Oklahoma Geological Survey
Open-File Report 5-96

SOURCE ROCK POTENTIAL AND SEDIMENT THERMAL MATURITY TRENDS IN THE OUACHITA OVERTHRUST OF SOUTHEAST OKLAHOMA AND SOUTHWEST ARKANSAS

REPORT: GE (CD) 01

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Modified Version of Report

March, 1986
5130G

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SOURCE ROCK POTENTIAL AND SEDIMENT THERMAL MATURITY TRENDS
IN THE OUACHITA OVERTHRUST OF
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ABSTRACT

The Ouachita Overthrust of southeast Oklahoma and southwest Arkansas is a relatively unexplored hydrocarbon province. The Lower Ouachita Facies are composed of "starved basin" sediments (Ordovician-Devonian) and exhibit good potential source rock characteristics. The Upper Ouachita Facies are composed of Carboniferous flysch sediments and demonstrate poorer hydrocarbon source potential. This study compiles results of more than 2,000± TOC and 800± thermal maturity analyses of well cuttings, outcrops, and seismic shothole samples in order to evaluate the source rock potential and thermal maturity of this segment of the Central Overthrust Belt. The limited oil and bitumen analyses are also briefly discussed.

Source richness (%TOC) and pyrolysis results (S_2 yield) have been used to identify four source rock intervals within the "starved basin" section. These are the Devonian Arkansas Novaculite, Ordovician Polk Creek Shale, Bigfork Chert and the Womble Shale. TOC for the shaly intervals range from 1.0% to 10.0% with S_2 values as high as 100 Kg/ton (immature sediments). Pyrolysis-gas chromatography techniques show the kerogen assemblages to be predominantly oil prone. The Carboniferous flysch section is poor in source rock characteristics. The organic carbon values range from 0.05% to 1.5% and display neglectible S_2 pyrolytic yield. The hydrocarbon product(s) found in the Ouachitas have been tentatively correlated to their respective source rocks. The correlation supports the suspected source rock intervals.

Regional thermal maturity trends (based on vitrinite or vitrinite-like reflectance values-R_o) relate to the original depth of burial of the sediments as revealed by well data. The least mature (0.5-0.6% R_o) rocks are located in the Frontal Imbricate Thrust Belt where original depth of burial was no more than 8,000'. In the core area, the Arkansas Novaculite measures greater than 4.0% R_o and indicates depths of burial greater than 35,000'.

Sediment thermal maturity profiles [redacted] are similar for the Sohio 1-24 Campbell, Sohio 1-29 Trotter-Dees, Sohio 1-15 Weyerhaeuser, Sohio 1-7 Weyerhaeuser and Vierson-Cochran 1-25 Weyerhaeuser wells. [redacted] The [redacted] vitrinite behavior in the structural framework indicate that the level of maturity is a function of depth of depositional and tectonic burial with a relatively constant geothermal gradient of 1.0-1.1°F/100'. Burial history modeling results are identical to observed R_o values.

We believe that the thermal maturity was set post thrusting (295 mybp) and prior to the doming that resulted in the Broken Bow-Benton uplift (230-200 mybp). Modeling suggests that the generation and migration of hydrocarbons was completed prior to the Broken Bow-Benton uplift event for the more deeply buried (20,000')

section consisting of Lower Mississippian and older rocks. The level of maturity decreases away from the uplifted regions due to diminishing effects of erosion on the domal structure.

INTRODUCTION

The Ouachita Overthrust extends for 1,300 miles from the southern end of the Appalachian Mountains on the east to northern Mexico in the west. The belt is only exposed in two locales: SW Arkansas/SE Oklahoma and the Marathon Uplift in West Texas (Figure 1). All [redacted] samples and further discussion in this report relate to the former.

The allochthonous Ouachita section can be divided into two genetic units. The Cambrian-Devonian section is representative of a "starved basin" type of sedimentation with suspected local anoxic periods. The upper section, Carboniferous in age, represents an active flysch basin. The stratigraphic column for the allochthonous section is displayed in relative time as well as relative thickness of section (Figure 2).

Along the Ouachita trend, only three currently producing fields exist: Isom Springs, McKay Creek, and Thistle (Figure 1). All of these fields are located within the Frontal Imbricate thrust belt and produce from the Devonian-Ordovician section.

[redacted] The purpose of this report is twofold:

1) to identify and quantify potential source rocks;
2) to use regional maturity trends and [redacted] generalized well profiles to assess commercial hydrocarbon potential in the Ouachita trend.

In order to achieve these goals more than two thousand (2,000+) total samples were analyzed for source rock potential. All well cuttings available and pertinent to the study have been analyzed. Extensive surface sampling programs [redacted] have provided surface and seismic shothole samples. [redacted] Data from Matthews (1982) have been included.

METHODS

Formations sampled for source rock evaluation and maturity assessment spanned the entire stratigraphic section of the Ouachita facies. However, sampling was biased toward the Carboniferous flysch section due to outcrop availability, quality, shotline locations, and the location of previously drilled wells. "Starved Basin" sediments (Devonian-Silurian-Ordovician) were collected from their outcropping areas of Black Knob Ridge, Potato Hills, Broken Bow-Benton Core, Cross Mountains, the Trapp Mountains.

Samples were analyzed for source richness (% Total organic carbon), potential productivity (S2 pyrolysis) and maturity (% Ro) using standardized [redacted] methods. Total organic carbon (%TOC) measurements via a Leco Carbon Analyzer for extracted/decarbonated samples or a Rock-Eval Pyrolysis/TOC instrument were made to establish source richness. The potential

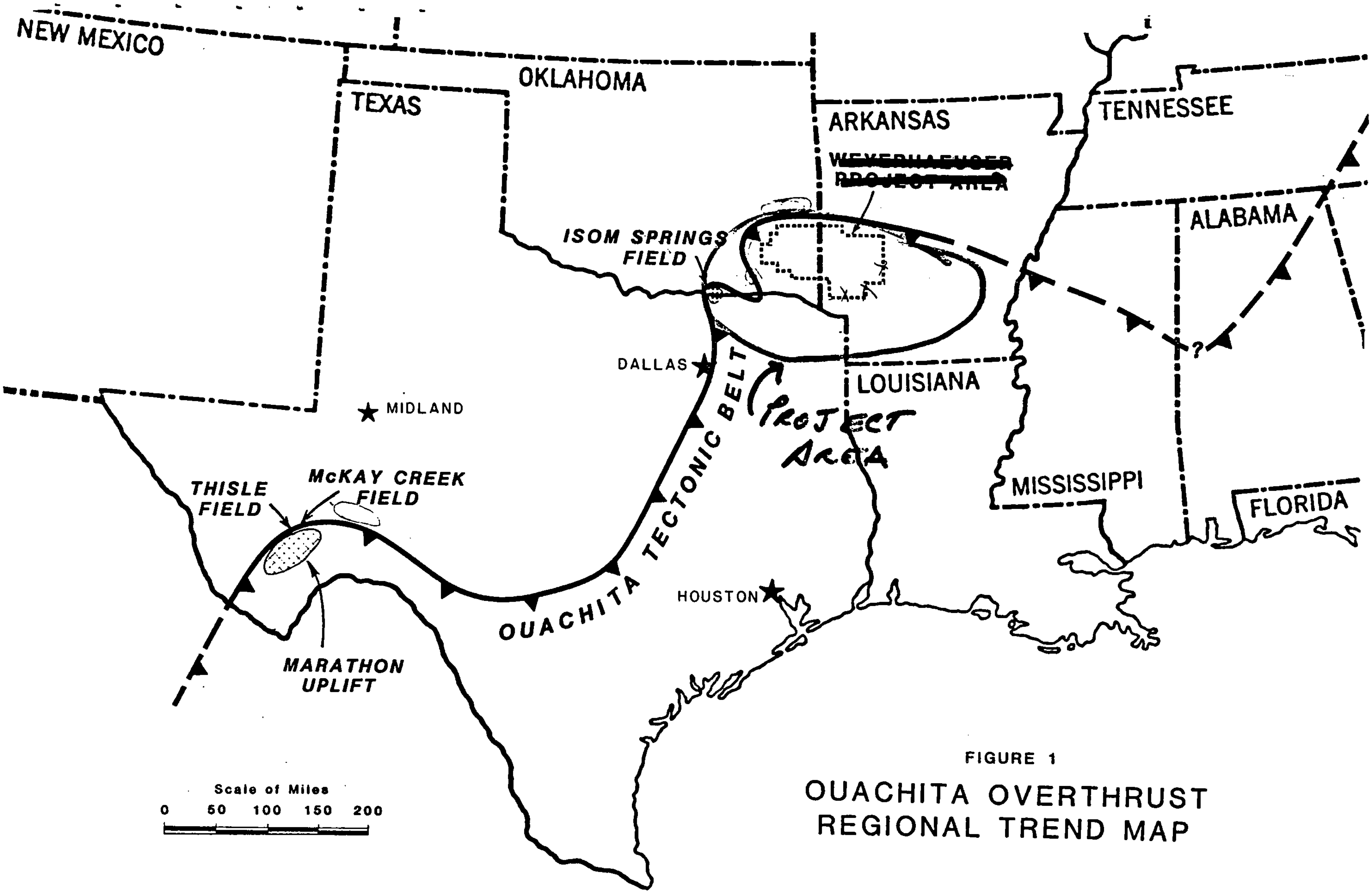
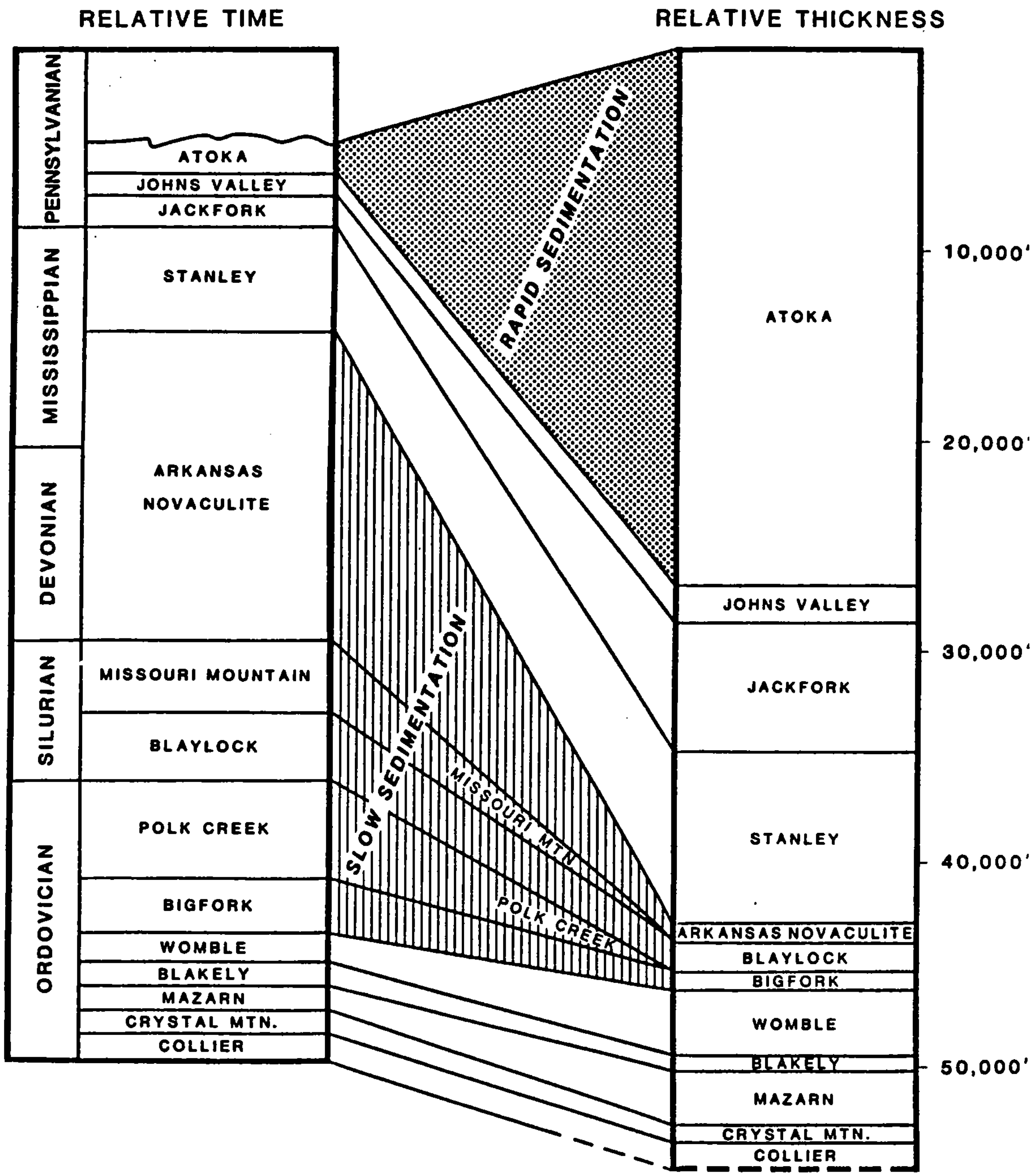


FIGURE 1

OUACHITA OVERTHRUST
REGIONAL TREND MAP



ALLOCHTONOUS OUACHITA STRATIGRAPHIC SECTION SHOWING SEDIMENTATION RATES OF THE PALEOZOIC ROCKS (Modified from Stone, McFarland, and Haley, 1981)

FIGURE 2

productivity of a sample was determined by using the S_2 yield from Rock-Eval pyrolysis. The hydrocarbon proneness (oil or gas) of any interval of interest was assessed by pyrolysis-gas chromatography (PGC) which established the GOGI (gas-oil generation index).

Thermal maturity analyses consisted of organic petrographic determinations (vitrinite reflectance, bitumen reflectance, qualitative fluorescence, and thermal alteration index) to establish the maturity trends and well profiles (Figure 3). Vitrinite (R_o) values were determined for the Devonian and younger samples, but alternative methods were used for lower Paleozoic sediments. Since R_o is measured on the vitrinite maceral (derived from woody plants), it is only useable on sediments of Devonian age or younger since higher vascular plants (wood tissues) had not evolved prior to this time. Within the Ouachita Overthrust samples were collected from sediments older than the Devonian; thus, maturity quantification was more difficult. To measure the maturity on the Silurian and Ordovician sediments, three methods were used:

1) R_o measurement of the solid bitumen (or vitrinite-like) component: At R_o values less than 1.0%, bitumens usually have lower R_o values than the vitrinite component, for R_o values greater than 1.0%, bitumen values are consistent with vitrinite in most cases. In this study bitumens (or vitrinite-like materials) were used to extend the maturity (R_o) profile when comparable to overlying younger strata and for the core area.

2) Qualitative fluorescence: As maturity increases, the fluorescence spectra of the liptinite group shifts from green to red and finally disappears to equivalent R_o values between 1.1-1.2%.

3) Thermal alteration index (TAI): As maturity increases, the color of liptinites (spores, pollens, etc.) become progressively darker. This change in color has been correlated to R_o through all levels of maturity. This is a very subjective analysis.

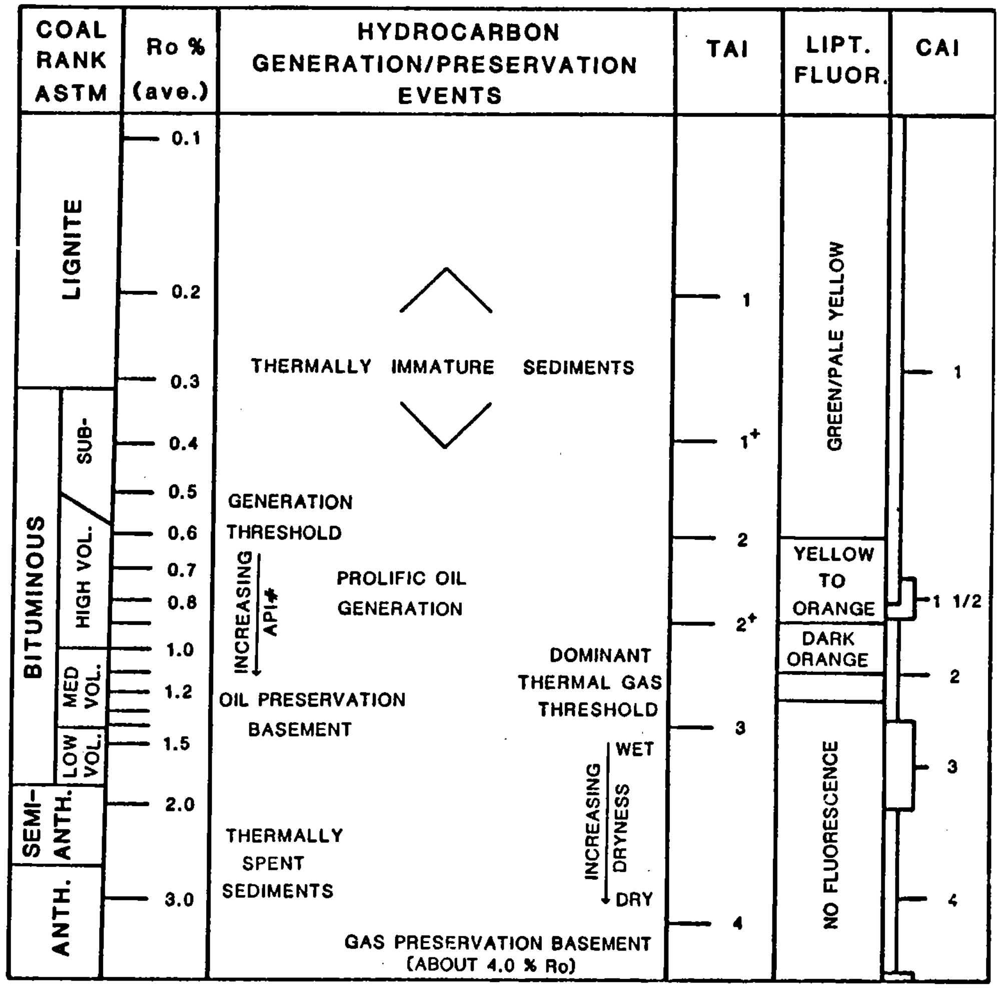
[redacted] Burial history/thermal models were conducted on several wells which used concepts from Waples (1980).

POTENTIAL SOURCE ROCKS

A total of 1354 total organic carbon (TOC) measurements from surface samples have been conducted on the Ouachita Facies of the Weyerhaeuser Contract Area. [redacted] TOC data from well cuttings are not included within this sample set. Figures 4 and 5 graphically illustrate by formation the TOC results for Oklahoma [redacted] and Arkansas, respectively. Interpretation of the results were quantified by using the guide below:

% TOC	Source Richness Terminology
0.5	Poor
0.5-1.0	Moderate
1.0-2.0	Good
2.0-3.0	Very Good
3.0+	Excellent

The Carboniferous flysch section composed 90% analyzed TOC samples with the Stanley Group dominating the sample set. Sampling sites were sparce for the "starved basin" sediments (Ordovician-Devonian) due to the limited outcrop exposure and the weathered nature of the shales. The general results of the TOC analyses are itemized by formation below:



SEDIMENT THERMAL MATURITY PARAMETERS AND CORRELATION

Figure 3

FORMATION/GROUP	SOURCE RICHNESS
Carboniferous flysch Sediments	
Atoka(Lynn Mountain Shale)	Poor to moderate; occasional good zones
Johns Valley Shale	Poor to moderate
Jackfork Group	Poor to moderate; occasional good zones
Stanley Group	Poor
Starved Basin Sediments	
Arkansas Novaculite	Good to excellent in shales
Missouri Mountain/Blaylock	Poor
Polk Creek Shale	[redacted] excellent in the Black Knob Ridge area
Bigfork Chert	Good to excellent in shales
Womble Shale	Moderate to excellent
Mazarn Shale	Insufficient data
Crystal Mountain Sand	Insufficient data
Collier Shale	Poor to moderate

In general, the shales of the Arkansas Novaculite, Polk Creek, Bigfork Chert and Womble are identified as good to excellent source rocks for the Ouachita Overthrust region with respect to TOC weight percent analysis. The Jackfork Group and Atoka could locally provide an adequate source potential.

Two other analytical methods were used to evaluate the potential productivity and oil to gas proneness of the most potential source rocks (Arkansas Novaculite, Polk Creek Shale, Bigfork Chert, Womble Shale). The potential productivity of a sediment is determined by measuring the S_2 yield from pyrolysis [redacted] (Rock-Eval instrument) and is interpreted as follow:

S_2 Yield (Kg/ton)	Potential Productivity
0.5	Poor
0.5-1.0	Poor to Moderate
1.0-2.0	Moderate
2.0-10.0	Good
10.0-20.0	Very Good
20.0+	Excellent

The oil or gas proneness of a sediment is measured using a pyrolysis-gas chromatography [redacted] methods resulting in a gas-oil generation index (GOGI):

	GOGI	Proneness
less than	0.23	oil
	0.23-0.50	mixed oil-gas
greater than	0.50	gas

It should be noted however, that the S_2 yield and GOGI are maturity dependent methods; the most reliable results are determined when maturity is less than 0.8% R_o.

In order to identify the sediments with the best potential productivity and with oil prone kerogen assemblages, the results from studies along Black Knob Ridge and Potato Hills were used. These results were from the Stringtown Quarry [redacted] the Sohio 1-24 Campbell (Section 24-T3S-R11E) well [redacted], and the 1981 field program [redacted]. Figure 6 shows the %TOC, S_2 yield, and GOGI values for the 58' section of Polk Creek Shale at Stringtown quarry. This section contained threshold mature, excellent source richness and potential productivity with oil prone kerogen assemblages. Similar results were found in the Sohio 1-24 Campbell well cuttings and core for the Polk Creek Shale (TOC max.=5.0%; S_2 max.=27.61 Kg/ton). The 1-24 Campbell also contained good to excellent source richness and potential productivity for the Arkansas Novaculite (TOC max.=3.15%, S_2 max.=10.93 kg/ton); the Bigfork Chert (TOC max.=1.16%, S_2 max.=4.62

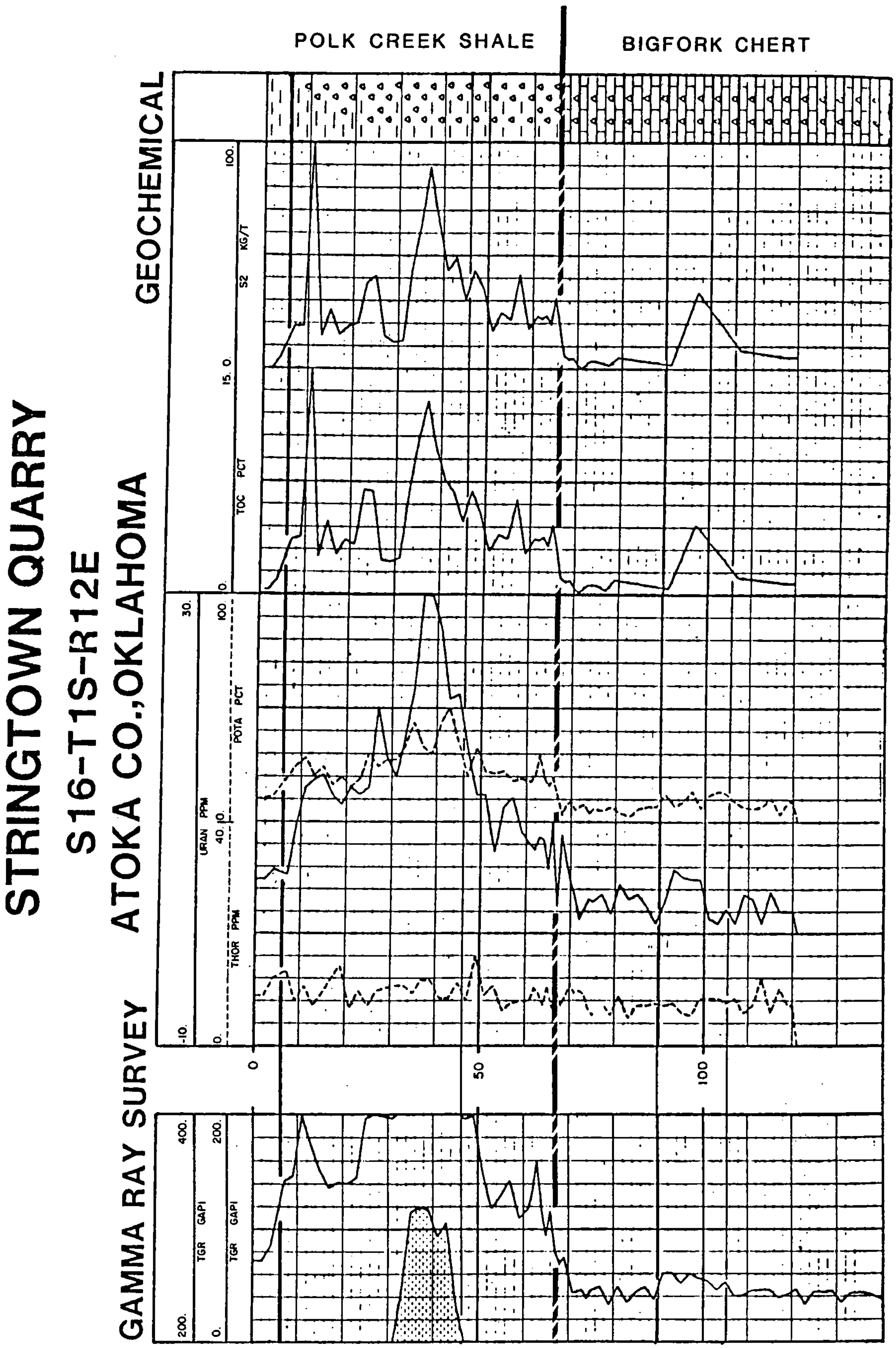

STRINGTOWN QUARRY
S16-T1S-R12E
ATOKA CO.,OKLAHOMA
GAMMA RAY SURVEY
GEOCHEMICAL
POLK CREEK SHALE
BIGFORK CHERT
TGR GAPI
TGR GAPI
THOR PPM
URAN PPM
POTA PCT
TOC PCT
S2 KG/T
0
50
100

FIGURE 6

kg/ton); and the Womble Shale (TOC max.=3.82%, S_2 max.=20.42 kg/ton). All the kerogen assemblages were dominant oil/ minor gas prone.

Analyses of [redacted] field samples [redacted] showed good to excellent source richness and potential productivity for "starved basin" outcrop samples. For example, ~~the~~ one Arkansas Novaculite sample [redacted] from Black Knob Ridge had a TOC of 11.8% and a S_2 of 75.7 kg/ton; ~~the~~ a Bigfork Chert sample [redacted] had a TOC of 12.3% in the frontals in Atoka County. The Potato Hills also displayed similar results where a Bigfork Chert sample [redacted] had a TOC of 7.53% and a S_2 of 34.8 kg/ton and an ~~the~~ Arkansas Novaculite sample [redacted] had a TOC of 15.3%. Similar TOC results were seen in Arkansas in the Benton uplift and Trapp Mountain areas, but with neglectable pyrolytic yield due to the higher thermal maturity of the sediments.

Correlation of the identified source beds to the respective hydrocarbon product has not provided an unquestionable relationship. Oils from the Isom Springs Field in Marshall County, Oklahoma have been compared to total soluble extracts (TSE) from the sediments penetrated in the Westheimer Nuestadt 3 Victor well [redacted] Although some scatter of the data resulted from whole TSE and hydrocarbon fraction $\delta^{13}C$ values for the formational extracts, the Arkansas Novaculite extracts did reflect a superficial resemblance to the produced oils. Some of the scatter in the data has been attributed to the immature nature of the sampled source rocks and to differences in migration histories. The TXO 1-36 Anson (Section 36, T.2S, R.12E, Atoka County, Oklahoma) reflected an obvious correlation to the Isom Springs Field oil samples [redacted]). Although no total soluble extract samples from the proposed source (Arkansas Novaculite) were analyzed in this well, a relationship similar to that observed at Isom Springs could be postulated. Curiale (1981) supports these results and identifies the primary source rocks as the Siluro-Ordovician section (Missouri Mountain Shale, Polk Creek Shale and Womble Shale) based on carbon isotopes, V/Ni ratios, and chromatography. Tables to be added

When the Oklahoma isotopic δC^{13} values are examined and compared to the Arkansas δC^{13} values, the Arkansas asphalt/oil samples suggest a different and younger source (Stahl, 1978). In Oklahoma, the stable carbon isotopic data ($\delta^{13}C$) from the sampled oils (Isom Springs) and asphalts (Black Knob Ridge trend) ranges from -31.2 ppt to - 31.6 ppt and reveals an average of -31.36 ppt. These results tend to demonstrate slightly lighter values than Curiale's (1981) analysis of oils and asphalts from the western portion of the Oklahoma segment of the Overthrust. Curiale's $\delta^{13}C$ range for the seven sampled asphalts was -29.6 to -30.2 ppt, with an average of -29.8 ppt. The $\delta^{13}C$ range for the four sampled oils (Bald, South Bald, Redden, and North Daisy) is -29.7 ppt to -29.9 ppt with a -29.7 ppt. average. The occurence of the oils and asphalts analyzed in the Oklahoma segment ranged in age from Ordovician to Mississippian, but the oils were believed to be from a common source interval (Arkansas Novaculite, Polk Creek Shale, and Womble Shale). Fault planes could serve as conduits to allow hydrocarbon migration from source to reservoir as described by Curiale (1981). This hypothesis is also supported by the occurence of asphaltic material in shot hole samples along the Octavia Fault Trend (along this trend the greater concentration of asphalts (5-10%) in pore space were observed in the shot hole samples were associated to thrust faults).

In Arkansas, the carbon isotopic values of the oil and asphalts sampled in the Sevier Oil & Gas B-1 Nix (Section 1, T.10S, R.30W, Sevier County) and along the Cretaceous Fall Line, respectively, reveal a carbon isotopic average of -25.5 ±0.4 ppt [redacted]. Although the asphalts are highly biodegraded, they do display a sufficiently close isotopic similarity to the B-1 Nix petroleum to propose a common origin. The isotopic range of these asphalts reflect a relative age of post Mississippian to Cretaceous (Stahl, 1978). The stratigraphic position of the oils and asphalts is primarily situated along the Ouachita Facies and basal Cretaceous unconformity. Only the HMB-Quarry sample (Section 11, T.8S, R.30W, Sevier County, Arkansas) suggests a Pennsylvanian aged source. The HMB Quarry asphaltic occurence is situated within the fractured Jackfork sands. Reason would argue that the hydrocarbon would migrate up along the fractured/faulted zone from shales in the Jackfork rather than for the Cretaceous sediments to generate hydrocarbons to the south. The latter scenario would require a forty mile updip migration pathway along a most heterogeneous basal Cretaceous unconformity. The forty mile distance is based on the position of the basal Cretaceous sediments attaining a vitrinite reflectance of 0.6% R_o from the Fall Line to the south.

The results of the 3260'-3800' interval encountered in the Sohio 1-15 Taylor well in Atoka County, Oklahoma lends credibility to the proposed age of the source beds for the asphalts in Arkansas. The interval displayed TOC values greater than 2.0% with correspondingly high S_2 results. Initially thought to be Womble Shale, this interval was defined as Atoka (Pennsylvanian) age by palynology. The carbon isotope value ranged from -25.0 to -26.6 ppt. for the Atoka aged shales [redacted]. The structural and stratigraphic position of this measured Atoka zone in Oklahoma in relation to the oils and asphalts in Arkansas, and the observed isotopic similarities discussed above indicate that the Atoka and Jackfork sections are valid candidates for potential hydrocarbon generating source beds.

Move to Conclusion Section

Source Rock Summary: The formations with the best potential source rock characteristics (good to excellent source richness, potential productivity and oil prone kerogen assemblages) are the Devonian Arkansas Novaculite and the Ordovician Polk Creek Shale, Bigfork Chert and Womble Shale. The Pennsylvanian Atoka and Jackfork sections also contain viable source rocks, but the respective zones would not be as rich as those represented by the lower Ouachita Facies.

REGIONAL MATURITY TRENDS

Surface Data

The sediment thermal maturation for the outcropping Ouachita Facies were determined from samples collected during the 1981 and 1983-1985 field seasons. As referenced in the Methods section of this report, maturities of the sediments were quantified by vitrinite reflectance, qualitative fluorescence, or by the thermal alteration index (TAI). Approximately 600 surface samples were utilized in defining the regional maturity trends in the area of interest.

The resultant map of the maturity study of the Ouachita Facies is provided as Enclosure 1. The maturity values are already plotted and indexed as to data set. [redacted] The isoreflectance contours are constructed by averaging all maturity values within a given township (less the high and low values) and contouring the averaged values. This method is irrespective of formational boundaries and is in part a "pseudo-residual". By averaging the maturity values more areal coverage is provided and a better picture of the regional trends can be established. Locally, maturity values from specific points were utilized to constrain the contours.

The resultant isoreflectance contours of the Ouachita Overthrust were attempted to be tied into the southern flank of the Arkoma Basin. Isocarb maps from Hendricks (1935) and Wilson (1961) display the fixed carbon ratios of the Atoka coal beds (Pennsylvanian). These fixed carbon ratios can be translated into ~~their~~ approximate vitrinite equivalent values for maturity comparison. Except for the westernmost region near Black Knob Ridge, the maturity values, for the Ouachita Facies do not coincide with those from the Arkoma Basin (Lower Atoka) sediments. However, Ro values determined from fixed carbon values can be highly subjective and prone to gross errors for different types and compositions of coal. Although this correlation is uncertain, the Ouachita isoreflectance contours have been drawn to abut against the Choctaw fault to the north. This, in part (if the correlation is accurate), may be due to late stage rejuvenation of the frontal faults by the Broken Bow-Benton Uplifts. This subject will be further addressed later within this report.

The Stanley Group (Moyers and Upper Tenmile Creek formations) bias the sample set. The isoreflectance contours can be considered to be drawn within the Upper Stanley Group. Isoreflectance contours can be drawn specifically on the Moyers/Jackfork formation contact which do coincide with the averaged results of Enclosure 1. Therefore we feel that the averaged data set does support the true thermal gradient as observed on the surface for a particular horizon.

When surface sampling results were compared to well results, the vitrinite reflectance data obtained from seismic shothole samples (80-100' dd) provide more accurate values than the "freshest" obtainable surface samples. This is particularly true within the lower Tenmile Creek formation (lower Stanley Group). Some Tenmile Creek formation samples tended to yeild maturity values (R_o) of 1.5-2.0% less in the "surface samples" as compared to the shothole and well cutting samples. Due to this discrepancy, only the shothole sample data (where available) were utilized for the contouring within the outcrop limits of the Tenmile Creek formation. The general rule that "weathered" samples exhibit a higher vitrinite value than "unweathered" shales as expressed, in part, by Leythaeuser (1973) does not seem to apply at all times to this stratigraphic section and possibly others within the Ouachita Facies. Two possible explanations of this phenomenon within the lower Ten Mile Creek formation are:

1. bad polish of the rocks/organics due to extensive weathering. The organics tend to become very scratched and pitted due to this problem, resulting in low vitrinite values.

2. some organic particles appeared to have absorbed weathering products which decreased the vitrinite values. These organics were hazy with a purplish-gray color, not the clear-gray to white of definite vitrinite particles.

Subsurface Data

In order to obtain the third dimension of the sediment thermal maturity behavior in the Ouachitas, all wells available were sampled and analyzed by SOHIO [redacted] A total of 54 sets of well data were examined in North Texas, SE Oklahoma, and SW Arkansas (Figure 7). The measured thermal maturity for these wells encompass the autochthonous and allochthonous sections ranging in age from Cambrian to Early Cretaceous. From this original set of data 16 wells exhibited excellent data quality and were utilized to establish the standard thermal maturity profile for Ouachita Facies as well as for the deformed foreland basins (see Appendix I). The resultant maturity profile (Figure 8) of this report has utilized a representative sampling of wells based on tectonic setting and stratigraphic sequence to best display the universal fit of the maturity profile for this large region. The maturation profile illustrates that the maturity was primarily influenced by the amount of burial under a relatively "constant" geothermal gradient for the sediments. Two recent papers also reinforce this interpretation for the Ouachita Overthrust.

references need updating

1) Houseknecht and Matthews (1985) concluded that the maturation trends for the Oklahoma portion of the Ouachitas were dominated by sedimentary burial with minor tectonic influenced maturation.

2) Cardott (1985) defined for the Woodford Shale in the Anadarko Basin similar maturity trend where maturity was due to depth of burial with constant geothermal gradients.

The significance of the maturity profile in Figure 8 reveals that the well data, regardless of age, location, thermal maturity, or depth, lies along one major profile. The profile has tentatively tested sediments from the Gulf Coastal Plain (Arkansas); Ouachita Overthrust of West Texas, Northeast Texas, Southeast Oklahoma, and Southwest Arkansas; the marginal deformed Atoka Foreland Basin; the deep Anadorko Basin; and the Illinois Basin (Devonian-Pennsylvanian section). The profile has primarily addressed the Devonian-Pennsylvanian aged rocks, but the entire section from Cambrian to Early Cretaceous seems to coincide quite well to the defined profile. Although more testing of the profile is required to substantiate its reliability away from the Ouachita Overthrust Trend, the data examined to date suggested that the applications of the profile could be extended to the entire mid-continent region. In addition to predicting hydrocarbon windows, the profile could aid in the interpretation of basin sedimentation/development and structural deformation by the detection of un/disconformation and faults, respectively. Continued testing by quality data will either prove or disprove the broad regional applications of this maturity profile.

Analysis of the profile with respect to Ouachita tectonic setting of the wells reflect that the timing of the setting of the sediment thermal maturity occurred post-thrusting of the allochthonous section and prior to the Broken Bow-Benton uplift (also refer to the Burial History Modeling of the report). This is most dramatically demonstrated by the Sohio 1-15 Weyerhaeuser (Section 15-T1S-R20E) and Sohio 1-7 Weyerhaeuser (Section 7-T4S-R23E) well profiles (Figure 9) as well as from outcrop samples in the Arkansas Imbricate Thrust Belt. A constant geothermal gradient would set the sediment thermal maturation purely as a function of depth and time. The Sohio 1-15 Weyerhaeuser proves this point. The 1-15 Weyerhaeuser well cut one of the major Ouachita thrust faults (Octavia) at 7,060'±. The log-determined throw along this fault is estimated to be 5,400'. However, as displayed in Figure 9, no thrust signature is observed on the maturity profile. This phenomena can also be seen at the surface from vitrinite values obtained from seismic shot hole samples (refer to Enclosure I) as well as other well data sets (refer to Appendix I).

The Sohio 1-7 Weyerhaeuser well is situated within the structurally complex Tenmile Creek formation approximately 18 miles northwest of the axis of the Broken Bow Core. The well penetrated repeated sections of the starved basin sediments. The offset segments along the maturity profile for this section demonstrates the thrust faulting quite well. It is postulated that a renewed southeasterly to northwesterly compressional component within the crust resulting from the Broken Bow uplift created a structural overprint on the previously set maturity trends. When compared to the 1-15 Weyerhaeuser well, the 1-7 Weyerhaeuser well demonstrates the Broken Bow uplift event to be post- Ouachita thrusting and post maturity setting of the allochthonous section. The results from the Sohio 1-7 Weyerhaeuser also coincide with the Conoco 1 Moore (4,000' FWL, 500' FSL, G. Kennedy Survey, A-504, Lamar County, Texas) and the Viersen-Cochran 1-25 Weyerhaeuser (Section 25-T5S-R23E, McCurtain County, Oklahoma) wells to reflect this late stage tectonic reactivation. This zone of tectonic reactivation is prevalent within 25 miles of the axis of the uplift (in the Foreland direction) within the lower Mississippian and older sediments. An analogous zone in the hinterland direction has not been documented.

Minor translation of movement from the uplift is also observed in the frontal fault system in the Arkansas segment of the Overthrust. This is best expressed south of the Y-City fault in Yell and Perry Counties as folds reflected by the maturity contours (See Enclosure 1). Also within the Atoka section and after the primary thrust event, late stage thrust motion translated from the Benton Uplift reactivated the frontal faults to generate the phenomenon within the deformed Arkoma Foreland Basin [redacted] of Arkansas and possibly Oklahoma.

In order to tie the observed profile analysis into a regional structural picture, a diagrammatic cross section for S.E. Oklahoma is provided as Enclosure 2. All pertinent well data available have been integrated into this section with respect to structure and geochemical results.

BURIAL HISTORY MODELLING

In order to test the time factor upon the thermal maturation of the sediments and establish the geothermal gradient reflected by the maturity profile, geochemical modelling of the Ouachita Facies was conducted. [redacted] Burial history data was obtained from four sites within the Ouachita Overthrust and utilized for this exercise. Sediments of possible source interest were those of the Arkansas Novaculite (Devonian), Polk Creek Shale (Ordovician), Bigfork Chert (Ordovician) and Womble Shale (Ordovician). The actual modelling was accomplished by using a 60°F surface temperature, an 18°F doubling rate, and a standard 1.0°F/100' geothermal gradient (Houseknecht and Matthews (1985), and Cardott (1985)), for all sites. By using the regression method of Waples (1980), an attempt was made to match observed vitrinite reflectance values (% R_o) to those calculated by the program. By matching the observed R_o values, the thermal conditions to which the sediments were subjected could be approximated. Therefore, a more accurate estimation of the thermal history of the region could be determined and subsequently applied to future well(s) of interest.

The geologic burial histories for four study sites modeled within the Oklahoma Ouachitas are the Sohio 1-24 Campbell, Sohio 1-29 Trotter-Dees, the Glover Bend prospect (Stanley Tectonic Zone) and the Broken Bow Core area.

A simplified synopsis of the burial history utilized for the Ouachita Overthrust is as follows:

a. Womble Shale, Bigfork Chert, and Polk Creek Shale (all Ordovician Age) source rocks deposited from 468 to 395 MYA.

b. Devonian Arkansas Novaculite source rocks deposited from 395 to 350 MYA.

c. Carboniferous flysch section deposited from 350 to 300 MYA. These sediments include the Mississippian Stanley Group and Pennsylvanian Jackfork through Atoka Formations. Thickness of these sediments increase from the Frontal Zone towards the Core Area (Morris, 1976). Thrust event coincident with deposition of middle Atoka.

d. Erosion from 300 to 230 MYA.

e. Broken Bow-Benton Uplift event (major uplift and erosion) from 230 to 200 MYA.

f. Erosion from 200 to 120 MYA.

g. Minor deposition during the Early Cretaceous.

h. Erosion of the Cretaceous cover and continued erosion of Ouachita facies.

The burial history/thermal maturity models for the four Ouachita sites are illustrated in Appendix II. By comparing the calculated Ro values to the observed R_o data, excellent correlation was achieved in almost every case when a 60°F surface temperature and a 1.0°F/100' geothermal gradient was assumed. Table 1 compares the calculated vs. observed R_o data for the four sites.

TABLE 1

SITE	FORMATION	CALCULATED Ro (%)	OBSERVED Ro (%)	AMOUNT OF ARK NOV OVERBURDEN
Campbell 1-24	L.Stan/Ark Nov	.51 at 2,100'	0.5 at 2,250'	7,850'
	L.Bgfk/Womble	.60 at 3,700'	0.6 at 3,870'	
Trotter-Dees 1-29	Stanley	1.0 at 3,900'	1.0 at 3,830'	29,200'
	Stanley	2.0 at 10,800'	2.0 at 10,900'	
	Ark Nov	---	---	
N. Glover Bend (Line 745)	Stanley	3.08 at 1,000'	2.75 to 3.0 at surface	30,000'
Broken Bow (Weyer 1-7)	L. Stanley	4.08 at surface	4.0 at surface	33,000'
	Ark Nov	4.72 at surface	4.5 at surface	35,000'

From Table 1 note the excellent correlation of calculated vs. observed data and the amount of overburden needed to attain these maturities using a 1.0°F/100' geothermal gradient. The thickness of overburden listed is that amount needed to attain the observed/calculated R_0 values for the Arkansas Novaculite. A thickness of 33,000' is needed to generate an R_0 of 4.0% at the core area, but only a thickness 7,850' is needed to generate an R_0 of 0.5% in the frontals. These thicknesses are compatible with postulated sedimentary and tectonic overburden occurring in the listed area (refer to Figure 2).

COMMERCIAL HYDROCARBON POTENTIAL

We have identified the potential source rocks and the regional maturity profile for the Ouachita facies. In order to assess these geochemical parameters and their impact upon hydrocarbon exploration in the Ouachita Overthrust of Oklahoma, we have defined five (5) major zones:

1. Frontal Imbricate Thrust Belt
2. Potato Hills/Kiamichi Anticline
3. Interior Foldbelt /Athens Plateau
4. Core Area
5. Subcropping Athens Plateau.

Enclosure 3 displays these geochemical trends somewhat oblique to the structural strike of the overthrust belt. This is due to the variable depositional/tectonic thickness of the Carboniferous flysch section and to the oblique orientation of the late stage Broken Bow-Benton uplift event. The maturity decreases from the core towards the Frontal Imbricate Thrust Belt and towards the eastern portion of the Athens Plateau. This is in part due to original burial depth and exposure of the deeply buried sediments by the uplift.

ZONE 1 - Frontal Imbricate Thrust Belt

The frontal zone of the Ouachita Overthrust includes the faulted and/or folded strata between the Choctaw and Jackfork Mountain, and Lane fault systems, which represent a 10-18 mile wide (dip measured) belt of rocks (Enclosure 3). Zone 1 encompasses the entire Ouachita stratigraphic section from Ordovician (Womble) to Pennsylvanian (Atoka). This belt is structurally composed of steep imbricate thrust faults with some minor folding. The general surface maturity values range from 0.5 to 0.7% R_0 in a south to northeasterly direction. The slight increase of maturity within Zone 1 is attributed to an increasing Atoka thickness to the east.

Utilizing the maturity profile of Figure 8 and a mean surface vitrinite value of 0.6% R_o, one can project downward and estimate the depth to oil and gas thresholds within this belt as seen in Table 2.

TABLE 2
Projected Hydrocarbon Windows Within The
Frontal Imbricate Thrust Belt: Zone 1

Hydrocarbon Threshold		Projected Depth
Oil Generation Window	(0.6-1.0% R_o)	Surface-5,250'
Gas Generation Threshold	(1.0% R_o)	5,250'
Oil Preservation Basement	(1.3% R_o)	8,000'
End of Gas Generation/ Spent Source Rocks	(2.0% R_o)	12,000'
Gas Preservation Basement	(4.0% R_o)	19,500'

Given an oil prone source rock (Arkansas Novaculite, Polk Creek, Womble) above a depth of 8,000', oil would represent the primary hydrocarbon to be exploited. Gas prospects would be expected from 8,000' to 19,500' from surface utilizing average vitrinite reflectance of 0.6% R_o. A depth of 19,500' may not encompass the stratigraphic section below the Ouachita decollement. However, the Atokan and older aged sediments contain producing gas reservoirs within this area. When these theoretical results are compared to actual occurrences of hydrocarbons, the projected results coincide with Ouachita field discoveries. As seen on Enclosure 3, the majority of the discovered fields are found within this zone. These fields produce oil from the Stanley sands from a depth of 200'+ with past production ranging from 0.5-3.0 BOPD. Curralie (1981) examined the asphaltites of this zone and geochemically concluded that the grahamite deposits were not thermally derived, but suggested a mechanism of biodegradation, oxidation and water washing of oil to generate these surface asphaltites. Curralie (1981) also established that the source rocks for these observed oil occurrences to be starved basin sediments (Arkansas Novaculite, Polk Creek, Womble). The inferred depths to these source rocks, confined within the geochemical constraints, allows the generation of oil to a depth of 8,000'. Subsequent migration along faults (Curralie, 1981) would bring the oil to the Stanley reservoir sands.

It is also interesting to note that the oil fields found with the best potential in the Ouachita Overthrust (McKay Creek and Thistle in West Texas, Isom Springs in southern Oklahoma) are found within the Frontal Imbricate Thrust Zone. We feel that this is primarily due to the relatively thin Carboniferous overburden, keeping the rocks within the oil generation window. Also, the structural setting is most favorable for the development of secondary fracture porosity within the chert section of the lower Arkansas Novaculite (Devonian) and Bigfork Chert (Ordovician).

In summary, the Frontal Imbricate Thrust Belt displays the best potential for oil and/or gas production. Depth from a mean surface 0.6% R_o value to oil preservation basement is 8,000'. Gas can theoretically be preserved to a depth of 19,500'. Source rocks for oil and related oil entrapment would be exploited in Atoka, Bryan and Marshall Counties, Oklahoma. Southeast Pittsburg and southern Latimer Counties, Oklahoma would be a prospective area for gas fields utilizing the Stanley, Jackfork and or Atoka rocks as source and reservoir. The only cautionary statement to be made within this area is toward immature source rocks in the allochthonous section (e.g. Sohio 1-24 Campbell and the Sohio 1-15 Taylor).

ZONE 2 - The Potato Hills/Kiamichi Anticline

Zone 2 lies immediately to the south and east of the Frontal Imbricate Thrust Belt. This zone is comprised of the structural elements of the Tuskahoma Syncline, Faris Syncline, Jumbo Anticline, Kiamichi Anticline, Potato Hills and the western portion of the Lynn Mountain Syncline in Oklahoma. Dominant surface outcropping formations are the Stanley, Jackfork, and Atokan (Carboniferous). The structurally anomalous Potato Hills represents exposure of the Womble (Ordovician) through Stanley (Mississippian) section. We believe the Potato Hills to be a duplex structure overriding a Jackfork-Stanley section at depth. The remaining structures are relatively uncomplicated broad synclines and narrow anticlines composed of Carboniferous flysch.

The average surface thermal maturity for this region ranges from 0.6-0.85% R_o. Utilizing an average R_o value of 0.7% and applying the maturity profile of Figure 8, we can again project downward to define the hydrocarbon thresholds. Table 3 reveals the results of these downward projections.

TABLE 3
PROJECTED HYDROCARBON WINDOWS WITHIN THE
POTATO HILLS/KIAMICHI ANTICLINE: ZONE 2

HYDROCARBON THRESHOLD	PROJECTED DEPTH
Oil Generation Window (0.6-1.0% R_o)	Surface - 3,250'
Gas Generation Threshold (1.0% R_o)	3,250'
Oil Preservation Basement (1.3% R_o)	6,500'
End of Gas Generation/Spent Source Rocks (2.0% R_o)	11,000'
Gas Preservation Basement (4.0% R_o)	18,000'

As shown in Table 3, oil generation would be viable down to 3,250' with preservation to a depth of 6,500'. Gas generation would be initiated at 3,250' and be theoretically preserved to a depth of 18,000'. The geochemical results observed are consistent with actual well results. The starved basin sediments (Arkansas Novaculite, Polk Creek Shale, Bigfork Chert and Womble Shale) range in depth from surface outcrop to 15,000'. Oil is found in Potato Creek, Jumbo Anticline and Moyers Field at shallow depths (500') in the Stanley sands. Jumbo Field's Novaculite and Bigfork Chert tests (US Mineral 1-16 Brame (Section 16-T2S-R15E) and U.S. Mineral 1 Denton Perrin (Section 9-T2S-R15E)) discovered gas from perforations ranging from 6,588' to 9,250' dd. These wells are currently shut in with a IPCAOF of up to 3600 MCFPD. The observed field results coincided with predicted results.

The Sohio 1-29 Trotter-Dees well on the Kiamichi Anticline displayed oil staining and C_3 component in the gas shows down to a depth of 5,830'. A significant gas show was encountered at 6,436' and tested 1.23 MMCFPD. Below this gas show no further oil staining or gas shows with the C_3 gas component were observed.

The anomalous Potato Hills structure continues to be anomalous with respect to the hydrocarbon type verses depth. The Sinclair 1 Reneau and Wyoming 1 Allen tested gas in the Bigfork Chert at perforating depths of 2,340-410' and 2,787-3,195', respectively. Theoretically, based on profile analysis and source rock character (oil prone), these two wells should have tested oil. However, due to the duplex structuring of the Potato Hills the gas may have been generated by the Stanley-Jackfork section at depths below 6,000' and migrated upward into the Bigfork reservoir.

In summary, the well data in the Potato Hills/Kiamichi Anticlines generally matched the predicted geochemical results. This zone is conducive to gas plays utilizing the Arkansas Novaculite and Bigfork Chert as reservoirs. The gas window ranges from 3,250' to 18,000'. Minor Stanley oil prospects do hold some interest for depths above 6,500'. However, due to the nature of the Stanley reservoir (low permeability) and field production results to date, oil would have to be considered as a secondary objective in any economic calculations unless a quality reservoir could be identified.

ZONE 3 - Interior Foldbelt/Athens Plateau

The Interior Foldbelt encompasses the area south of the Kiamichi Anticlinal Trend to the Stanley Tectonic Zone (proximal to the Core Area) and the eastern exposed portion of the Athens Plateau in Arkansas. The major structural elements seen within this zone are the Bethel Syncline, Boktukola Syncline, Big One Anticline, Cloudy Syncline, Athens Plateau's Imbricated Jackfork Thrust Sheets, eastern portion of the Lynn Mountain syncline and the edge of the frontals in Polk County, AR and southern LeFlore County, OK (Enclosure 3). The zone is composed of Carboniferous flysch (middle-upper Stanley, Jackfork, and Atoka). The starved basin sediments (Arkansas Novaculite, Polk Creek, Bigfork Chert, and Womble Shale) are believed to be at least 18,000' below surface in Oklahoma, and locally somewhat shallower in Arkansas (e.g. SWEPI 1-26 Arivett well) near the core area.

The range of surface thermal maturation for this zone ranges from 0.85% R_o in the western segment of the zone to 2.0% R_o in the eastern portion. The increased maturity trend to the south and northeast within Oklahoma and to the west in the Athens Plateau is attributed to combined effects of the Broken Bow-Benton Uplift events (bringing deeply buried sediments to the surface) and increased depositional thickness of the Atoka formation in LeFlore County. The Atoka deposition pre-dated the Broken Bow Uplift.

Utilizing an average surface maturity value of 1.1% R_o for this zone, Table 4 displays the results of the downward maturity projections and resident hydrocarbon windows.

TABLE 4
PROJECTED HYDROCARBON WINDOWS WITHIN THE
INTERIOR FOLDBELT/ATHENS PLATEAU: ZONE 3

HYDROCARBON THRESHOLD	PROJECTED DEPTHS
Oil Generation Window (0.6-1.0% R_o)	Eroded
Gas Generation Threshold (1.0% R_o)	Eroded
Oil Preservation Basement (1.3% R_o)	2,000'
End of Gas Generation/ Spent Source Rocks (2.0% R_o)	6,500'
Gas Preservation Basement (4.0% R_o)	13,500'

Based on the average 1.1% R_o maturity, Zone 3 represents a predominant gas type play. Within the large synclines of Oklahoma, the Atoka/Jackfork sediments exhibit maturity values of 0.8% R_o at the surface and could be favorable as an oil play based on our proposed maturity profile analysis and the presence of oil prone kerogens. The Athens Plateau of Arkansas would be less optimistic due to its overall higher maturities.

Examination of the Sohio 1-15 Weyerhaeuser well (Section 15-T1S-R20E), situated on the hanging wall of the Octavia fault, reveals gas shows from 1,500' to 11,880'. No oil shows were observed, nor logged. The Unlimited, Ltd. 27-221 Weyerhaeuser well (Section 27-T2S-R21E) tested the Pickens anticline and reported gas shows from 7,344' to 10,267' with the best show at 7,344' to 7,412'. Surface vitrinite values for these two wells are 0.85% and 1.1% R_o, respectively. The SWEPI 1-26 Arivett (Section 26-T5S-R25W, Pike County, Arkansas) failed to log any reliable hydrocarbon shows. This is in part due to an extremely lean Stanley source potential. This well also spudded in more mature sediments (1.65% Ro) and thus the hydrocarbon window was only viable down to 2500' (Ro = 2.0%). These wells coincide with the maturity profile results and interpretation.

In summary, the Interior Foldbelt/Athens Plateau represents a gas play with a minor potential for oil in the broad synclines of Oklahoma and only a gas play within the Athens Plateau. The gas prone, although poor to marginal source, Stanley would have to be the predominate source reservoir seal package for establishing any substantial reserves. An alternative to the Stanley source scenario lies with gas generation occurring deep in the section (Ordovician-Devonian) and migrating into Stanley reservoirs. However, the poor reservoir character found within the Stanley sands to date decreases the potential of this zone. The Jackfork or Atoka have not been tested. Little or no potential exists within the Arkansas Novaculite-Bigfork Chert package. Depth of drilling and resulting thermal maturity are the primary components which downgrade the Lower Paleozoic section. We propose a surface 1.3% R_o value as a cut-off for any active exploration within this zone.

ZONE 4 - Core Area

The core area is defined by the exposed starved basin sediments and the lower Stanley sands and shales adjacent to the structural uplift (Enclosure 3). This area is separated from the Interior Foldbelt of Oklahoma by the Buffalo Creek Fault. The Cross Mountains and the Trapp Mountains as well as the associated outcropping lower Stanley Group are included within Zone 4. The 2.0% isoreflectance contour serves as the boundary. The stratigraphic section represented ranges from Collier (Ordovician) to middle Stanley-lower Tenmile Creek formation (Mississippi). The currently defined edge of the Broken Bow-Benton Uplift is represented by the outcropping Arkansas Novaculite within the region. However, within this report, we will include the lower Stanley Group (Tenmile Creek Fm) as part of the structural uplift. In Oklahoma and Northeast Texas the late stage structural event, the Broken Bow Uplift, trends N 40°E and continues into Arkansas as the Benton Uplift trending N 75°E up to the edge of the Mississippi Embayment/Reelfoot Rift. From this point east, the Benton trend is orientated N 60°W. Results of wells drilled along this major trend coincide with the surface data in the exposed core area.

The surface sediment thermal maturation for this zone range from 2.0 to 5.0+% R_o (Solid bitumen R_o values for Ordovician Womble and Bigfork Chert sediments were 5.0%). In some cases; vitrinite R_o data for sparce Arkansas Novaculite (Devonian) samples attained values of 6.0% R_o [redacted]

[redacted] Due to the decreasing amount of thermal energy required to increase the maturity values (R_o), the relative sedimentation thickness required for rapid increases in sediment maturity would not be as great as those needed to increase the maturity at lower levels (i.e. an R_o of 4.0% could be increased to 5.0% with less temperature than 0.5% to 1.5% required). Therefore, although the range within this zone appears to be quite large, it only represents 9,000' of stratigraphic section as defined by the maturity profile and stratigraphic section. Utilizing the average surface maturity of 3.0% R_o, Table 5 exhibits the results of the downward maturity projections and resident hydrocarbon windows.

TABLE 5
PROJECTED HYDROCARBON WINDOWS WITHIN THE CORE AREA: ZONE 4

HYDROCARBON	PROJECTED DEPTHS
Oil Generation Window (0.6-1.0% R_o)	Eroded
Gas Generation Threshold (1.0% R_o)	Eroded
Oil Preservation Basement (1.3% R_o)	Eroded
End of Gas Generation/Spent Source Rocks (2.0% R_o)	Eroded
Gas Preservation Basement (4.0% R_o)	2,750'

Given that the Broken Bow Uplift was a late stage thrust related crustal event, reactivation along faults and superimposed folds are common within the zone. This reactivation of faults could destroy any sealing mechanism. The fault reactivation is displayed in the Frontal Imbricate Zone of Arkansas. Sparce surface vitrinite reflectance measurements adjacent to the Y-City and Panther Creek Faults in Arkansas show indications of rejuvenation structural attitudes in the northeast section of Enclosure 1. Another case in point is the Highway 259 road cut, 1 1/2 mile south of Mt. Herman. This lower Stanley road cut displays a sharp contrast in maturity across an unnamed fault. The north block of the fault exhibits average maturity values of 4.36% R_o and the south block reveals average values of 2.65% R_o [redacted]. Fault reactivation would serve as the proposed mechanism for the estimated 7,500' of displacement observed between these two fault blocks. The Conoco 1 Moore, Sohio 1-7 Weyerhaeuser and Viersen-Cochran 1-25 Weyerhaeuser wells also show similar fault offsets (defined by maturity and structure) in the subsurface (refer to Appendix I). Each of these wells failed to produce any acceptable show of hydrocarbons and were plugged and abandoned.

Houseknecht and Matthews (1985) have proposed that the plutonic activity along the western edge of the Reelfoot Rift resulted in thermal overprints of the exposed core area of the Ouachitas in Pulaski County, Arkansas. The age dating of the intrusives reveal a Cretaceous timing of these features (Kidwell, 1951 and Zartman, et al, 1967). This timing would be consistent with the proposed modeling sequence. Due to the sparsity of data in the effected region only vague statements can be drawn at this time. However, this hypothesis could be viable. The Magnet Cove intrusive (Sec. 21, T.3S, R.17W, Hot Spring County, Arkansas) represents a similar aged event and does reflect a decreasing maturity away from the intrusive body (Keller, 1985). The intrusive bodies in the region as defined by outcrop and gravity (Hendricks, et al, 1981) are shown on Enclosures 1 and 3.

In summary, the sediments of the core area of the Broken Bow Uplift would have to be considered as non-prospective for hydrocarbon exploration. At present, the gas preservation limit is about 3.2 to 4.0% R_0 (Dow and O'Connor, 1981; Robert, 1981; van Gizel, 1982). The effects of the high maturities and limited section in which to explore would fail to produce any substantial gas reserves. Even if a structure was identified within the gas preservation window, the late stage structural overprint could destroy the integrity of any sealing mechanism. Also, quartz veining seems to be related to a $R_0 \geq 2.0\%$, (Compare to Miser's quartz veining map) thus the quality of the reservoir would be highly suspect with this zone. We believe that the high maturities and limited section, structural rejuventation, and reservoir destruction probably precludes any substantial gas reserves.

ZONE 5 - Subcropping Athens Plateau

The subcropping Athens Plateau represents the portion of the Overthrust covered by Mesozoic aged rocks immediately south of the exposed Athens Plateau in southwest Arkansas. This zone is somewhat similar to Zone 2 in Oklahoma, except the mean thermal maturity of the Carboniferous flyset is somewhat higher (±0.9% Ro). The area is structually defined by imbricated thrust and folded thrust sheets as revealed by seismic and residual gravity studies. To the west in Little River and Sevier Counties, the thrust sheets become broken by tear faults/lateral ramps.

Utilizing an average top Ouachita facies maturity value of 0.9% Ro, Table 6 reveals the result of the downward maturity projections and resident hydrocarbon windows.

TABLE 6
PROJECTED HYDROCARBON WINDOWS WITHIN THE
SUBCROPPING ATHENS PLATEAU: ZONE 5

HYDROCARBON THRESHOLD	PROJECTED DEPTHS*
Oil Generation Window (0.6-1.0% Ro)	0-1000'
Gas Generation Threshold (1.0% Ro)	1,000'
Oil Presentation Basement (1.3% Ro)	4,000'
End of Gas Generation/Spent Source Rocks (2.0% Ro)	8,500'
Gas Preservation Basement (4.0% Ro)	15,500'

*below top of subcropping Ouachita Facies

The hydrocarbon potential of Zone 5 is defined from maturity analyses of well cuttings from 4-5 wells (refer to Figure 7) [redacted]. Only one of these wells had a significant hydrocarbon show. The remaining wells did not have reported shows.

The Evergreen Oil and Gas B-1 Nix well (Section 1-T.10S., R.30W, Sevier Co., Arkansas) encountered 20° API gravity oil at the Cretaceous/Ouachita unconformity. Maturity values from this interval in the Jackfork Group were measured at 0.9-1.0% Ro. [redacted] Carbon isotope work was conducted on the oil and similarly stratigraphic positioned asphalts occurances along the Cretaceous Fall Line, 10-15 miles to the north (refer to Enclosure 1). The carbon isotopic profiling strongly suggested a generic relationship between the residual asphalts and the thermally mature, non-biodegraded oils. [redacted]. The relative age of this oil ranges from late Paleozoic to Cretaceous. However, the lower Cretaceous section in this region is immature and the potential for the oil to have migrated updip from the more mature Cretaceous shales in the south to this locale is not realistic. Thus, the oil is believed to have been generated from the shales in the Jackfork and migrated updip to the leaky basal Cretaceous "seal". Structural and stratigraphic settings of the asphalts along the Fall Line in the HMB Quarry (Sec. 11, T.30W R.8S) also support this conclusion.

In summary, the sparce, but widely distributed well data and isotopic analyses of hydrocarbons support the Zone 5 hydrocarbon potential for oil and gas. The Jackfork and Atoka sections would represent the potential source/reservoir/ trapping components of a sub-Cretaceous play. Oil would be expected to a depth of 4000' and gas would be viable to a depth of 8500' below the top Ouachita unconformity.

<u>CONCLUSIONS</u>

1. Extensive outcrop, shothole, and well sample collections have identified potential source rocks within the Ouachita Overthrust of Oklahoma and Arkansas. The formations with the best source rock characteristics (TOC 1.0%; S_2 2.0 kg/ton where R_o=1.0%) were the Devonian Arkansas Novaculite and the Ordovician Polk Creek Shale, Bigfork Chert and Womble Shale. TOC values in some samples exceeded 10% TOC and 100 kg/ton S_2 yield (where immature). These samples also contained oil prone kerogen assemblages.

   The Carboniferous flysch series (Stanley Group-Jackfork Group Atoka) were generally poor in source rock characteristics. TOC values were usually 0.5% with no S_2 yield. However, local horizons of the Jackfork and Atoka did contain moderate to good source richness and may provide an adequate source.

2. Correlation of identified source beds to their respective hydrocarbon product have produced inconclusive results. However, two different aged source rock packages have been identified by carbon isotopic analysis. Early Paleozoic sources, were assigned to the majority of the Oklahoma oils and asphalts observed; whereas a late Paleozoic/Cretaceous(?) aged source(s) has (have) provided the hydrocarbons found in Arkansas to date. These results were in agreement with the structural and stratigraphic interpretations for each of the areas.

3. The four major well sites for the Oklahoma Ouachitas had similar maturity gradients implying that the geothermal gradient was constant throughout the region. This conclusion was also observed in for Arkansas. The higher maturities, therefore, were caused by deeper depths of burial. Other conclusions that can be made are:

   a. The maturity values were set post-thrusting during Middle Atoka time.

   b. Maturities were caused by depth of burial only. We believe that no heating event was involved during the Broken Bow-Benton Uplift. However, some Cretaceous aged plutons may have affected the eastern end of the exposed Benton Uplift.

c. Since the maturities of the Cretaceous, Desmoinesian, and Atoka-Foreland intervals have similar profiles, we can conclude that the geothermal gradient of 1.0°F/100' was constant from Mississippian time to present. (Geothermal gradients from wells ranged from 0.95 to 1.05°F/100'.)

4. The general maturity/depth profile can be utilized to determine faulting, and to predict maturity from any point of reference.

5. Sediment maturities greater than 2.0% Ro result in a substantial decrease in reservoir quality due to quartz overgrowths and quartz veining. This is observed in outcrop and in well cuttings.

6. The best prospects for oil to wet gas would be located along the Ouachita Frontals (Zone 1), the Potato Hills/Kiamichi Anticline (Zone 2), and the Subcropping Athens Plateau (Zone 5). The least prospective region is the Core Area (Zone 4) of the Broken Bow-Benton Uplift.

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APPENDIX I

Maturity Profiles of Significant Wells Located Along the Ouachita Overthrust and adjacent Tectonic Region of NE Texas, SE Oklahoma and Central Arkansas.

CONTENTS

NE TEXAS

Conoco #1 Lloyd Moore Lamar County	Stanley-Bigfork Core Area
Gulf #1 Steel Grayson County	Frontal Thrust Belt
Texaco #1 Moore Grayson County	Frontal Thrust Belt
[redacted]	[redacted]
Wayne Harper #1-A Shaw Collin County	Frontal Thrust Belt
Humble Oil & Ref. #1 Miller Collin County	Foreland Basin

OKLAHOMA

Sohio #1-15 Taylor Atoka County	Stanley-Womble/Atoka Frontal Thrust Belt
Sohio #1-24 Campbell Atoka County	Stanley-Womble Frontal Thrust Belt
[redacted]	[redacted]
Quinton Little #1-18 King Ranch Bryan County	Frontal Thrust Belt
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

OKLAHOMA (CONT.)

[redacted]	[redacted]
[redacted]	[redacted]
Getty #1-20 Morris Pushmataha County	Stanley-Jackfork Interior Fold Belt
Sohio #1-29 Trotter-Dees Pushmataha County	Jackfork-Mo. Mtn. Interior Fold Belt
[redacted]	[redacted]
Sohio #1-15 Weyerhaeuser Pushmataha County	Stanley Interior Fold Belt
Viersen-Cochran #1-25 Weyerhaueser McCurtain County	Womble + Older Section? Core Area

ARKANSAS

Sheraton #1 Bean Clark County	Stanley Stanley Tectonic Zone
Tom Ray #1 Harris Hempstead County	Carboniferous Interior Imbricate
Sinclair #1 Douglas Hempstead County	Desmoinesian-Jackfork Interior Imbricate
[redacted]	[redacted]
[redacted]	[redacted]
SWEPI #1-26 Arivett Pike County	Stanley-Blaylock Stanley Tectonic Zone

CONOCO INC.
NO. 1 LOYD MOORE
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SOHIO PETROLEUM GEOCHEM
JOB NO. PGW/TM 132
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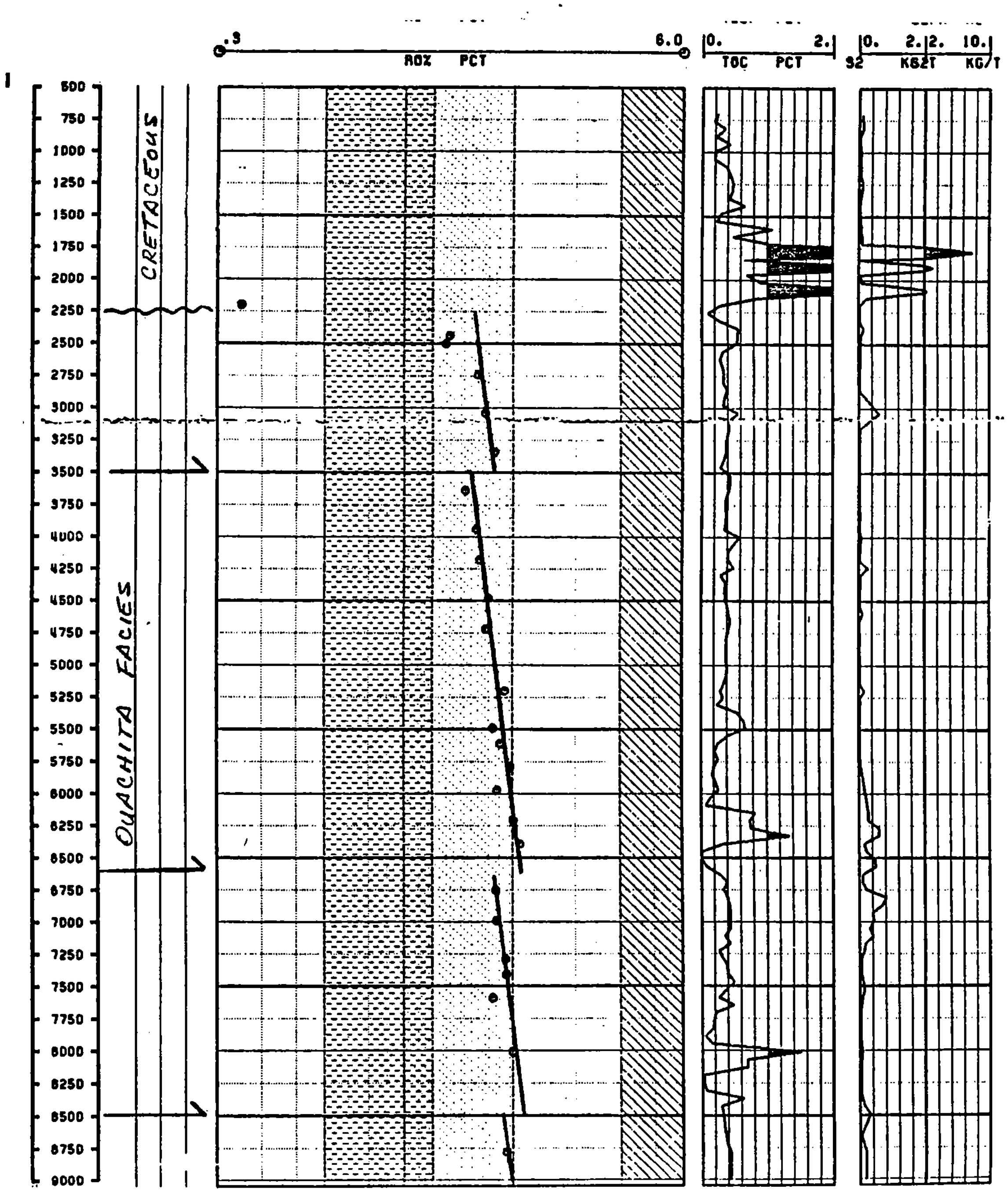

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NO. 1 NINA STEEL
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SOHIO PETROLEUM GEOCHEM GROUP
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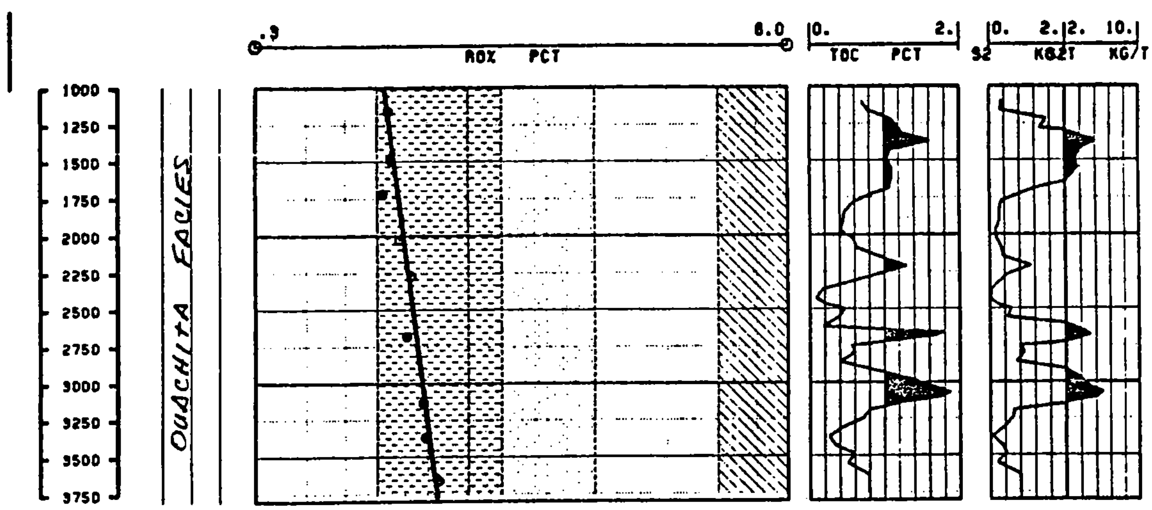

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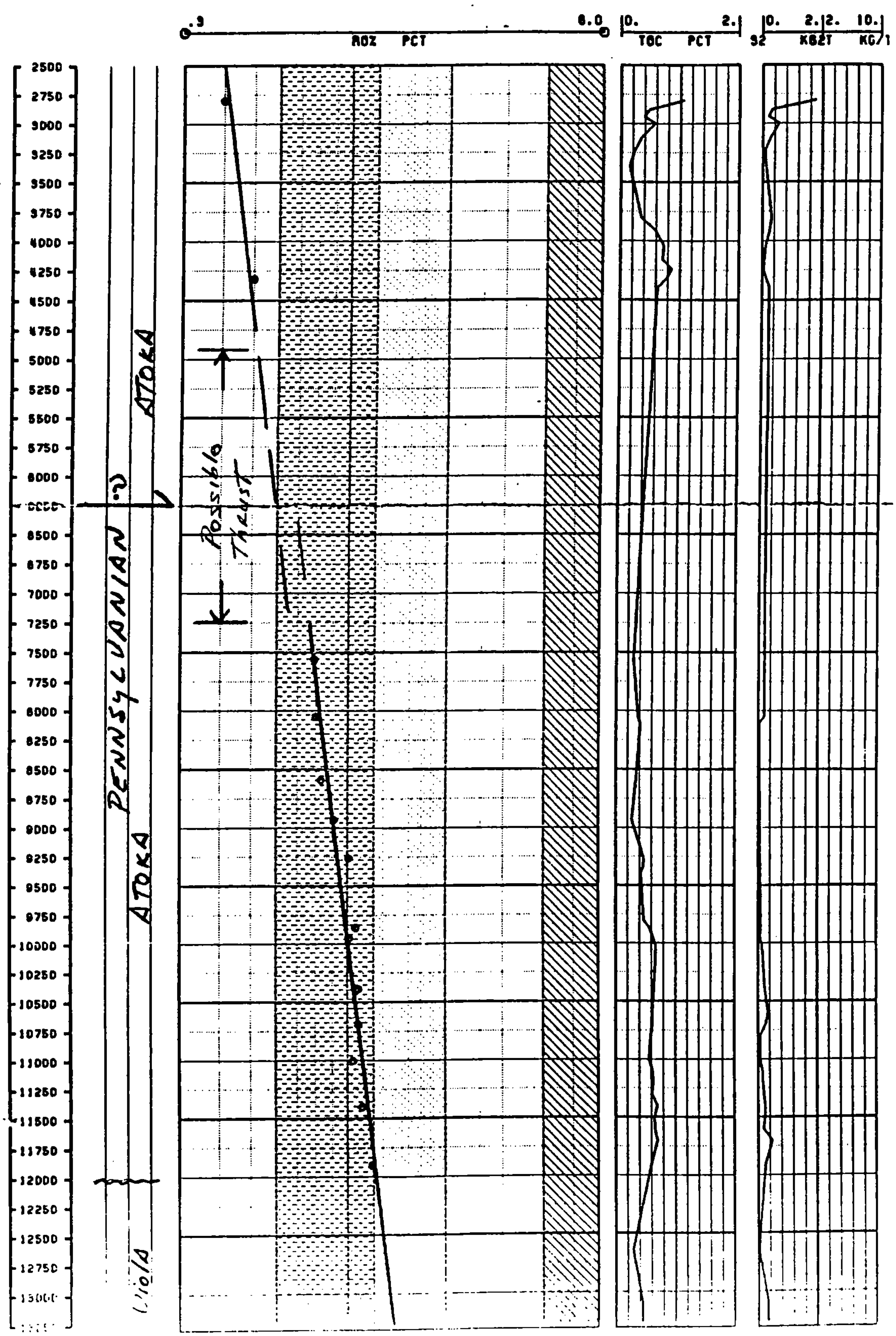

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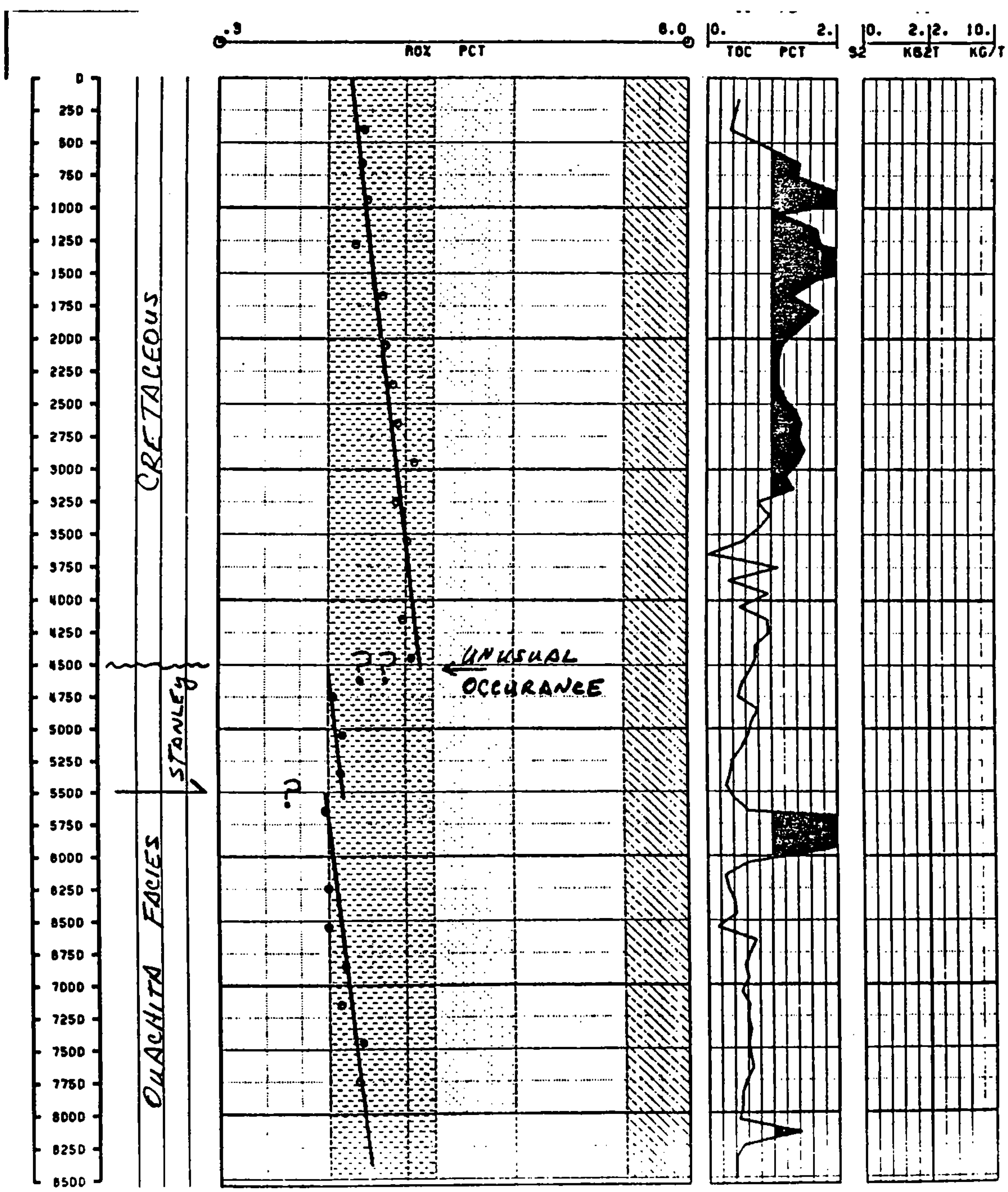

HUMBLE OIL AND REFINING CO.
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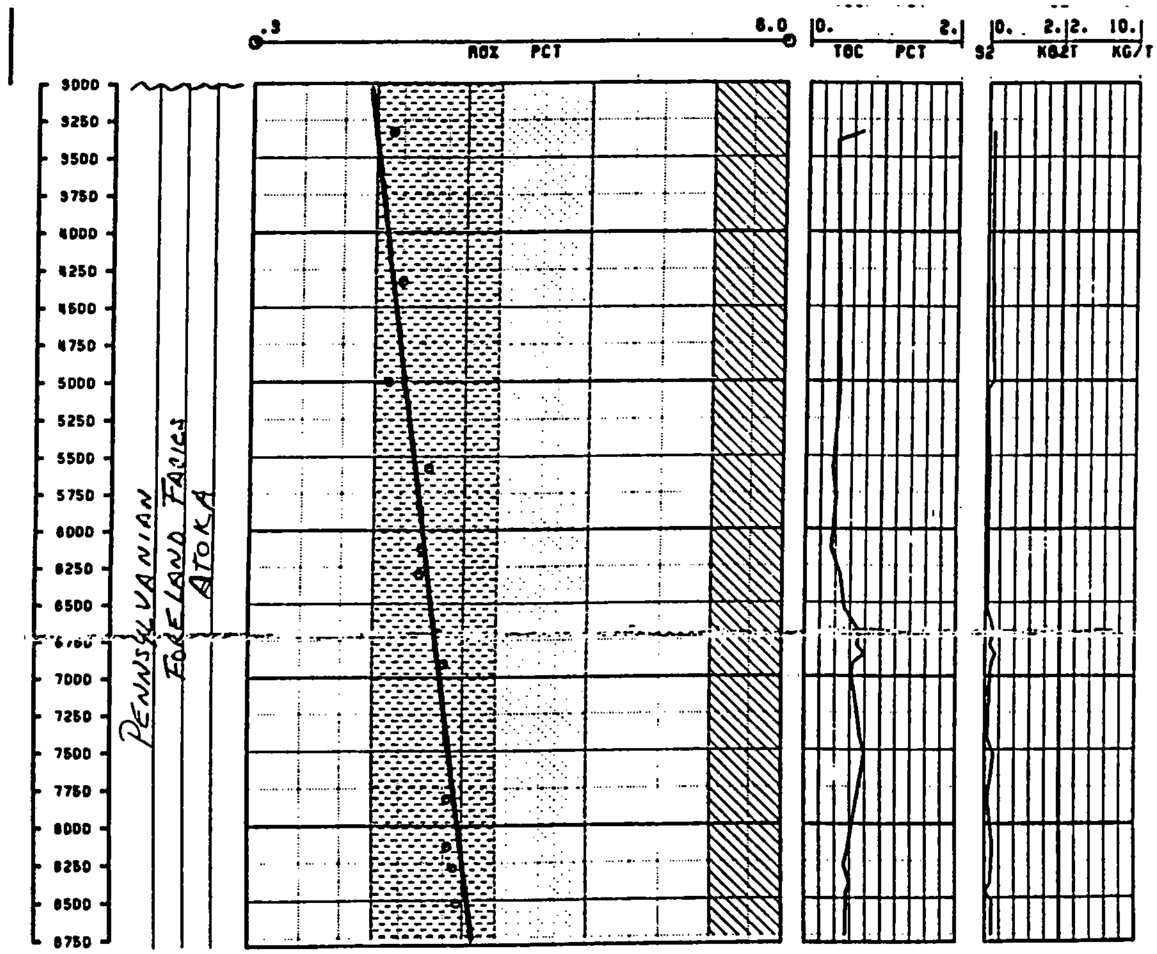
COLLIN COUNTY TEXAS
SOHIO PET.GEOCHEM GROUP



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ATOKA COUNTY, OKLAHOMA
SOHIO PETROLEUM GEOCHEMISTRY GROUP
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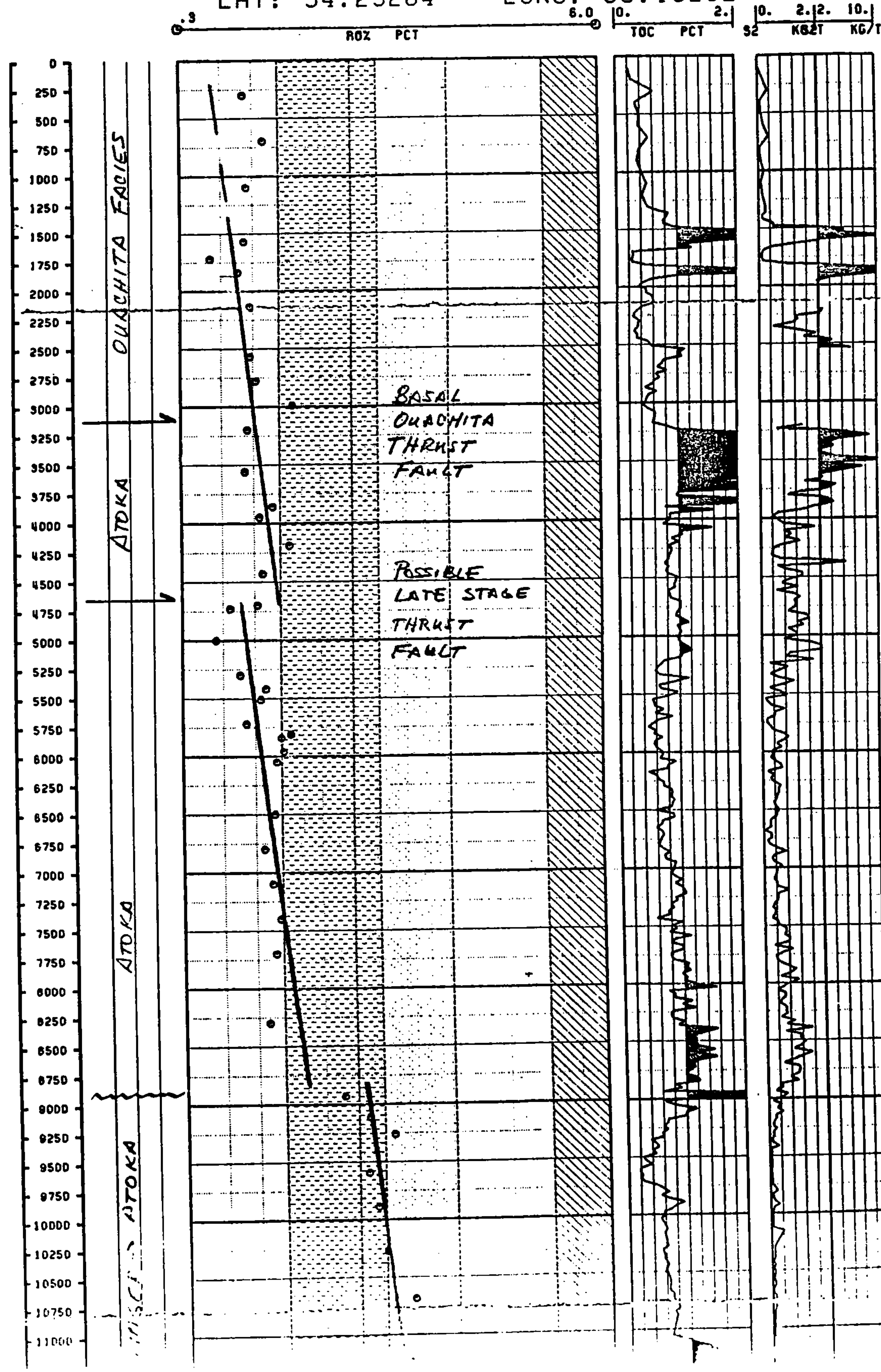

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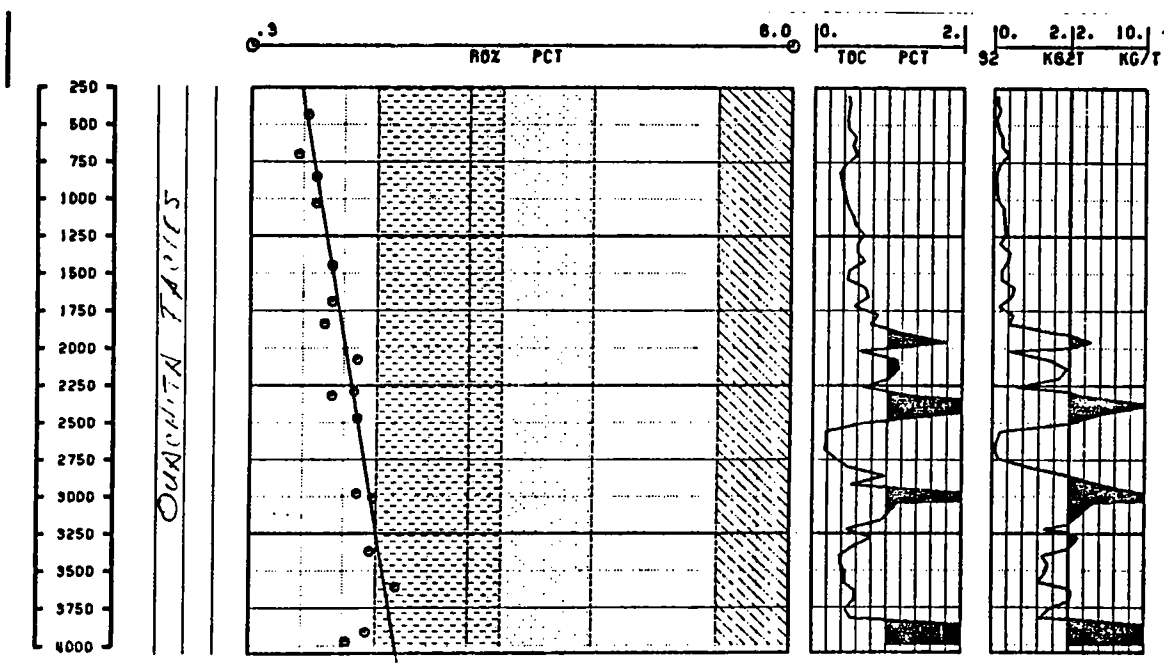

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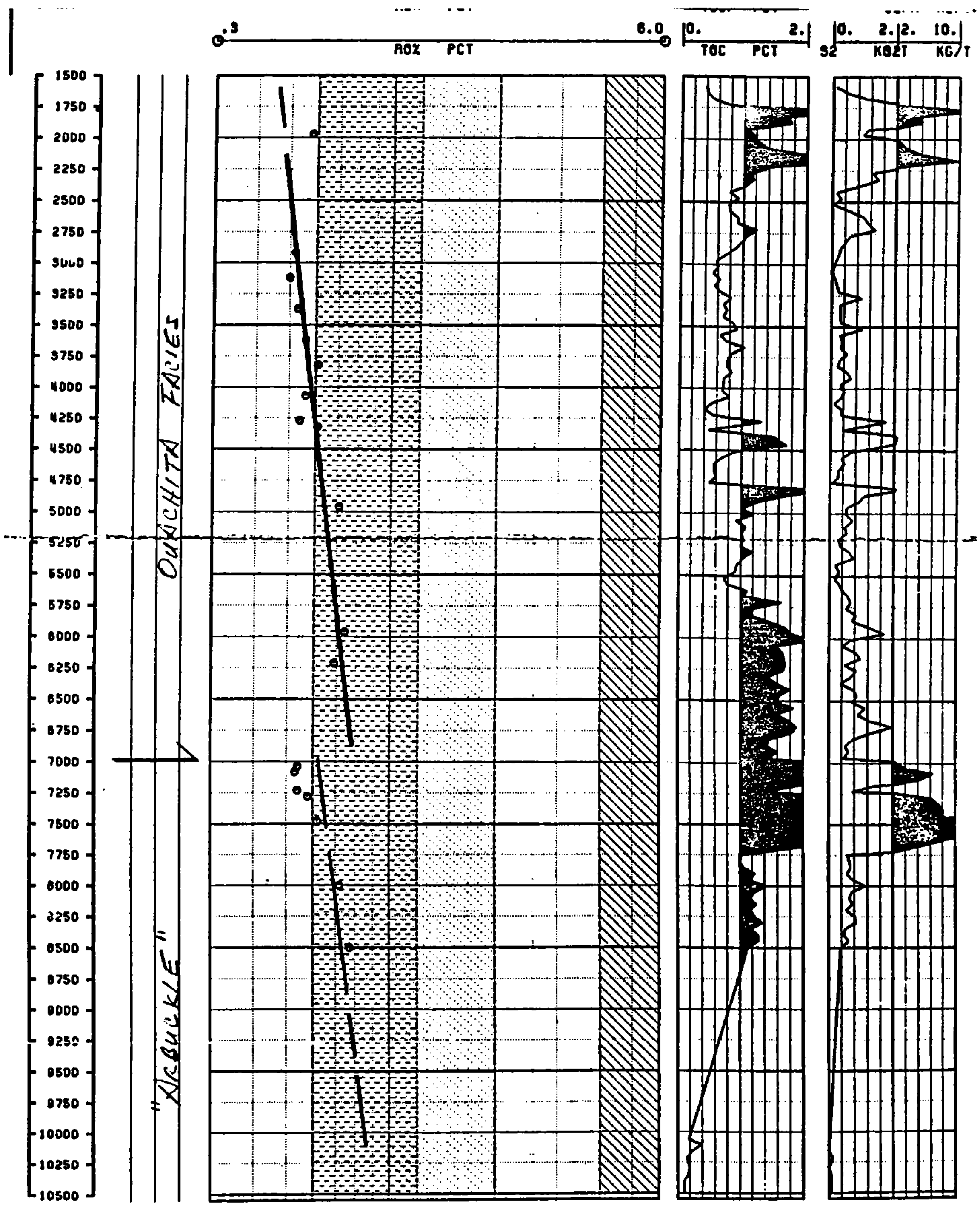

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SEC 20 T3S R17E
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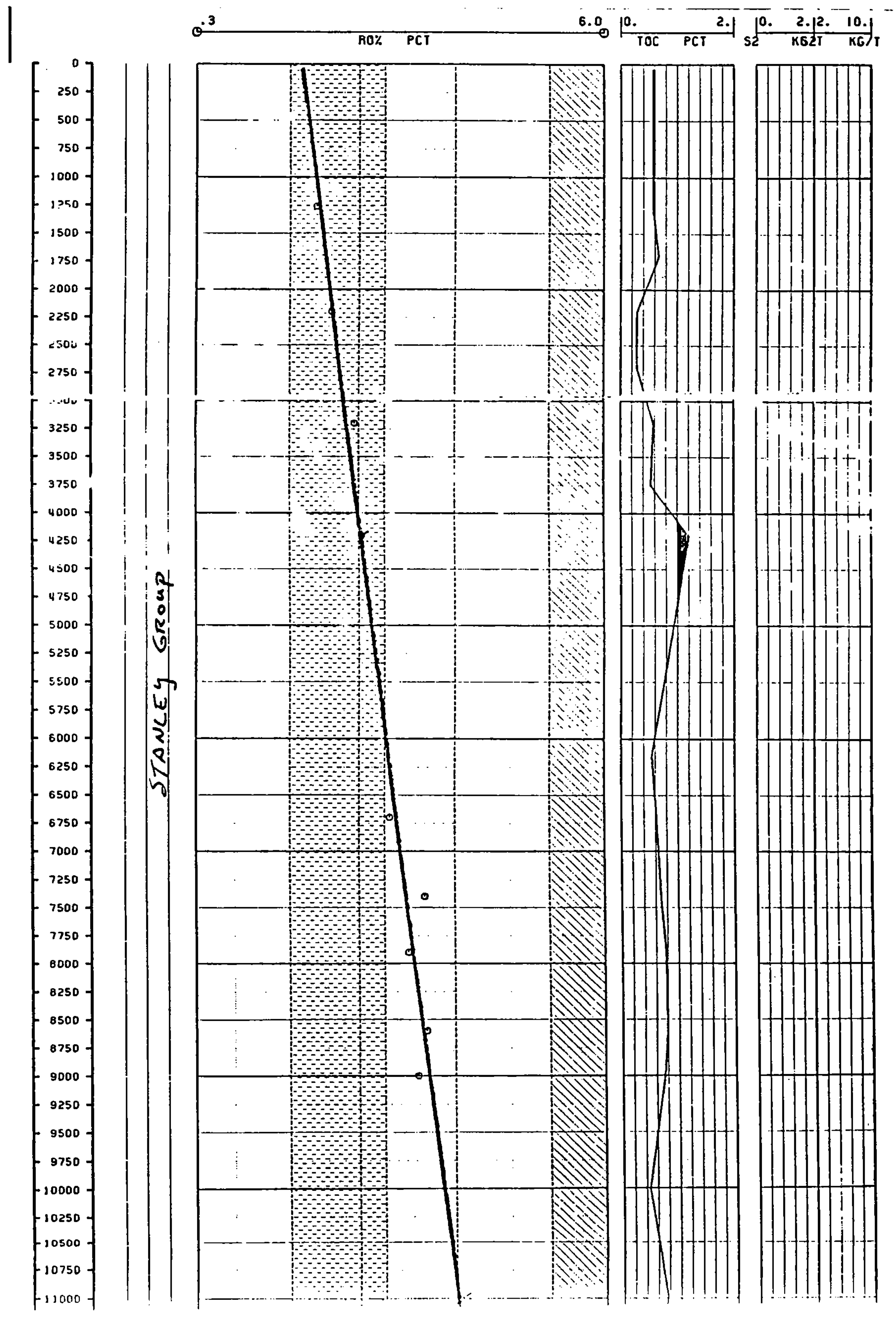
REPORT PGG/EB280



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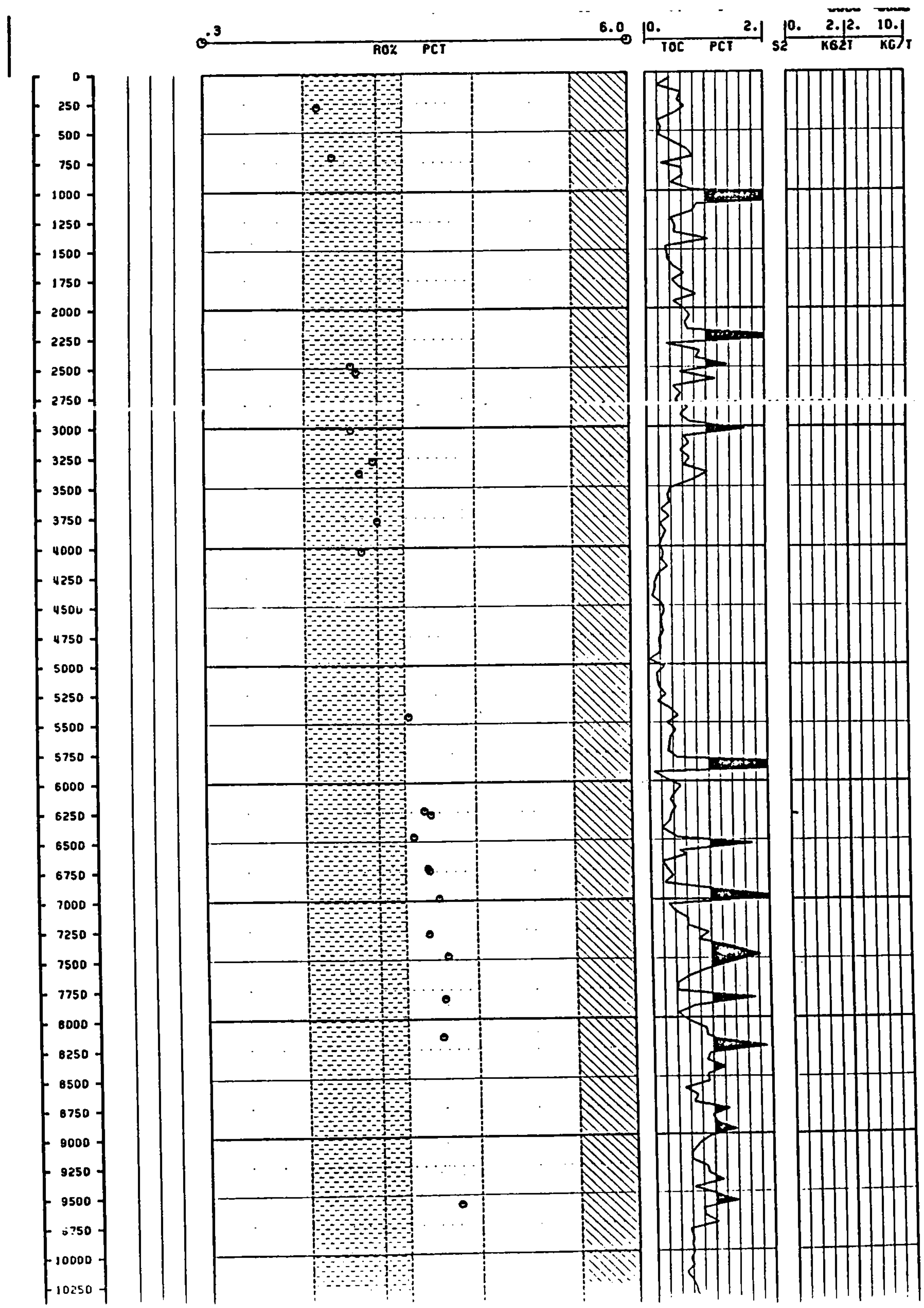
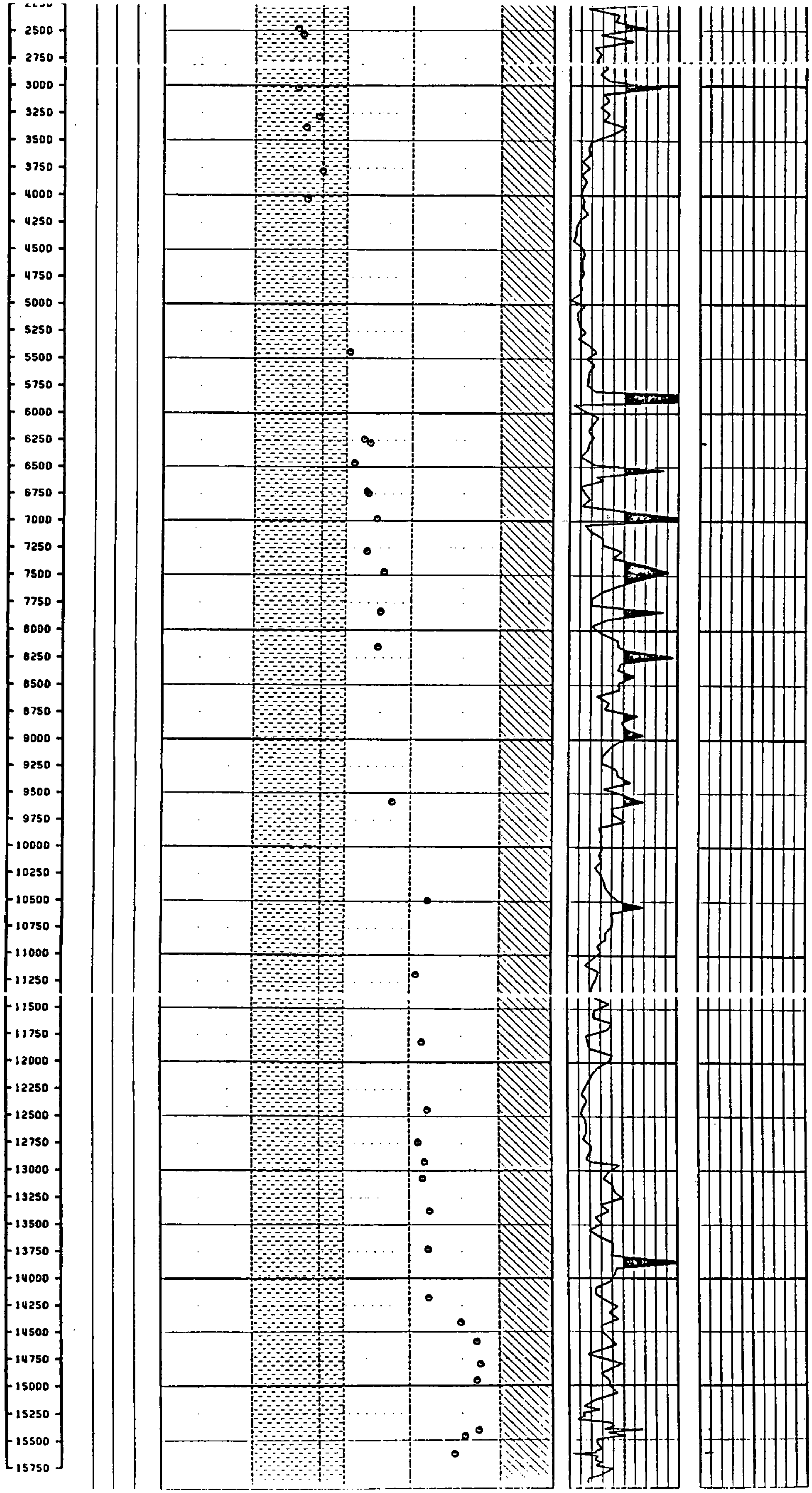
REPORT PGG/030485/GC/2-5

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13000
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14750
15000
15250
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15750

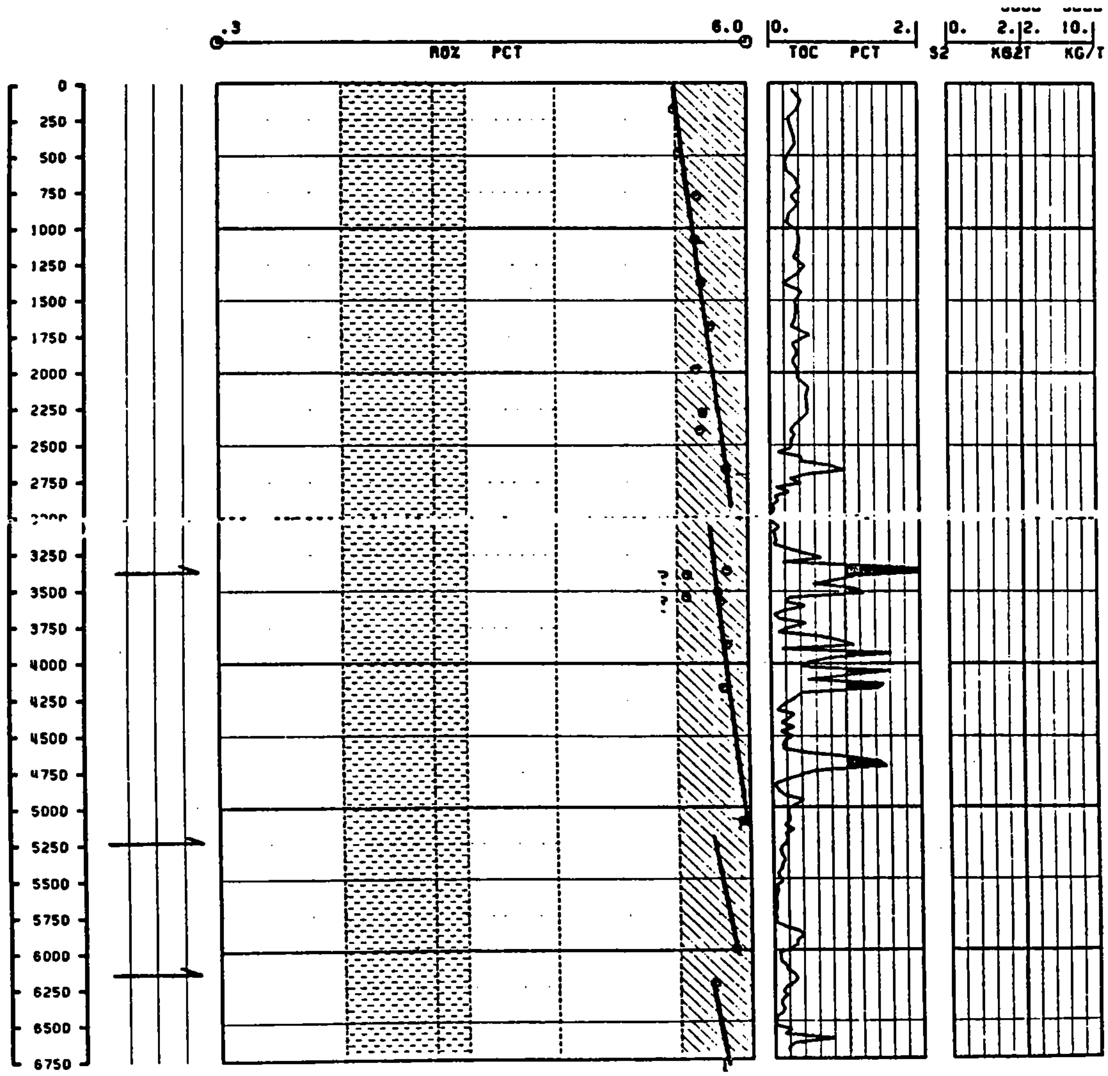
WEYERHAEUSER 1-7

MCCURTAIN CO.OKLA.

SEC7 T4S R23E

SOHIO PET. GEOCHEM GROUP

REPORT PGG/TM204



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PUSHMATAHA.CO OKLA.
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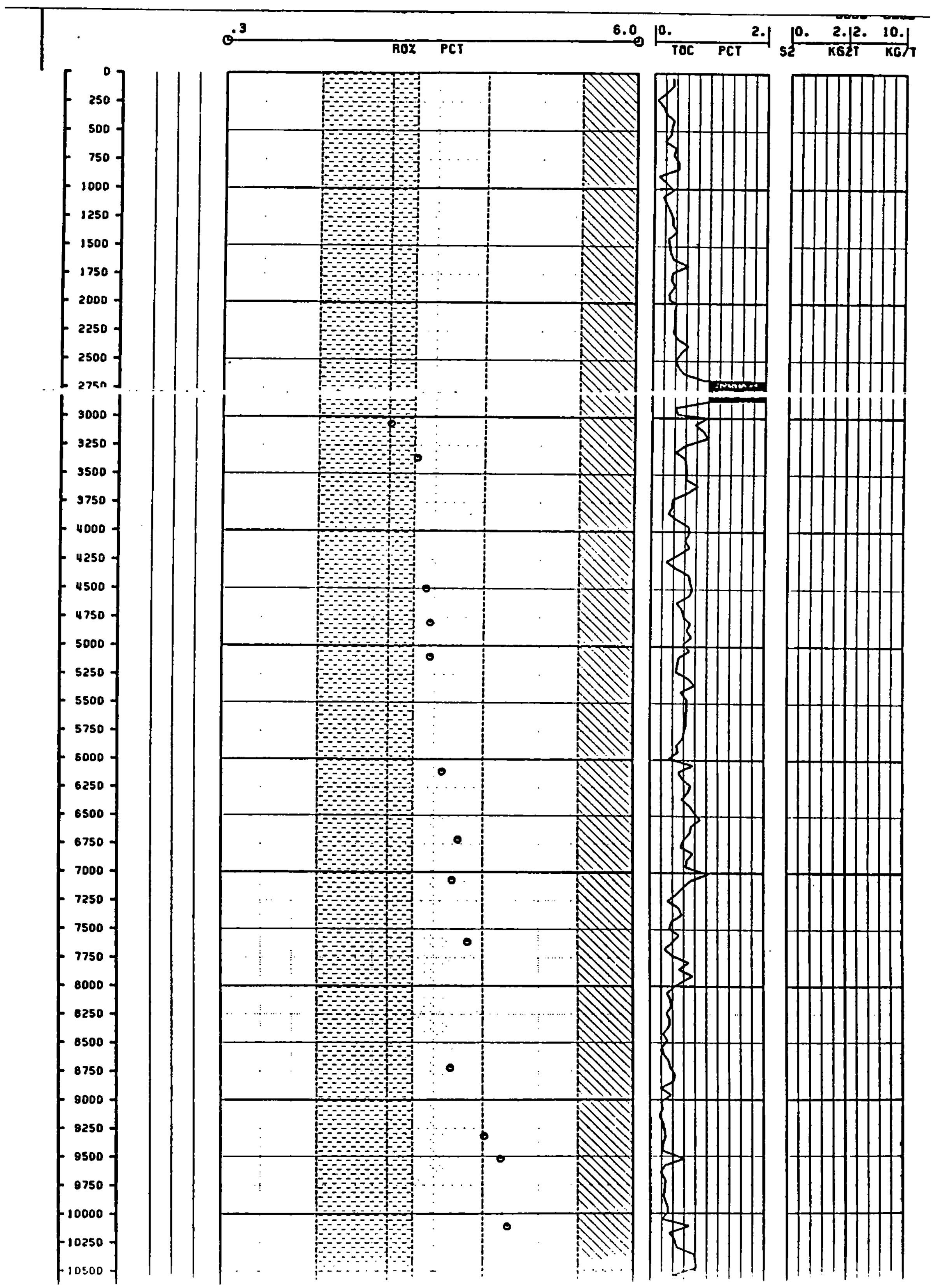

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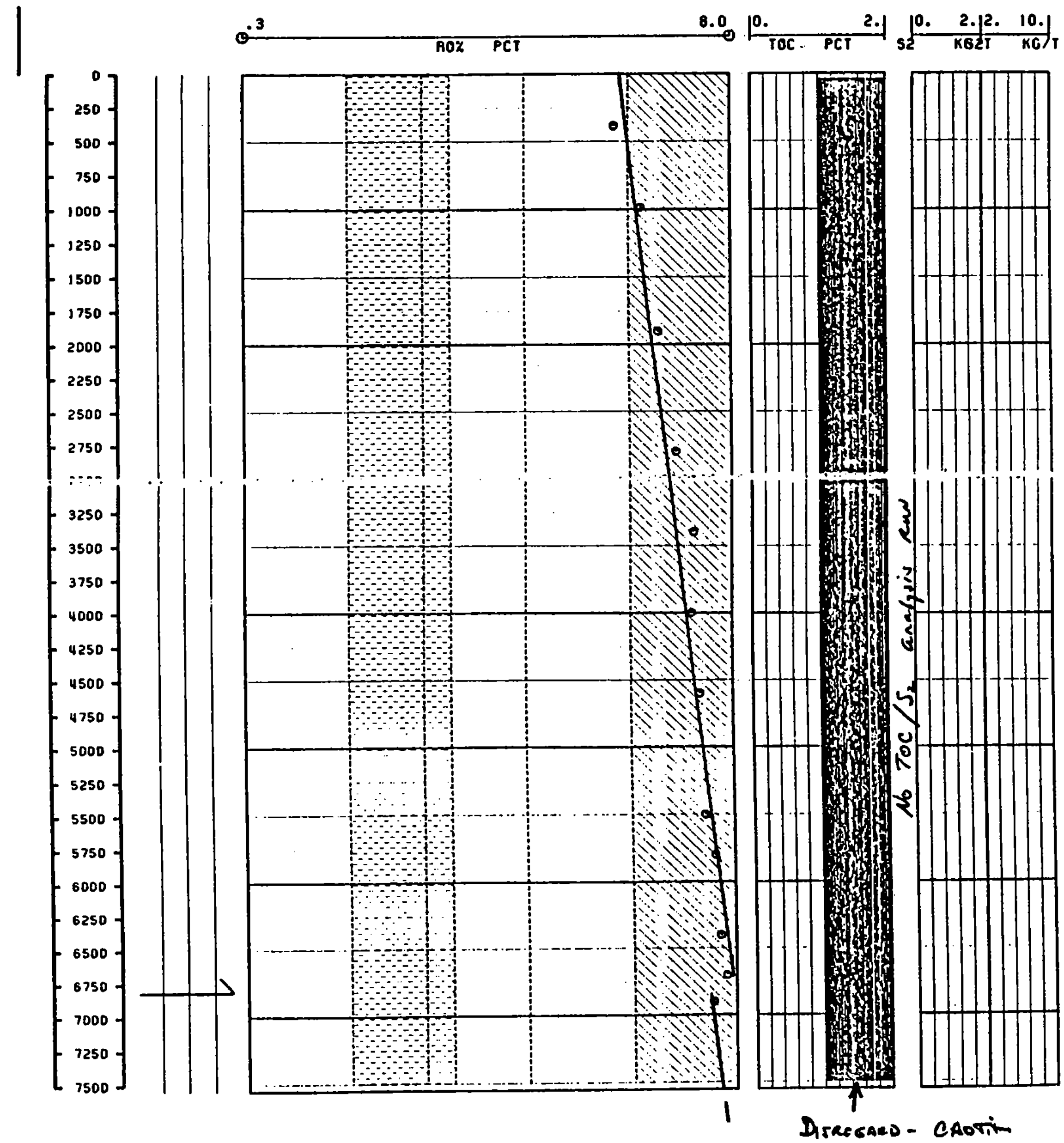

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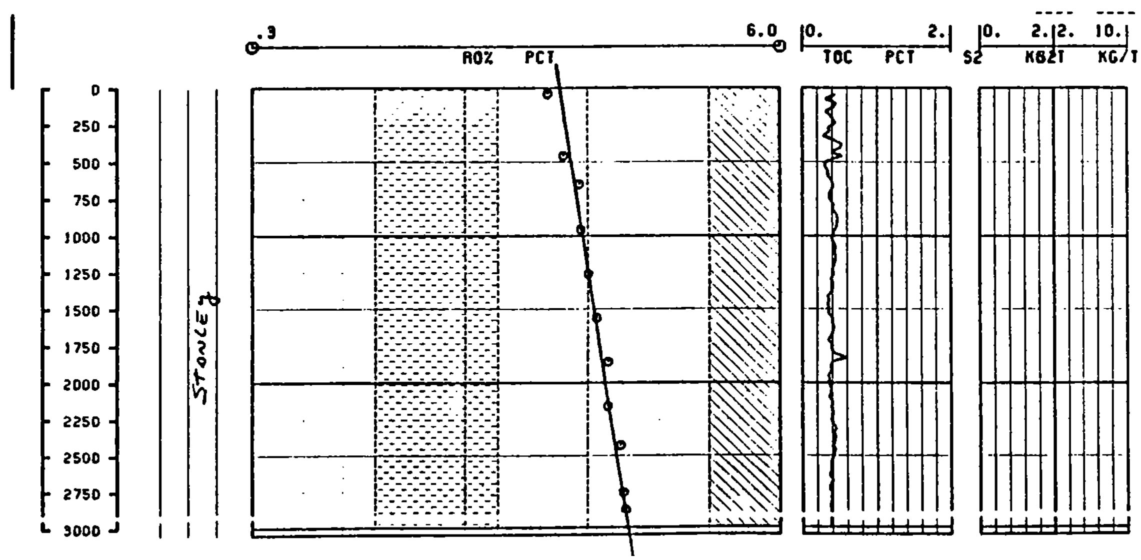
REPORT PGW/TM 50



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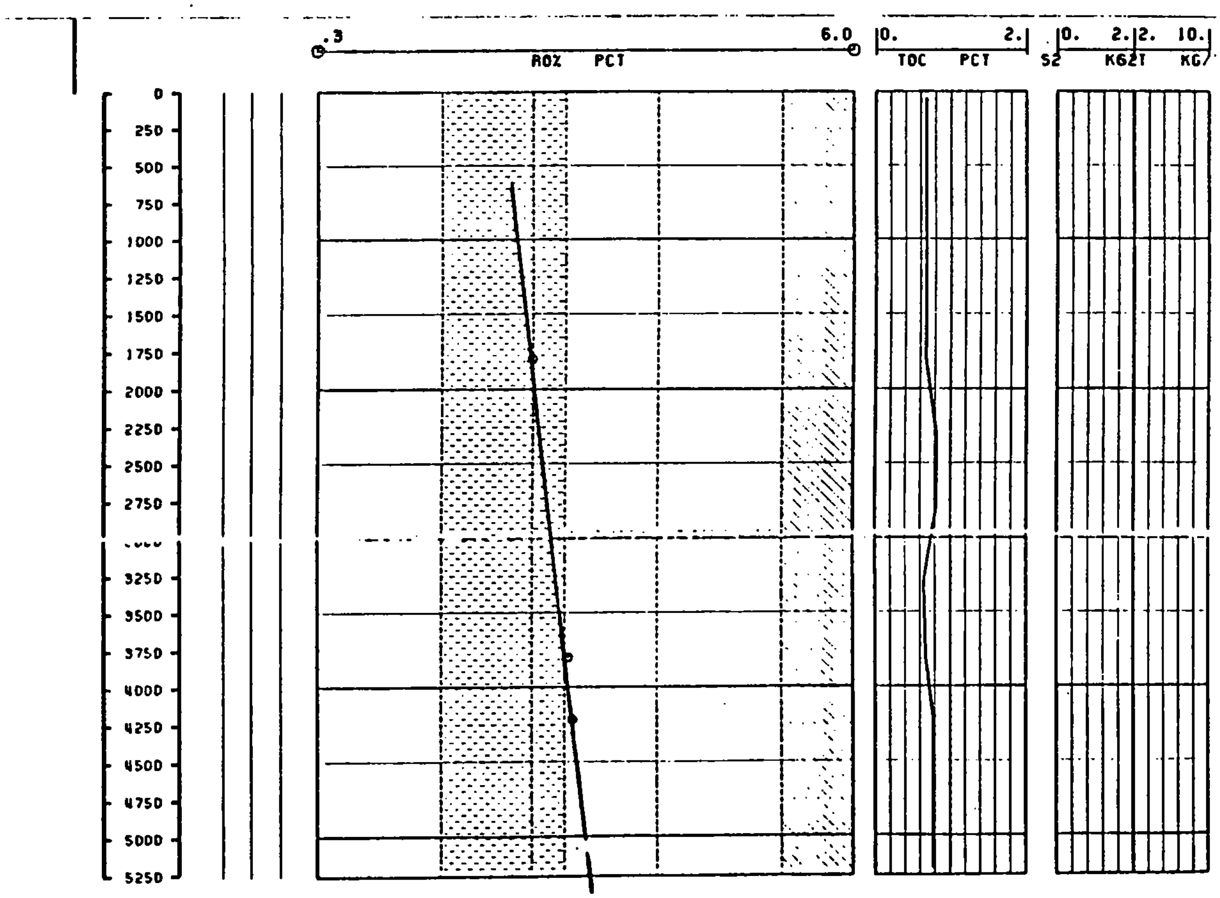

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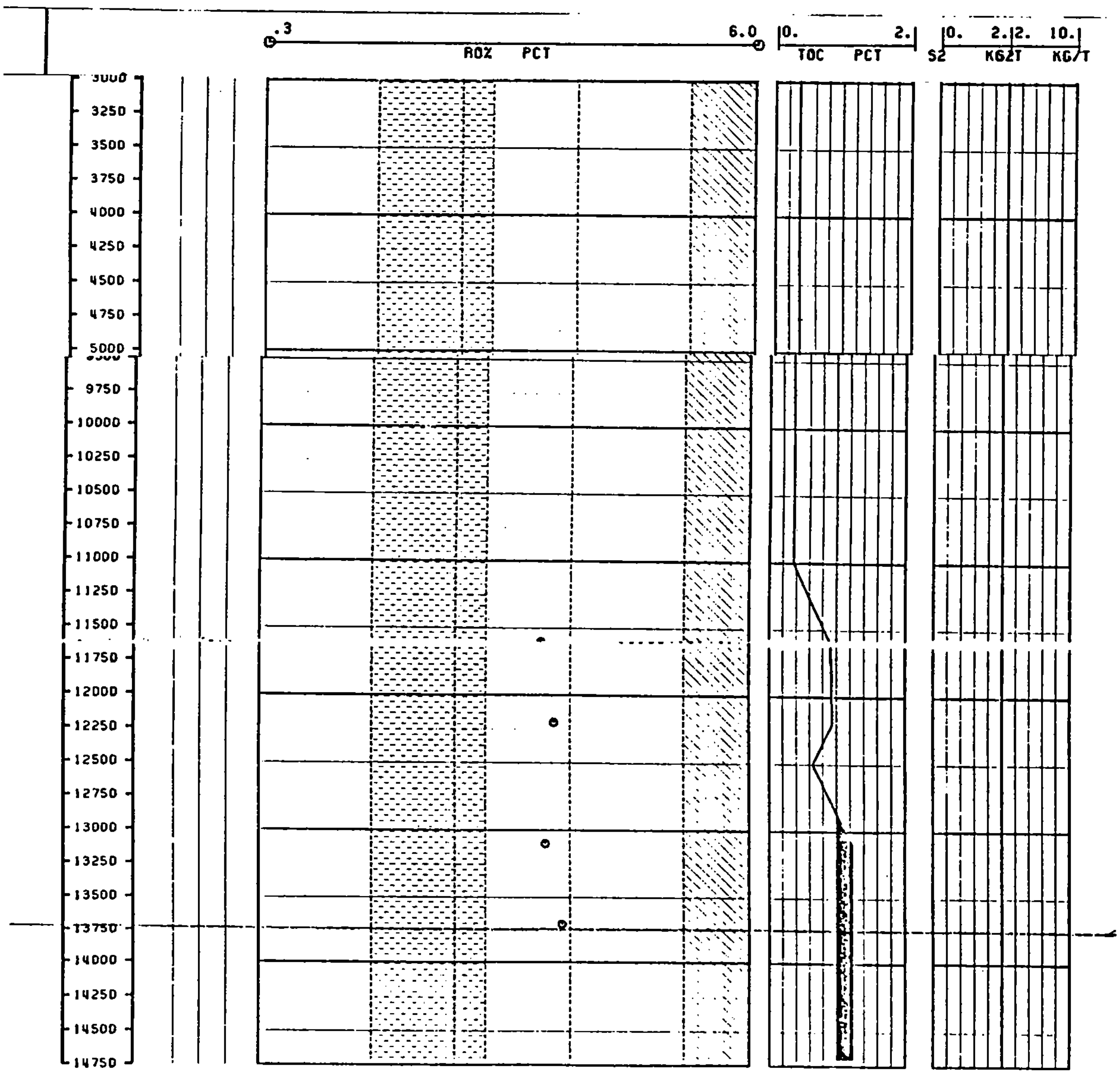

1-26 ARIVETT
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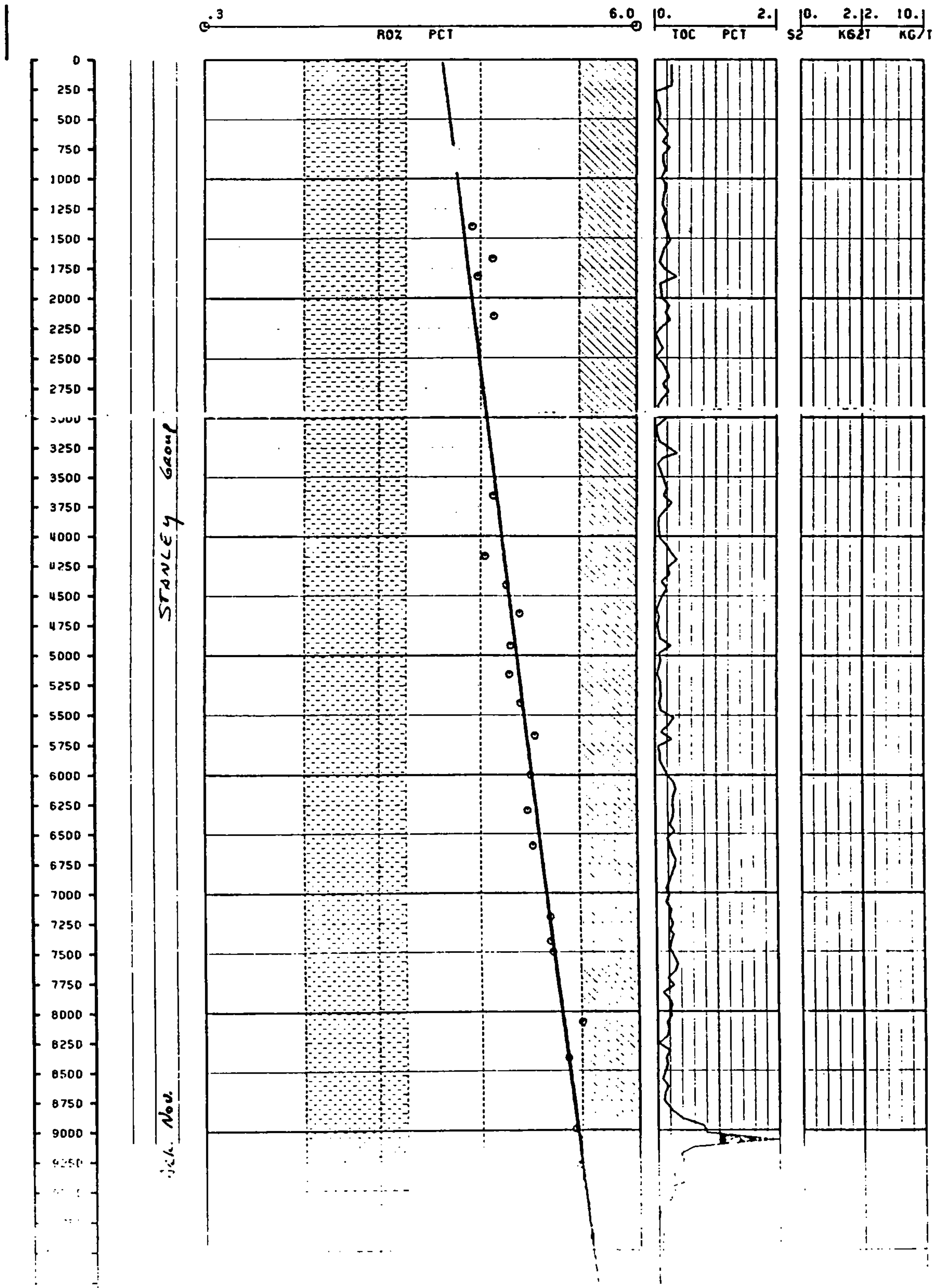
SOHIO PET. GEOCHEM GROUP
REPORT PGG/TM213



APPENDIX II

Geologic Burial History Curves and Resultant Maturity Modelling of Four Ouachita Sites.

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********************************************************************************
*                                                                              *
*                                                                              *
*         LL        OOOO    PPPPP      AA     TTTTTT    II     NN   NN         *
*         LL       OOOOOO   PPPPPP    AAAA    TTTTTT    II     NNN  NN         *
*         LL       OO  OO   PP  PP   AA  AA     TT      II     NNNNNN          *
*         LL       OO  OO   PPPPPP   AAAAAA     TT      II     NN NNN          *
*         LL       OO  OO   PPPPP    AAAAAA     TT      II     NN  NN          *
*         LLLLLL   OOOOOO   PP       AA  AA     TT      II     NN  NN          *
*         LLLLLL    OOOO    PP       AA  AA     TT      II     NN  NN          *
*                                                                              *
*                                                                              *
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L O P A T I N - 1 P G W

VERSION 1.1

10/01/83

WELL TITLE : CAMPBELL 1-24

DATE : 04/25/85

RUN ID : RUN1

COMMENTS :

WAPLES REGRESSION/60 DEG SURFACE
1.0 DEG PER 100'

LIST OF INPUT VARIABLES

USING FINE INTEGRATION

SURFACE TEMPERATURE : 60.0 DEG. F

DOUBLING TEMPERATURE : 18.0 DEG. F

LIST OF GEOTHERMAL GRADIENT INFORMATION

GEOTHERMAL GRADIENT : 1.00 TIME : CONSTANT THICKNESS : CONSTANT

LIST OF BURIAL HISTORY INFORMATION

AGE :	468.0	THICKNESS :	0.0	FORMATION TOPS :	
AGE :	408.0	THICKNESS :	1000.0	FORMATION TOPS :	LPAL
AGE :	395.0	THICKNESS :	300.0	FORMATION TOPS :	MOMT
AGE :	350.0	THICKNESS :	300.0	FORMATION TOPS :	ARKN
AGE :	320.0	THICKNESS :	4250.0	FORMATION TOPS :	STAN
AGE :	310.0	THICKNESS :	1600.0	FORMATION TOPS :	JKFK
AGE :	300.0	THICKNESS :	2000.0	FORMATION TOPS :	ATOK
AGE :	120.0	THICKNESS :	-4550.0	FORMATION TOPS :	
AGE :	100.0	THICKNESS :	1200.0	FORMATION TOPS :	
AGE :	0.0	THICKNESS :	-2400.0	FORMATION TOPS :	

THE RO/TTI MATURITY LIMITS

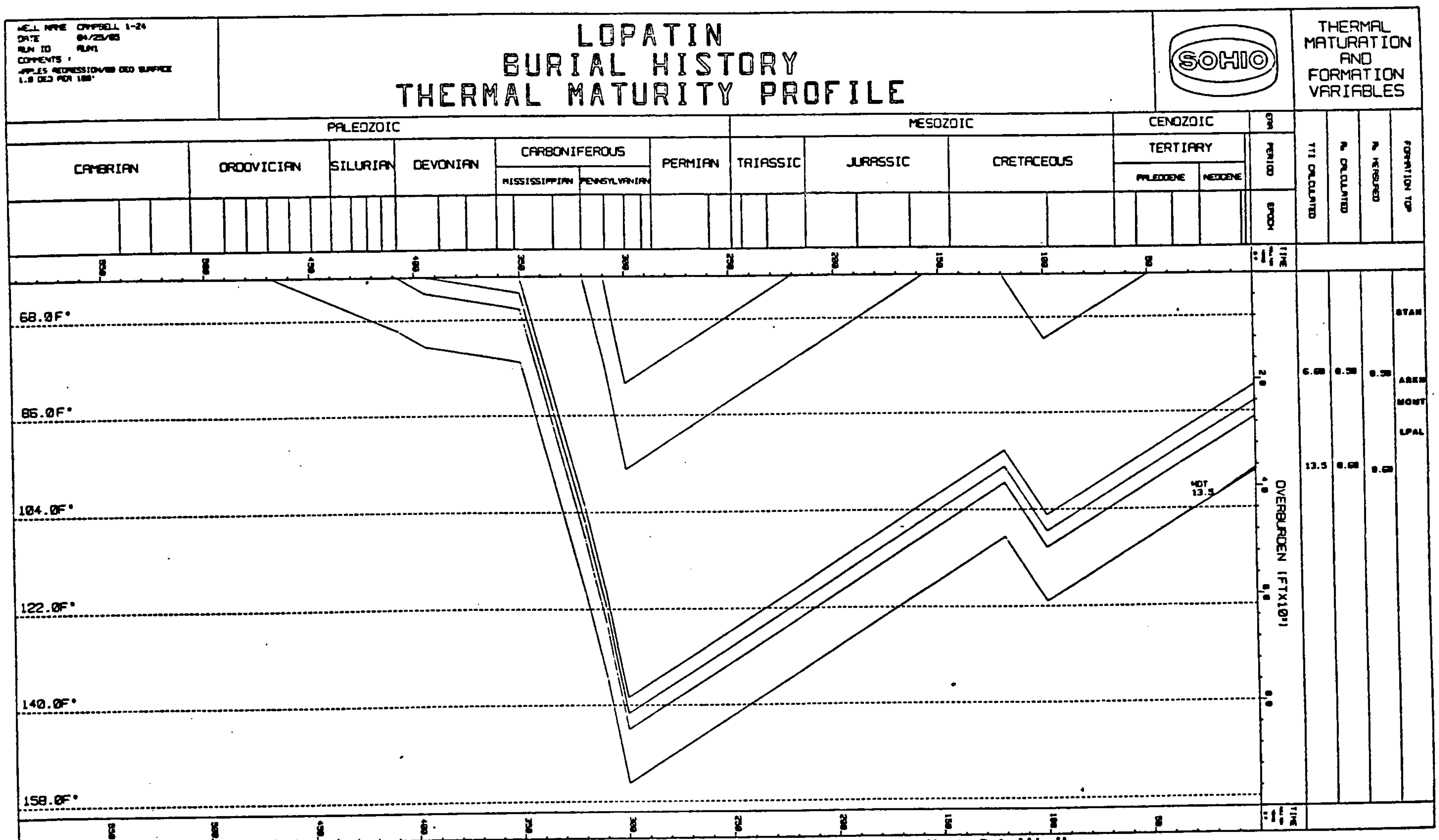
OIL GENERATION RO : .60 TTI : 13.51
GAS GENERATION RO : 1.00 TTI : 100.49

LIST OF OBSERVED RO VALUES

RO : .50 DEPTH : 2000.0

RO : .60 DEPTH : 3800.0

THE REGRESSION METHOD : WAPLES
SLOPE : 3.92805 INTERCEPT : 2.00211



Burial History Plot for the Campbell 1-24 Well.

```
*****************************************************************************
*                                                                           *
*                                                                           *
*          LL        0000   PPPPP      AA     TTTTTT     II      NN  NN     *
*          LL       000000  PPPPPP    AAAA    TTTTTT     II      NNN NN     *
*          LL       00  00  PP  PP   AA  AA     TT       II      NNNNNN     *
*          LL       00  00  PPPPPP   AAAAAA     TT       II      NN NNN     *
*          LL       00  00  PPPPP    AAAAAA     TT       II      NN  NN     *
*          LLLLLL   000000  PP       AA  AA     TT       II      NN  NN     *
*          LLLLLL    0000   PP       AA  AA     TT       II      NN  NN     *
*                                                                           *
*                                                                           *
*****************************************************************************
```

L O P A T I N - 1 P G W

VERSION 1.1

10/01/83

WELL TITLE : TROTTER-DEES 1-29

DATE : 04/25/85

RUN ID : RUN1

COMMENTS :

WAPLES REGRESSION/60 DEG SURFACE
1.0 DEG PER 100'

LIST OF INPUT VARIABLES

USING FINE INTEGRATION

SURFACE TEMPERATURE : 60.0 DEG. F

DOUBLING TEMPERATURE : 18.0 DEG. F

LIST OF GEOTHERMAL GRADIENT INFORMATION

GEOTHERMAL GRADIENT : 1.00 TIME : CONSTANT THICKNESS : CONSTANT

LIST OF BURIAL HISTORY INFORMATION

AGE :	395.0	THICKNESS :	0.0	FORMATION TOPS :	
AGE :	350.0	THICKNESS :	300.0	FORMATION TOPS :	ARKN
AGE :	320.0	THICKNESS :	14200.0	FORMATION TOPS :	STAN
AGE :	310.0	THICKNESS :	7000.0	FORMATION TOPS :	JKFK
AGE :	300.0	THICKNESS :	8000.0	FORMATION TOPS :	ATOK
AGE :	230.0	THICKNESS :	-5000.0	FORMATION TOPS :	
AGE :	200.0	THICKNESS :	-5000.0	FORMATION TOPS :	

AGE : 0.0 THICKNESS : -4000.0 FORMATION TOPS :

THE RO/TTI MATURITY LIMITS

OIL GENERATION RO : .60 TTI : 13.51
GAS GENERATION RO : 1.00 TTI : 100.49

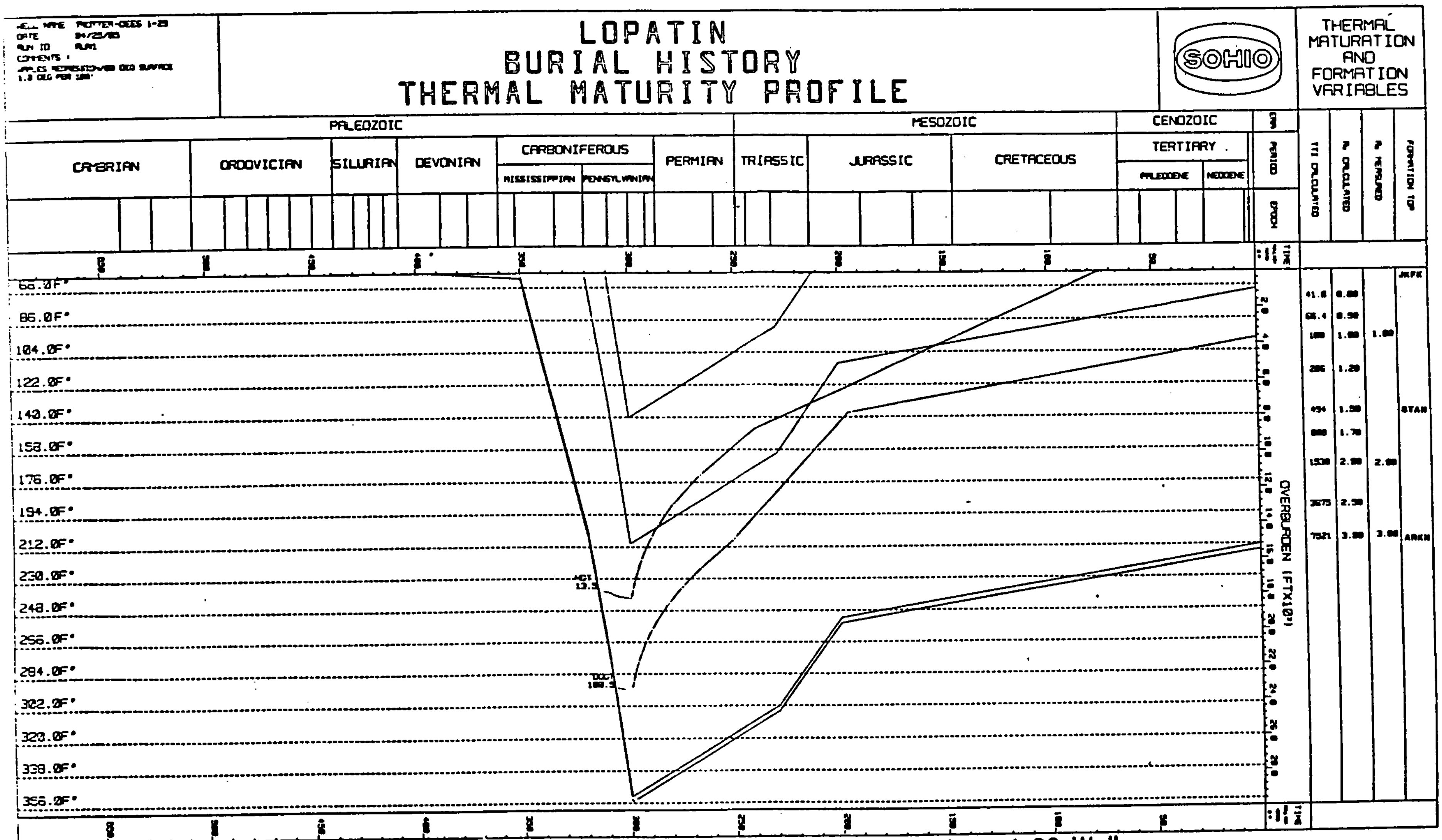
LIST OF OBSERVED RO VALUES

RO : 1.00 DEPTH : 3800.0

RO : 2.00 DEPTH : 11000.0

RO : 3.00 DEPTH : 15000.0

THE REGRESSION METHOD : WAPLES
SLOPE : 3.92805 INTERCEPT : 2.00211



Burial History Plot for the Trotter-dees 1-29 Well.

```
**********************************************************************************
*                                                                                *
*                                                                                *
*          LL        0000    PPPPP      AA     TTTTTT    II     NN  NN           *
*          LL       000000   PPPPPP    AAAA    TTTTTT    II     NNN NN           *
*          LL       00  00   PP  PP   AA  AA     TT      II     NNNNNN           *
*          LL       00  00   PPPPPP   AAAAAA     TT      II     NN NNN           *
*          LL       00  00   PPPPP    AAAAAA     TT      II     NN  NN           *
*          LLLLLL   000000   PP       AA  AA     TT      II     NN  NN           *
*          LLLLLL    0000    PP       AA  AA     TT      II     NN  NN           *
*                                                                                *
*                                                                                *
**********************************************************************************
```

L O P A T I N - 1 P G M

VERSION 1.1

10/01/83

WELL TITLE : GLOVER BEND NORTH

DATE : RUN1

RUN ID : RUN1

COMMENTS :

WAPLES REGRESSION/60 DEG SURFACE
1.0 DEG PER 100'

WELL TITLE : GLOVER BEND NORTH

RUN ID : RUN1

COMMENTS :

WAPLES REGRESSION/60 DEG SURFACE
.0 DEG PER 100'

DATE : 04/25/85

LIST OF INPUT VARIABLES

USING FINE INTEGRATION

SURFACE TEMPERATURE : 60.0 DEG. F

DOUBLING TEMPERATURE : 18.0 DEG. F

LIST OF GEOTHERMAL GRADIENT INFORMATION

GEOTHERMAL GRADIENT : 1.00 TIME : CONSTANT THICKNESS : CONSTANT

LIST OF BURIAL HISTORY INFORMATION

AGE :	468.0	THICKNESS :	0.0	FORMATION TOPS :	BGFK
AGE :	438.0	THICKNESS :	4000.0	FORMATION TOPS :	MONT
AGE :	395.0	THICKNESS :	200.0	FORMATION TOPS :	ARKN
AGE :	350.0	THICKNESS :	400.0	FORMATION TOPS :	OUAC
AGE :	300.0	THICKNESS :	30000.0	FORMATION TOPS :	
AGE :	230.0	THICKNESS :	-10000.0	FORMATION TOPS :	
AGE :	200.0	THICKNESS :	-10000.0	FORMATION TOPS :	
AGE :	0.0	THICKNESS :	-9000.0	FORMATION TOPS :	

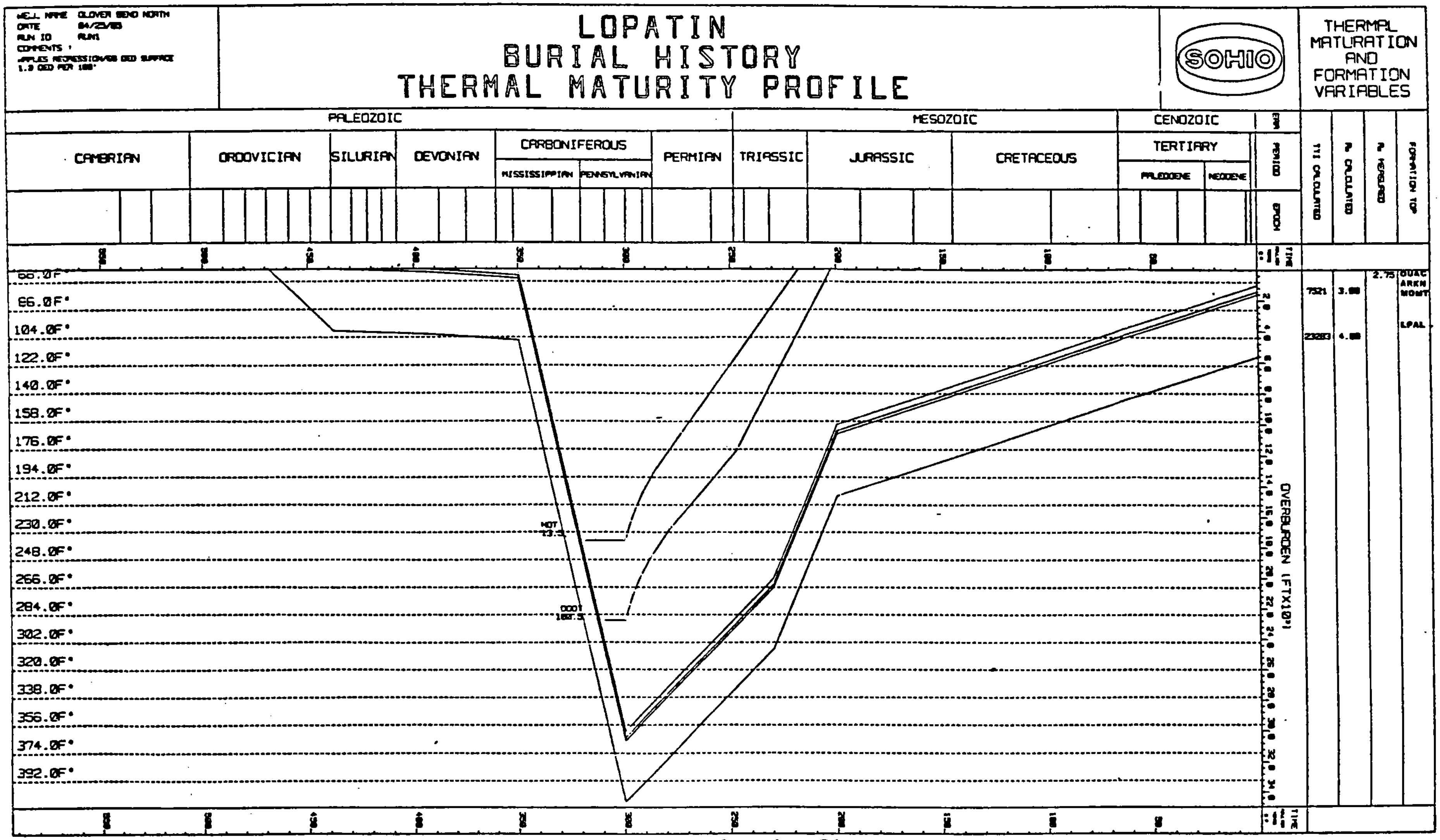
THE RO/TTI MATURITY LIMITS

OIL GENERATION RO : .60 TTI : 13.51
GAS GENERATION RO : 1.00 TTI : 100.49

LIST OF OBSERVED RO VALUES

RO : 2.75 DEPTH : 500.0

THE REGRESSION METHOD : WAPLES
SLOPE : 3.92805 INTERCEPT : 2.00211



Burial History Plot for the Glover Bend Prospect.

```
*******************************************************************************
*                                                                             *
*         LL       OOOO   PPPPP    AA    TTTTTT   II   NN  NN                 *
*         LL      OOOOOO  PPPPPP  AAAA   TTTTTT   II   NNN NN                 *
*         LL      OO  OO  PP  PP AA  AA    TT     II   NNNNNN                 *
*         LL      OO  OO  PPPPPP AAAAAA    TT     II   NN NNN                 *
*         LL      OO  OO  PPPPP  AAAAAA    TT     II   NN  NN                 *
*         LLLLLL  OOOOOO  PP     AA  AA    TT     II   NN  NN                 *
*         LLLLLL   OOOO   PP     AA  AA    TT     II   NN  NN                 *
*                                                                             *
*******************************************************************************
```

L O P A T I N - 1 P G M

VERSION 1.1

10/01/83

WELL TITLE : BROKEN BOW UPLIFT

DATE : 04/29/85

RUN ID : RUN1

COMMENTS :

WAPLES REGRESSION/60 DEG SURFACE
1.0 DEG PER 100'

LIST OF INPUT VARIABLES

USING FINE INTEGRATION

SURFACE TEMPERATURE : 60.0 DEG. F

DOUBLING TEMPERATURE : 18.0 DEG. F

LIST OF GEOTHERMAL GRADIENT INFORMATION

GEOTHERMAL GRADIENT : 1.00 TIME : CONSTANT THICKNESS : CONSTANT

LIST OF BURIAL HISTORY INFORMATION

AGE :	395.0	THICKNESS :	0.0	FORMATION TOPS :	
AGE :	350.0	THICKNESS :	400.0	FORMATION TOPS :	ARKN
AGE :	300.0	THICKNESS :	35000.0	FORMATION TOPS :	OUAC
AGE :	230.0	THICKNESS :	-12000.0	FORMATION TOPS :	
AGE :	200.0	THICKNESS :	-10000.0	FORMATION TOPS :	
AGE :	0.0	THICKNESS :	-11400.0	FORMATION TOPS :	

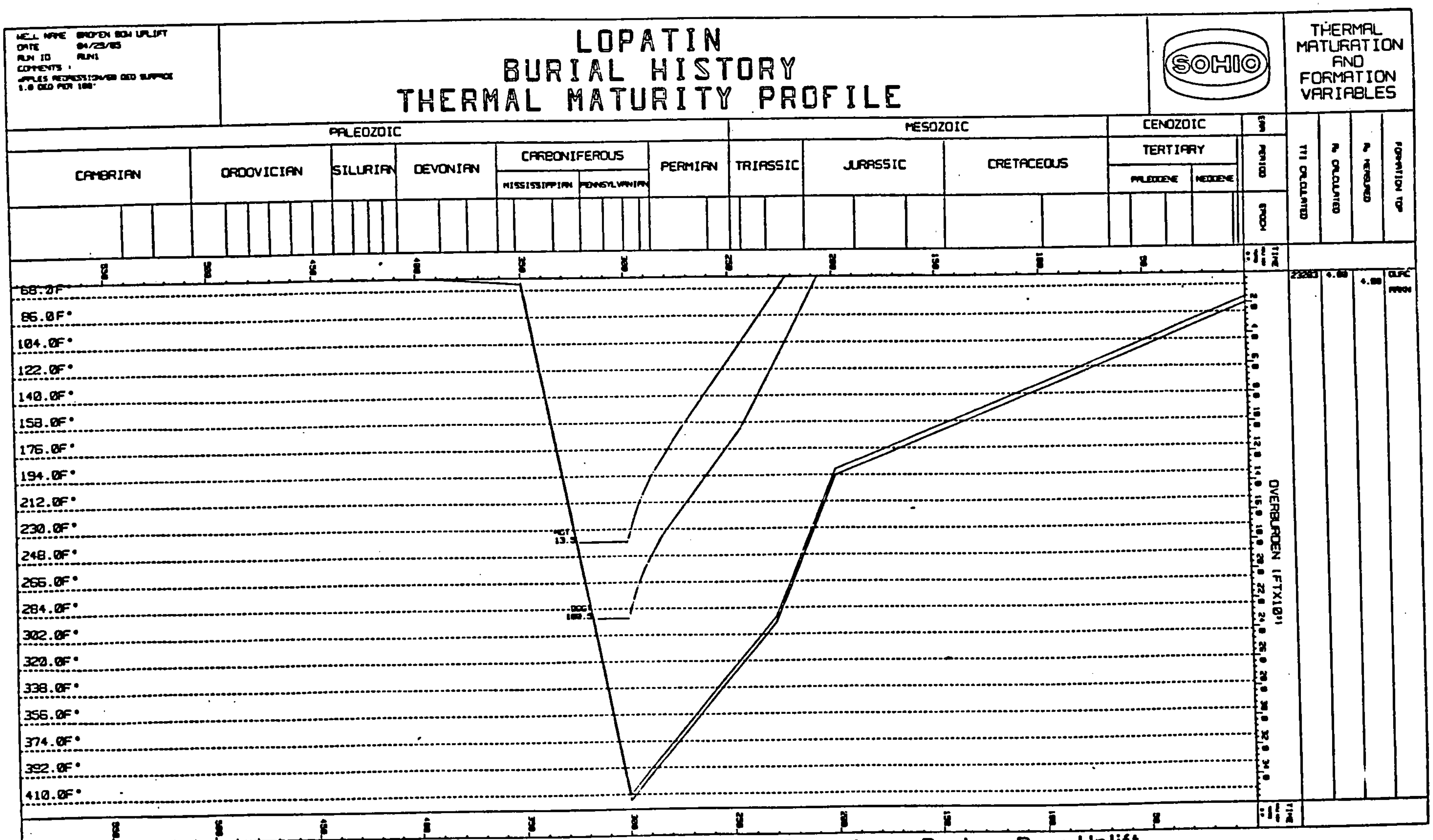
THE RO/TTI MATURITY LIMITS

OIL GENERATION RO :	.60	TTI :	13.51
GAS GENERATION RO :	1.00	TTI :	100.49

LIST OF OBSERVED RO VALUES

RO : 4.00 DEPTH : 1000.0

THE REGRESSION METHOD : WAPLES
SLOPE : 3.92805 INTERCEPT : 2.00211



Burial History Plot for the Core Area, Broken Bow Uplift.