in southwestern New Mexico, as in the central Peloncillo Mountains (Gillerman, 1958). Pre-Cretaceous erosion patterns are not established and cannot be related to early growth of the northeast-trending Winkler anticline. Zeller and Alper (p. 70) also illustrated a fault on the north side of the Winkler anticline, in NE1/4NW1/4 sec. 3, T. 31 S., R. 18 W., that cuts Pennsylvanian and Permian rocks but did not cut the overlying Cretaceous U-Bar Formation. According to E. C. Brooks (personal communication, 1977), this fault probably does not end at the base of the U-Bar Formation but continues as a silicified zone along the U-Bar-Earp contact. Outcrops of the U-Bar Formation are very patchy here. We would treat all evidence of this sort with great caution. Accurate tracing of faults through these intensely altered and disturbed rocks is difficult. Elsewhere, on the south side of the Winkler anticline, at least some large blocks of U-Bar Formation seem to have slumped into their present position during collapse of the Juniper cauldron.

Laramide deformation is well documented in southwestern New Mexico, and possibly the Winkler anticline was active in late Cretaceous or early Tertiary time. Direct evidence is lacking in areas we have examined to date, mainly on the southeast and northeast side of the Winkler anticline. If the Cowboy Spring-Timberlake conglomerate is post-Laramide, its distribution may give a clue to the location of Laramide uplifts. The presence of Paleozoic clasts shows that about 2 km of Cretaceous rocks had been stripped away at its source, but it is not known whether the source was at the present-day Winkler anticline. Cowboy Spring-Timberlake conglomerate is best exposed south of the Winkler anticline. The unit is present on the southeast and northeast sides of the anticline, but its thickness cannot be measured because it occurs only in blocks that are part of Bennett Creek Breccia and Oak Creek Tuff, in fault slices, and in erosional remnants.

Average dips of Paleozoic and Cretaceous rocks on the south flank of the Winkler anticline, 30° to 40°S, are about the same as those of Tertiary volcanic rocks on the north face of the Cowboy Rim. The steepest dips, 70° to 90°, are in the faulted area north of the Cowboy Rim, where the Mojado, Bennett Creek, and Basin Creek Formations have their mutual contacts. There is no evidence here for a post-Mojado prevolcanic period of folding. We have not yet examined the northwest side of the Winkler anticline, where Zeller and Alper (1965, p. 72) have mapped an angular unconformity between Cretaceous and Tertiary rocks.

In sec. 8, T. 31 S., R. 17 W., Zeller and Alper showed tightly folded U-Bar Formation overlapped by tilted but unfolded Timberlake Formation and Tertiary volcanic rocks. The trend of the fold axes is northwesterly, which is the general Laramide trend elsewhere in Hidalgo County, but this trend is almost at right angles to the Winkler anticline. The Winkler anticline more closely parallels the margin of the Juniper cauldron.

Oligocene and Later History

In Oligocene time the area of the Winkler anticline remained structurally high while ash-flow tuff cauldrons collapsed on either side. First, the source of the Bluff Creek Formation formed, probably to the south, then the Juniper cauldron formed in the Winkler anticline area and to the north. Avalanches, landslides, and mudslides developed on escarpments of the inner and outer walls of the Juniper cauldron, contemporaneously with ash-flow tuff eruptions.

Next, the Juniper cauldron was domed by emplacement of the Animas stock during a resurgent stage. Within the ring-fracture zone of the cauldron, the Winkler anticline was probably arched during emplacement of the intrusion encountered by the KCM well. Some faults on the flanks of the anticline may have leaked igneous material, mainly Oak Creek Tuff. Basin Creek Tuff accumulated in the moat and Cedar Hill Andesite formed ring-fracture domes and flows. Volcanism then seems to have shifted to new centers farther south, where the Gillespie and Park Tuffs and associated rocks erupted.

Faulting continued after mid-Tertiary volcanism ceased. The Playas and Animas Valleys subsided relative to the Animas Mountains during Basin and Range faulting, probably beginning in the early Miocene. Elsewhere in New Mexico many of the faults associated with mid-Tertiary volcanic structures were reactivated during that time, just as Laramide faults were reactivated during mid-Tertiary volcanism. For example, the Mimbres fault, east of Santa Rita, was active during Laramide, mid-Tertiary, and Basin and Range episodes.

Basin and Range reactivation may well be responsible for much of the structural relief in the Winkler anticline area. The steeper dips shown on the south side of the Winkler anticline in fig. 4, compared with dips in fig. 5c, reflect Basin and Range tilting. Park Tuff is the youngest dated rock of the Animas Mountains affected by Basin and Range faulting. By the time that basalt, approximately 7 m.y. old, erupted in the San Luis Pass area (unpublished whole-rock K-Ar date by P. E. Damon), structure and relief of the Animas Mountains were essentially as they are today. A similar history has been documented for other volcanic areas of New Mexico, such as the Emory cauldron.

CONCLUSIONS

Over much of Hidalgo County, Laramide tectonic activity and a disturbance between the late Permian and the early Cretaceous are evident, but there is no conclusive evidence for folding of the Winkler anticline before the Oligocene. Of course, pre-Tertiary structures may have influenced later structures. The early stages of folding of the Winkler anticline can be explained by doming above an intrusion into the ring-fracture zone of the Oligocene Juniper cauldron. Later, structural relief was exaggerated by Basin and Range faulting.

REFERENCES

Alper, A. M., and Poldervaart, Arie, 1957, Zircons from the Animas stock and associated rocks, New Mexico: Econ. Geology, v. 52, no. 8, p. 952-971

Bornhorst, T. J., 1976, Volcanic geology of the Crosby Mountains and vicinity, Catron County, New Mexico: Univ. New Mexico, M.S. thesis, 113 p.

Christiansen, R. L., Lipman, P. W., Orkild, P., and Byers, F. M., Jr., 1965, Structure of the Timber Mountain caldera, southern Nevada, and its relation to Basin-Range structure: U.S. Geol. Survey, Prof. Paper 525-B, p. B43-B48

Coney, P. J., 1976, Structure, volcanic stratigraphy, and gravity across the Mogollon Plateau, New Mexico, *in* Cenozoic volcanism in southwestern New Mexico: New Mexico Geol. Soc., Spec. Publ. No. 5, p. 29-41

Elston, W. E., Rhodes, R. C., Coney, P. J., and Deal, E. G., 1976, Progress report on the Mogollon Plateau volcanic field, southwestern New Mexico, No. 3-Surface expression of a pluton, *in* Cenozoic volcanism in southwestern New Mexico: New Mexico Geol. Soc., Spec. Publ. No. 5, p. 3-28

Elston, W. E., Seager, W. R., and Clemons, R. E., 1975, Emory cauldron, Black Range, New Mexico: Source of the Kneeling Nun Tuff: New Mexico Geol. Soc., Guidebook 26th field conf., p. 283-292

Gillerman, E. G., 1958, Geology of the central Peloncillo Mountains, Hidalgo County, New Mexico and Cochise County, Arizona: New Mexico Bureau Mines Mineral Resources, Bull. 57, 152 p.

Lasky, S. G., 1947, Geology and ore deposits of the Little Hatchet Mountains, Hidalgo and Grant Counties, New Mexico: U.S. Geol. Survey, Prof. Paper 208, 101 p.

Lipman, P. W., 1976, Caldera-collapse breccias in the western San Juan Mountains, Colorado: Geol. Soc. America, Bull., v. 87, p. 1397-1410

Seager, W. R., 1973, Resurgent volcano-tectonic depression of Oligocene age, south-central New Mexico: Geol. Soc. America, Bull., v. 84, p. 3611-3626

Smith, R. L., and Bailey, R. A., 1966, The Bandelier Tuff-a study of ash-flow eruption cycles from zoned magma chambers: Bull. Volcanologique, ser. 2, **v.** 29, p. 83-104

Smith, R. L., Bailey, R. A., and Ross, C. S., 1961, Structural evolution of the Valles caldera, New Mexico, and its bearing on the emplacement of ring dikes: U.S. Geol. Survey, Prof. Paper 424-D, p. 145-149

Steven, T. A., and Ratté, J. C., 1965, Geology and structural control of ore deposition in the Creede district, San Juan Mountains, Colorado: U.S. Geol. Survey, Prof. Paper 487, 87 p.

Zeller, R. A., Jr., 1958, Reconnaissance geology of Dog Mountains quadrangle: New Mexico Bureau Mines Mineral Resources, Geol. Map 8

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

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